



Research article

Hydrogeochemical characterization and assessment of factors controlling groundwater salinity in the Chamwino granitic complex, central Tanzania

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ABSTRACT

Chamwino district, central Tanzania is a semi-arid granitic complex province, where groundwater is the major source of water for domestic and other uses. However, groundwater in the area is affected by salinity, thus, lowering the availability of potable water for various uses, decrease in crop production, taste less, wastage of soap, and abnormal pain. Due to this, this study sought to characterize groundwater using hydrogeochemical facies and signatures in order to identify the factors influencing the distribution of salt water in the Chamwino Granitic Complex. A total of 141 groundwater samples were collected from wells spatially distributed within the study area from January 2023 to April 2023, (a season of relatively low rainfall). All samples were subjected to in situ analyses of physicochemical parameters pH, temperature (T), total dissolved solids (TDS), electrical conductivity (EC), and salinity using a multi-parameter water analyzer and analyses of major ions (Ca^{2+} , Mg^{2+} , K^+ , Na^+ , Cl^- , SO_4^{2-} , HCO_3^- , and NO_3^-). The study revealed that the dominant cations in the groundwater are $\text{Na}^+ > \text{Ca}^{2+} > \text{Mg}^{2+}$, and the anions are $\text{Cl}^- > \text{HCO}_3^- > \text{SO}_4^{2-}$. Five geological formations (granodiorite, tonalitic orthogenesis, migmatite, tonalite, and alluvium) were identified, and each is characterized by its unique groundwater facie. In the areas that are dominated with granodiorite, the major hydrogeochemical facies were Ca-HCO₃, Na-Cl, Ca-Na-HCO₃, Ca-Mg-Cl, and Ca-Cl water types; tonalitic orthogenesis was dominated by Ca-HCO₃, Na-Cl, Ca-Mg-Cl, and Ca-Cl water types; migmatite was dominated by Ca-HCO₃, Na-Cl, Ca-Mg-Cl, and Ca-Cl water types; tonalite was dominated by Na-Cl, Ca-Mg-Cl, and Ca-Cl water types; and alluvium was dominated by Na-Cl and Ca-Mg-Cl and Ca-Cl water types. The common hydrogeochemical facies in all five geological units are Na-Cl, Ca-Mg-Cl, and Ca-Cl water types. It is revealed that the groundwater in the study area is alkaline in nature and slightly saline with salinity level between 0.2 mg/L (fresh water) and 2.8 mg/L (brackish water) with mean 1.07 mg/L (of 141 samples). The factors controlling groundwater salinity distribution are mainly rock-water interaction and ion exchange reactions. Groundwater salinity in the study area is largely attributed to the abundance of Na^+ , Ca^{2+} , Cl^- and SO_4^{2-} . Abundance of Na^+ and Ca^{2+} is the results of both, weathering of feldspar minerals particularly plagioclase (Na-Ca feldspars) which are the major mineral in granites, and evaporation crystallization cycles of evaporates in semi-arid areas such as Chamwino. Also, such evaporation crystallization cycles

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account for the abundance of Cl^- and SO_4^{2-} especially in areas dominated by alluvium. However, anthropogenic activities as evidenced by elevated nitrate up to 212.6 mg/L in congested areas are also likely to contribute in area) to the elevated Cl^- and SO_4^{2-} . In other geological units such as tonalitic orthogneiss, migmatite and granodiorite, there was an ostensible mixing of saline water with fresh water from local recharge as indicated by the abundance of HCO_3^- ions. Nonetheless, the hydrogeochemical characterization of groundwater in the Chamwino granitic complex suggests that there is little possibility for groundwater to evolve to a carbonate water type (fresh water) because the groundwater salinity is mainly geogenic, unless artificial recharge through rainwater harvesting is applied.

1. Introduction

Globally, the provision of clean and safe water to some billions of people to fulfill their daily domestic demands depends on groundwater [1,2]. The dependence of this resource justifies that groundwater is the core water source for domestic uses and human development [3–8].

Salinity in groundwater worldwide is among the most pressing problems in regions that are water-stressed particularly in semi-arid zones where groundwater is the principal source of water [9–14].

A review of 15 countries in sub-Saharan Africa revealed that salinity is largely caused by natural factors including rock dissolution, saltwater intrusion, climate, hydrological change and human factors like anthropogenic activities [15–19].

In Tanzania, salinity varies from one place to another in some of regions [20,21]. For instance, in the coastal areas of Tanga, Lindi, Mtwara, and Dar es Salaam have a high concentration of salinity in groundwater influenced by seawater intrusion [5,21]. On the other hand, salinity in groundwater is problematic in the central regions of the country, like Dodoma, Singida, and Shinyanga, where there is a high evaporation rate, low precipitation, and a hot, dry climate, causing much water to evaporate and salts to be left behind [22,23]. It is also a result of groundwater and surface water mixing within an aquifer [24].

For the Dodoma region, salinity varies with total dissolved solids between 1000 and 3000 mg/L [15,25,26]. In the Makutupora and Hombolo areas of Dodoma municipality, salinity is influenced by irrigation water, rock dissolution, and other climatic factors, including evaporation, diminishing rainfall, and warming trends [25,27,28].

The Chamwino granitic complex area in central Tanzania is among the most water-stressed areas, lacking perennial rivers, and communities depend largely on groundwater sources [20,29]. Available borehole data indicate that the area has potential for groundwater in the south area of the region, impacted by fractures due to their proximity to fault zones and dykes [23,28]. However, fresh groundwater is limited in a few specific areas [30,31].

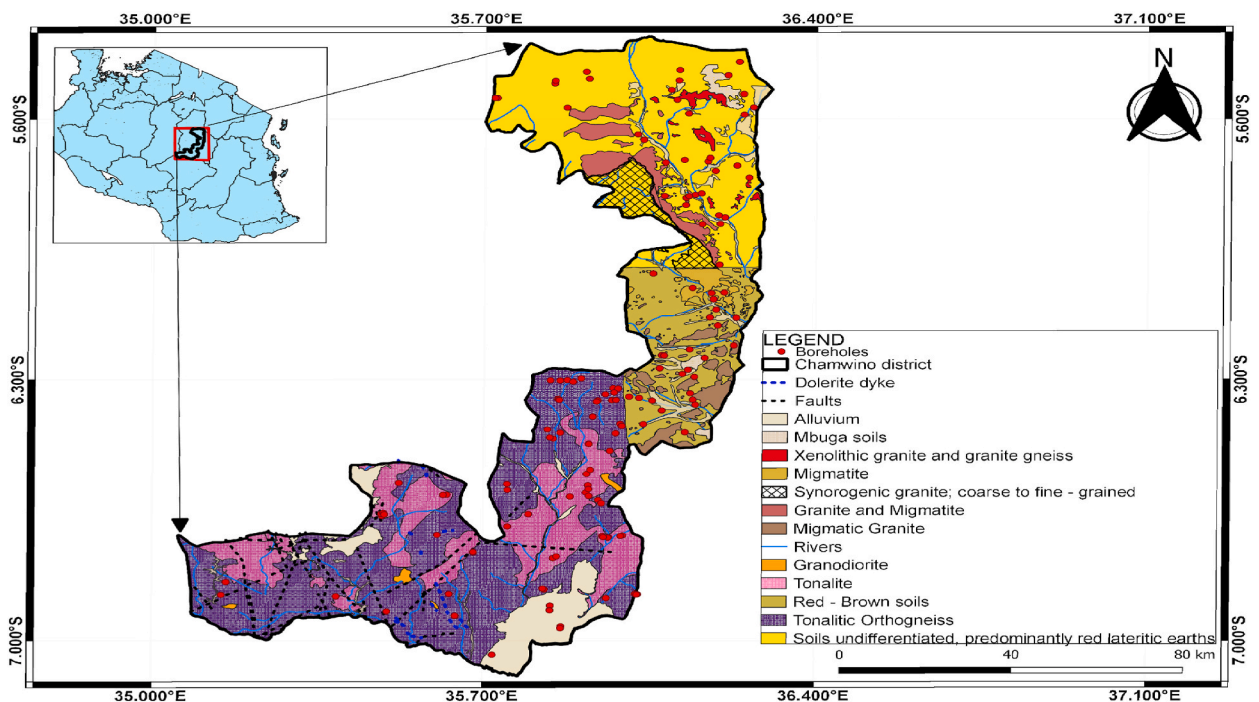


Fig. 1. The study area with sampling points (geological map based on quarter degree sheets (QDS) No. 179, 178, 163, and 1440 modified from the Geological Survey of Tanzania 2014).

There are limited studies in the study area regarding the spatial distribution of salinity and the extent of the problem. Existing studies [32–36] did not reveal this predicament in groundwater resource development at all. Hitherto, salinity has remained one of the most tenacious problems that lead to water deficits for domestic and other uses. This gap underscores the need for succinct studies that focus on evaluating spatial variation and the extent of salinity in the study area. This is because there is a paucity of knowledge on groundwater salinity variations, which has made groundwater development in the area primarily a trial-and-error exercise. This has resulted in high borehole development costs and a waste of time and human resources.

It is therefore imperative to carry out hydrogeochemical characterization so as to assess salinity variation and identify the factors controlling saline water distribution in the study area, to touch its primary objective of assessing salinity variations and hydrogeochemical characteristics of groundwater; the results will inform stakeholders, including local people and the central government, on the areas for concentration in borehole allocation and exploitation to enhance their general understanding and decision-making on sustaining useable domestic water supply in the study area. This will foster and promote science-based groundwater development in the Chamwino granitic complex and elsewhere in the world.

2. Materials and methods

2.1. Study area description

2.1.1. Location and accessibility

The study area is located in the central part of Tanzania between latitudes of 5° 00' to 8° 0' S and longitudes of 35° 00' to 37° 30' E, covering an area of about 8984 km² (Fig. 1). The area is fairly accessible in all seasons of the year through the tarmac and rough roads.

2.1.2. Population, land use and water demand

Administratively, the study area is divided into two parliamentary electoral constituencies, namely Chamwino and Mvumi, with five divisions, 36 wards, 107 villages, and 820 hamlets, with a total population of 486,176 [37]. The land use (Fig. 2 and Table 1) includes vegetation (14.91%), bare soil (11.43%), built-up area (6.98%), and water (0.56%). The current domestic water demand in 2023 is estimated at approximately 5.72 million m³/year, as described in Table 2, based on the design manual for water supply (2009).

2.1.3. Climate, topography and vegetation

The study area exhibits a semi-arid climate condition called dry savannah, characterized by temperatures ranging between 18° and 31° C [32]. It receives low and unreliable precipitation of about 400–650 mm annually, starting from late December to mid-April, followed by a prolonged dry season from late April to early December [34]. The topography is natural plains in most parts and a minor chain of hills from the northwest to the southwest zone (Chenene hills, 1,358 m a.s.l). The altitude varies between 1200 and 1400 m above sea level [32,33,38]. The vegetation types include both native and nonnative plants. Bushland dominated by natural and man-made species including the *baobab* (*Adansonia digitata*), *Acacia*, *Combretum* *Conniphora*, and *Brachystegia*, as well as *tamarind* trees in some locations are the most prevalent types of vegetation in the region [34,39].

2.1.4. Geology and hydrogeology

The study area is underlain by Precambrian crystalline basement rocks, mainly granitic rocks with meta-igneous rocks and meta-sedimentary rocks, along with sandy, gravelly, silty, and alluvial sediments (Fig. 1). The dominant water-bearing formations in general

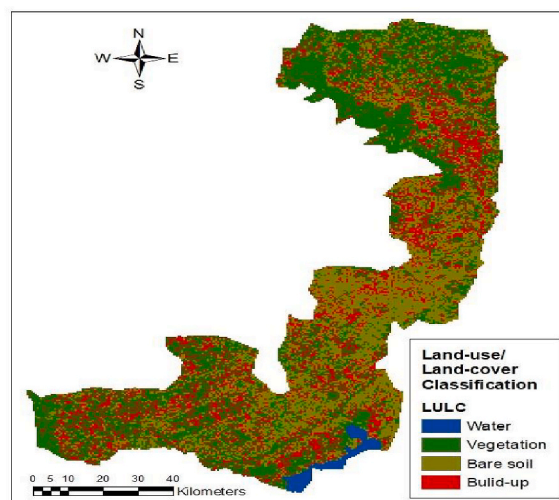


Fig. 2. Land use and land cover map produced from Landsat 8.

Table 1
Land use in the study area.

Class	Percentage %	Area [km ²]
Vegetation	14.914	4056.171
Bare soil	11.436	3110.460
Built-up area	6.983	1899.327
Water	0.559	152.289

Table 2
Water demand projection.

S/ N	Division	Population Census (2022)	Projected Population 2023 (r = 3.9)	Population Projected 2043	Water Consumption (L/day/capital)	Water Demand (m ³ /year) 2023	Water Demand (m ³ /year) 2043
1	Chilonwa	117,025	121,590	261,343	50	2,219,018	4,769,510
2	Makangwa	88,430	91,880	197,484	25	838,405	1,802,042
3	Itiso	106,742	110,905	238,375	25	1,012,008	2,175,172
4	Mvumi	101,308	105,259	226,241	25	960,488	2,064,449
5	Mpwayungu	72,671	75,506	162,290	25	688,992	1,480,896
	Total	486,176	505,140	1,085,733		5,718,911	12,292,069

are weathered and/or fractured granites or gneisses, and the drilling depth for most boreholes ranges from 70 to 120 m [20,30]. Groundwater is primarily distributed in the fractured parts of the grabens and horst formed by faults running northeast to southwest; The tonalitic orthogenesis in the southern portion of the study area is where there are more faults and dyke structures (Fig. 1) and where we can have wells with more yield (Fig. 8) because faulting and dyke can influence the rapid movement of groundwater recharge through fault gouges [40,41].

2.2. Data collection and measurements

Groundwater samples were collected from 141 wells spatially distributed within the study area from January 2023 to April 2023 (Fig. 1). Water sample collection, preservation, and transportation were governed by the standard procedures [42].

Specific steps involved in water sample collection were:

- Identification of sampling points through reconnaissance survey with the aid of a GPS tool and a notebook.
- Purging of wells/boreholes to evacuate stagnant water.
- Taking water sample and store in prewashed polyethylene bottles after wash hands and wear gloves.
- Performing in situ measurement of physio chemical parameters such as temperature (T), pH, total dissolved solids (TDS), electrical conductivity (EC), and salinity using a multi-parameter water analyzer.

Depending on the results of the physiochemical parameters some of the sample with EC range above 2500 $\mu\text{S}/\text{cm}$ were selected for geochemical analysis. Analytical methods (Table 3) for 141 water samples around the study area were used for major ions analysis.

The charge balance error Eqn. (1) was used to check if water sample results are acceptable (CBE $\leq 5\%$) [43,44].

$$\%CBE = 100 \times \frac{\sum(Cations) - \sum(Anions)}{\sum(Cations) + \sum(Anions)} \left(\frac{meq}{L} \right) \quad (1)$$

2.3. Methods of data analysis

2.3.1. Hydrochemical composition analysis

The physical parameters and major ion results were analyzed using statistical methods, which are means and standard deviations.

Table 3
Major ions analytical methods.

S/No.	Parameter	Method Name
1	Calcium (Ca ²⁺)	EDTA Titrimetric method
2	Magnesium (Mg ²⁺)	Calculation (TH - Ca ²⁺)
3	Sodium (Na ⁺)	Flame Photometric
4	Potassium (K ⁺)	Flame Photometric
5	Chloride (Cl ⁻)	Argentometric method
6	Sulfate (SO ₄ ²⁻)	Turbidimetric method
7	Bicarbonate (HCO ₃ ⁻)	Titrimetric method
8	Nitrate (NO ₃ ⁻)	Colorimetric method

The correlation between hydrogeochemical parameters, principal components, piper, and Gibbs diagrams was analyzed using the OriginPro_2022_v.9.9 software. A Pearson correlation matrix was used to identify the chemical parameters that affect major ion groundwater chemistry in the study area. The relationship between parameters was assessed by the coefficient of correlation r , between -1 and $+1$. Principal component analysis (PCA) was carried out in order to group samples with similar characteristics in the study area. The Kaiser criterion of varimax rotation was used in order to drop the PCs with less than 1 eigenvalue. Original matrix containing the X and Y observations of the Z variables were broken down using the PCA method into factor scores and factor loading matrices [23] as shown in Eqn. (2).

$$X = TP' + E \quad (2)$$

Where X = are standardized variables in matrix x; T (Y, Z) = Z corresponds to a matrix of principal components; P' = transpose of the original data; E = residual matrix.

The groundwater samples were plotted and interpreted on a piper trilinear diagram in meq/L, which classifies the type of groundwater based on the dominant chemical species [45]. Lastly, Gibbs ratios and diagrams were used to analyze the relationship between the geological characteristics of an aquifer and water composition in order to determine the controlling factors of groundwater salinity [46].

Gibbs [47] recommended two indices: first, TDS (mg/L) vs. Na^+/Na^++Ca^{2+} for cations, and second, TDS (mg/L) vs. $Cl^-/Cl^- + HCO_3^-$ for anions. Gibbs indices were calculated using the formula in equations (3) and (4).

ArcMap 10.5 and QGIS version 3.16 were employed to generate all maps, and interpolations were done by using ordinary kriging technique.

Gibbs ratio 1 (Cations).

$$\frac{[Na^+]}{[Na^+ + Ca^{2+}]} \quad (3)$$

Gibbs ratio 2 (Anions)

$$\frac{[Cl^-]}{[Cl^- + HCO_3^-]} \quad (4)$$

3. Results and discussion

3.1. Descriptive results of physicochemical parameters and major ions

A descriptive statistic (Table 4) provides an overview of the hydrochemical composition of groundwater samples collected in the study area. The hydrogen ion concentration (pH) varies between 6.0 and 9.1, indicating a slightly acidic to slightly alkaline condition, thus suggesting acceptable limits (5.5–9.5) within the drinking water standards for Tanzania Bureau of Standard (TBS, 2016) and the World Health Organization (WHO, 2017).

The alkalinity in the area is linked to a significant concentration of bicarbonate ions, which is known to gradually rise [48]. The pH implies a lack of HCO_3^- depletion since HCO_3^- does not form carbonic acid (H_2CO_3). The study area has a TDS concentrations range of 220–2940 mg/L, with an average of 1125 mg/L. According to Freeze and Cherry [49] proposed TDS classification, groundwater was classified as fresh (with 64 samples having a TDS <1000 mg/L in equivalent to 45.4% from granodiorite and tonalitic geological units) and brackish (with 77 samples with TDS of >1000 mg/L in equivalent to 54.6% from alluvium, tonalite, and migmatite geological units). The groundwater in the study area is slightly saline (brackish water), with TDS levels raised by high concentrations of Cl^- , Na^+ , and Ca^{2+} (Table 4). The high level of TDS (1800–3000 mg/L) and Salinity (1.7–2.8 mg/L) is evident to the south of the study area

Table 4

Descriptive statistics for the 141 Chamwino groundwater samples and comparison of quality to TBS and WHO drinking water standards.

Field Data						
Parameters (unit)	Min.	Max.	Mean	Std. Dev	TBS (2016)	WHO (2017)
Ca ²⁺ (mg/L)	16.0	420.0	133.6	78.3	150	100–300
Mg ²⁺ (mg/L)	8.5	228.6	73.5	48.1	100	50
Na ⁺ (mg/L)	29.3	671.5	165.6	95.5	200	50–200
K ⁺ (mg/L)	5.0	87.2	13.7	9.4	50	20
SO ₄ ²⁻ (mg/L)	22.0	690.0	233.0	143.5	400	250
HCO ₃ ⁻ (mg/L)	28.0	780.0	299.4	96.5	n.m	125–325
NO ₃ ⁻ (mg/L)	0.3	212.6	32.1	31.2	45	50
Cl ⁻ (mg/L)	42.5	1311.7	349.1	270.9	250	250
pH	6.0	9.1	7.2	0.6	5.5–9.5	7.0–8.0
Temp (°C)	21.7	28.9	25.2	1.0	n.m	12–25
EC (µs/cm)	400.0	5600.0	2118.4	1039.8	2500	400
TDS (mg/L)	220.0	2940.0	1125.0	546.5	1500	600–1000

(Fig. 3a and b), in some of the areas at Chiboli, Ng'ambaku, Loje, Fufu, and Manzase wards, mostly in alluvium, tonalite, and migmatite geological units caused by the dissolution of silicate minerals, particularly alkali feldspar and plagioclase, leading to elevated Na^+ and Ca^{2+} . The low and moderate level of TDS (200–1400 mg/L) and Salinity (0.2–1.1 mg/L) is evident in the north and middle of the study area, in some areas at Dabalo, Membe, Itiso, Haneti, Mvumi Mission, Muungano, Mvumi Makulu, Makang'wa, and Iringa Mvumi wards, mostly from granodiorite and tonalitic geological units caused by groundwater passing through dense rocks such as granodiorite and tonalitic that leach very few minerals, as indicated by low TDS.

Comparative analyses of groundwater samples show that, with the exception of chloride (Cl^-), the majority of major ions and physicochemical parameters (Table 4) had mean ranges within the desired limits recommended for drinking purposes by the Tanzania Bureau of Standards -TBS, 2016 [50] and the World Health Organization -WHO, 2017 [51]. The Cl^- value of the water sample ranged from 42.5 to 1311.7 mg/L, with a mean value of 349.1 mg/L. This suggests a longer rock-water interaction and more silicate weathering [28,52]. It also suggests a result from halite dissolution in semi-arid areas such as Chamwino with pronounced evaporation crystallization circles [25,53].

3.2. Correlation matrix of major ions and physicochemical parameters

A Pearson correlation matrix (Table 5) was used to determine the chemical parameters that affect water salinization in this study. The results show a strong relationship between TDS and the various chemical parameters. TDS and EC demonstrated significant positive correlations with calcium, magnesium, sodium, sulfate, and chloride. The important parameters Ca^{2+} , Mg^{2+} , Na^+ , and Cl^- (Table 5) were highly associated ($0.9 < r > 0.7$). Also, it was found that Ca^{2+} , Mg^{2+} , Na^+ , SO_4^{2-} , Cl^- , and electrical conductivity (EC) were well correlated ($0.7 < r > 0.5$). According to Tafrount [54], gypsum and other sulfate minerals may dissolve, possibly as a result of the dedolomitization of calcite due to a high correlation between Ca^{2+} and SO_4^{2-} ($r = 0.61$). Ca^{2+} and Cl^- exhibited a considerable positive association ($r = 0.70$), Mg^{2+} and Cl^- had a strong positive correlation ($r = 0.83$), and Ca^{2+} and Mg^{2+} had a major positive relationship ($r = 0.63$). This demonstrates that Mg^{2+} and Ca^{2+} originate from carbonate vapor sources and that MgCl_2 dissolution also contributes to salinization of the groundwater in the Chamwino granitic complex. Na^+ and Cl^- have a high correlation ($r = 0.75$). Chloride in groundwater can be an important source of excess salinity due to mineral decomposition processes. In general, this analysis reveals that salinity in the groundwater of the study area is contributed to a greater part by calcium and chloride which occur together and possibly as magnesium and chloride, sodium and chloride as well. For example, in Table 5, calcium, magnesium, sodium, and chloride all have a strong correlation that is significant at the 0.01 significance level. Such relationship also suggests evaporation crystallization circles. This is supported by the high TDS in alluvium (Fig. 2) and the stability of meta-igneous rocks. However, there is indication of the dissolution of silicate minerals, particularly alkali feldspar and plagioclase, leading to elevated Na^+ and Ca^{2+} [55]. These minerals are common in felsic meta-igneous rocks and tonalites. For SO_4^{2-} , it also supports evaporation crystallization circles. These can be from evaporates related to anthropogenic sources.

3.3. Principal component analysis

The Principal Component Analysis (PCA) model produced 12 principal components (PCs) in 12 parameters (Fig. 4), which represent 100% cumulative variances, and where eigenvalues were less than 1, those PCs were dropped from further analyses. The most significant PCs were three (PC1, PC2, and PC3), which contributed 64.92% of the total variance in the dataset (Fig. 3 and Table 6).

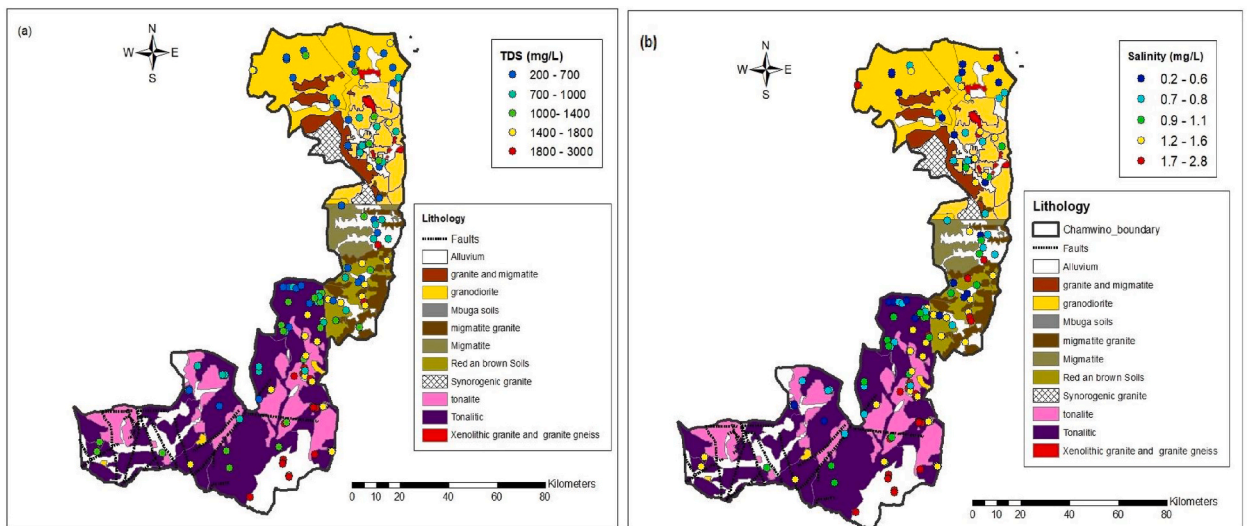


Fig. 3. Maps showing spatial distribution of (a) TDS and (b) Salinity (mg/L) by geological location in the study area.

Table 5
Correlation matrix of hydrogeochemical indicators of groundwater samples (n = 141).

	Ca ²⁺	Mg ²⁺	Na ⁺	K ⁺	SO ₄ ²⁻	HCO ₃ ⁻	NO ₃ ⁻	Cl ⁻	pH	Temp	EC	TDS
Ca ²⁺	1											
Mg ²⁺	0.637 ^a	1										
Na ⁺	0.386 ^a	0.491 ^a	1									
K ⁺	0.344 ^a	0.384 ^a	0.326 ^a	1								
SO ₄ ²⁻	0.619 ^a	0.370 ^a	0.415 ^a	0.298 ^a	1							
HCO ₃ ⁻	0.379 ^a	0.457 ^a	0.338 ^a	0.180 ^b	0.192 ^b	1						
NO ₃ ⁻	0.313 ^a	0.466 ^a	0.254 ^a	0.178 ^b	0.176 ^b	0.207 ^b	1					
Cl ⁻	0.700 ^a	0.834 ^a	0.753 ^a	0.436 ^a	0.316 ^a	0.310 ^a	0.389 ^a	1				
pH	0.085	-0.035	-0.024	-0.111	0.107	0.019	-0.158	-0.042	1			
Temp	0.026	0.123	0.023	-0.021	-0.003	-0.141	0.243 ^a	0.076	-0.123	1		
EC(μS/cm)	0.592 ^a	0.611 ^a	0.673 ^a	0.387 ^a	0.512 ^a	0.334 ^a	0.297 ^a	0.709 ^a	-0.080	-0.066	1	
TDS	0.590 ^a	0.602 ^a	0.685 ^a	0.378 ^a	0.525 ^a	0.337 ^a	0.279 ^b	0.704 ^a	-0.072	-0.072	0.995 ^a	1

All parameters are in mg/l except where otherwise stated.

^a Correlation is significant at the 0.01 level (2-tailed).

^b Correlation is significant at the 0.05 level (2-tailed).

The first component (PC1), which accounted for 45.01% of the total variance, includes Ca²⁺, Mg²⁺, Na⁺, Cl⁻, EC, and TDS. This factor represents the most important process controlling groundwater chemistry and appears as the huge determinant of groundwater salinization (Table 6). The second principal component (PC2), representing 11.45% of the total variance, is characterized by NO₃⁻ concentrations and temperature (0.47 and 0.62 respectively). This factor suggests that groundwater is contaminated by anthropogenic activities [56]. The third principal component (PC3), representing 8.47% of total variance, is explained by pH and temperature concentrations (0.66 and 0.48 respectively). This factor indicates that an increase in temperature causes in an increase in pH, but a decrease in temperature can also cause a decrease in pH [57].

3.4. Hydrogeochemical facies of groundwater

In Fig. 5, the piper trilinear diagram displays the hydrogeochemical facies of the groundwater in different geologies by classifying prominent groundwater types based on hydrogeochemical processes and the dominant ions present. These reveal the origins of ions and their composition and the prospective evolution of groundwater in the study area [44,58,59]. Cation sequence is in the order of Na > Ca > Mg and anions by Cl > HCO₃ > SO₄. The major hydrogeochemical facies were identified in every geological unit. It was observed that granodiorite (Fig. 5a) was dominated by Ca-HCO₃, Na-Cl, Ca-Na-HCO₃, Ca-Mg-Cl, and Ca-Cl water types; migmatite (Fig. 5b) was dominated by Ca-HCO₃, Na-Cl, Ca-Mg-Cl, and Ca-Cl water types; tonalitic orthogenesis (Fig. 5c) was dominated by Ca-HCO₃, Na-Cl, Ca-Mg-Cl, and Ca-Cl water types; tonalite geology (Fig. 5d) was dominated by Na-Cl, Ca-Mg-Cl, and Ca-Cl water types; and alluvium geology (Fig. 5e) was dominated by Na-Cl and Ca-Mg-Cl and Ca-Cl water types. Overall, three hydrogeochemical facies were identified in all geological units that include Na-Cl, Ca-Mg-Cl, and Ca-Cl water types. These suggest mineral dissolution of halite, dolomite, and calcite (with gypsum dissolution and ion exchange), respectively [60].

Evaluation of water types by means of piper plots suggests the influence of saline water within the study area, where Na-Cl and Ca-Cl type in all geological units is an indicator of extreme salinity in groundwater [61].

In general, Na-Cl and Ca-Cl water types indicate a high salinity distribution to the south of the study area at Chiboli, Ng'ambaku, Loje, Fufu, and Manzase wards, mostly in alluvium, tonalite, and migmatite geological units. However, evaporation-crystallization circles propose a significant role as all alluvial samples are brackish.

(Fig. 5e); while Ca-HCO₃ water types suggest fresh water from local recharge in the north and middle part of the study area in some

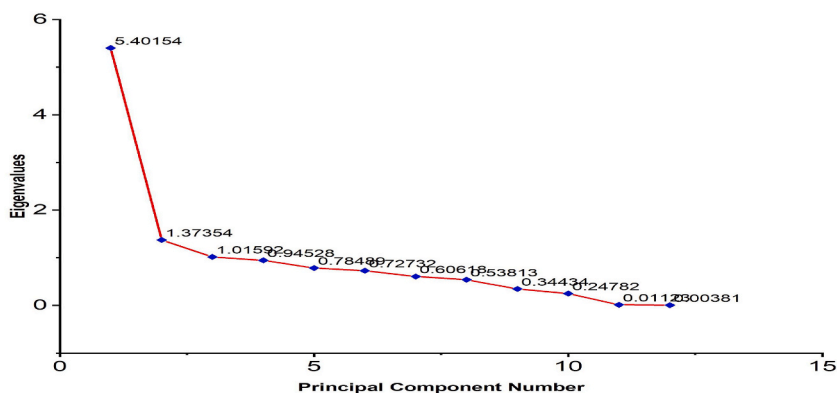


Fig. 4. Indicating screen plots of 12 principal components.

Table 6
Principal components analysis of the study area aquifer hydrogeochemical parameters.

Extracted Eigenvectors	PC1	PC2	PC3
Ca ²⁺	0.33770	-0.08772	0.26831
Mg ²⁺	0.35704	0.15389	0.08341
Na ⁺	0.32733	-0.03382	-0.12886
K ⁺	0.22332	0.03061	-0.26402
Cl ⁻	0.38167	0.10305	-0.02198
SO ₄	0.26691	-0.22975	0.29098
NO ₃	0.19846	0.47934	0.15424
HCO ₃	0.20828	-0.13819	-0.12814
pH	-0.01421	-0.49664	0.66980
Temp	0.01226	0.6214	0.48428
EC	0.38857	-0.09525	-0.11637
TDS	0.38781	-0.11113	-0.11261
Total eigenvalues	5.40154	1.37354	1.01592
%Variance	45.01	11.45	8.47
Cumulative variances %	45.01	56.46	64.92

parts of Dabalo, Membe, Itiso, Haneti, Mvumi Mission, Muungano, Mvumi Makulu, Makang'wa, and Iringa Mvumi wards in granodiorite and tonalite geological units. The hydrogeochemical facies of the study area imply that groundwater is likely to evolve into polluted water. For example, the Ca–Mg–Cl mixed water type is dominant in all geological units, which means Cl ions could be part of halite dissolution or it might be associated with anthropogenic activities.

3.5. Mechanism controlling groundwater chemistry

The Gibbs diagram (Fig. 6a–e) represents a control mechanism for water chemistry, describing that most samples from the study area are confined to a predominantly rock-water interaction area in all geological units. This indicates that the chemical composition of groundwater in the study area is a result of the chemical change of the aquifer material (mineral dissolution), which indicates an interaction between granite rocks and water [62,63]. The predominance of the rock-water interaction suggests that groundwater in the study area had enough time to interact with the geological materials, and as a result, various ions were released into the water. For example, mineral dissolution in granodiorite (Fig. 6a) and tonalitic orthogenesis geology (Fig. 6c) mostly releases Ca²⁺, HCO₃⁻ and Cl⁻ ions associated with TDS levels between 200 and 1400 mg/L (Refer Fig. 3a), while in migmatite, tonalite, and alluvium geology formations (Fig. 6 b, d and e) release mostly Na⁺, Ca²⁺, Mg²⁺, and Cl⁻ ions associated with TDS levels between 1400 and 3000 mg/L. However, it can be noted that there is also a likelihood of the evaporation process of groundwater in alluvium geology (Fig. 6e), thus contributing to observed salinity in groundwater. In general, the salinization of water in the study area appears to be mainly governed by rock-water interaction due to the high residence time in the aquifer and ion exchange as opined by Tafrount [54].

3.6. The origin of the major factors

To emphasize the different factors that control the salinization of the study area groundwater, an ionic correlation diagram generated by the molar concentrations of the major elements was used. The most common dissolved mineral, salt rock (NaCl), can be used to assess the ion source in groundwater based on the Na⁺/Cl⁻ ratio. If this ratio is equal to 1, all Na⁺ and Cl⁻ in groundwater are due to the dissolution of salt rock [44,64,65]. Na⁺ versus Cl⁻ determines the mechanism of salinity acquisition of water in semi-arid regions [54,66]. As represented in Fig. 7a, the ratio of Na⁺ to Cl⁻ shows samples were mostly distributed close to the ratio line, indicating the main source of this groundwater type is the dissolution of salt rock (halite), with the exception of some brackish water samples which were widely varied, being located below the y = x ratio line. This indicates that Cl⁻ in this type of groundwater comes from other sources. The high concentration Cl⁻ suggests that it is part of the dissolution of minerals like NaCl (halite), MgCl, CaCl, or associated with anthropogenic sources or cation exchange by Na⁺ reduction and reverse ion exchange [67,68].

For the Ca²⁺ and Mg²⁺ contribution plot, Fig. 7b shows almost all water samples are located in the region of sulfate weathering, which suggests that the Ca²⁺ and Mg²⁺ in this groundwater type were closely related to weathering processes. There are three possibilities however; the first being dissolution of gypsum (Mg²⁺ and Ca²⁺ = 0.64), the second being alteration of dolomitic limestone (Mg²⁺ and Ca²⁺ < 0.64), and the third being dissolution of dolomite and calcite (Mg²⁺ and Ca²⁺ > 0.64) as reported by Refs. [54,69]. It has also been observed that brackish water samples are distributed within the solubility range of granite rocks and that the Ca²⁺ and Mg²⁺ sources in these groundwater facies are thought to be closely related to ion exchange. The HCO₃⁻ + SO₄²⁻ and Ca²⁺ + Mg²⁺ graphs (Fig. 7c) indicate most of the samples fall within the 1:1 aquiline range and show the predominance of alkaline earth over bicarbonate, indicating silicate weathering in the study area. The Ca²⁺ and Cl⁻ pair (Fig. 7d), shows an average between the elements indicating that the cations Ca²⁺ contribute to the groundwater salinization. In general, salt rock (chiefly NaCl) dissolution is most likely responsible for the observed salinization of groundwater in the study area aquifer, associated with ion exchange processes. The findings imply that groundwater is most likely to evolve into polluted water, due to the fact that it was observed Cl could be part of salt-rock dissolution or it might be possibly associated with anthropogenic activities.

However, the contribution of the latter process is negligibly small due to the fact that the vast part of the study area is not urbanized.

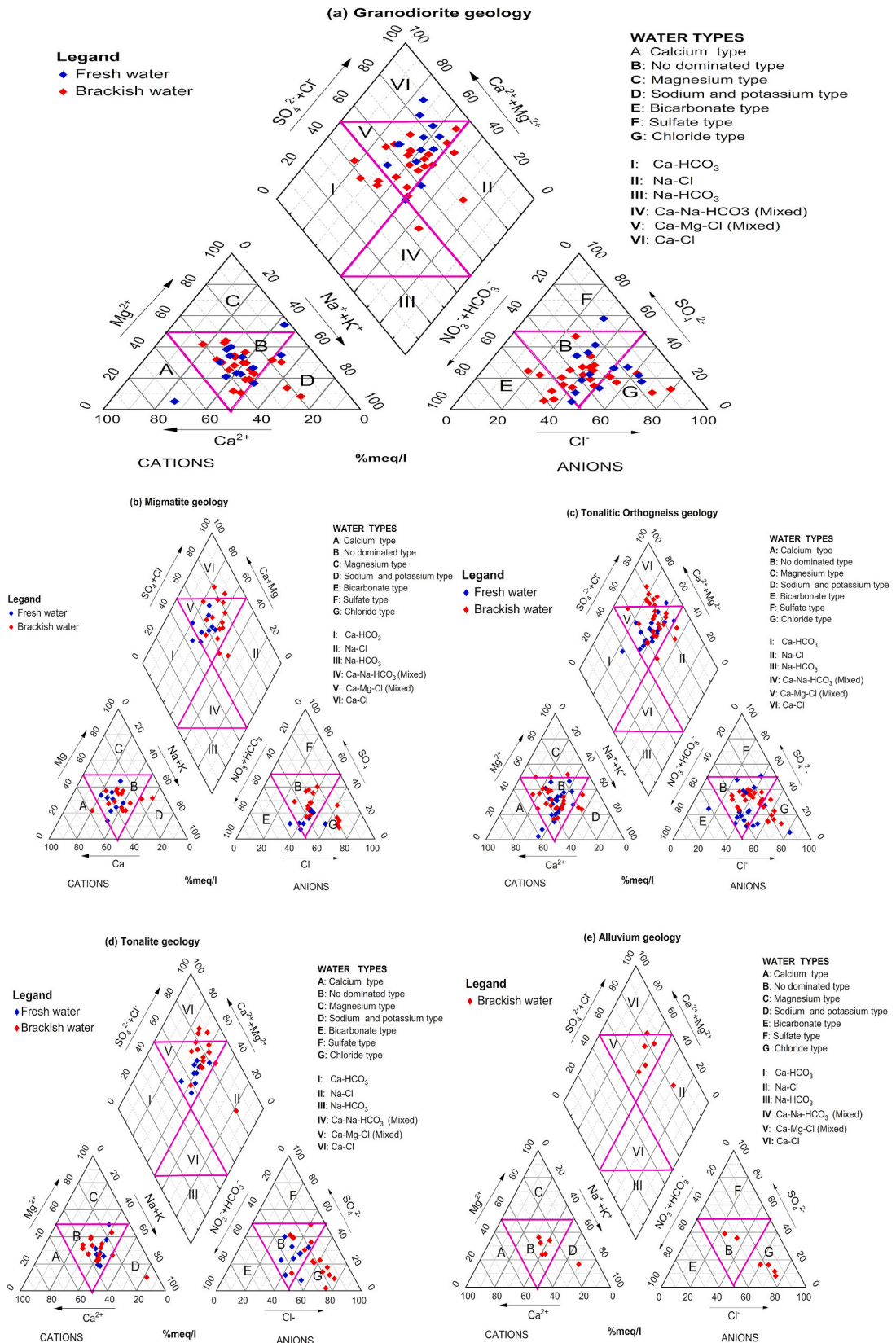
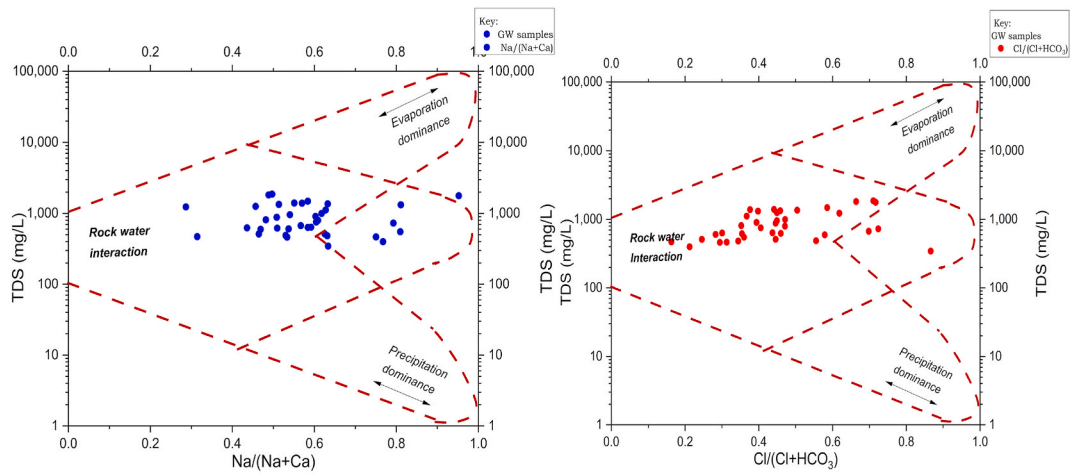
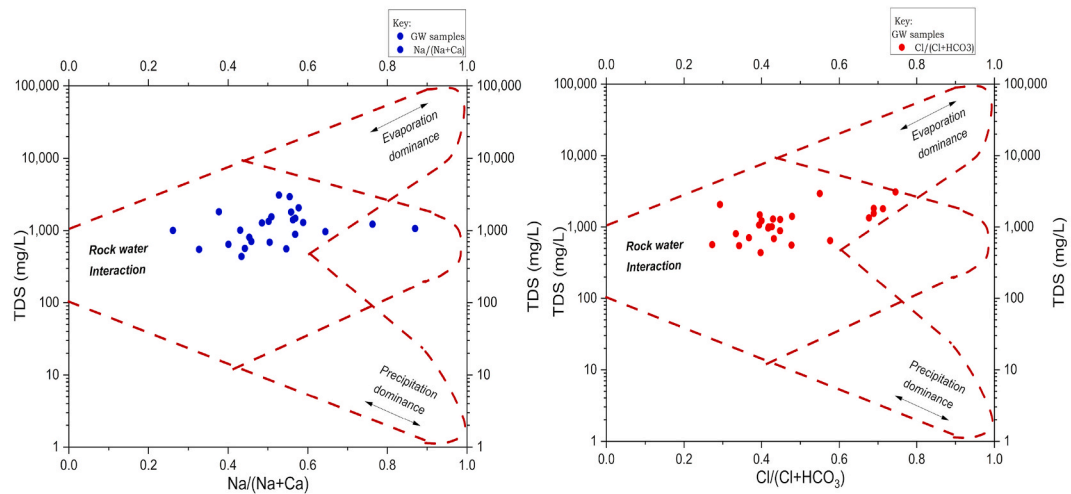


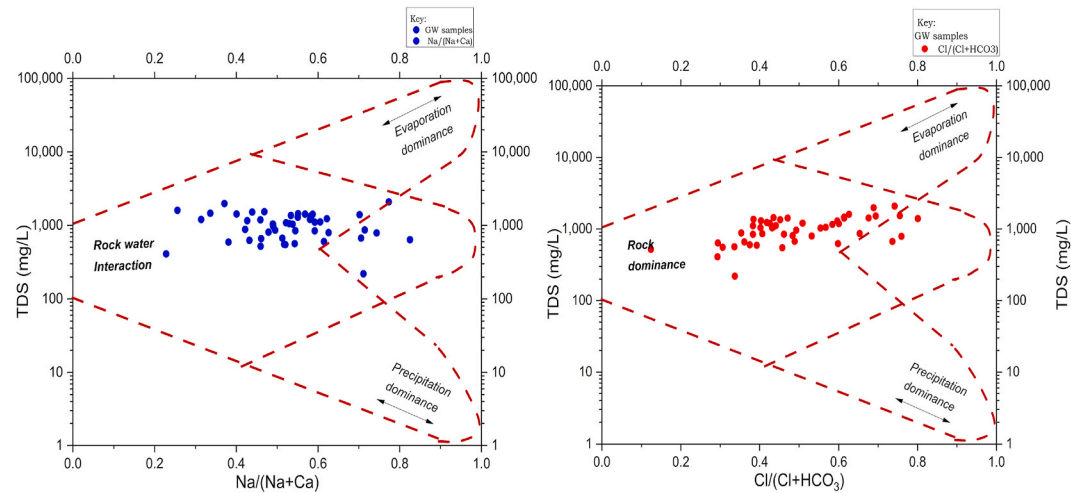
Fig. 5(a-e). Piper trilinear diagram describe hydrogeochemical facies of the groundwater type in different geological units.



(a) Granodiorite geology



(b) Migmatite geology



(c) Tonalitic Orthogneiss Geology

Fig. 6. Gibbs diagram representing the major mechanisms controlling groundwater salinity in five different geological formations (a–e) based on Gibbs (1970).

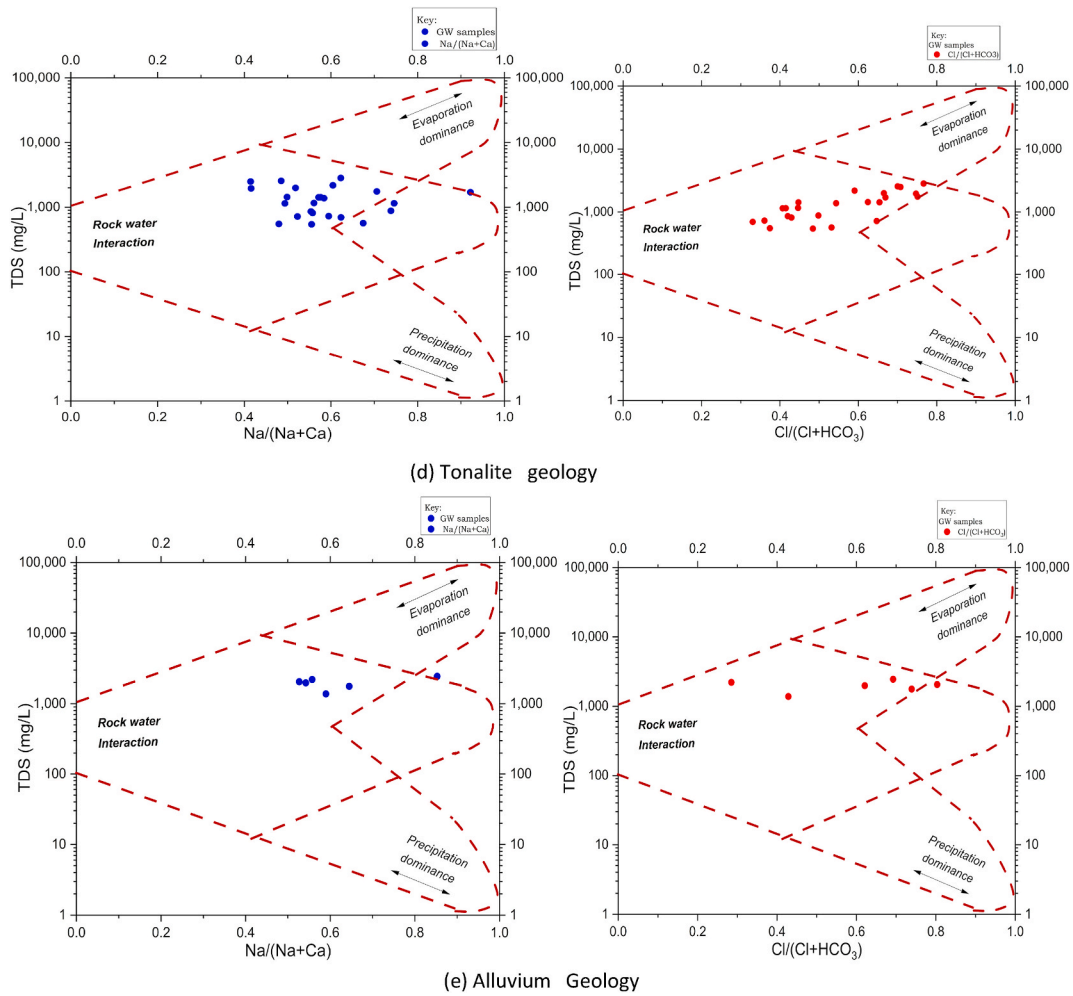


Fig. 6. (continued).

3.7. The relation between geology, depth, yield and salinity

In Fig. 8, the lithology section displays the relationship between yield, depth and total dissolved solids of the groundwater in different geologic formations. Ilangali well (Fig. 8a) with 100 m depth is located in tonalitic orthogneiss geology with 1st water strike intersected at 35 m depth, which is controlled by fractured weathered granite rocks which have more faults and dyke structures. This suggests that these types of wells have high yield because faulting and dykes can influence the rapid movement of groundwater recharge through fault gouges as reported elsewhere by Stephens [41]. Segala well (Fig. 8b) with 200 m depth is located in granodiorite geology with 1st water strike intersected at 50 m depth. This is controlled by granite rocks which is moderately weathered, leading to minimum pore space, suggesting low yield. Chibwe chini well (Fig. 8c) with 190 m depth is located in migmatite geology with 1st water strike intersected at 120 m depth. This is controlled by granite rocks which is not strongly weathered, leading to poor pore space, suggesting lowest yield. Furthermore, the three lithology sections suggest that TDS increases with depth, implying that the salinity increases with depth because water at greater depth has more time to interact with rocks and is less likely to be washed away when recharged as discussed by Rivett [11]. Other sources of high chloride concentration are discussed in [70, 71].

4. Conclusions

The hydrogeochemical investigation was carried out to determine the factors controlling saline water distribution in the Chamwino granitic complex in central Tanzania.

- Salinization of groundwater in the study area is mainly controlled by rock-water interaction process which is confirmed by Gibbs diagrams. The predominance of the rock-water interaction suggests that groundwater in the study area interact with the geological materials, and as a result, various ions like Na^+ , Ca^{2+} , Mg^{2+} , and Cl^- are continuously released into the groundwater. The

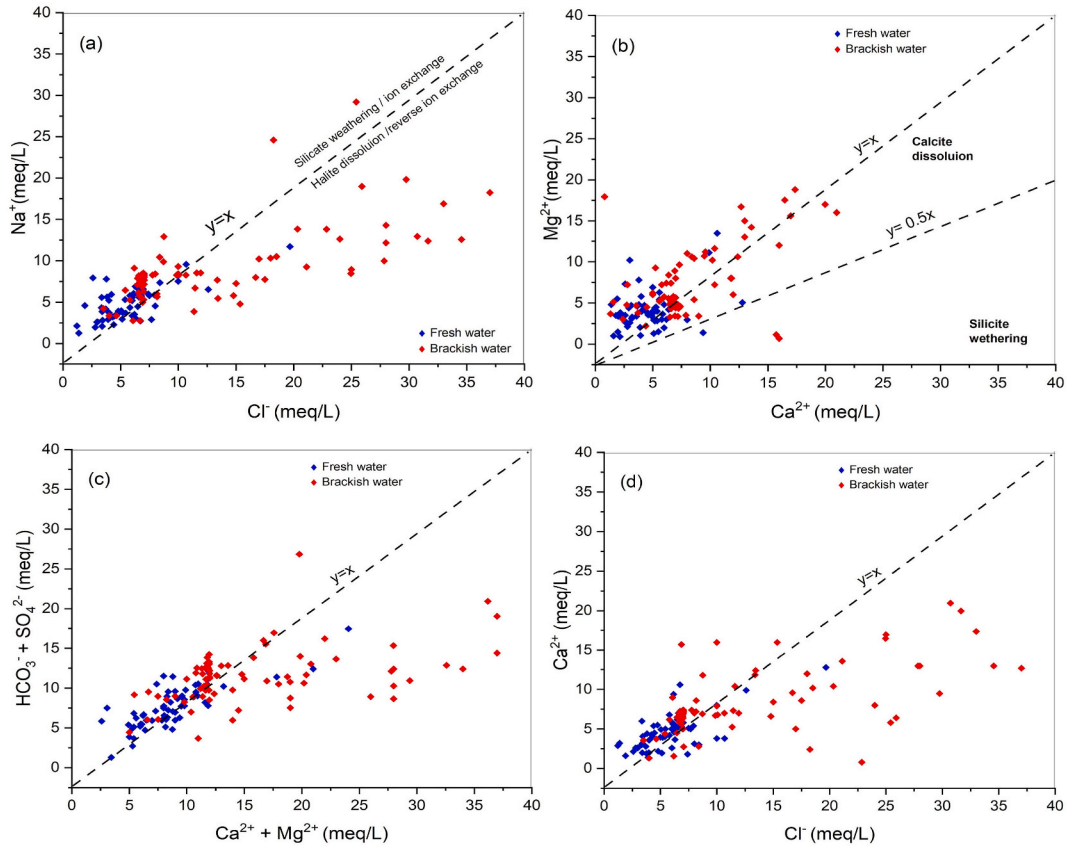


Fig. 7. Ionic correlation diagrams (a) Na^+/Cl^- ratio, (b) Ca^{2+}/Mg^{2+} ratio, (c) $Ca^{2+} + Mg^{2+}/HCO_3^- + SO_4^{2-}$ ratio, and (d) Cl^-/Ca^{2+} ratio.

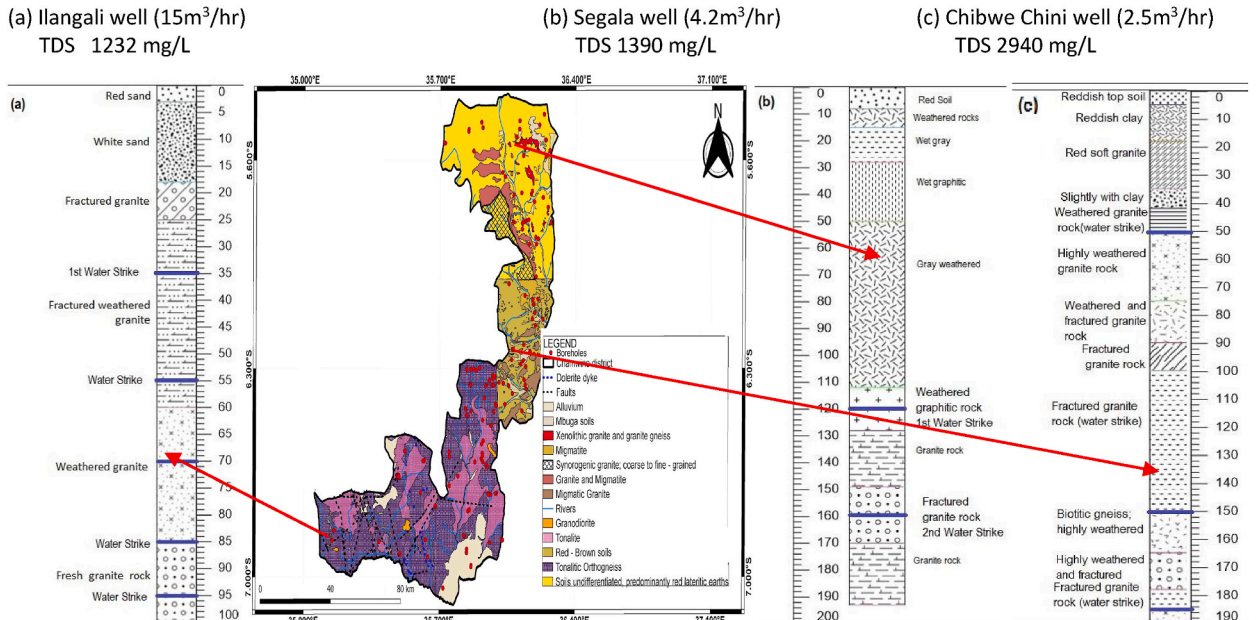


Fig. 8. Lithological borehole logs for three boreholes at Ilangali (a), Segala (b) and Chibwe chini (c) indicating variation in depth, yield and salinity in relation to groundwater occurrence in some of geological units.

geological processes that drive rock-water suggest a results of evaporation crystallization cycles led to formation of high salinity in groundwater, and anthropogenic effects in congested areas, are the causative factors in semi-arid areas such as Chamwino (the study area).

- The evaluation of hydrogeochemical facies of groundwater by means of piper plots suggests the presence of Na–Cl and Ca–Cl water type in all geological units. This is an indicator of salinity source in the groundwater systems of the study area. However, the piper plots revealed the presence of Ca–HCO₃ and Mg–HCO₃ water types, suggesting the presence of fresh water from local recharge. It was further observed that alluvium geology was dominated by the abundance Ca–Cl > Ca–Mg–Cl > Na–Cl water types; followed by tonalite geology with dominance of Na–Cl > Ca–Mg–Cl > Ca–Cl water types; Tonalitic orthogenesis geology was dominated by Ca–HCO₃, followed by Na–Cl, Ca–Mg–Cl, and Ca–Cl water types; Migmatite geology was dominated by Ca–HCO₃, Na–Cl, Ca–Mg–Cl, and Ca–Cl water types; and granodiorite geological unit was dominated by Ca–HCO₃, Na–Cl, Ca–Na–HCO₃, Ca–Mg–Cl, and Ca–Cl water types.
- The study revealed that the abundance of chloride ion was the source of high salinity of groundwater in some geologic units, especially in alluvium and tonalite geology caused by high dissolution of chloride-rich minerals in the aquifer. It also suggests a result from evaporation crystallization circles in semi-arid areas such as Chamwino. However, in other geological units of tonalitic Orthogneiss, migmatite and granodiorite geology, there was an ostensible mixing of saline water and fresh water from local recharge as indicated by the HCO₃ ions.
- Generally, three hydrogeochemical facies were identified in all geological units. These are Ca–Cl, Ca–Mg–Cl, and Na–Cl water types in order of the abundances. The observed high-salinity groundwater is associated with halite, dolomite, and calcite (with gypsum dissolution and exchange processes of the cation) being evident to the south of the study area. This is a specific case of areas like Chiboli, Ng'ambaku, Loje, Fufu, and Manzase wards, which are mostly dominated by alluvium, tonalite, and migmatite geological units, lying in low topography, thus groundwater has more contact with rocks and is less likely to be flushed by rapid recharge.
- The evolution processes have revealed that rock-water interaction and ion and reverse exchange reactions are the key processes of salinization of groundwater in the study area.
- The hydrogeochemical characterization of groundwater in the Chamwino granitic complex suggest that there is little possibility for groundwater to evolve to a carbonate water type (fresh water) in all geologic formations because the groundwater salinity is mainly geogenic, unless artificial recharge through rainwater harvesting is applied.
- The correlation results show that the key parameters Ca²⁺, Mg²⁺, Na⁺, and Cl⁻ are strongly correlated ($0.9 < r > 0.7$). It suggest the possible influences of these ions on the increase in water salinity in the study area. It was also found that Ca²⁺, Mg²⁺, Na⁺, SO₄²⁻, Cl⁻, and electrical conductivity (EC) were well correlated ($0.7 < r > 0.5$). Moreover, Ca²⁺ and Cl⁻ exhibited a considerable positive association ($r = 0.70$), Mg²⁺ and Cl⁻ had a strong positive correlation ($r = 0.83$), and Ca²⁺ and Mg²⁺ had a major positive relationship ($r = 0.63$). This demonstrates that Mg²⁺ and Ca²⁺ originate from granite sources and that MgCl₂ dissolution also contributes to salinization. Na⁺ and Cl⁻ have a high correlation ($r = 0.75$). Generally, the relationship of these ions suggests the increase in water salinity in the study area is contributed to a greater part by calcium and chloride that they occur together and possibly as magnesium and chloride, sodium and chloride as well. Also, Chloride is a good indicator of evaporation and evapotranspiration as well.
- In principal component analysis, the most three components extracted (PC1, PC2, and PC3) represented 64.92% of the total variance. PC1 reveals that the groundwater salinity is mainly contributed to by rock-water interaction, leading to the release of chemical species which define the salinity of the groundwater in the study area, while PC2 reveals the possibility of anthropogenic effects in congested areas associated with agricultural activities has influence on groundwater salinity from local recharging (infiltration irrigation). However, the contribution of anthropogenic activities is less dominant.
- These findings will inform stakeholders, including local people and the central government, on the areas for concentration in groundwater development and exploitation with respect to salinity distribution. Further, the findings will enhance the general understanding and decision - making on sustaining a useable domestic water supply within the study area.
- Future research works are urged to confirm the role of faulting on salinity structures in the study area. Geophysical approaches (2D Electrical Resistivity Tomography (ERT) & well logging) and three-dimensional modeling to simulate salinity distribution are recommended.

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Data availability statement

Question	Response
Has data associated with your study been deposited into a publicly available repository?	Data will be made available on request

CRediT authorship contribution statement

Christina M. Msengi: Conceptualization. **Ibrahimu C. Mjemah:** Supervision. **Edikafubeni E. Makoba:** Supervision. **Kassim R. Mussa:** Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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