



HYDROGEOCHEMICAL AND SUITABILITY ASSESSMENT OF GROUNDWATER DURING THE DRY SEASON IN DOMASI IRRIGATION SCHEME, MALAWI

Grant Kuntumanji^{1*}, Samson Sajidu², Jimmy Namangale³

¹University of Malawi, P. O. Box 280 Zomba

²Department of Chemistry, University of Malawi, P.O. Box 280 Zomba

³Natural Resources and Environment Centre, University of Malawi, P.O. Box 280 Zomba.

*Corresponding Author

Grant Kuntumanji

University of Malawi, P. O. Box 280 Zomba.

Article History

Received: 27.04.2024

Accepted: 03.05.2024

Published: 20.05.2024

Abstract: The study aimed to explain the chemistry of groundwater and assess its suitability for drinking and irrigation purposes for people living within and around the Domasi Irrigation Scheme. The dominance of cations in the Domasi Irrigation Scheme was in the order $\text{Na} > \text{Ca} > \text{Mg} > \text{K}$ and that for anions was $\text{HCO}_3 > \text{Cl} > \text{CO}_3 > \text{SO}_4 > \text{NO}_3 > \text{F}$. The study revealed that the groundwater for the study area is predominantly of sodium-bicarbonate type due to weathering, cation exchange and other anthropogenic activities. The groundwater was generally suitable for drinking based on Malawi standards but with elevated levels of bicarbonates, sodium, chloride and total hardness. In the absence of a piped-treated water system in the area, there is a need to introduce water treatment technologies such as water softening. The groundwater in this area is suitable for irrigation purposes but with some caution to balance levels of magnesium and calcium with organic and inorganic fertilizers. The study advocates for the use of pumping technology to use groundwater for irrigation purposes during the dry season to maximize agricultural productivity. There is a need for a specific study to be done to look at the soil chemistry of the area so that more appropriate crops might be identified to diversify agriculture in this area. This will ensure proper and maximum utilization of both soil and groundwater for this agricultural area.

Keywords: Hydrogeochemistry, Principal Component Analysis, Sodium Absorption Ratio, Ion Exchange.

Cite this article:

Kuntumanji, A.G., Sajidu, S., Namangale, J., (2024). HYDROGEOCHEMICAL AND SUITABILITY ASSESSMENT OF GROUNDWATER DURING THE DRY SEASON IN DOMASI IRRIGATION SCHEME, MALAWI. *ISAR Journal of Multidisciplinary Research and Studies*, 2(5), 29-44.

1.0 INTRODUCTION

Groundwater has been widely recommended notwithstanding its scarce accessibility, availability and cost for usage for domestic and irrigational purposes (Sunkari et al., 2019). Groundwater is the finite source of daily water supply to about 3.0 billion people worldwide and 60% of the groundwater abstraction is used in agriculture (Aggarwal et al., 2021; Ahmed et al., 2019). Groundwater quality assessment is an important task and a fundamental factor for socio-economic development in places with a lack of surface water, low rainfall and recharge, high evaporation, and high salinity (Rajmohan et al., 2021). Climate change has a severe global impact on water resources, agriculture, human health and flooding in coastal areas. It is, however, imperative that we maximize agricultural production to match the projected global population of 10 billion by 2050 (Khondoker et al., 2023). Many countries or regions are facing increasing competition for water resources particularly between domestic and agricultural purposes. One primary reason for inadequate access to potable water is the

lack of sustainable drinking water projects and infrastructure throughout the Sub-Saharan Africa region (Avidar, 2024).

Estimates of the potential area for irrigated agriculture in Malawi fall within the range of 0.25 -0.5 million hectares, which lie adjacent to the shores of Lake Malawi, Lake Chilwa, Lower Shire and along the many flood plains of the various river systems (Chafuwa, 2017). As land pressure and climate change intensify, Malawi is increasingly turning to irrigated agriculture as a means of increasing crop production. Irrigated agriculture is regarded as a means to boost incomes and food security. Thus, Irrigated agriculture is considered to be a way to reduce poverty, malnutrition, disease burden and economic inequalities by government and donors (Ferguson & Mulwafu, 2004; Nkhoma, 2011). However, in recent years, Malawi has experienced climatic variability which has affected agricultural productivity in the Domasi Irrigation Scheme.

In Malawi, groundwater is a key resource providing 82% of domestic, agricultural, and industrial water needs. Despite this importance, there is minimal groundwater monitoring and

measurement thereby limiting proper understanding of Malawi's water security (Hinton, et al., 2024). The suitability of groundwater (GW) and the corresponding health risks have become prime concerns in the recent era. Hence, the determination of GW quality for drinking, agricultural, and domestic purposes is the foremost responsibility of researchers (Ruidas, et al., 2023). Potential groundwater contamination in the Domasi Irrigation Scheme can emanate from infiltrating surface water and from the dissolution of minerals. Kambombe et al. (2023) reported an increasing trend in the proportion of cropland in the Domasi watershed. This implies a significant decrease in forest cover as well as an increase in agricultural activity in the watershed. Therefore, such anthropogenic activities help different chemicals to migrate from the watershed to the irrigation scheme. Heavy metals easily bind themselves to the soil sediments but sink into the groundwater due to frequent tilling of the farmland. (Mussa et al., 2019).

In recent years, people have migrated to the Domasi Irrigation Scheme to establish permanent residences and chiefdoms. The only improved sources of drinking water in this area are boreholes and shallow that are heavily prone to contamination. During the rainy season, the scheme experiences floods and people's mobility to the boreholes is limited. Therefore, communities rely on hand-dug wells close to their houses as the main source of water for drinking and other domestic uses. In the dry season, water is scarce and agricultural activity is significantly decreased. Some studies have been done in the area but have not focused on groundwater of the irrigation scheme (Bandason et al., 2014.; Ferguson & Mulwafu, 2004.; Kambombe et al., 2021). The provision of knowledge about the quality of groundwater for drinking and irrigation purposes is therefore necessary for the area. This study was carried out to establish the hydrogeochemical and suitability characteristics of the groundwater used by communities staying within and around the Domasi Irrigation Scheme. Processes governing the groundwater chemistry were established. Integrated water quality index models were used to assess groundwater suitability for drinking (Mukate et al., 2019) and irrigation (Islam & Mostafa, 2022) purposes

1.1 General Description of the Study Area

1.1.1. Location

Domasi Irrigation Scheme is located in the Lake Chilwa Basin along the latitude 15° 13' E and longitude 35° 29' E (Figure 1). The scheme was built in the early 1970s by the Government of Malawi (GOM) together with the Taiwanese Agricultural Technical Mission (TATM), on the Machinga side of the Domasi River and covers an area of approximately 500 hectares (Chilivumbo, 1971). Domasi Irrigation Scheme is fed by the Domasi River which has its source high up in the Zomba mountains 20km to the west of the scheme. Five kilometres downstream of the scheme's intake, the river empties into Lake Chilwa, a shallow (average depth 2 meters) 683 km² saline lake that lies on the border between Malawi and Mozambique (Jamu et al., 2003). The establishment of the scheme was aimed at increasing peasant agricultural productivity, and improving economic development (Garside, 2010).

1.1.2 Climate

Sporadic winter rainfall (May to October) only occurs in the highlands. The mean annual temperature is 21–24 °C, with a climate described as tropical wet and dry

Domasi Irrigation Scheme experiences two distinct seasons: the rainy season which runs from November to April and the dry season which runs from May to October. The dry season is also separated into cool-dry and hot-dry. Around 80% of rainfall occurrence between November and April is due to a convergence of northeasterly monsoon and south-easterly trade wind (Karlin et al., 2022). Annual rainfall averages from 1100 to 1600 mm, but may vary from 800 mm in the lowland plains to over 2000 mm in the mountains (Kuntumanji et al., 2024). The climate of the area has been problematic for the development of irrigation. Most of the areas within and around the scheme experience floods and drought during the rainy season. It was further shown that an average annual rainfall below 1000mm is likely to yield a dry-up of Lake Chilwa in recent times than before, which may be attributable to anthropogenic pressure (Kambombe et al., 2021). General temperatures fluctuate between 28 °C and 10 °C with a mean annual temperature of 21–24°C.

1.1.3 Farming Seasons in Domasi Irrigation Scheme

The scheme uses a double cropping system for rice production. Maize and other vegetables are also grown in conjunction with rice in the dry season. A rainy season crop runs from January to June and a dry season crop runs from July to December. The scheme uses gravity-fed irrigation into paddies or basins termed as plots. Farmers heavily rely on inorganic fertilizers, particularly NPK and UREA. However, due to the availability of livestock and advocacy for conservation agriculture, the application of organic manure is also common. Intensified use of stream banks and wetlands for agriculture poses erosion risks (Rivett et al., 2020).

1.1.4 Hydrogeology

Most of the Lake Chilwa basin is underlain by ancient metamorphic and igneous rocks of the Malawi Basement complex represented by a group of high-grade metamorphic rocks, mostly chamokitic granulites of quartz and feldspar (Mussa et al., 2019). Domasi Irrigation Scheme is located in a region where colluvium and alluvium deposits overlie the weathered basement. As we move towards the eastern part of the irrigation scheme, fluvium overlies the colluvium and alluvium (Figure 2). predominantly underlain by an alluvial aquifer. Alluvial aquifers are fluvial and lacustrine sediment successions with variations in both vertical and lateral extent. The main lithological component of the alluvial aquifers is clay with significant occurrences of poorly sorted sands in some localities. Unconfined aquifers are prone to ionic contamination by surface waters. In the Lake Chilwa Basin, which is perched on the eastern side of the rift valley, most of the alluvium aquifers are clayey with the highest yields obtained from sand and gravel. Lacustrine deposits of low-energy deposition that comprise predominantly finer-grained lithologies are more common across the basin (Karlin et al., 2022)

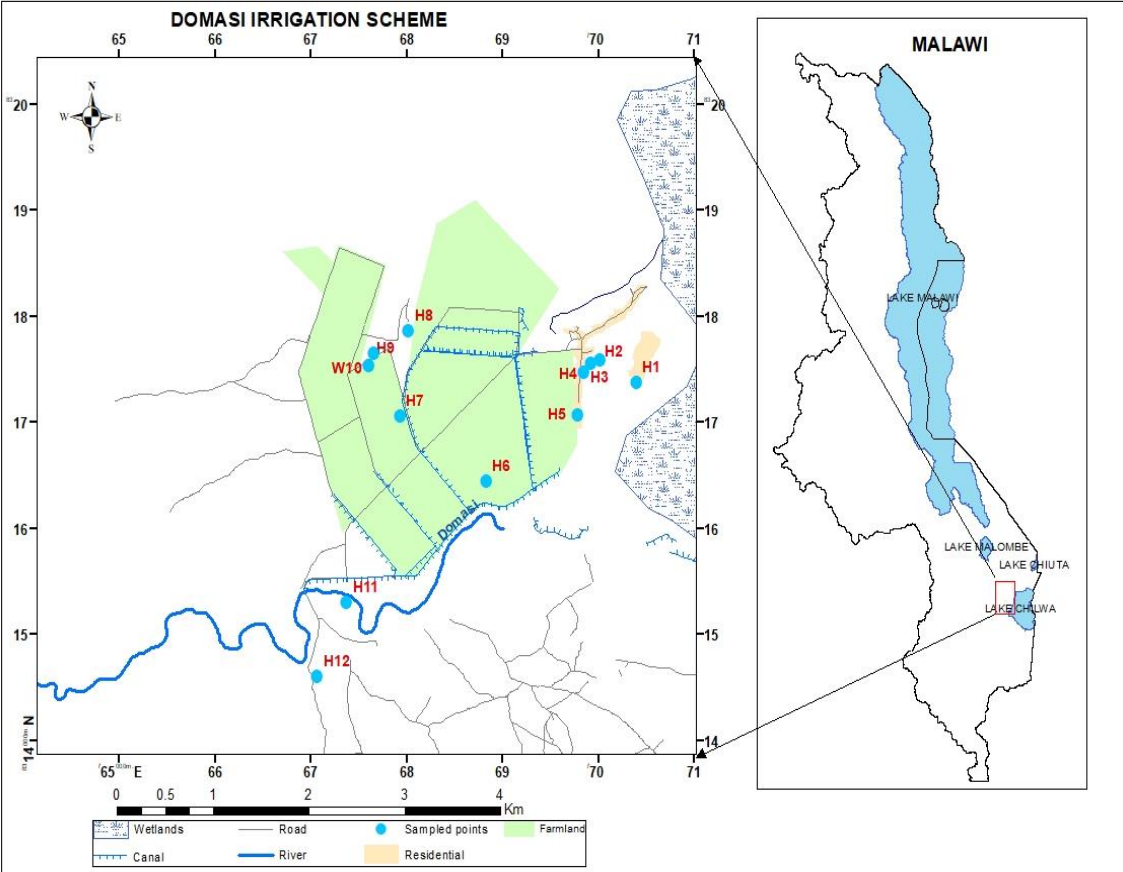


Figure 1: Location of Domasi Irrigation Scheme and Sampling Points

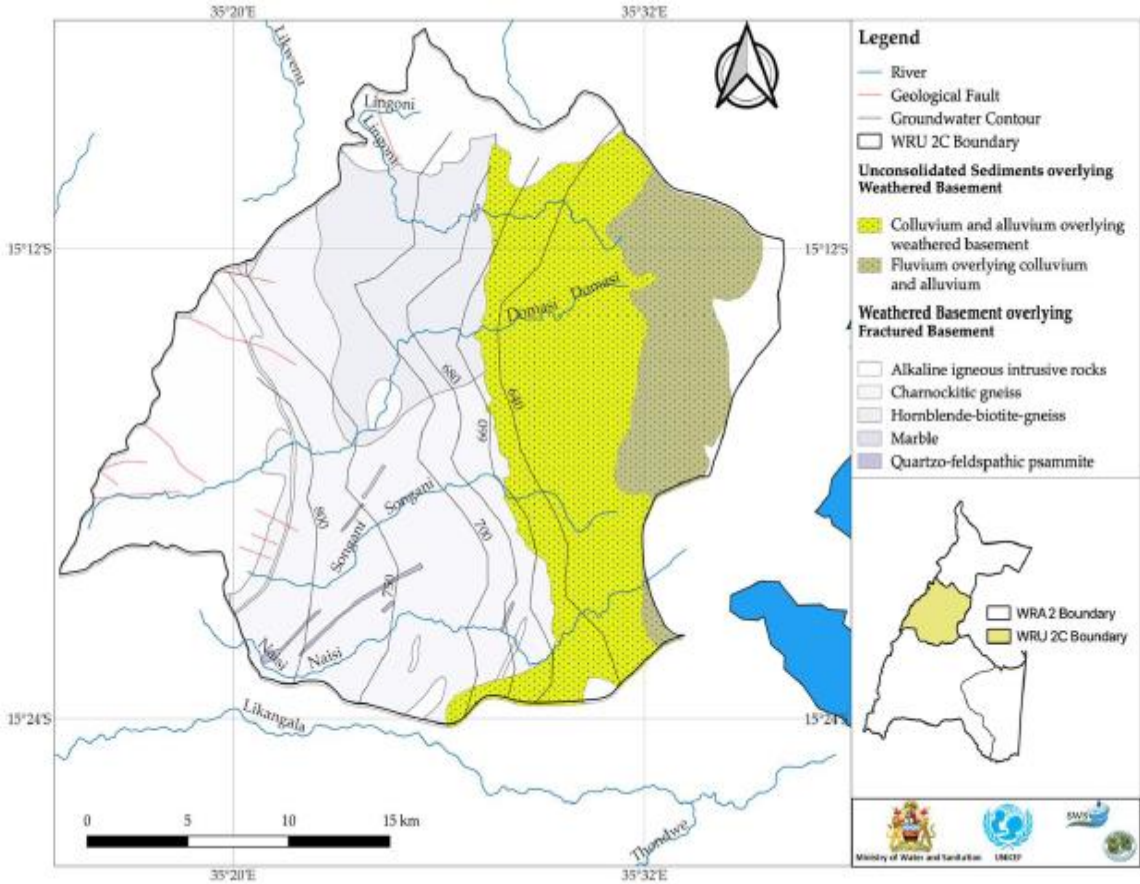


Figure 2: Hydrogeologic units of the study area (Source: Karlin et al., 2022)

2.0.MATERIALS AND METHODS

2.1 Sampling

To assess the groundwater quality, all 12 boreholes (Mphepo, Mpheta 1, Mpheta 2, Kachere School, Mpheta HQ, Mtambo HQ, Khweche, Chrombo, Chataika 1, Domasi HQ and Namasalima) and a shallow well (Chataika 2) located within and around the Domasi Irrigation Scheme were sampled. Sampling was carried out during the dry season between September and October 2021. Water samples were collected in polypropylene bottles. Samples meant for cation analysis were filtered through a 0.45 µm nylon to remove excess suspended solids before acidifying to a pH < 2 with high-purity nitric acid (Rice et al., 2012). Samples for analysis of anions were collected and stored in a mobile refrigerator. All samples were transported to the University of Malawi Laboratory for storage and analysis.

2.2 Sample analysis

Water quality variables analyzed, following standard methods of examination of water and wastewater (Rice et al., 2012), were pH, electrical conductivity (EC), turbidity, total dissolved solids (TDS), nitrate (NO_3^-), chloride (Cl^-), fluoride (F^-), carbonates (CO_3^{2-}), bicarbonates (HCO_3^-), total hardness (TH), sulfate (SO_4^{2-}), calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^+) and potassium (K^+). TDS, pH, EC and turbidity were analyzed in the field. TDS, EC and pH were measured by using a Hanna model HI-991300N pH/EC/TDS meter (Hanna Instruments Limited) after calibrating it as described by the manufacturer. The values were recorded as corrected to 25°C. Distilled water, pH 4 and pH 7 solutions were used in the calibration of the meter to ascertain accuracy. Turbidity measurement was also done using the OAKTON turbidimeter T-100 model after calibrating the meter with four recommended standards of 0.02NTU, 20.0NTU, 100NTU and 800NTU from the manufacturer. Chlorides, carbonates and total hardness were determined using titrimetric methods. Nitrates and fluorides were determined using an ion-selective electrode (ISE). All cations (Ca^{2+} , Mg^{2+} , Na^+) were analyzed using an Atomic Absorption Spectrophotometer (AAS, Agilent technologies). The concentration of sulphates in the water samples was determined turbidimetrically using precipitation using BaCl_2 .

2.3 Data Analysis

Physico-chemical parameters were compared to both Malawi Standards (MS 733: 2005) and international standards (WHO 2017) to check suitability for drinking purposes. Integrated Water Quality indices were used to provide an overall judgement of the suitability of water for drinking and irrigation purposes. Pearson correlation coefficient, principal component analysis (PCA), and Piper and Gibb's plots were used to describe relationships between variables, hydrogeological facies and controlling factors for the chemistry of water. Saturation index (SI), Chloro-alkaline Index (CAI), Reveille's Index (RI), and Na^+/Cl^- ratios were determined to further elucidate the underlying mechanisms contributing to the hydrogeochemistry of the groundwater.

3.0 RESULTS AND DISCUSSION

3.1 Observation and Consumer Perception

Consumers expressed quality satisfaction with water from Mpheta 2, Mtambo HQ, Chirombo, Chataika 2 and Domasi HQ water points. The salty taste was reported at Mphepo, Mpheta, Kachere School and Chataika 1. Consumers also reported the existence of muddy (turbid) water during the rainy season. Researcher observations were also recorded as provided in Table 1.

Table 1: Description of Waterpoints

WATERPOINT	ID	CONSUMER PERCEPTION	OBSERVATION
Mphepo	H1	Salty and muddy during the rainy season	Very low yield
Mpheta 1	H2	Very salty	Surrounding dirty
Kachere School	H3	Salty	Close to school toilets
Mpheta 2	H4	Good	Surrounding dirty
Mpheta HQ	H5	Muddy water during the rainy season	Poor civil works
Mtambo HQ	H6	Good,	Very close to latrine
Khweche	H7	Muddy and salty water during the rainy season	On rice farm
Chirombo	H8	Good	Close to a dysfunctional H6 which was 36m but yielded too salty water
Chataika 1	H9	Very salty	Only used in the rainy season, close to a graveyard and rice garden
Chataika 2	W10	good	Alternative to H9
Domasi HQ	H11	good	Located between two irrigation tunnels
Namasalima	H12	Metallic taste	Close to a cultivated area by the riverbank

Table 2: Results of Physico-chemical Parameters

ID/Parameter	Turb.	PH	EC	TDS	T. Alk.	CO ₃ ²⁻	HCO ₃ ⁻	F ⁻	NO ₃ ⁻	Cl ⁻	SO ₄ ²⁻	Mg ²⁺	Ca ²⁺	Na ⁺	K ⁺	TH
	NTU		mS/cm	(mg/l)	mg/lCaCO3	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/lCaCO3
H1	2.25	8.7	653	326	518	110	407	0.75	0.63	202	9.77	23.9	31.1	275	1.06	176
H2	1.04	9.1	761	380	575	131	434	0.43	0.85	224	7.15	30.1	37.7	332	1.09	218
H3	2.98	8.7	813	406	513	159	301	0.23	2.18	303	3.8	43.4	54.3	246	2.75	314
H4	0.53	8.6	262	131	383	71.8	321	0.63	0.87	51.6	2.58	8.7	9.6	109	0.64	59.7
H5	4.02	8.4	289	145	304	81.3	206	0.45	0.72	43.5	2.5	7.89	9.2	129	1.01	55.4
H6	0.68	7.7	339	170	350	142	138	0.44	0.82	24.2	18.51	8.34	11.21	166	2.04	62.4
H7	0.23	7.1	459	229	397	90.9	300	0.43	2.64	62	86.4	26.52	29.04	163	0.97	182
H8	0.15	7.0	684	342	460	105.2	348	1.01	0.86	203	59.36	34.04	41.68	241	1.48	244
H9	0.8	6.8	1004	502	536	92.3	466	0.59	0.97	322	133.7	49.81	65.99	379	1.66	370
W10	111	5.7	31.7	16	118	ND	144	0.53	1.26	9.7	20.38	10.8	11.33	8.27	1.38	72.8
H11	0.41	6.0	265	133	169	44.42	116	1.2	1.47	37.12	59.11	14.81	16.53	76.3	0.92	102
H12	1.63	5.6	121	60	156	46.47	96.58	0.23	1.26	16.88	6.01	10.73	9.99	27.4	0.35	69.2
Min.	0.15	5.6	31.7	16	118	44.42	96.58	0.23	0.63	9.7	2.5	7.89	9.2	8.27	0.35	55.4
Max.	111	9.1	1004	502	575	159	466	1.2	2.64	322	133.7	49.81	65.99	379	2.75	597
Mean	10.5	7.5	473.5	236.7	373.3	97.7	273.1	0.6	1.2	124.9	34.1	22.4	27.3	179.3	1.3	205.2
SD	31.7	1.3	303.9	151.8	158.2	36.8	129.9	0.3	0.6	117.2	42	14.6	19.4	117.3	0.6	161
MS 733:2005	25	6-9.5	3500	2000	-	-	-	6	45	750	800	200	250	500	-	800
WHO 2017	5	6-8.5	1000	500	500	75	150	1.5	50	250	250	150	200	250	12	200

ND: Not Detected T.Alk. : Total Alkalinity

3.2 Physico-Chemical Parameters

3.2.1 pH, Turbidity, Electrical Conductivity and Total Dissolved Solids

The analytical results, description of waterpoints and descriptive statistics of the physico-chemical parameters are summarized in Table 2. Samples in the study area showed elevated pH levels, ranging from 5.60 to 9.10 with a mean of 7.45. Noncompliance with local (MS 733:2005) and international guidelines (WHO 2017) existed for samples collected from Chataika 2 (W10) and Namasalima (H12) water points. The two water points registered pH values of 5.7 and 5.6 which are lower than the recommended minimum value of 6.0 (MS 2005). The low pH for W10 and H12 may be attributed to infiltration of surface water containing acidic species (Shigut et al., 2017). On the other hand, H1, H2, H2 and H4 registered slightly higher pH values above the maximum permissible limit for the World Health Organization. This trend can be attributed to high levels of carbonates in the area.

Turbidity is one of the important physical parameters for water quality, defining the presence of suspended solids in water and causing the muddy or turbid appearance of the water body (Tiwari et al., 2017). In the present study area, turbidity for boreholes and shallow wells ranged from 0.15 NTU to 111 NTU with a mean of 10.5NTU. Based on both Malawi standards and the World Health Organization guidelines, 92% of the groundwater samples complied with the guideline. The shallow well at W10 registered a turbidity value of 111NTU because the well is usually not covered and the water level was very low during sampling. However, this shallow well is preferred as it provides water which is not as saline as that from the Chataika 1 (H9) borehole located close by. Generally, groundwater from boreholes has very low turbidity levels. The high turbidity level registered for H5 (4.02NTU) suggests engineering problems resulting in leakage and short-circuiting of groundwater across the well casing and screen. This encourages water mixing during pumping.

Electrical conductivity at 25 °C for the Domasi Irrigation Scheme ranged from 31.7 to 1004 $\mu\text{S}/\text{cm}$ with a mean of 473.5 $\mu\text{S}/\text{cm}$. All the groundwater samples in this scheme fell under type I ($\text{EC} < 1500 \mu\text{S}/\text{cm}$). In terms of mineralization, 92% of the samples were very weakly mineralized while H9 was weakly mineralized ($\text{EC} = 1004 \mu\text{S}/\text{cm}$). Except for H9, all the groundwater samples fell below the recommended limit as guided by both local and international guidelines. Up to 76.9% of the groundwater samples in this study area showed low enrichment of salts and 23.1% showed medium enrichment of salts. In terms of mineralization (Rao, 2018), 76.9% of the samples were very weakly mineralized, 7.8% were weakly mineralized and 15.3% were slightly mineralized. Large variations in EC ($\text{SD} = 303.9$) can be attributed to geochemical processes such as ionic exchange, reverse exchange, evaporation, silicate weathering, rock–water interaction, sulphate reduction and oxidation processes, as well as anthropogenic activities (Ramesh & Elango, 2012).

TDS values ranged from 16 mg/L at W10 to 502 mg/L at H9. All the samples analyzed belonged to the freshwater category and were within the standard permissible limit as specified by Malawi Standards (2000 mg/L).

3.2.2 Magnesium, Calcium, Total Hardness and Carbonates

Concentrations of magnesium (Mg) and calcium (Ca) ions in water are beneficial to human health at some levels. Mortality mainly for cardiovascular, oncological diseases and diseases of the gastrointestinal and respiratory systems have been associated with increased ranges of calcium and magnesium (Rapant et al., 2017).

In the Domasi Irrigation Scheme, levels of magnesium ranged from 7.89 mg/L to 49.81 mg/L with a mean of 22.4mg/L. Thus, all the values fell below the maximum international guideline of 150mg/L (WHO 2017) and the local guideline of 200mg/L (MS 733: 2005). Calcium levels ranged from 9.2mg/L to 66mg/L with a mean of 27.3mg/l. All Calcium levels were below the maximum limits for both WHO guidelines and Malawi standards.

The hardness of groundwater results from the presence of divalent metallic cations of which concentrations of Ca^{2+} and Mg^{2+} are most abundant in groundwater (Nazzal et al., 2014). Water can be grouped into four classes from soft to very hard depending on the concentration levels of the cations. Therefore based on hardness, water is classified as soft, moderately hard, hard and very hard (Rawat et al., 2018) as illustrated in Table 3.

Table 3: Classification of Total Hardness ((Rawat et al., 2018)

Total Hardness (mgCaCO ₃ /L)	Waterpoints	Class
<60	Mpheta 2, Mpheta HQ, Namasalima (25.0%)	Soft water
60 -120	Mtambo HQ, Chataika 2, Domasi HQ (25.0%)	Moderately hard water
120-180	Mphepo (8.3%)	Hard water
>180	Mpheta 1, Kachere School, Khweche, Chirombo, Chataika 1 (41.7%)	Very hard water

3.2.3. Sodium and Potassium

The concentrations of sodium in the Domasi Irrigation Scheme varied from 8.27 to 379 mg/L with a mean of 179.3 mg/L. The maximum permissible limit of sodium is 250 mg/L (WHO 2017) and 500 mg/L for Malawi standards. While there was total compliance based on MS 733:2005, the WHO 2017 guideline was exceeded by 25% (3) of the analyzed samples. The concentrations of potassium fell below the WHO maximum permissible limit of 12mg/L (WHO 2017). Potassium concentration ranged from 0.04 mg/L to 3.80m/L with a mean of 1.28mg/L.

3.1.4. Chlorides and Fluorides

The higher concentration of chloride in water makes it hazardous to human health which is subjected to laxative effects (Ghalib, 2017; Maghrebi et al., 2021; Umadevi et al., 2021). Concentrations above 250mg/L can give rise to detectable taste in water. In the Domasi Irrigation Scheme, chloride levels ranged from 9.7mg/L to 322mg/L with an average of 125mg/L. Based on WHO guidelines there were exceedances above 250mg/L for Kachere School (303mg/L) and Chataika 1(322mg/L) boreholes.

Fluoride is one of the main trace elements in groundwater, which generally occurs as a natural constituent. All water points registered fluoride levels below the maximum permissible limits for Malawi standard (6mg/L) and WHO guideline (1.5mg/L). The levels of fluoride ranged from 0.23mg/L to 1.2mg/L with an average of 0.6mg/L.

3.1.5. Sulphates and nitrates

The presence of elevated sulfates in drinking water can cause noticeable taste, and very high levels might cause a laxative effect in unaccustomed consumers (Sharma & Kumar, 2020). Excessive use of fertilizers can lead to leaching of sulphates into groundwater. Sulphate concentrations for the Domasi Irrigation Scheme ranged from 2.5 mg/L to 133.7 mg/L with an average of 34.1mg/L. All the waterpoints in this scheme complied with both Malawi standard and WHO guidelines of 800mg/L and 250mg/L respectively.

Nitrate levels ranged from 0.63mg/L to 2.64mg/L with an average value of 1.21mg/L. Groundwater also contains nitrates due to leaching and percolation of water from the surface. Groundwater can also be contaminated by sewage and other wastes rich in nitrates (Shigut et al., 2017). Across the scheme, elevated levels were manifested at Kachere School (H3) and Khweche (H7) boreholes. This portrays the effect of sanitary facilities located close to the borehole at Kachere School. The elevated nitrate levels at Khweche are presumably due to both sanitary effects as well as agricultural influence from artificial fertilizers. The water points could be influenced by the leaching of nitrates from agricultural fertilizers and sanitary facilities. However, the major causative source of nitrate is anthropogenic activities such as agriculture (Adimalla & Li, 2019; Yu et al., 2020)

3.3 Hydrogeochemistry

3.3.1. Ion Dominance, Saltwater Intrusion and Cation Exchange

The dominance of cations in Domasi Irrigation Scheme was in the order $\text{Na} > \text{Ca} > \text{Mg} > \text{K}$ and that for anions was $\text{HCO}_3 > \text{Cl} > \text{CO}_3 > \text{SO}_4 > \text{NO}_3 > \text{F}$. Sodium in groundwater occurs from the dissolution of minerals or cation exchange or both. High sodium in groundwater could also result from sewage contamination and infiltration of agricultural runoff (Keesari et al., 2016). The major source of Ca^{2+} in groundwater is the ion exchange of minerals from the rocks in the area. The presence of Ca^{2+} could also be due to the presence of CaCO_3 and CaSO_4 minerals (calcite, dolomite, gypsum and anhydrite) in the soil (Zakaria et al., 2021). Bicarbonate (HCO_3^-) occurrence in groundwater could be an indication of the interaction of water with weathered granites and granitic gneisses. Chloride (Cl^-) occurrence in groundwater could result from anthropogenic activities such as the application of manure and chemical fertilizers, over-pumping of groundwater and leaching of chloride from topsoil during irrigation.

The possibility of saltwater intrusion (SWI) is supported by Na/Cl ratios less than 0.86, while anthropogenic sources of contamination are demonstrated by Na/Cl ratio > 1 (Bagus Eka Putra et al., 2020). In the area of study, the Na/Cl ratio ranged from 1.25 to 10.61 with an average of 3.23 indicating the contribution of anthropogenic influence on groundwater quality. Reveille's Index (RI) is another relevant parameter for determining seawater intrusion in groundwater samples as guided by Eq.1 where the parameters are in mEq/L.

$$RI = \frac{Cl}{(HCO_3 + CO_3)} \quad (1)$$

Reville's index, $RI > 1$ indicates an intrusion of salt water to the groundwater aquifers According to Reville (1941), RI values are classified into three categories; <0.5 mEq/L as unaffected by saltwater intrusion, 0.5- 6.6meq/l as slightly affected, and >6.6 -meq/l as strongly affected (Antony et al., 2020). In the areas of study, 83% of the waterpoints ruled out any possibility of saltwater intrusion.

Possible ion exchange in the study area was done through calculation of the chloralkaline indices 1 & 2 as in Eq. 2 and Eq. 3. When a sample yields negative indices for both CIA-1 and CAI-2, it shows cation ion exchange between sodium and potassium from water with calcium and magnesium in rock or soil, while positive chloralkaline indices indicate a reverse cation exchange of magnesium and calcium from water with sodium and potassium.

$$CAI - 1 = \frac{[Cl - (Na + K)]}{Cl} \quad (2)$$

$$CAI - 2 = \frac{[Cl - (Na + K)]}{(SO_4 + HCO_3 + CO_3 + NO_3)} \quad (3)$$

In the Domasi Irrigation Scheme, 100% of the water points indicated negative chloralkaline indices for both CAI-1 and CAI-2 revealing the likelihood of cation exchange between sodium and potassium from water with magnesium and calcium ions (Adimalla & Li, 2019).

3.3.2. Piper plots and Gibb's diagrams

Domasi Irrigation Scheme depicted that 92% (11) of the samples are sodium-bicarbonate waters, with 8% (1) of the samples being calcium-magnesium bicarbonate water type, implying that sodium and bicarbonates are the predominant ions in the groundwater (Figs 3 & 4). Gibb's diagrams (Fig. 5) revealed that generally rock weathering is the main process governing the chemistry of water. However, 8% of the water points showed that precipitation influenced the water chemistry due to reduced concentration of TDS resulting from the dilution effect coming from infiltrating rainfall.

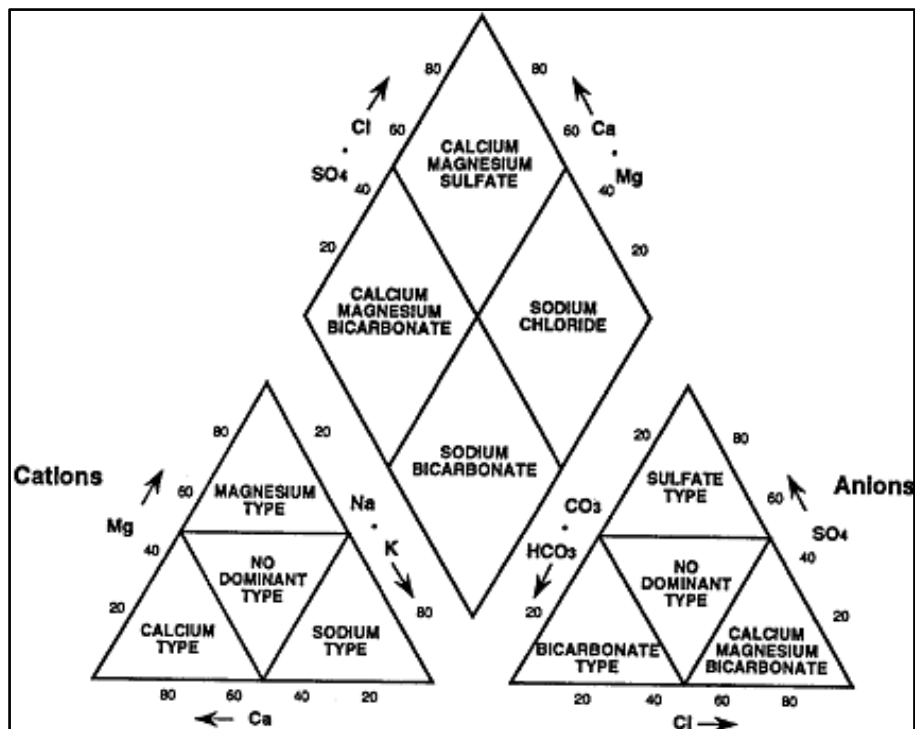


Figure 3: Interpretation of Piper plots(Source: Musa & Omali, 2014)

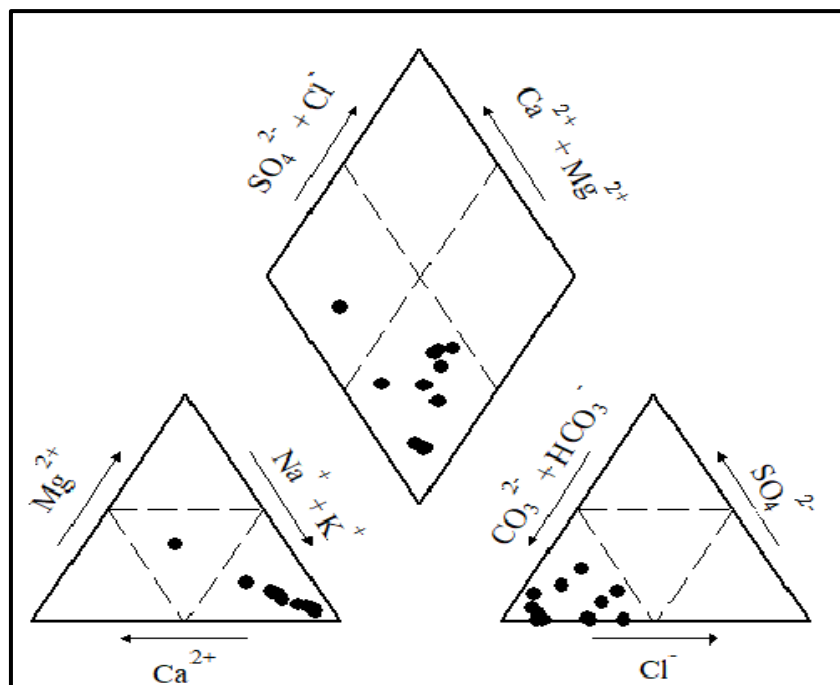


Figure 4: Piper plot for Domasi Irrigation Scheme

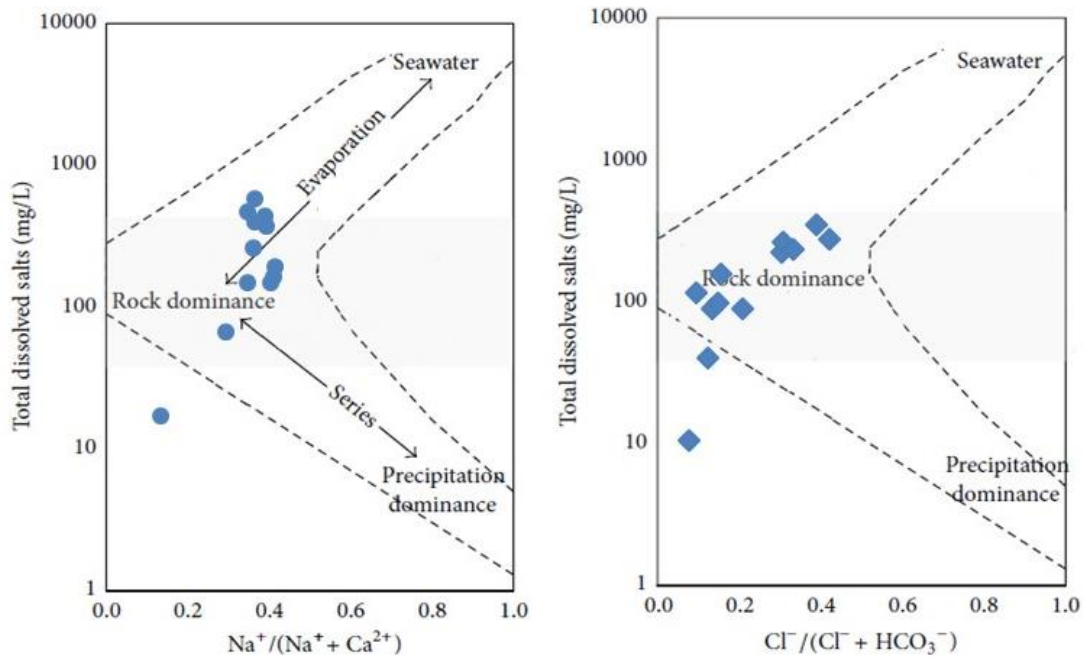


Figure 5: Gibb's Diagram for Domasi Irrigation Scheme

3.3.3. Correlation matrix

The correlation between any two parameters is summarized in Table 4 with a correlation value greater than 0.5 considered significant (Ahmed et al., 2019). Total Dissolved Solids (TDS) were found to be very highly correlated with Chlorides ($r = 0.96$), Magnesium (0.928), Calcium (0.942), Total hardness (0.935), Alkalinity ($r = 0.910$) and Sodium (0.967). TDS was highly correlated with bicarbonates ($r = 0.852$) and Carbonates ($r = 0.706$). Such strong relationships with TDS entail that the salinity load in the study area is controlled by Cl, Ca, Na, K and Mg which mainly depend on mineral solubility, mineral dissolution, ion exchange, evaporation and anthropogenic activities (El Ghali et al., 2020). Similarly, a high positive correlation between Na and Cl ($r = 0.894$) is indicative of the presence of high saline groundwater and groundwater intermixing in the study area. There is a positive correlation between pH and carbonates due to the basic nature of bicarbonates.

Calcium correlated highly with both bicarbonate ($r = 0.754$) and total hardness since total hardness is an approximate measure of calcium and magnesium and is expressed as the amount of calcium carbonate. Therefore, the correlation between total hardness and carbonates can be explained by the dissolution of calcite and dolomite. As calcite and dolomite dissolve, the concentrations of magnesium, calcium and carbonates increase increasing total hardness and total dissolved solids. Similarly, the correlation between calcium and sulphates suggests the possible dissolution of gypsum and agricultural sources through the continuous application of fertilizers (Li et al., 2013).

Table 4: Correlation Matrix for Physico-Chemical Parameter

	pH	Turb.	TDS	CO ₃	HCO ₃	F	NO ₃	Cl	SO ₄	Mg	Ca	TH	Na	K
pH	1.000													
Turb.	-0.433	1.000												
TDS	0.463	-0.458	1.000											
CO ₃	0.741	-0.619	0.706	1.000										
HCO ₃	0.574	-0.315	0.852	0.497	1.000									
F	-0.200	-0.066	0.016	-0.252	0.045	1.000								
NO ₃	-0.227	0.021	0.010	0.026	-0.146	-0.257	1.000							
Cl	0.414	-0.305	0.960	0.611	0.816	-0.023	-0.001	1.000						
SO ₄	-0.411	-0.122	0.431	-0.083	0.326	0.337	0.256	0.319	1.000					
Mg	0.197	-0.245	0.928	0.507	0.747	0.013	0.259	0.936	0.563	1.000				
Ca	0.206	-0.261	0.942	0.522	0.754	-0.001	0.191	0.953	0.552	0.996	1.000			
TH	0.201	-0.252	0.935	0.514	0.751	0.007	0.229	0.945	0.559	0.999	0.999	1.000		
Na	0.553	-0.460	0.967	0.721	0.888	0.009	-0.160	0.894	0.372	0.823	0.847	0.834	1.000	
K	0.252	0.056	0.506	0.610	0.167	-0.190	0.213	0.538	0.082	0.548	0.553	0.551	0.421	1.000

3.3.4. Principal Component Analysis

Principal component analysis is a statistical method designed to analyze the interrelationships within a set of variables by reducing the complex information to an easily interpretable form (Selvakumar et al., 2017). Principal component analysis (PCA) using Varimax rotation with Kaiser Normalization was carried out using *SPSS Statistics 20* to establish the variables related to the principal components. This helped to identify and characterize the factors that affect the hydrochemical composition of the study area. The PCA results comprising the loadings, eigenvalues, and percentages of total variance are summarized in Table 5. Loading close to ± 1.00 indicates a strong correlation between a parameter and the component or factor. Loading greater than ± 0.75 is considered strongly correlated, while loadings between ± 0.50 and ± 0.74 are moderately correlated. A weak correlation implies any loadings between 0 and ± 0.50 (Mohapatra et al., 2011)

In the study area, four factors explain 92.13 % of the total variance in the dataset. PC-1, which explained 57.26 % of the total variance, had strong positive loadings on calcium, magnesium, sodium, total dissolved solids, carbonates, bicarbonates, sulphates and chlorides as well as manganese. This suggests that PC-1 is related to the dissolution or precipitation of carbonate/sulphate minerals. PC-2 contributes 14.11% of the variance and has positive loadings with pH and carbonates but with a negative loading for sulphates. Sulphate ions in the water are partly because of the dissolution of gypsum and from inorganic fertilizers. PC-3 has positive loading with potassium (K), confirming the effect of agricultural fertilizers such as NPK in the study area. The deficiency of sulphate ions suggests water has relatively more cations of magnesium and calcium in the groundwater. However, the availability of more calcium ions from calcite will result in a rise in pH due to carbonates. The only source of nitrogen is from anthropogenic pollution. Therefore, a decrease in nitrates (PC- 4) is suggestive of a dilution effect in the groundwater.

Table 5: Varimax Rotated Principal Component Analysis for Water Samples

Parameter	PC-1	PC-2	PC-3	PC-4
TH	0.97	-0.127	0.13	-0.121
Ca	0.969	-0.12	0.141	-0.093
Mg	0.968	-0.132	0.122	-0.144
TDS	0.967	0.127	0.169	0.072
Cl	0.952	0.123	0.098	0.023
Na	0.908	0.228	0.154	0.223
HCO₃	0.88	0.253	-0.21	0.224
pH	0.343	0.894	0.089	0.134
SO₄	0.515	-0.733	0.07	0.000
CO₃	0.555	0.583	0.5	-0.008
K	0.414	0.1	0.799	-0.244
NO₃	0.118	-0.206	0.016	-0.914
Eigenvalues	8.589	2.237	1.71	1.283
% Variance	57.26	14.911	11.4	8.554
Cumulative	57.26	72.17	83.57	92.13

3.3.5. Saturation Index

The hydrogeochemical equilibrium model, PHREEQC interactive 3.5.0 -14000, was used to calculate the saturation indices of the groundwater samples collected in this study (Appelo & Postma, 2010). However, closer attention was given to minerals containing the major cations (Ca^{2+} , Mg^{2+} , Na^+ , K^+) and anions (CO_3^{2-} , SO_4^{2-} , Cl^- , F^-). Saturation indices for aragonite, calcite, dolomite, fluorite, gypsum, anhydrite, halite and sylvite are summarized in Table 7. Super-saturation ($\text{SI} > 0$) necessitates precipitation of the species from the solution (Aghazadeh et al., 2021). A solution with $\text{SI} = 0 \pm 0.5$ is considered to be at equilibrium condition (Chidambaram et al., 2012)

The supersaturation of carbonate minerals in the Domasi Irrigation Scheme was observed with dolomite, calcite and aragonite for H1, H2, H3 and H4. The order of supersaturation was calcite > aragonite > dolomite for 25% of the samples (W10, H11, H12). The rest of the groundwater samples indicated undersaturation for aragonite, calcite and dolomite as summarized in Table 6.

Table 6: Saturation Indices for Some Minerals

	ARAGONITE	CALCITE	DOLOMITE	FLUORITE	GYPSUM	ANHYDRITE	HALITE	SYLVITE
SAMPLE	CaCO ₃	CaCO ₃	CaMg(CO ₃) ₂	CaF ₂	CaSO ₄ ·2H ₂ O	CaSO ₄	NaCl	KCl
H1	1.02	1.16	2.30	-1.94	-1.95	-2.25	-9.32	-10.35
H2	1.39	1.53	2.83	-2.40	-1.89	-2.20	-9.11	-10.21
H3	1.14	1.29	1.87	-2.70	-1.53	-1.83	-8.54	-9.40
H4	0.48	0.62	1.08	-2.37	-2.79	-3.09	-9.65	-10.38
H5	0.15	0.29	0.45	-2.68	-2.86	-3.17	-9.75	-10.27
H6	-0.50	-0.36	-0.02	-2.68	-3.12	-3.43	-9.61	-9.91
H7	-0.60	-0.46	-0.06	-2.36	-2.39	-2.69	-8.71	-9.75
H8	-0.39	-0.25	0.09	-1.52	-1.79	-2.10	-9.05	-10.07
H9	-0.71	-0.57	-0.36	-1.96	-1.57	-1.87	-8.83	-9.99
W10	-3.31	-3.16	-5.70	-2.28	-3.26	-3.57	-9.38	-9.86
H11	-2.65	-2.51	-4.07	-1.59	-2.73	-3.03	-9.18	-10.00
H12	-3.58	-3.43	-6.63	-3.10	-3.12	-3.42	-9.43	-10.45

3.4 Suitability for Irrigation Purposes

Different parameters were used to assess the suitability of the groundwater for irrigation purposes. Ten (10) parameters were used to assess the suitability of the groundwater for irrigation purposes. The units for parameters used to calculate sodium absorption ratio (SAR), sodium hazard (Na%), magnesium hazard (MH), Kelly ratio (KR), permeability index (PI) and residual sodium carbonate (RSC) were in milliequivalents/L. The results are summarized in Table 7.

Table 7: Irrigation Parameter Assessment Scores

WATERPOINT	ID	PH	TDS	Ca	Mg	SAR	Na%	RSC	PI	KR	MH
Mphepo	H1	✖	✓	✖	✖	✓	✓	✓	✓	✖	✖
Mpheta 1	H2	✖	✓	✖	✖	✓	✓	✓	✓	✖	✖
Kachere School	H3	✖	✓	✖	✖	✓	✓	✓	✓	✓	✖
Mpheta 2	H4	✖	✓	✓	✓	✓	✓	✓	✓	✖	✖
Mpheta HQ	H5	✓	✓	✖	✓	✓	✖	✓	✓	✖	✖
Mtambo HQ	H6	✓	✓	✖	✖	✓	✖	✖	✓	✖	✖
Khweche	H7	✓	✓	✖	✖	✓	✓	✓	✓	✓	✖
Chirombo	H8	✓	✓	✓	✓	✓	✓	✓	✓	✖	✖
Chataika 1	H9	✓	✓	✓	✓	✓	✓	✓	✓	✖	✖
Chataika 2	W10	✓	✓	✖	✖	✓	✓	✓	✓	✓	✖
Domasi HQ	H11	✓	✓	✖	✖	✓	✓	✓	✓	✓	✖
Namasalima	H12	✓	✓	✖	✖	✓	✓	✓	✓	✓	✖
Overall (%)		75	100	25	33	100	83	92	100	42	0

✓: Recommended

✖ : Not recommended

3.4.1. pH and Total Dissolved Solids

Higher pH values of more than 8.5 increase carbonate content in the soils, which causes soil sodicity hence not preferred for irrigation purposes (Bauder et al., 2011). Mphepo, Mpheta 1, Kachere School and Mpheta 2 boreholes had pH values above 8.5. A value of more than 2000mg/L of total dissolved solids is not fit for agricultural use (Aravinthasamy et al., 2020). All groundwater samples in the study area fell within acceptable TDS values for irrigation purposes.

3.4.2. Calcium, Magnesium and Sodium Absorption Ratio (SAR)

Calcium and magnesium are important elements for plant growth. However, for irrigation purposes, they should not exceed the ranges of 40 - 100 mg/L and 30-50 mg/L for calcium and magnesium respectively (Adhikary et al. 2009). Only 25% of the samples in the Domasi Irrigation Scheme (H4, H8, H9) fell within the recommended range for calcium for irrigation purposes. For magnesium levels, 33.3% of water points (H4, H5, H8, H9) fell within the recommended range for magnesium ion concentration. Such instances would require the incorporation of natural or artificial fertilizers into the soil.

Sodium adsorption ratio (SAR) is one of the most vital irrigation suitability indicators which measures the relative proportion of sodium ions in a water sample to those of calcium and magnesium (Eq 4).

$$SAR = \frac{Na^+}{\sqrt{\frac{(Ca^{2+} + Mg^{2+})}{2}}} \quad (4)$$

When Sodium increases replacing Ca^{2+} and Mg^{2+} , that soil turns into hard soil and reduces soil permeability (Kaur et al., 2017; Roy et al., 2018). The groundwater quality can be classified into four categories based on the sodium absorption ratio excellent for irrigation ($SAR < 10$), good ($10 \leq SAR < 18$), doubtful ($18 \leq SAR < 26$) and unsuitable ($SAR \geq 26$). In the area under study, all the groundwater samples fell under the excellent category for irrigation based on SAR.

3.4.3. Sodium Hazard (Na %)

The surplus amount of sodium with carbonate ions in water will help to convert the soil into alkaline soil. Sodium hazard is expressed as a percentage using Eq 5.

$$Na \% = \frac{Na^+ \times 100}{(Ca^{2+} + Mg^{2+} + Na^+ + K^+)} \quad (5)$$

Sodium mixed with chloride ions will accelerate the formation of saline soil, which ultimately deteriorates the infiltration capacity of the soil and reduces plant growth (Rao and Latha, 2019). According to Sutradhar & Mondal, 2021, Sodium hazard has been classified into five categories; excellent ($Na\% < 20$), good ($20 \leq Na\% < 40$), permissible ($40 \leq Na\% < 60$), doubtful ($60 \leq Na\% < 80$) and unsafe ($Na\% \geq 80$). In the area under study, 16.7% (H5 and H6) belong to the unsafe category for irrigation purposes.

3.4.4. Residual Sodium Carbonate

Residual sodium carbonate (RSC) is an index for the measurement of the sodicity hazard of irrigation water as presented in Eq. 6. The RSC describes the amount of sodium carbonate ($NaCO_3$) and sodium bicarbonate ($NaHCO_3$) present in the irrigation water (Rawat et al., 2018).

$$RSC = (HCO_3^- + CO_3^{2+}) + (Ca^{2+} + Mg^{2+}) \quad (6)$$

The high concentration of sodicity enhances the pH level of the groundwater, which causes the dissolution of organic matter (Singaraja, 2017). Based on the RSC range, sodicity hazard has been classified into three classes; low ($RSC < 1.25$), medium ($1.25 - 2.5$) and high (> 2.5) (Sutradhar & Mondal, 2021). Low RSC is good while medium RSC is doubtful for irrigation purposes implying that this condition is unsatisfactory for most crops. Only Mtambo HQ borehole (H6) was found unsuitable for irrigation purposes based on RSC ($RSC = 3.51$).

3.4.5. Permeability index (PI)

The permeability index (PI) is an indicator to study the suitability of water for irrigation purposes as a percentage. The capability of water to move into the soil is influenced by its salt concentration and by the long-term use of irrigation water with high concentrations of sodium, calcium, magnesium and bicarbonates (Eq. 7).

$$PI = \frac{(Na^+ + \sqrt{HCO_3^-}) \times 100}{(Ca^{2+} + Mg^{2+} + Na^+ + K^+)} \quad (7)$$

The greater the total concentrations of sodium, calcium, magnesium and bicarbonates, the smaller the PI value. Thus, continuous utilization of groundwater with these ions may deteriorate soil quality and affect seed growth (Xu et al., 2019). According to Doneen (1964), PI can be categorized into three classes: class I ($> 75\%$, suitable), class II ($25 - 75\%$, good) and class III ($< 25\%$, unsuitable). All the water points in the Domasi scheme were fit for irrigation purposes based on the permeability index ($PI > 25\%$).

3.4.6. Kelly Ratio (KR)

Kelly ratio defines the hazardous impact of sodium on irrigation water quality (Kelly, 1963). The Kelly ratio evaluates irrigation water quality based on sodium ions against calcium and magnesium ions (Rawat et al., 2018). It is simply a ratio of sodium concentration to the total concentration of calcium and magnesium ions (Eq. 8).

$$KR = \frac{Na^+}{Ca^{2+} + Mg^{2+}} \quad (8)$$

$KR > 1$ indicates an excess level of Na^+ in waters. Kelley ratio having less than 1 is suitable for irrigation, 1 to 2 is marginally suitable, and more than 2 is unsuitable for irrigation (Ramesh & Elango, 2012; Sutradhar & Mondal, 2021). In the Domasi Irrigation Scheme, 58.3% of the samples fell in the unsuitable category (H1, H2, H4, H5, H6, H8, H9).

3.4.7. Magnesium Hazard (MH)

The high degree of magnesium hazard hampers the physical properties of soil. Magnesium hazard relates the proportion of magnesium to the ionic concentrations of both magnesium and calcium (Eq. 9).

$$MH = \frac{(Mg^{2+} \times 100)}{(Mg^{2+} + Ca^{2+})} \quad (9)$$

The higher amount of magnesium concentration in irrigation water leads to an increase in the alkalinity of soil and affects crop yields. An increase in the concentrations of magnesium results in a decrease in the availability of phosphorous for crop growth. MH >50 is not recommended for irrigation purposes (Khodapanah et al., 2009). In the study area, MH ranged from 55% to 64% implying that all the groundwater samples (100%) were unsuitable for irrigation purposes. Increasing the calcium levels in the soil through organic and inorganic fertilizers would help reduce the magnesium hazard ratio in the soil.

4.0 CONCLUSION

The study revealed that groundwater in the Domasi Irrigation Scheme is predominantly of sodium-bicarbonate type. The chemistry of the groundwater in this area is governed by geologic processes, anthropogenic activities and ion exchange. The study could not confirm the effect of saltwater intrusion from the saline Lake Chilwa, presumably due to the distance from the lake that has receded during this dry season. The groundwater for the Domasi irrigation scheme was found to be generally undersaturated thereby encouraging rock dissolution. However, the study revealed that the northeastern part of the scheme was supersaturated for carbonate minerals such as aragonite, calcite and dolomite.

The groundwater for the Domasi Irrigation Scheme is suitable for drinking purposes based on parameters of health concerns such as nitrates and fluorides by Malawi standard MS 733:2005. The study however revealed noncompliance to WHO guidelines observed for some water points for sodium, carbonates, bicarbonates, and turbidity. However, these parameters are not of great and serious concern to human health implications (WHO 2017) and can be rectified by treating the water before consumption.

Although it was observed during the study that there was very minimal utilization of groundwater for irrigation purposes, the groundwater is suitable for irrigation purposes. The study, however, implicated poor levels of calcium and magnesium as limiting factors in using the water for irrigation purposes. The study therefore recommends utilization of organic and inorganic manure when using the groundwater for irrigation purposes.

A study done by Mlangeni, A. et al (2022) found that most paddy sites in Malawi, including that of Domasi Irrigation Scheme, are of high quality to produce rice safe from toxic metal(oids) and recommended further research on irrigation water sources. This research findings on groundwater quality invite more research on how to technologically exploit the groundwater in this area to be used for irrigation purposes during the dry season to maximize food security. There is also a need to do soil chemistry research that would guide suitability for other types of crops besides rice.

Declaration of competing interest

The authors declare that there is no conflict of interest.

Acknowledgements

Furthermore, I would like to acknowledge with much appreciation the financial aid provided by the Water Research Fund for Southern Africa (WARFSA) for financially supporting this research project.

REFERENCES

1. Adhikary, P. P., Chandrasekharan, H., Chakraborty, D., Kumar, B., & Yadav, B. R. (2009). Statistical approaches for hydrogeochemical characterization of groundwater in West Delhi, India. *Environmental monitoring and assessment*, 154, 41-52.
2. Adimalla, N., & Li, P. (2019). Occurrence, health risks, and geochemical mechanisms of fluoride and nitrate in groundwater of the rock-dominant semi-arid region, Telangana State, India. *Human and Ecological Risk Assessment: An International Journal*, 25(1-2), 81-103. <https://doi.org/10.1080/10807039.2018.1480353>
3. Aggarwal, A., Soni, J., Sharma, K., Sapra, M., Chitrakshi, Karaca, O., & Haritash, A. K. (2021). Hydrogeochemical assessment of groundwater for drinking and agricultural use: a case study of rural areas of Alwar, Rajasthan. *Environmental Management*, 67, 513-521. <https://doi.org/10.1007/s00267-020-01361-x>
4. Aghazadeh, V., Shayanfar, S., & Hassanpour, P. (2021). Aluminum hydroxide crystallization from aluminate solution using carbon dioxide gas: effect of pH and seeding. *Mineral Processing and Extractive Metallurgy*, 130(3), 218-224. <https://doi.org/10.1080/25726641.2019.1599601>
5. Ahmed, N., Bodrud-Doza, M., Islam, S. D. U., Choudhry, M. A., Muhib, M. I., Zahid, A., ... & Bhuiyan, M. A. Q. (2019). Hydrogeochemical evaluation and statistical analysis of groundwater of Sylhet, north-eastern Bangladesh. *Acta Geochimica*, 38, 440-455. <https://doi.org/10.1007/s11631-018-0303-6>
6. Appelo, C. A. J., & Postma, D. (2004). *Geochemistry, groundwater and pollution*. CRC press.
7. Aravinthasamy, P., Karunanidhi, D., Subba Rao, N., Subramani, T., & Srinivasamoorthy, K. (2020). Irrigation risk assessment of groundwater in a non-perennial river basin of South India: implication from irrigation water quality index (IWQI) and geographical information system (GIS) approaches. *Arabian Journal of Geosciences*, 13, 1-14. <https://doi.org/10.1007/s12517-020-06103-1>
8. Avidar, O. (2024). A holistic framework for evaluating and planning sustainable rural drinking water projects in sub-Saharan Africa. *Journal of Rural Studies*, 107, 103243.

9. Bandason, E., Pemba, D., Chiotha, S., Dudley, C., & Mzilahowa, T. (2014). Hydro-Physicochemical Changes in Domasi River Associated with Outbreak of Blackflies (Diptera; Simuliidae) in Zomba, Malawi. *Malawi Journal of Science and Technology*, 10(1), 1-7.
10. Chafuwa, C. (2017). Priorities for Irrigation Investment in Malawi: Strategy Support Program Policy Note (28). *International Food Policy Research Institute*. https://massp.ifpri.info/files/2017/08/MaSSP-Policy-Note-28-_Irrigation-formatted-revised.pdf
11. Chidambaram, S., Anandhan, P., Prasanna, M. V., Ramanathan, Al., Srinivasamoorthy, K., & Senthil Kumar, G. (2012). Hydrogeochemical Modelling for Groundwater in Neyveli Aquifer, Tamil Nadu, India, Using PHREEQC: A Case Study. *Natural Resources Research*, 21(3), 311–324. <https://doi.org/10.1007/s11053-012-9180-6>
12. Chilivumbo, A. (1971). The Response to Planned Change: A Study of the Rice Scheme in Chief Mwambo's Area (Lake Chilwa, Zomba, Malawi). *Cahiers d'études Africaines*, 11(42), 314–326. <https://doi.org/10.3406/cea.1971.2807>
13. Doneen, L.D. (1964). Water quality for agriculture, Department of Irrigation. University of California. Davis: p48
14. El Ghali, T., Marah, H., Qurtobi, M., Raibi, F., Bellarbi, M., Amenouz, N., & El Mansouri, B. (2020). Geochemical and isotopic characterization of groundwater and identification of hydrogeochemical processes in the Berrechid aquifer of central Morocco. *Carbonates and Evaporites*, 35(2), 37. <https://doi.org/10.1007/s13146-020-00571-y>
15. Ferguson, A. E., & Mulwafu, W. O. (n.d.). *Irrigation Reform on Malawi's Domasi and Linkangala Smallholder Irrigation Schemes*. 32.
16. Garside, P. (2010). Irrigation Management Transfer in Malawi: A Case Study on the Process of Irrigation Management Transfer on Domasi Irrigation Scheme in Southern Malawi (Unpublished master's thesis) Wageningen University, The Netherlands
17. Ghalib, H. B. (2017). Groundwater chemistry evaluation for drinking and irrigation utilities in east Wasit province, Central Iraq. *Applied Water Science*, 7(7), 3447–3467. <https://doi.org/10.1007/s13201-017-0575-8>
18. Hinton, R., Smilovic, M., Fridman, D., Willaarts, B., Banda, L., Macleod, K., ... & Kalin, R. (2024). A stakeholder-driven, holistic water resources model for Malawi: applying the CWatM hydrological model (No. EGU24-5783). Copernicus Meetings.
19. Kaur, T., Bhardwaj, R., & Arora, S. (2017). Assessment of groundwater quality for drinking and irrigation purposes using hadrochemical studies in Malwa region, southwestern part of Punjab, India. *Applied Water Science*, 7, 3301-3316
20. Kalin, R. M., Mleta, P., Addison, M. J., Banda, L. C., Butao, Z., Nkhata, M., ... & Hinton, R. (2022). Hydrogeology and Groundwater Quality Atlas of Malawi: Water Resource Area 2: Lake Chilwa Catchment.
21. Kambombe, O., Ngongondo, C., Eneya, L., Monjerezi, M., & Boyce, C. (2021). Spatio-temporal analysis of droughts in the Lake Chilwa Basin, Malawi. *Theoretical and Applied Climatology*, 144(3–4), 1219–1231. <https://doi.org/10.1007/s00704-021-03586-0>
22. Keesari, T., Ramakumar, K. L., Chidambaram, S., Pethperumal, S., & Thilagavathi, R. (2016). Understanding the hydrochemical behaviour of groundwater and its suitability for drinking and agricultural purposes in Pondicherry area, South India – A step towards sustainable development. *Groundwater for Sustainable Development*, 2–3, 143–153. <https://doi.org/10.1016/j.gsd.2016.08.001>
23. Kelly, W.P. (1963). Use of saline irrigation water. *Soil Science* 95(4), 355-391.
24. Khodapanah, L., Sulaiman W.N.A., & Khodapanah, N. (2009) Groundwater quality assessment for different purposes in Eshtehard district, Tehran, Iran; *European Journal of Scientific Research*.36(4).543-553
25. Khondoker, M., Mandal, S., Gurav, R., & Hwang, S. (2023). Freshwater shortage, salinity increase, and global food production: A need for sustainable Irrigation water desalination—A scoping review. *Earth*, 4(2), 223-240.
26. Kuntumanji, G., Sajidu, S., & Namangale, J. (2024). Groundwater Evaluation in a Rain-Fed Likangala Irrigation Scheme in Malawi. *Malawi Journal of Science and Technology*, 16(1), 33-61.
27. Maghrebi, M., Noori, R., Partani, S., Araghi, A., Barati, R., Farnoush, H., & Torabi Haghighi, A. (2021). Iran's Groundwater Hydrochemistry. *Earth and Space Science*, 8(8). <https://doi.org/10.1029/2021EA001793>
28. Mlangeni, A. T., Raab, A., Kumambala, P., Monjerezi, M., Matumba, L., & Feldmann, J. (2022). Evaluation of Metal(loids) Concentrations in Soils of Selected Rice Paddy

- Fields in Malawi. *Agronomy*, 12(10), 2349. <https://doi.org/10.3390/agronomy12102349>
29. Mohapatra, P. K., Vijay, R., Pujari, P. R., Sundaray, S. K., & Mohanty, B. P. (2011). Determination of processes affecting groundwater quality in the coastal aquifer beneath Puri city, India: A multivariate statistical approach. *Water Science and Technology*, 64(4), 809–817. <https://doi.org/10.2166/wst.2011.605>
30. Mukate, S., Wagh, V., Panaskar, D., Jacobs, J. A., & Sawant, A. (2019). Development of a new integrated water quality index (IWQI) model to evaluate the drinking suitability of water. *Ecological Indicators*, 101, 348–354. <https://doi.org/10.1016/j.ecolind.2019.01.034>
31. Musa, O. K., Kudamnya, E. A., Omali, A. O., & Akuh, T. I. (2014). Physico-chemical characteristics of surface and groundwater in Obajana and its environs in Kogi state, Central Nigeria. *African Journal of Environmental Science and Technology*, 8(9), 521-531.
32. Mussa, C., Biswick, T., Changadeya, W., Junginger, A., & Vunain, E. (2019). *Levels and Spatial Distribution of Heavy Metals in Lake Chilwa Catchment, Southern Malawi*. 8.
33. Nazzal, Y., Ahmed, I., Al-Arifi, N. S. N., Ghrefat, H., Zaidi, F. K., El-Waheidi, M. M., Batayneh, A., & Zumlot, T. (2014). A pragmatic approach to studying the groundwater quality suitability for domestic and agricultural usage, Saq aquifer, northwest of Saudi Arabia. *Environmental Monitoring and Assessment*, 186(8), 4655–4667. <https://doi.org/10.1007/s10661-014-3728-3>
34. Nkhoma, B. (2011). Irrigation development and its socioeconomic impact on rural communities in Malawi. *Development Southern Africa*, 28(2), 209–223. <https://doi.org/10.1080/0376835X.2011.570068>
35. Rajmohan, N., Masoud, M. H. Z., & Niyazi, B. A. M. (2021). Assessment of groundwater quality and associated health risk in the arid environment, Western Saudi Arabia. *Environmental Science and Pollution Research*, 28(8), 9628–9646. <https://doi.org/10.1007/s11356-020-11383-x>
36. Ramesh, K., & Elango, L. (2012). Groundwater quality and its suitability for domestic and agricultural use in the Tondiar River basin, Tamil Nadu, India. *Environmental Monitoring and Assessment*, 184(6), 3887–3899. <https://doi.org/10.1007/s10661-011-2231-3>
37. Rao, K.N. & Latha, P.S. (2019). Groundwater quality assessment using water quality index with a special focus on vulnerable tribal region of Eastern Ghats hard rock terrain, Southern India. *Arabian Journal of Geosciences*, 12(8), 267.
38. Rao, S.N. (2018). Groundwater quality from a part of Prakasam District, Andhra Pradesh, India. *Applied Water Science*, 8(1), 30. <https://doi.org/10.1007/s13201-018-0665-2>
39. Rapant, S., Cvečková, V., Fajčíková, K., Sedláková, D., & Stehlíková, B. (2017). Impact of Calcium and Magnesium in Groundwater and Drinking Water on the Health of Inhabitants of the Slovak Republic. *International Journal of Environmental Research and Public Health*, 14(3), 278. <https://doi.org/10.3390/ijerph14030278>
40. Rawat, K. S., Singh, S. K., & Gautam, S. K. (2018). Assessment of groundwater quality for irrigation use: A peninsular case study. *Applied Water Science*, 8(8), 233. <https://doi.org/10.1007/s13201-018-0866-8>
41. Rice, E. W., Bridgewater, L., & American Public Health Association (Eds.). (2012). *Standard methods for the examination of water and wastewater* (Vol. 10). Washington, DC: American Public Health Association (APHA).
42. Rivett, M. O., Symon, S., Jacobs, L., Banda, L. C., Wanangwa, G. J., Robertson, D. J. C., Hassan, I., Miller, A. V. M., Chavula, G. M. S., Songola, C. E., Mbemba, C., Addison, M. J., Kalonga, P., Kachiwanda, Y., & Kalin, R. M. (2020). Paleo-Geohydrology of Lake Chilwa, Malawi is the Source of Localised Groundwater Salinity and Rural Water Supply Challenges. *Applied Sciences*, 10(19), 6909. <https://doi.org/10.3390/app10196909>
43. Roy, A., Keesari, T., Mohokar, H., Sinha, U. K., & Bitra, S. (2018). Assessment of groundwater quality in hard rock aquifer of central Telangana state for drinking and agriculture purposes. *Applied Water Science*, 8, 1-18.
44. Ruidas, D., Pal, S. C., Chowdhuri, I., Saha, A., Biswas, T., Islam, A. R. M. T., & Shit, M. (2023). Hydrogeochemical evaluation for human health risk assessment from contamination of coastal groundwater aquifers of Indo-Bangladesh Ramsar site. *Journal of Cleaner Production*, 399, 136647.
45. Selvakumar, S., Ramkumar, K., Chandrasekar, N., Magesh, N. S., & Kaliraj, S. (2017). Groundwater quality and its suitability for drinking and irrigational use in the Southern Tiruchirappalli district, Tamil Nadu, India. *Applied Water*

- Science*, 7(1), 411–420. <https://doi.org/10.1007/s13201-014-0256-9>
46. Shigut, D. A., Liknew, G., Irge, D. D., & Ahmad, T. (2017). Assessment of physico-chemical quality of borehole and spring water sources supplied to Robe Town, Oromia region, Ethiopia. *Applied Water Science*, 7(1), 155–164. <https://doi.org/10.1007/s13201-016-0502-4>
47. Singaraja, C. (2017). Relevance of water quality index for groundwater quality evaluation: Thoothudi District. Tamil Nadu, India. *Applied water science* 7 (2017):2157-2173.
48. Sunkari, E. D., Abu, M., Bayowobie, P. S., & Dokuz, U. E. (2019). Hydrogeochemical appraisal of groundwater quality in the Ga West municipality, Ghana: Implication for domestic and irrigation purposes. *Groundwater for Sustainable Development*, 8, 501–511. <https://doi.org/10.1016/j.gsd.2019.02.002>
49. Sutradhar, S., & Mondal, P. (2021). Groundwater suitability assessment based on water quality index and hadrochemical characterization of Suri Sadar Sub-division, West Bengal. *Ecological Informatics*, 64, 101335. <https://doi.org/10.1016/j.ecoinf.2021.101335>
50. Tiwari, A. K., Singh, A. K., Singh, A. K., & Singh, M. P. (2017). Hydrogeochemical analysis and evaluation of surface water quality of Pratapgarh district, Uttar Pradesh, India. *Applied Water Science*, 7(4), 1609–1623. <https://doi.org/10.1007/s13201-015-0313-z>
51. Umadevi, P., Pradeep, T., Sampathkumar, V., & Manoj, S. (2021). Groundwater quality assessment in a North-East region of Erode district, Tamil Nadu. *Materials Today: Proceedings*, S2214785321008828. <https://doi.org/10.1016/j.matpr.2021.01.785>
52. World Health Organization. (2017). Guidelines for drinking-water quality: first addendum to the fourth edition.
53. Yu, G., Wang, J., Liu, L., Li, Y., Zhang, Y., & Wang, S. (2020). The analysis of groundwater nitrate pollution and health risk assessment in rural areas of Yantai, China. *BMC Public Health*, 20(1), 437. <https://doi.org/10.1186/s12889-020-08583-y>
54. Zakaria, N., Anornu, G., Adomako, D., Owusu-Nimo, F., & Gibrilla, A. (2021). Evolution of groundwater hydrogeochemistry and assessment of groundwater quality in the Anayari catchment. *Groundwater for Sustainable Development*, 12, 100489. <https://doi.org/10.1016/j.gsd.2020.100489>