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Evaluation of groundwater sustainability for agricultural irrigation in the Tolon District, Northern Region of Ghana

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Abstract: Groundwater quality assessment is vital for ensuring water security, sustainable agriculture, and the well-being of the local communities in arid and semi-arid regions. This research aims to evaluate the suitability of groundwater quality for irrigation in the Tolon District, Northern Region of Ghana, using various irrigation water quality indices (*IWQIs*), including sodium adsorption ratio (*SAR*), potential salinity (*PS*), permeability index (*PI*), magnesium hazard (*MH*), total hardness (*TH*), residual sodium carbonate (*RSC*), and specific ion toxicity integrated with the inverse distance weighting (IDW) interpolation method. The IDW interpolation method in ArcGIS was used to plot spatial distribution maps of *IWQIs*. Twelve physicochemical parameters taken from 97 wells, including pH, electrical conductivity (*EC*), total dissolved solids (*TDS*), Ca^{2+}, Na^{2+}, K^{+}, Mg^{2+}, Cl^{-}, NO^{3-}, SO_4^{2-}, CO_3^{2-}, and HCO_3^{-}, were analysed. The study revealed that several parameters, such as *EC*, *TDS*, *SAR*, *PS*, *PI*, *RSC*, Na, K, and Cl, indicate that 82, 89, 98, 83.6, 44, 87.7, 80, 57, and 85% of samples, respectively, range from good to excellent quality during the rainy season. In addition, the *MH* index indicates that 82% of the samples are suitable for irrigation use. The *IWQIs* can help decision-makers and farmers identify sustainable groundwater-based irrigation regions.

Keywords: geographic information system (GIS), groundwater, irrigation indices, irrigation water quality, physicochemical parameters

INTRODUCTION

Groundwater resources are vital in arid and semi-arid regions, where water scarcity is prevalent and competes with other uses such as irrigation (Roldán-Cañas and Moreno-Pérez, 2021). They are integral to semi-arid regions' economic, environmental, and social dynamics (Ahmed *et al.*, 2021; Priyan, 2021). However, climatic variability and intense human activities can lead to groundwater deterioration that could threaten water, food, and socioeconomic security in these regions; hence, evaluation of groundwater is an important input for achieving sustainable management of groundwater resources in these regions (Foster and Chilton, 2003; Ali and Armanuos, 2023).

Irrigation is a critical component of agriculture, and groundwater is an essential water source for irrigation, particularly in regions with limited surface water availability. Irrigation accounts for 70% of global freshwater withdrawals and 90% of consumptive water use (Siebert *et al.*, 2010). The growing population and food demand have increased global pressure on water resources. As a result, there is now widespread recognition of the need to improve the management of water resources in agriculture (OECD, 2006). Therefore, understanding the quality of groundwater used for irrigation is vital for ensuring crop health and productivity, as well as safeguarding human health through the consumption of crops irrigated with contaminated groundwater. Numerous factors, including the geology and hydrology of the region, agricultural practices, and human-induced activities, exert an impact on the quality of groundwater available for irrigation purposes. Several prevalent concerns associated with groundwater quality for irrigation include salinity, sodicity, nutrient pollution, heavy metal contamination, microbial contamination, crop health and productivity, and soil salinisation and degradation over time (Kumar *et al*., 2007; Ogunfowokan, Obisanya and Ogunkoya, 2013; Uyttendaele *et al*., 2015; Kalaivanan *et al*., 2018; El Baghdadi *et al*., 2019). Numerous researchers have conducted various studies to assess the suitability of groundwater for irrigation. They have utilised various irrigation water quality indices, including the sodium adsorption ratio (*SAR*), permeability index (*PI*), magnesium hazard (*MH*), potential salinity (*PS*), and residual sodium carbonate (*RSC*). These indices have been combined with visualisation tools such as Wilcox plots, Piper, Schoeller, United States Salinity Laboratory (USSL) diagrams, and GIS interpolation. The spatial distribution of groundwater quality parameters has been plotted. These methods, used in several studies, such as Khalaf and Hassan (2013), Çadraku (2021), Eid *et al.* (2023), Gaagai *et al.* (2023), Hosseininia and Hassanzadeh (2023), Ibrahim *et al.* (2023), and Kpiebaya *et al.* (2023), have proven effective and applicable for interpreting and predicting irrigation water quality in arid and semi-arid regions.

This study was conducted in the Tolon District, situated within a semi-arid zone in the Northern Region of Ghana (Ahmed *et al*., 2016). The district is part of the Voltaian Supergroup and features diverse rock formations, including sandstones, shale, limestone, conglomerate, mudstone, siltstone, and arkoses. The shallow aquifer system in the area has variable recharge potential, with different rock types influencing groundwater availability and quality. This research aims to evaluate the suitability of groundwater for irrigation purposes by utilising various irrigation water quality indices (*IWQIs*) incorporating the interpolation method to fill gaps in the study area regarding irrigation water quality assessment.

MATERIALS AND METHODS

STUDY AREA

The research was carried out in the Tolon District, Northern Region of Ghana, spanning approximately 1,355 km^2 between latitude coordinates 9°15' and longitude coordinates 10°02'N, and 0°53' and 1°25'W. It is bordered by Sagnarigu District to the east, Gonja to the west, Kumbungu to the north, and Central Gonja to the south (Fig. 1). The district's population is 118,090, predominantly engaged in agriculture (GSS, 2021). The topography features rising between 94 and 187 m in elevation, and the terrain is undulating, with several rivers that aid in drainage and sporadic depressions (Salifu, 2013; Abdul-Ganiyu *et al*., 2017).

Geologically, situated within the Voltaian Supergroup, the complex consists of ancient sedimentary rocks dating from the Neoproterozoic to the early Paleozoic era. These rocks comprise silty mudstones, sandstones, limestones, conglomerates, and glacial deposits (CIDA, 2011). The Voltaian Supergroup covers a significant portion of Ghana and extends into neighbouring countries like Togo, Burkina Faso, and Niger (Trompette, 1994; Affaton, Sougy, and Trompette, 1980). The geological formations in the Tolon District can be categorised into four central units (Jordan *et al*., 2009) – Figure 1.

1. Unit one – consists of diverse lithologies, including argillaceous and micaceous at the base, transitioning into medium-grained sandstones. Evidence suggests deposition in braided river systems and Aeolian dunes.

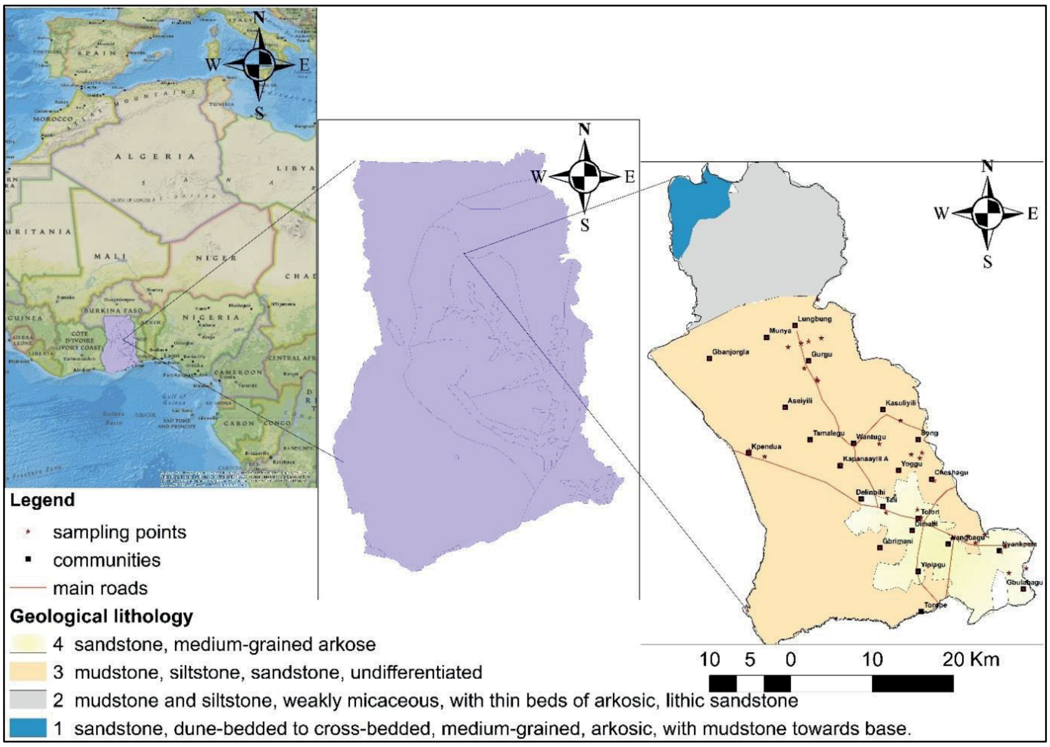

Fig. 1. Study and geological map; source: Jordan *et al.* (2009), modified

2. Unit two – predominantly located in the northern part and is characterised by green-grey mudstones, siltstones, and feldspathic, lithics-rich sandstones.
3. Unit three – the youngest in the Volta Basin, this formation includes flysch-type beds in the north and molasse-type sandstones in the south. It exhibits variegated shallow water deposits with occasional subaerial exposure, characterised by calcareous mudstones, siltstones, and conglomerates.
4. Unit four – found prominently in Tamale, this formation represents fluvial red-bed deposits from the Pan-African orogeny. It features medium-grained arkosic sandstones with cross-bedding, indicative of south-southeast currents, alongside pink-weathering laminated sandstones.

GROUNDWATER SAMPLING AND ANALYSIS PROCEDURES

Groundwater sampling and analysis were conducted over the rainy season (August–September 2023) and the dry season (March 2024). A total of 97 samples were collected from operational wells in the rainy (55 samples) and dry (42 samples) seasons. Boreholes typically vary in depth from 50 to 100 m, with a success rate of approximately 50%. Groundwater recharge is mainly driven by precipitation and runoff, affecting the flow of groundwater from highlands to valleys and rivers. Seasonal fluctuations in groundwater levels are observed, with lower levels during the dry season and higher levels in the wet season (CIDA, 2011). However, the samples for this study were collected from depths ranging between 5 and 63 m. The sampling sites were mapped using GPS (maps.me), as shown in Figure 1. Before sampling, wells were purged for 5–10 min to stabilise physicochemical parameters. Pre-cleaned 1-dm^3 polyethylene bottles labelled with masking tape were used for sampling, stored at 4°C, and transported to WAWISA and the Water Research Institute (WRI) laboratories. The sampling protocol established by Weaver, Cave, and Talma (2007) was followed to ensure accuracy and consistency.

In this study, 12 parameters were analysed. Physicochemical parameters, including *TDS*, pH, and *EC*, were measured using a handheld water quality meter LAQUA WQ-330 (HORIBA Advanced Techno, Co., Ltd., Kyoto, Japan) probe calibrated with standard solutions. Cations such as K^+, Na^+, and Ca^{2+} were detected at the WACWISA laboratory using an FP 910-5 flame photometer (PG Instruments Ltd, Lutterworth, United Kingdom), as well as NO_3^- using HydroTest Photometer HT1000 (Trace2o Ltd, United Kingdom). Anions like Cl^-, SO_4^{2-}, and HCO_3^- were analysed at the WRI laboratory using a Janeway 6305 spectrophotometer (Janeway Laboratory equipment supplier, Felsted, United Kingdom) for SO_4^{2-}; the alkalinity strong acid titration method for HCO_3^-; the argentometric titration method for Cl^-; and the EDTA titration method for Mg^{2+}. During the dry season, analyses were conducted at the WACWISA laboratory using a DR6000 spectrophotometer (HACH, London, United Kingdom) for SO_4^{2-} and titration methods for Mg^{2+}, Cl^-, SO_4^{2-}, CO_3^-, and HCO_3^-.

DATA ANALYSIS

STATA/MP (version 17.0) was used for summary and descriptive analysis. The ArcGIS (version 10.6.1) was used to create maps and spatial distributions for different parameters. In contrast, the USSL and Wilcox diagrams were created using DIAGRAMMES software (version 8.1), and Excel (version 2010) was used for organising and calculating data.

MODIFIED US SALINITY DIAGRAM

The modified US salinity diagram (Richards, 1954) is a water classification diagram used to evaluate the water suitability of samples designated for irrigation purposes using *EC* and *SAR* values (USL Staff, 1954). The diagram was modified later by Shahid and Mahmoudi (2014) to extend to higher water salinity up to 30,000 $\mu S \cdot cm^{-1}$. This diagram categorises groundwater quality into sixteen classes. In our study, we specifically identified six irrigation water quality classes for the Tamale Sandstone Formation (Ta) and an additional six irrigation water quality classes for the Undivided Obosum Group (Os) using this diagram.

WILCOX DIAGRAM

Irrigation water quality was assessed using the Wilcox diagram (Wilcox, 1955), which employs *EC* and Na% to categorise water into five classes: excellent, good, permissible, poor, and unsuitable. This classification helps determine the suitability of water for irrigation purposes.

IRRIGATION WATER QUALITY INDICES

The physicochemical data of the groundwater samples were used to calculate the *IWQI*s presented in Table 1.

RESULTS AND DISCUSSION

HYDROCHEMICAL PARAMETERS OF GROUNDWATER

The suitability of the study area's groundwater for irrigation purposes has been assessed based on various physicochemical parameters. Statistical summaries of these parameters are provided in Table 2. The study area's highly diverse distribution of these parameters indicates varying process control. The pH values of the groundwater samples ranged from 5.9 to 9.4. During the rainy season, 5 out of 55 samples exceeded the permissible limits of irrigation water standards. When pH levels exceed the permissible standard (>8.5), it usually results from high concentrations of HCO_3^- and CO_3^{2-} forming alkalinity. The presence of high carbonates leads to the formation of insoluble minerals from calcium and magnesium ions, leaving sodium as the dominant ion in the solution. Alkaline water can exacerbate the effect of high sodium adsorption ratio (*SAR*) water on sodic soil conditions. Moreover, excessive bicarbonate concentrations can cause problems for drip or micro-spray irrigation systems, reducing flow rates through emitters due to calcite or scale build-up (Bauder *et al.*, 2011).

The minimum and maximum values for electrical conductivity (*EC*) and total dissolved solids (*TDS*) are 24 to 2,580 $\mu S \cdot cm^{-1}$ and 30.4 to 25,700 $\mu S \cdot cm^{-1}$, 12 to 1,290 $mg \cdot dm^{-3}$, and 14.90 to 12,870 $mg \cdot dm^{-3}$, for the rainy and dry seasons, respectively. These values are within the acceptable range for irrigation standards according to Ayers and Westcott (1985),

Table 1. Equations used to calculate the irrigation water quality indices (*IWQIs*)

IWQIs parameter	Equation	Reference
SAR	$SAR = \frac{Na^{2+}}{\sqrt{(Ca^{2+} + Mg^{2+})/2}}$	Richards (1954), Oster and Sposito (1980)
PS	$PS = Cl^{-} + \frac{SO_4^{2-}}{2}$	Doneen (1975)
PI	$PI = \frac{Na^{+} + \sqrt{HCO_3^{-}}}{Ca^{2+} + Mg^{2+} + Na^{+}}\ 100$	Das and Nag (2015)
MH	$MH = \left(\frac{Mg^{2+}}{Ca^{2+} + Mg^{2+}}\right) 100$	Zhang *et al.* (2018)
TH	$TH = (2.5\ Na^{+}) + (4.12\ Mg^{2+})$	Çadraku (2021)
RSC	$RSC = (CO_3^{2-} + HCO_3^{-}) - (Ca^{2+} + Mg^{2+})$	Eaton (1950), Wilcox, Blair, and Bower (1954)

Explanations: *SAR* = sodium adsorption ratio, *PS* = potential salinity, *PI* = permeability index, *MH* = magnesium hazard, *TH* = total hardness, *RSC* = residual sodium carbonate. All *IWQIs* are calculated in meq·dm^{-3}, except *TH* – in mg·dm^{-3}.
Source: own elaboration.

Table 2. Statistical summary of physicochemical parameters in groundwater

Parameter	Mean	*SD*	Min.	Max.	Mean	*SD*	Min.	Max.	FAO 2017
	rainy season (*n* = 55)				dry season (*n* = 42)				
pH	7.39	0.64	5.91	9.36	7.56	0.33	6.74	8.32	8.5
EC	891.18	628.32	24.00	2,580.00	1,614.75	3,872.23	30.4	25,700	3,000
TDS	446.16	314.63	12.04	1,290.00	932.16	2,079.94	14.90	1,2870.00	2,000
Ca^{2+}	7.03	4.68	0.00	16.00	49.40	150.19	4.50	960.00	400
Na^{+}	96.20	64.41	1.00	291.00	163.50	156.22	2.00	853.00	400
Mg^{2+}	23.24	29.62	1.27	157.00	47.65	60.59	1.20	321.50	60
K^{+}	12.41	17.46	0.10	67.00	3.78	2.45	1.00	12.90	2
CO_3^{2-}	45.77	80.12	0.03	488.58	34.60	26.57	0.00	117.00	30
HCO_3^{-}	242.95	197.92	12.20	805.00	403.80	267.85	12.80	1,003.70	610
Cl^{-}	52.74	71.89	4.00	424.00	425.02	1,336.22	9.70	6,277.00	1,063
SO_4^{2-}	93.98	106.92	8.70	587.00	26.11	36.50	0.00	1,36.00	960
NO_3^{-}	12.18	19.23	0.00	79.60	3.12	5.62	0.00	26.40	10

Explanations: pH = potential of hydrogen, *EC* = electrical conductivity, *TDS* = total dissolved solids, parameters are expressed in mg·dm^{-3}, except pH (–) and *EC* (μS·cm^{-1}), *SD* = standard deviation.
Source: own study.

except at the Fihini well (TD56) and WACWISA well (TD63), which are unsuitable for irrigation. In the study area, the southern corner has lower *EC* and *TDS* values. In contrast, the maximum values were recorded in the extreme southeast corner, known as Gbulahagu (TD2), and increased towards the north-western zone. The larger standard deviations of *EC* and *TDS* (628.3 and 314.6) indicate that the data points are spread further from the mean. These variations may be attributed to geological changes, which consist of medium-grained quartz-rich sandstone with large-scale trough cross-bedding, pink-weathering laminated sandstone with ripple-drift cross-lamination, and well-cemented quartz sandstone (Affaton, Sougy, and Trompette, 1980; Jordan *et al.*, 2009).

The chemical parameters Ca^{2+}, Na^{+}, Cl^{-}, and SO_4^{2-} in the water designated for irrigation are within acceptable limits. However, samples TD15, TD39, TD10, and TD2, which correspond to Tolon Senior High School, Yoggu, Tolon, and Gbulahagu areas, respectively, and 23% of the samples during the dry season, exceed the acceptable irrigation limits due to the high concentration of Mg^{2+}. Most of these sample points are located in the south-eastern part of the study area. About 45 and 71% of the groundwater samples during the rainy and dry seasons had a high concentration of K^+ and fell out of the permissible limits for irrigation, with an average concentration value of 12.41 and 3.78 $mg \cdot dm^{-3}$, respectively. The high concentration of K^+ may be due to the weathering of potash feldspar minerals and the dissolution of chemical fertilisers (Gaagai *et al.*, 2022). High concentrations of CO_3^{2-} and HCO_3^- ions can have an impact on the uptake of mineral nutrients and their metabolism in plants. Sensitive plants may exhibit yellowing symptoms due to the direct or indirect effects of bicarbonate, for example, an increase in soil pH (Phocaides, 2007). In this study, were found that 40 and 62% of CO_3^{2-} samples during the rainy and dry seasons exceeded the standard irrigation water quality, while two samples (TD16 and TD39) during the rainy season and 28% of samples for the dry season of HCO_3^- were found to be above the permissible irrigation water limit (Ayers and Westcott, 1985).

More than 33% and 14% of the groundwater samples tested had high levels of nitrate during the rainy and dry seasons, respectively, making them unsuitable for irrigation due to anthropogenic activities such as excessive use of inorganic nitrogenous fertiliser, household and industrial waste dumping, and intensive irrigation (Das and Nag, 2015). The concentration of nitrate increases towards the southeast and centre of the study area, where agricultural activities are concentrated. High nitrate concentrations in water can lead to crop quality issues, such as excessive vegetative growth in some vegetables, as reported by Bauder *et al.* (2011).

IRRIGATION WATER QUALITY INDICES

Multiple indicators were used to evaluate irrigation water quality parameters, as outlined in Tables S1 and S2. These indicators have been utilized in various studies (Eid *et al.*, 2023; Gaagai *et al.*, 2023; Hosseininia and Hassanzadeh, 2023; Kpiebaya *et al.*, 2023) and have been proven effective in assessing the quality of irrigation water.

SALINITY HAZARD

The most important water quality parameters for determining the salinity hazard of irrigation water used in this study are *EC* and *TDS*. The problem of salinity is a major issue in agriculture, as it can affect the growth of plants when certain salts accumulate in the crop's root zone. The crop's potential yield is directly related to the amount of water it transpires; therefore, using irrigation water with high *EC* can decrease its potential yield (Ayers and Westcot, 1985; Bauder *et al.*, 2011).

There are four different categories of water quality (Wilcox, 1955): excellent, good, fair, and poor (Tabs. S1 and S2). During the rainy season, most samples fall into the excellent category, 42 and 60% for *EC* and *TDS*, respectively, followed by the good category with 40% and 29%, with fewer samples categorised as fair and none falling into the rejection category. During the dry season, most of the samples fell into the excellent category (38%), good (38%), followed by fair (17%) and poor (7%). This indicates that none of the samples exceeded the maximum thresholds. Based on the Wilcox diagram (Fig. S1), 29% and 31% were classified as excellent, 5% and 14% as good, 32% and 35% as permissible, and 4% and 14% as poor during the rainy and dry seasons, respectively. The percentage distribution for *TDS* is slightly higher than that for *EC*, especially in the excellent and good categories. The USSL (United States Salinity Laboratory) diagram (Fig. S2) illustrates the distribution of samples across various salinity classes. During the rainy season, most samples fall into class C2S1 (38%), followed by C3S1 (22%) and C3S2 (20%). In the dry season, the majority are also in class C2S1 (26%), with C3S2 (29%) and C3S1 (21%) following.

SODIUM ADSORPTION RATIO

The sodium adsorption ratio (*SAR*) is a useful index for predicting the tendency of salt solutions to produce excessive exchangeable sodium in soil (Zaman, Shahid, and Heng, 2018). It directly affects the soils of high Na^+ levels compared to Ca^{2+} in combination with low salt levels. This causes soil dispersion, leading to poor soil structure and dense soil layers (Hanson, Grattan, and Fulton, 2006; Wang *et al.*, 2012). Unlike salinity, sodicity has no clear visual symptoms. The best way to know it is by sampling and analysing it in a lab. The exchangeable sodium percentage (*ESP*) test has historically been used to analyse soils for sodicity. However, over time, *ESP* has been replaced by the *SAR* (Victoria University, 2002). The irrigation water samples are classified into four categories based on *SAR* values, as proposed by Richards in 1954 (Tabs. S3, S4). These categories are excellent (80%), good (18.2%), doubtful or fairly poor (1.8%), and unsuitable (0%) for the rainy season, while during the dry season, all samples were classified as excellent (100%). The majority of the water samples belong to the excellent category, indicating they are suitable for irrigation.

PERMEABILITY INDEX

The permeability index (*PI*) is a crucial measure for assessing the suitability of groundwater for irrigation, specifically in terms of the long-term impact of using irrigation water with high levels of Na^+ and HCO_3^- on soil permeability (Doneen, 1964). According to Tables S1 and S2, as well as Figures 2 and 3, 87.7% and 50% of samples fall into the good class I category, 12.3% and 48% into the suitable class II category, and 0% and 2% into the unsuitable class III category for irrigation, during the rainy and dry seasons, respectively.

POTENTIAL SALINITY

Potential salinity (*PS*) was defined as the sum of chloride and half of the sulphate concentrations (Doneen, 1975). Unlike the concentration of soluble salts, low-solubility salts can precipitate and accumulate in the soil over time due to successive irrigation, which can lead to soil salinisation, a condition that reduces soil fertility and crop yield, as the high salt concentrations can disrupt plant growth and water uptake (Gholami and Srikantaswamy, 2009; Ogunfowokan, Obisanya, and Ogunkoya, 2013). There are three categories of *PS*: excellent to good, good to injurious, and injurious to unsatisfactory. The analysis indicates that 83.6, 5.6, 10.9, and 60, 14, and 26% fell into these categories for the rainy and dry seasons, respectively. According to Figures 2 and 3, the unsatisfactory category is located in the south-eastern corner.

MAGNESIUM HAZARD

According to Paliwals' classification (1972), *MH* is classified into two categories. If *MH* is greater than 50%, it is considered suitable for irrigation, whereas if *MH* is less than 50%, it is deemed unsuitable. Based on this classification, it was concluded that out

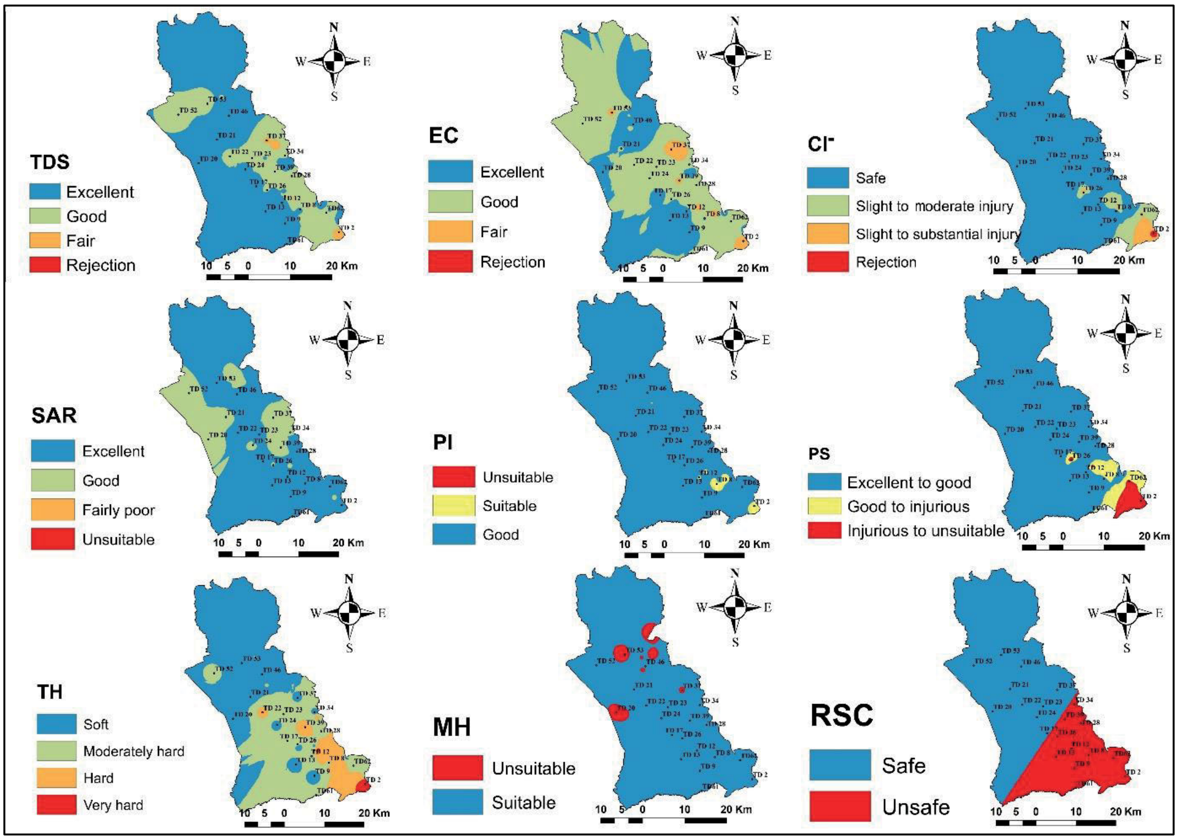

Fig. 2. Spatial distribution maps of irrigation water quality indices (*IWQIs*) during the rainy season; *TDS* = total dissolved solids, *EC* = electrical conductivity, *SAR* = sodium absorption ratio, *PI* = permeability index, *PS* = potential salinity, *TH* = total hardness, *MH* = magnesium hardness, *RSC* = residual sodium carbonate; source: own study

of the total samples tested, 82% and 33% of the samples were found to be suitable for irrigation purposes. In comparison, 18% and 67% of samples were classified as unsuitable for rainy and dry seasons, respectively, as visualised in Figures 2 and 3.

TOTAL HARDNESS

Water hardness is defined by the presence of Ca^{2+} and Mg^{2+} cations and quantified as the sum of their concentrations in $mg \cdot dm^{-3}$ of $CaCO_3$. Total hardness (*TH*) is usually classified into four categories based on its level: soft, moderately hard, hard, and very hard (Todd, 1980). Based on Tables S1 and S2, 49% and 7% were classified as soft, 27% and 5% as moderately hard, 16% and 19% as hard, and 7% and 69% as very hard in rainy and dry seasons, respectively. Soft water is generally considered suitable for irrigation as it reduces soil salinisation, maintains fertility, and minimises crop growth issues. In contrast, hard water can accumulate salts and negatively impact crop yield. The water hardness decreases from north to south in the study area, with northern water being softer and more suitable for irrigation than the harder southern water (Figs. 2 and 3).

RESIDUAL SODIUM CARBONATE

The residual sodium carbonate (*RSC*) is the measure of the amount of sodium carbonate and sodium bicarbonate in irrigation water (Eaton, 1950; Wilcox, Blair, and Bower, 1954). It is an important parameter as it indicates the potential for soil sodium activation and disruption of soil structure. An excess of CO_3^{2-} and HCO_3^- can cause precipitation of soil Ca^{2+} and Mg^{2+}, leading to impaired soil structure and potential activation of soil sodium. Based on the *RSC* range, sodium hazard is classified into three categories: safe ($RSC < 1.25$), marginal ($RSC \in \langle 1.25; 2.5 \rangle$), and unsafe ($RSC > 2.5$) (Raghunath, 1987). The analysis of the water samples revealed that 44% of the samples were considered safe, 5% marginal, and a significant 51% were classified as unsafe as represented in Figure 3 for the rainy season, and 38%, 14%, and 48% for the dry season respectively, which visually shows the distribution of the water samples among the different *RSC* categories.

SPECIFIC ION TOXICITY

Toxicity problems can be caused by an excess of certain ions in irrigation water. Therefore, while evaluating the quality of water designated for irrigation, it is important to consider the concentrations of these ions (Bauder *et al.*, 2011). In this study, Na, K, and Cl were selected due to their toxicity in irrigation water when they exceed a certain limit. For example, Na toxicity can lead to leaf burn, scorching, and the death of tissues along the outer edges of leaves. The study found that most of the samples, about 55%, are good for irrigation. Although a high potassium concentration is usually not harmful to plant growth, concentrations exceeding 10 $mg \cdot dm^{-3}$ might indicate water contamination due to fertilisers or other man-made sources (Lamont *et al.*, 2022). According to Tables S1 and S2, most of our sample results indicate that the water for irrigation is under the fair category. Chloride toxicity is the most common form of crop toxicity that

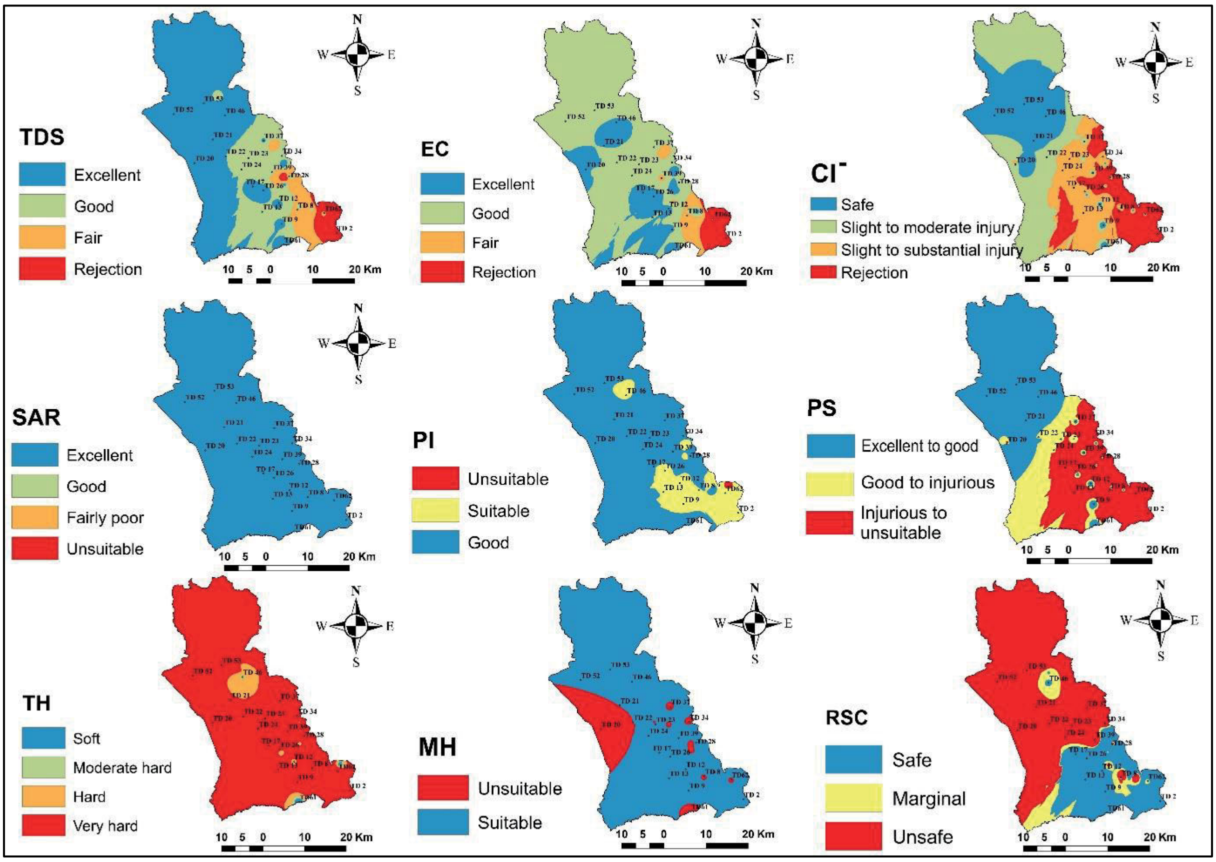

Fig. 3. Spatial distribution maps of irrigation water quality indices (*IWQIs*) during the dry season; *TDS*, *EC*, *SAR*, *PI*, *PS*, *TH*, *MH*, *RSC* as in Fig. 2; source: own study

occurs due to the presence of chloride in irrigation water. Chloride (Cl) is a necessary nutrient for the growth of plants. However, when it is present in high concentrations, it can hinder plant development and even become toxic to some plant species. According to Tables S1 and S2, 85% and 57% of the samples during the rainy and dry seasons are considered safe for all plants, while the remaining samples belong to other groups in similar proportions, which range from chloride-sensitive plants to severely toxic plants, as Ludwick *et al.* (1990).

WATER QUALITY INFLUENCE ON CROP YIELDS

Plant tolerance limits are quantified using *EC*. The salinity tolerance levels in the study area suggest that groundwater used for irrigation is affecting the yields of various crops. Sensitive and moderately sensitive field crops (such as bean, groundnut, maize, rice, sugarcane), vegetable crops (carrot, okra, onion, broccoli, cabbage, cucumber, lettuce, pepper, potato, spinach, sweet potato, tomato), and fruit crops (avocado, grape, grapefruit, lemon, orange, strawberry) are particularly affected. Conversely, the yields of moderately tolerant and tolerant crops (such as cowpeas, sorghum, soybeans, wheat, and sugarbeet) remain unaffected by irrigation with groundwater, except in two specific areas of the study region deemed unsuitable for irrigation. This is attributed to the high tolerance of these crops to salinity compared to the salinity levels of the irrigation water. The statistics on the potential yield percentages of selected crops based on their salinity tolerance limits when irrigated with groundwater are presented in Table S3. The data indicate that the salinity of irrigation water significantly affects the yield potential of sensitive and moderately sensitive crops across most study areas, with varying effects among different crops. In contrast, the potential yields of moderately tolerant and tolerant crops are generally unaffected, except in the two unsuitable areas (WACWISA and Fihini).

CONCLUSIONS

The study assessed groundwater quality in the Tolon District, Northern Region of Ghana, focusing on its suitability for agricultural irrigation. It covered a range of hydrochemical parameters, including pH, *EC*, *TDS*, major ions, and various water quality indices. Key findings include pH values ranging from 5.9 to 9.4, with a few samples exceeding irrigation standards. Levels of electrical conductivity (*EC*) and total dissolved solids (*TDS*) were generally acceptable, while high Mg^{2+} concentrations in certain areas raised concerns. Elevated K^+ and NO_3^- levels, influenced by agricultural activities, were observed, particularly in the southeast and central regions.

The study also evaluated plant tolerance using *EC*, revealing significant yield impacts on sensitive crops like beans and maize, while moderately tolerant crops remained largely unaffected except in specific areas classified as unsuitable. Overall, irrigation water quality indices showed predominantly excellent suitability, supporting targeted interventions and improved resource management in agricultural practices.

SUPPLEMENTARY MATERIAL

Supplementary material to this article can be found online at: https://www.jwld.pl/files/Supplementary_material_68_Nogara.pdf.

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This manuscript is dedicated to the memory of Ing. Professor Shaibu A. Ganiyu, the former Dean of School of Engineering, UDS. In recognition of his intellectual contributions to the fields of irrigation and drainage engineering, water resources engineering, and his dedication to academic excellence and national development in Ghana

CONFLICT OF INTERESTS

All authors declare that they have no conflict of interest.

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