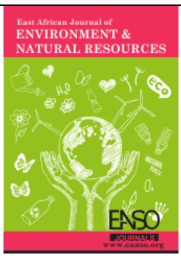

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Original Article

Spatiotemporal Variation of Shallow Groundwater Quality in Selected Parts of Kitui County, Kenya

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ABSTRACT

Many people living in dry areas of Kenya rely on groundwater for household and livelihood purposes. Notably, the demand for water has been on the rise due to population increase, livelihood diversification, among others. The resultant activities have had an effect on the quality of water, a situation aggravated by factors like deforestation, agricultural activities, and others. Natural pollutants, such as the weathering of rocks, minerals, also affect the water quality. In the current study, samples were collected from randomly selected 30 shallow wells during both the wet and dry seasons and analysed using a portable laboratory kit. Of concern were turbidity, pH, electrical conductivity, calcium, aluminium, magnesium, chloride, sulphates, nitrates, total dissolved solids, fluoride, zinc, calcium carbonate, and salinity. The results were compared with the prescribed water quality standards. From the results, all tested parameters other than turbidity, nitrates and sulphates complied with the recommended quality requirements. The research, therefore, concluded that the shallow groundwater sources in the study area are generally suitable for human consumption except for the shallow well water points which contain high levels of sulphates, nitrates and turbidity. The study found significant spatial variation ($p \leq 0.05$) in the physical and chemical characteristics of shallow groundwater resources in the areas, which were attributed to geologic materials and human activities carried out in the study area. Further, statistically significant temporal variations ($p \leq 0.05$) were observed in the shallow groundwater for both the wet and dry seasons. The study results also revealed a significant statistical association ($p \leq 0.05$) between the water quality parameters in the studied areas, which implies that the parameters have a similar source of origin in the environment. Based on the findings, the study proposes training programs for farmers on the sustainable application of quantities of farm inputs in crop production. Regular monitoring of groundwater is necessary to allow the taking of preventive and remedial measures.

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INTRODUCTION

Groundwater is a significant renewable natural resource that accounts for 95% of the Earth's freshwater supplies (Kumar et al., 2006). Many world regions rely on groundwater as their primary water supply source for household, livelihoods and industrial water needs (Gautam et al., 2015; Mallick, 2021). Kenya's arid and semi-arid lands (ASALs) largely rely on groundwater because surface water supplies are minimal owing to erratic rainfall patterns and geologic characteristics. Although protected by ground formations, the water is as prone to contamination as the surface water (Barakat et al., 2019) from natural and anthropogenic activities. Hassan (2006) appreciates water contaminated to be through of both point and non-point sources, with harmful compounds getting swept into shallow wells or through seepage and runoff. Leakages from septic tanks that are untreated, underground chemical storage tanks and leachate from landfills are also potential sources of contamination for shallow wells.

Kitui County, located in Kenya's ASAL belt, exemplifies such a region where communities predominantly rely on shallow wells, boreholes, and springs to meet their water demands. However, despite its critical role, the quality of groundwater in Kitui and similar regions is increasingly under threat from both natural processes and anthropogenic activities. Groundwater, although naturally filtered through soil and rock layers, is not immune to pollution. Subsurface protection does not guarantee immunity against contaminants, particularly in shallow aquifers that are more susceptible to infiltration from surface activities (Barakat et al., 2019).

Several factors contribute to the degradation of shallow groundwater quality. One major concern is non-point source pollution, which includes agricultural runoff, leakage from septic systems, infiltration from landfills, and improper waste disposal. Hassan (2006) classifies contamination pathways into point sources (e.g., leaking fuel storage tanks or sewage lines) and non-point sources, which are diffuse and harder to trace, such as agricultural runoff containing fertilisers and pesticides. As fertilisers dissolve and percolate through the soil, nitrates and sulfates often reach groundwater, compromising its potability and ecosystem health.

In regions like Kitui, land use changes have exacerbated these issues. Intensified agricultural practices, urban expansion, and sand harvesting disturb natural landscapes and hydrological balance. The unregulated use of agrochemicals leads to increased concentrations of nutrients and heavy metals in water supplies. Moreover, population growth and the associated rise in waste generation place additional stress on sanitation infrastructure, leading to higher risks of contamination through seepage and leachate (Likambo, 2014; Georgakakos, 2014).

Another key concern is the spatiotemporal variability in groundwater quality. Seasonal rainfall variations significantly affect the quantity and quality of recharge water. During the rainy season, runoff can carry a wide range of pollutants from agricultural lands, urban areas, and open waste disposal sites into water bodies and shallow aquifers. Flooding may also overload sanitation

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systems, increasing the movement of untreated effluents into groundwater systems.

Despite the critical importance of safe and sustainable water resources in semi-arid regions like Kauwi and Zombe, there is a significant lack of detailed,location-specific data on the spatial and temporal variations in water quality. Existing studies in the region are either outdated or limited in scope, often overlooking seasonal fluctuations and the contribution of anthropogenic activities that can drastically impact water safety. Furthermore, there is inadequate monitoring of emerging contaminants and limited understanding of how land use patterns and climatic conditions influence water quality over time. A comprehensive understanding of the interrelationship between geology, land use practices, hydrology, and human activities in Kitui is therefore essential. Regions such as Kauwi and Zombe present diverse topographical and socio-economic contexts that make them critical case studies for examining groundwater vulnerability. Developing strategies for groundwater quality protection in such areas requires evidence-based assessments and proactive policy interventions. This research seeks to bridge these gaps by providing comprehensive,time-sensitive assessments of water quality in both Kauwi and Zombe. The findings from this study are expected to inform sustainable groundwater management practices, including the need for regular monitoring, public awareness on pollution control, and improved land use planning. Moreover, they will provide a scientific basis for interventions aimed at ensuring safe and sustainable water supply for rural communities in water-scarce environments.

MATERIALS AND METHODS

Study Area

The research was conducted in Kauwi and Zombe Locations that respectively lie to the West and East of Kitui County in Kenya (Figures 1 and 2). The two zones were purposively selected, the selection being driven by observed growth in population coupled with adoption of new and intensified land use practices of varied magnitudes expected to have an impact on groundwater quality. The land in the study area is mainly used for small-scale farming of livestock and food crops. In Kauwi, the majority of the farmers apply animal manure. The case is different in Zombe where the majority of farmers use conventional fertilisers on their farms and only a few of them are into animal manure. Precambrian basement rocks, volcanic formations, sedimentary rocks, and alluvial deposits make up Kauwi's geology (Gevera et al., 2020). These rocks include gneisses and schists, which are part of the larger Kenya basement complex. The Nairobi rift valley sediments extend into the study area and have contributed to the formation of lowland plains, especially along the Tana River and other water courses. Notable mineral resources in the area include limestone. The geology of Zombe is comprised of Precambrian basement rocks, volcanic formations, and sedimentary rocks. The Precambrian rocks are more than 600 million years old, and the predominant rock types in this group are gneisses (metamorphic rocks) and schists. The volcanic activity in the area has resulted in the formation of basalts.

The metamorphic and volcanic rocks in this region dissolve in water sources, resulting in a high salt content in drinking water. This diverse geological composition provides a variety of natural resources, including minerals like limestone, gypsum, and phosphate. The sources of water in both Kauwi and Zombe include seasonal rivers, water pans, boreholes, shallow wells and roofwater harvesting. The only permanent river in the area is Tana, which runs through the periphery of Zombe, forming a vital source for agriculture and domestic water needs. Most residents of the study area rely on boreholes and shallow wells. The research location is characterised by hot and dry climatic conditions with unpredictable precipitation. Kauwi is semi-humid while Zombe is semi-arid, and temperatures range from 14 to 34°C all year round (Gevera et al., 2020). July is the coldest month of the year with temperatures falling to 14°C (Mwangi, 2018). September is the hottest period with high temperatures of 34°C

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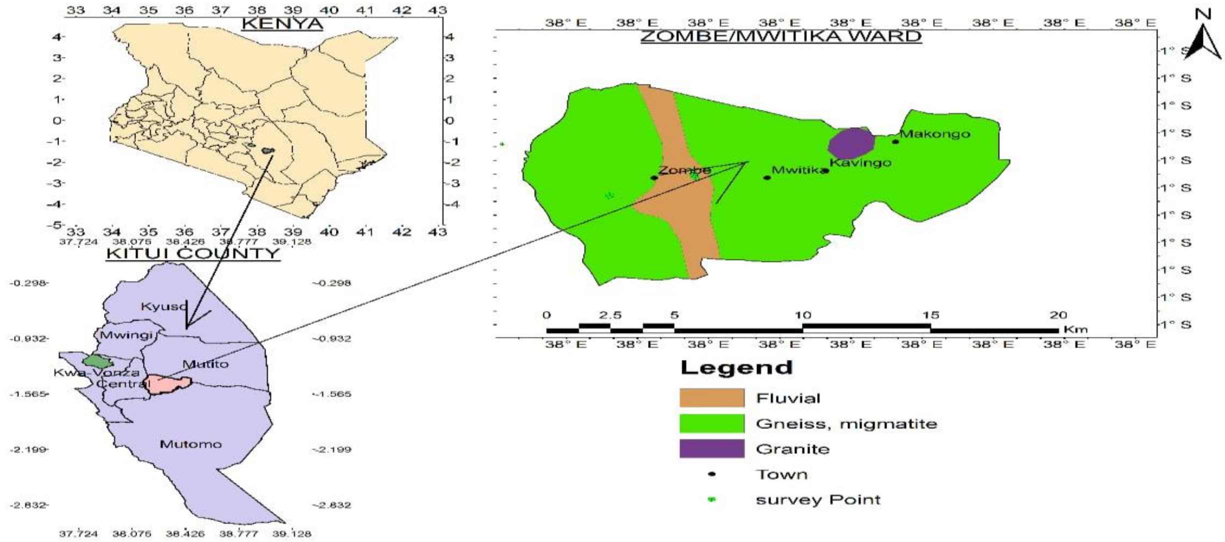
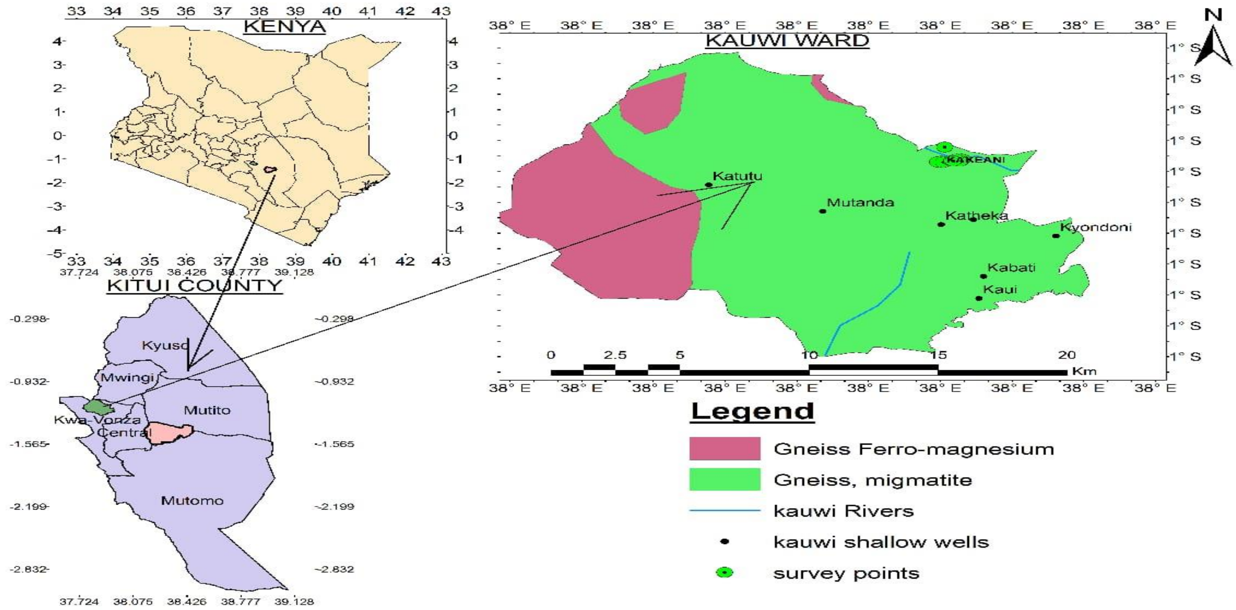
(Kenya Meteorological Department, 2019). There are two rainy seasons, which are erratic and unreliable. The long rains occur from March to May with an average of 500mm to 900 mm, and short rains fall between October – December with an average of 300mm to 600mm (Ngugi et al., 2021). The remaining months of the year are often dry, and rainfall patterns fluctuate from year to year, making it impossible to anticipate.

Figure 1: Study Area-Zombe



Source: *Dorcas, 2024*

Figure 2: Study area-Kauwi



Source: *Dorcas, 2024*

The Sampling Technique

Two study sites (Kauwi location and Zombe location) were purposively selected in Kitui West and Kitui East sub-counties, respectively. The shallow wells were purposefully selected. The wells were selected based on their accessibility and also the human activities taking place around such as farming, animal grazing, irrigation, sand mining, among others.

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Water Sampling and Analysis

Fifteen composite water samples were collected in triplicate from each of the two sub-locations during the wet month of December 2021 and the dry month of October 2022. The samples were collected in plastic sampling bottles, which had been thoroughly cleaned by washing in non-ionised detergent, rinsed with tap water, and soaked in 10% HNO3 for 24 hours and finally rinsed with non-ionised water prior to use. The bottles were rinsed with water from the same wells. The samples were analysed at the shallow well sites using portable water testing equipment. pH and TDS parameters were analysed using a Portable pH meter and a Portable TDS meter, respectively. Electrical conductivity (EC) was analysed using a Portable EC meter, while a turbidity meter standardised to 0.00 NTU using distilled water was used for turbidity assessment. Ca, Mg, Mn, K, Cl, Sulphates, Nitrates, Fluorides, Zinc, and Calcium carbonate were analysed by use of spectrometric methods.

Statistical Data Analysis

Microsoft Excel was applied to review accuracy and completeness as part of the data cleaning process, arranging and coding using dummy variables before being loaded for analysis using the Statistical Package for Social Sciences software for Windows to calculate the mean values, independent *t-test,* and to compute Pearson correlation coefficients.

RESULTS AND DISCUSSIONS

Spatial Variations in Physicochemical Properties of Groundwater

A comparison was made using an independent *t-test* on mean levels of physicochemical properties of shallow groundwater sources in Zombe and Kauwi Locations. The results are presented in Table 1.

Table 1: Mean Values of Water Quality Parameters of Groundwater Sources in Kauwi and Zombe Locations

Parameter	Kauwi mean	Zombe mean	P Value	WHO	KEBS
Ph	7.09*(0.08)*	7.09(*0.08*)	0.62	6.5-8.5	6.5-8.5
Calcium (mg/l)	148.33*(77.39)*	203.32(*65.38*)	0.004*	100	100
Magnesium (mg/l)	35.25(*16.32*)	45.67(*14.01*)	0.01*	50	50
Aluminium (mg/l)	0.13(*0.05*)	0.18(*0.18*)	0.13	0.2	0.2
Electrical conductivity (mg/l)	452.13(*149.10*)	342.21(*147.28*)	0.006*	1000	1000
TDS (mg/l)	455.37(*172.28*)	540.78(*172.28*)	0.06	500	500
NaCl (mg/l)	36.62(*96.59*)	61.95(*96.59*)	0.17	-	-
Sulphates (mg/l)	186.58(*88.57*)	252.43(*88.57*)	0.002*	250	250
Nitrates (mg/l)	61.02*(20.26)*	66.47(*14.92*)	0.24	10	50
$CaCO_3$ (mg/l)	137.30(*121.76*)	144.87(*107.03*)	0.80	300	300
Chlorides (mg/l)	184.11(*78.99*)	238.17(*112.04*)	0.04*	250	250
Fluoride (mg/l)	0.52(*0.38*)	0.50(*0.39*)	0.86	4.0	4.0
Zinc (mg/l)	1.56(*2.13*)	1.12(*1.12*)	0.31	5.0	5.0
Turbidity (NTU)	5.76(*6.01*)	7.26(*10.28*)	0.49	5	5

Note: The variables in parentheses are the standard deviation

* P values are significant ($p \leq 0.05$)

Calcium, Magnesium, Electrical conductivity, Sulphates, and Chlorides in the study area were found to be significantly different between Kauwi and Zombe locations ($p \leq 0.05$) (Table 1).

The observed significant spatial differences in chlorides, Sulphates, Electrical conductivity, Magnesium and Calcium could be attributed to weathering of gneiss, migmatite and fluvial rocks occurring in the area of study. Additionally, different land use practices that involve conventional fertiliser application, when farming, animal grazing and sand harvesting are carried out

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in the study area, may also enhance these spatial variations. Studies by Gevera *et al.* (2020) established spatial differences in the parameters studied, whereby they attributed the differences to rock weathering and evaporation. Further, Mwamati (2017) observed spatial variations in the parameters studied. He attributed the differences to the geologic formations and composition of rocks. The lack of significant differences in the rest of the parameters is probably due to similar anthropogenic activities affecting the changes in these parameters being carried out in the study areas.

Calcium

The presence of spatial variations in Calcium may be due to the dissolution of carbonates like calcite, dolomite, gypsum, and marble. This finding is consistent with the findings of Gevera *et al.* (2020), who reported that there were spatial Calcium differences in groundwater, associated with the weathering of rocks. Rocks and minerals in contact with water determine the chemical composition or the concentration rates of different parameters in water (Tavassoli and Khasar, 2002).

Magnesium

The spatial differences in relation to the magnesium element could have been as a result of the different types of magnesium-bearing minerals found in the study areas. Gevera et al. (2020) noted similar spatial differences in Mg. The study attributed the differences to the dissolution and weathering of silicate rocks. In another study by Johnson et al. (2019), similar spatial differences in Mg were attributed to the varying rates of weathering of carbonate and silicate rocks across different regions.

Electrical Conductivity

The spatial variations observed in Electrical conductivity ($p \leq 0.05$) can be credited to the geological rock formations of the study areas. Kauwi consists of gneiss and migmatite rocks, while fluvial rocks characterise Zombe. The two are known to exhibit different electrical conductivity characteristics due to the contrasting nature of their rock compositions. The electrical conductivity may also be affected by the dissolution of various anions and cations by different chemical materials. Makhokha (2019) made similar observations where the electrical conductivity values differed between different locations, where the salt mining areas recorded a high electrical conductivity. On his part, Gevera *et al*. (2020) observed spatial differences in the electrical conductivity of groundwater in their studies. In all the cases, the differences were linked to the local geological formations.

Sulphates

The significant difference in sulphate mean levels in Kauwi and Zombe can be linked to the prevailing human activities conducted in the study area, which are dominated by crop growing. The shallow wells are surrounded by crops that, at times, receive water from the sources. Consumption of water containing sulphates above the recommended levels can cause a laxative effect (Olonga *et al.,*2015). Similar studies reported by Alexander (2017), where intensive agricultural and mining activities are carried out in the area with high levels of sulphates, have similar findings. Further, Gevera *et al. (*2020) attributed the spatial variation in sulphates to the weathering of rocks.

Chlorides

The regional variations in concentrations of chloride can be related to geological variables such as rock composition, as well as differences in human activity in the studied locations. The results are supported by the findings in Makhokha (2019), who observed spatial differences in chloride levels. The differences were associated with geologic formations and surface run-off of leachates. Contrast findings by Jain et al. (2005) point to spatial chloride variations to be associated with industrial pollution. Similar observations on chloride variations were also made by Mani (2015), where he associated the variations with domestic sewage.

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Temporal Variations in the Physicochemical Properties of Shallow Groundwater

Temporal variations of shallow groundwater quality were determined by use of the Independent t-test, and the mean levels of physicochemical properties of shallow groundwater during the wet and dry seasons are presented in Tables 2 and 3.

Table 2: Mean Values of Selected Seasonal Water Quality Parameters of Water Resources in Kauwi Location

Parameter	Wet season mean	Dry season mean	P Value
pH	7.14(*0.07*)	7.03(*0.05*)	0.00*
Calcium(mg/l)	118.91(*77.81*)	177.77(*67.04*)	0.03*
Magnesium(mg/l)	36.57(*12.73*)	44.35(*18.04*)	0.379
Aluminium(mg/l)	0.21(*0.28*)	0.15(*0.06*)	0.372
Electrical conductivity(mg/l)	390.11(*74.64*)	514.15(*179.68*)	0.020*
TDS (mg/l)	419.57(*129.38*)	491.18(*225.91*)	0.26
Nacl(mg/l)	28.67(*14.03*)	43.61(*23.46*)	0.04*
Sulphates(mg/l)	233.25(*42.64*)	139.93(*57.59*)	0.00*
Nitrates(mg/l)	67.52(*10.70*)	54.52(*25.41*)	0.08
CaCO3(mg/l)	220.18(*125.60*)	54.43(*14.79*)	0.00*
Chlorides(mg/l)	138.87(*88.42*)	229.34(*26.89*)	0.001*
Fluoride(mg/l)	0.67(*0.64*)	0.61(*0.37*)	0.12
Zinc(mg/l)	1.41(*2.42*)	1.70(*1.87*)	0.76
Turbidity (NTU)	5.71(*6.90*)	5.80(*5.22*)	0.42

Note: The variables in parentheses are standard deviations

* P values are significant (p≤ 0.05)

The table shows that the significant differences between the wet and dry seasons in Kauwi were determined and tabulated in Table 2. The mean values for the pH, Ca, Ec, salinity, Sulphates, CaCo3 and Chlorides indicated statistical temporal differences (p≤ 0.05).

Table 3: Mean Values of Selected Seasonal Water Quality Parameters of Water Resources in Zombe Location

Parameter	Wet season mean	Dry season mean	P Value
Ph	7.15(*0.07*)	7.04(*0.53*)	0.00*
Calcium(mg/l)	226.47(*62.31*)	180.17(*61.83*)	0.05*
Magnesium(mg/l)	40.56(*9.71*)	50.78(*16.02*)	0.04*
Electrical conductivity(mg/l)	452.52(*96.94*)	231.89(*97.23*)	0.00*
TDS (mg/l)	537.09(*139.0*)	544.48(*205.27*)	0.91
Nacl (mg/l)	83.09(*131.56*)	39.31(*19.72*)	0.22
Sulphates(mg/l)	298.23(*86.47*)	206.62(*69.40*	0.003*
Nitrates(mg/l)	68.52(*9.44*)	64.41(*19.06*)	0.46
$CaCO_3$(mg/l)	229.71(*89.67*)	60.02(*16.19*)	0.00*
Chlorides(mg/l)	177.03(*82.89*)	299.31(*105.46*)	0.001*
Fluoride(mg/l)	1.71(*2.48*)	0.67(*0.29*)	0.12
Zinc(mg/l)	1.27(*1.53*)	1.40(*1.79*)	0.41
Turbidity (NTU)	9.08(*14.35*)	5.43(*2.38*)	0.42

Note: The variables in parentheses are standard deviations

* P values are significant (p≤ 0.05)

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The t-test results at a 95% confidence level indicated that there was a significant difference in the concentration of the pH, Ca, Mg, Sulphates, CaCo3, and chlorides between the wet and dry seasons.

pH

The observed significant seasonal differences in Kauwi and Zombe could be attributed to run-off and deposits with acidic components such as sulphuric or nitric acid from the atmosphere in the rainy season, which may cause an increase in pH. The results are in agreement with Mwangi (2014), who noted higher pH of water in Kiambu County during the wet season than the dry season. A high pH was attributed to dissolved substances. Further, similar studies by Kanyaru (2012) on the assessment of shallow wells in Tharaka-Nithi indicated a higher pH during the wet season compared to the dry season. This study associated the high pH levels during the wet season with organic matter decay, while during the dry season, there is reduced water volume, which may lead to a decrease in pH level. At low pH, heavy metals are easily dissolved in water, and the water is also very corrosive and may corrode water pipes and home appliances.

Calcium

The significant seasonal variations observed in both Kauwi and Zombe locations could be attributed to groundwater recharge containing calcium ions during the rainy season. The results are in agreement with the research carried out in Chuka town, which found that calcium levels were greater in the rainy season than in the dry season by Ombaka et al. (2013). Calcium levels were found to be higher than acceptable WHO and KEBS guidelines in both seasons, with the potential effect of causing kidney stones and hypercalcemia when consumed by human beings. A study by Adongo et al. (2022) in the Kamiti-Marengeta subcatchment of Kiambu County, Kenya, also observed significant seasonal variations in groundwater quality, including calcium concentrations. The study found that calcium levels in boreholes and shallow wells varied between the wet and dry seasons, with some concentrations exceeding the Kenya Bureau of Standards (KEBS) and World Health Organization (WHO) guidelines for drinking water quality.

Electrical Conductivity

The study results reveal that electrical conductivity concentrations were significantly different between the wet and dry seasons in both study areas ($p \leq 0.05$). This could be attributed to high water evaporation, which raises the concentration of ions, unlike during the rainy season when the ions are diluted as rainwater increases the amount of water. These results are consistent with those of Ngabirano *et al.* (2016), who reported greater electrical conductivity values during the rainy season. Further, a study by Tamaugee *et al*. (2020) found that electrical conductivity levels in hand-dug wells increased during the wet season, which the authors attributed to higher surface runoff and leaching of dissolved solids into groundwater. In contrast, boreholes exhibited less seasonal variation in EC.

Salinity

Salinity differed significantly between the wet and the dry season in Kauwi. This could be a result of less dilution effect during the dry season, as the groundwater table declines due to less groundwater recharge. This is similar to the study results arrived at by Ladipo *et al.* (2011), where salinity showed strong seasonal variations, with the dry season recording higher salinity than the wet season. This was attributed to a high rate of evaporation during the dry season, leading to increased concentration of salinity. Further, the findings of this study have also been supported by Dan *et al. (2014),* who noted higher salinity levels during the dry season. This could be attributable to high evaporation rates, poor water flow, and saltwater intrusion.

Sulphates

The observed significant temporal variations ($p \leq 0.05$) in sulphate were attributed to run-offs carrying fertilisers into the shallow wells during

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the rainy season, as there is intensive agriculture carried out near the shallow wells. The aspect is a rainy season characteristic, as realised in the findings of Mwangi (2014), who noted higher sulphate levels during the wet season. Further researches by (Gaber, 2016; Sharma et al., 2019; Ombaka *et al*., 2013) conclude on the same.

Total Hardness (Calcium Carbonate)

The temporal fluctuations in $CaCO_3$ revealed spatial differences between the wet and dry seasons ($p \leq 0.05$). The mean $CaCO_3$ levels were greater during the rainy season than in the dry season (229.71and 60.02), respectively. The changes might have been caused by groundwater replenishment with calcium and magnesium ions, which are contained in the minerals of the study area. Previous investigations in Tharaka-Nithi by Kanyaru (2012), Ombaka *et al*. (2013), Makwe *et al*. (2013), and Olonga *et al*. (2015) found greater levels of $CaCO_3$ during the rainy season compared to the dry season. The studies attributed the high levels to groundwater recharge with Calcium and Magnesium ions, which result from leaching from the rocks (Olonga *et al.,*2015).

Chlorides

The introduction of the chloride in the shallow wells could be from natural minerals, particularly those containing rock salt or other chloride-bearing minerals or leaching of salts from the soil to the wells (Mutua *et al*.,2020). High levels of Chloride give water a salty taste. It also causes damage to home appliances, and if consumed in excess, it may cause hypochloraemia. The results of the investigation showed that chloride concentrations in water varied substantially between the rainy and dry seasons. The differences could be attributed to the diluting effect that occurs during the rainy season, hence this may lower the concentrations of chloride ions. Various researchers conclude on the same (Mwangi, 2014; Harrison & Rojas, 2012; Quedraogo, 2015)

Statistical Correlation between the Water Quality Parameters

Correlation analysis was done to determine if there exists a statistical relationship between the water quality parameters in the study area, and the results are presented in Table 4.

Table 4: Correlation Results for Selected Water Quality Parameters

	Mg (mg/L)	Ca (mg/L)	Al (Mg/L)	EC (mg/L)	TDS (Mg/L)	Turbidity (NTUs)	Salinity (mg/L)	$CaCO_3$ (mg/L)	NO_3 (mg/L)	SO_4 (mg/L)	Cl^- (mg/L)	F^- (mg/L)	PH	Zn (mg/L)
Mg (mg/L)	1													
Ca (mg/L)	$.394^{**}$	1												
Al (Mg/L)	.177	.132	1											
EC (mg/L)	.065	$.327^{*}$	$.266^{*}$	1										
TDS (Mg/L)	$.479^{**}$	$.445^{**}$	.180	$.424^{**}$	1									
Turbidity (NTUs)	.014	.037	-.027	.088	-.026	1								
Salinity (mg/L)	.252	$.446^{**}$	.032	$.309^{*}$	$.434^{**}$	-.011	1							
$CaCO_3$ (mg/L)	$.469^{**}$	.226	-.153	.079	$.409^{**}$	-.012	$.476^{**}$	1						
NO_3 (mg/L)	$.377^{**}$	$.391^{**}$	$.271^{*}$	.178	$.375^{**}$	.062	$.294^{*}$	.163	1					
SO_4 (mg/L)	$.256^{*}$	$.376^{**}$	$.274^{*}$	.166	$.457^{**}$	.010	.174	-.240	$.423^{**}$	1				
Cl^- (mg/L)	.234	$.278^{*}$	.228	$.302^{*}$	$.445^{**}$	.079	.190	-.229	$.415^{**}$	$.691^{**}$	1			
F^- (mg/L)	$.276^{*}$	-.020	-.001	.044	$.390^{**}$	.012	$.374^{**}$	$.563^{**}$	.002	-.089	-.166	1		
PH	-.092	-.003	.248	.048	-.143	.068	-.239	$-.503^{**}$	.201	$.399^{**}$	$.409^{**}$	$-.314^{*}$	1	
Zn(mg/L)	.134	-.147	.033	.151	-.076	.020	-.030	-.147	.081	-.038	-.056	-.009	.076	1

**Correlation is significant at the 0.01 level (2-tailed)

*Correlation is significant at the 0.05 level (2-tailed)

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The chart indicates that there exists a positive correlation between SO_4 and CL^-, TDS and $CaCO_3$, Mg and $CaCO_3$, $CaCO_3$ and TDS, Salinity and $CaCO_3$(0.69,0.41,0.47,0.41,0.48) among others. A negative correlation exists between Mg and pH, Ca and F-, Ca and pH, Ca and Zn, AL and F-(-0.09-0.02,-0.0032,-0.147,-0.001), respectively. This means that as one variable increases, the other decreases and vice versa. As a result, the physicochemical parameters correlate with one another, both positively and negatively. The significant positive correlation between magnesium and calcium carbonate suggests that higher magnesium concentrations are associated with increased levels of calcium carbonate. This is expected, as both magnesium and calcium are major cations found in water and are involved in processes such as water hardness. The formation of calcium carbonate (CaCO3) typically occurs in hard waters, and magnesium is often found alongside calcium in such systems, leading to their concurrent increase. This aligns with study findings by Liu *et al. (*2005), who found a direct relationship between these cations and calcium carbonate saturation in groundwater. Similarly, Rapant *et al*. (2017) documented that calcium and magnesium concentrations in groundwater significantly influence health outcomes, indicating their pivotal role in water chemistry and quality.

The positive correlation between TDS and calcium carbonate suggests that higher TDS concentrations are linked to elevated levels of calcium carbonate. TDS includes various dissolved salts, and a significant portion of these may be contributed by calcium and magnesium salts, both of which are components of calcium carbonate. Therefore, higher TDS levels often correspond to harder water, which typically contains more calcium carbonate. The positive correlation between TDS and calcium carbonate is also consistent with other research. According to the World Health Organization (WHO, 2017), TDS in natural waters is largely composed of calcium, magnesium, and bicarbonate ions—key constituents of calcium carbonate. Tiwari & Singh (2014) also reported a significant relationship between TDS and calcium carbonate in rural groundwater, showing that elevated TDS typically signals increased hardness.

TDS is a measure of the total concentration of dissolved solids in water, including ions such as calcium, magnesium, and sodium. The positive correlation between TDS and magnesium concentrations indicates that as the total concentration of dissolved solids increases, so does the concentration of magnesium, which is a major contributor to TDS. This is consistent with the understanding that higher TDS levels often reflect higher concentrations of divalent cations like magnesium and calcium. Srinivasamoorthy *et al.* (2008) demonstrated that magnesium significantly contributes to the TDS load, particularly in regions with dolomite or basaltic geology. Subba Rao (2006) also reported a strong link between magnesium and TDS in hard rock aquifers of India, noting that geogenic processes such as rock-water interaction and weathering of magnesium-bearing minerals were key contributors.

Salinity and calcium carbonate also show a significant positive correlation. Salinity in water is primarily due to the presence of dissolved salts, which may include compounds like sodium chloride, calcium chloride, and magnesium sulfate. As salinity increases, calcium carbonate levels tend to increase as well, likely due to the common presence of calcium and carbonate ions in saline environments. Appelo & Postma (2005) described how saline water introduces not only sodium and chloride but also calcium and bicarbonate, leading to increased calcium carbonate precipitation. This relationship is further supported by findings from Mazor (2004), who observed that groundwater systems in semi-arid climates often exhibit co-enrichment of salinity and calcium carbonate due to prolonged water-rock interaction and dissolution of carbonate-bearing minerals.

A strong positive correlation between sulphate and chloride suggests that these two ions often occur together in water. Both sulphate and chloride are commonly found in groundwater and

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surface water, often originating from natural sources like mineral deposits or from human activities such as industrial processes. This correlation may indicate the presence of both ions in certain water sources, reflecting common geochemical processes or pollution sources. Jalali (2005) identified similar co-occurrence in groundwater affected by agricultural runoff and evaporative concentration, suggesting a shared origin or transport pathway. Similarly, Sarin & Chatterjee (2014) observed a significant positive correlation between sulphate and chloride in the groundwater of the Indo-Gangetic Basin, noting that these ions often co-occur in regions with heavy irrigation and industrial contamination. Their study emphasised that both sulphate and chloride can be leached from soils or industrial effluents, where they may mix with naturally occurring groundwater constituents. Additionally, Smedley & Kinniburgh (2002) highlighted the role of geogenic processes, such as the dissolution of evaporite minerals (e.g., halite and gypsum), in promoting the co-occurrence of these ions, especially in arid and semi-arid regions where evaporation exceeds precipitation.

A slight negative correlation between magnesium and pH indicates that higher magnesium concentrations are associated with a slight decrease in pH (Zubair *et al*., 2002). This may be due to the fact that magnesium salts, when dissolved in water, can slightly lower the pH, especially in waters with high mineral content. However, the correlation is weak, suggesting that other factors may also influence the pH levels in the water. The correlation between calcium and pH is negligible, suggesting that there is no significant relationship between calcium concentration and pH in the analysed samples. This could imply that pH variation is governed by other factors, such as the presence of acidic or basic compounds, rather than calcium alone (Mazor, 2004).

A negative correlation between aluminium and fluoride suggests that as the concentration of aluminium increases, the fluoride concentration tends to decrease. This relationship may be due to the fact that aluminium can form complexes with fluoride, reducing the available fluoride ions in the water. This is particularly relevant in natural waters, where aluminium and fluoride may interact to form insoluble compounds. For instance, Pillai *et al. (*2007) demonstrated that aluminium and fluoride ions can interact in water systems, where aluminium ions, particularly in the form of aluminium hydroxides, have a high affinity for fluoride, leading to the formation of stable complexes that reduce free fluoride concentrations. Similarly, Liu *et al.* (2011) investigated the interaction between aluminium and fluoride in groundwater samples from industrial areas in China, finding that aluminium fluoride complexes contributed to lower free fluoride concentrations, especially in waters with high aluminium content. The study also indicated that under acidic conditions, the formation of aluminium-fluoride complexes is more prominent, further reducing the fluoride available in the solution.

The observed significant correlation between SO_4 and Cl^-; $CaCO_3$ and TDS; Mg and $CaCO_3$; TDS and SO_4; $CaCO_3$ and Salinity implies that if the concentration of any of these variables increases, the concentration of the other variables increases. It is also an implication that they originate from similar sources in the environment. This means that to control groundwater quality, you only need to control either of them. This is in agreement with the results obtained by (Daraigon *et al., 2011*; Jothivenkatachalam *et al.,* 2010; Patil and Patil, 2010).

Limitations of the Study

Despite the valuable insights gained from the assessment of groundwater quality in Kauwi and Zombe, this study was subject to several limitations that may have influenced the results and their interpretation: Firstly, data collection was limited to a single year and two specific locations, reducing the ability to capture seasonal and inter-annual variability or broader regional patterns. The study lacked detailed land use, hydrogeological, and socioeconomic data, which impeded the analysis of potential anthropogenic influences and health implications. Shallow wells

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were the sole sampling sources, omitting deeper aquifer dynamics, and no groundwater table monitoring was conducted. Additionally, the absence of hydrogeochemical tracer techniques, geochemical modelling, and microbial assessments limited the capacity to accurately trace contaminant sources or understand biogeochemical processes. Analytical limitations were also present, with insufficient detail on quality assurance/quality control procedures and instrumental precision. Correlation analysis was used without complementary multivariate or causal modelling, leading to possible misinterpretation of relationships between parameters. Overall, these methodological and data constraints limit the study's robustness, spatial relevance, and applicability to long-term groundwater quality management.

Theoretical Implications of the Study

This study highlights important theoretical implications related to spatial variations in groundwater quality between Kauwi and Zombe. It reinforces hydrogeochemical models by demonstrating how geological formations such as gneiss, migmatite, and fluvial rocks directly influence water chemistry through mineral weathering. It also supports existing theories on the combined role of natural and anthropogenic factors, such as land use practices, in shaping groundwater quality. The findings of this study support existing hydrogeological theories that groundwater quality parameters, including pH, calcium, magnesium, sulphates, $CaCO_3$, and chlorides, are significantly influenced by seasonal variations. The observed seasonal differences between the wet and dry seasons align with models of groundwater recharge and dilution, where the influx of rainwater during the wet season leads to fresh water inputs and the dilution of solutes, while the dry season is characterised by reduced precipitation and increased evaporation, which concentrates dissolved ions. This seasonal fluctuation confirms the theoretical concept of evapotranspiration effects, where increased evaporation during the dry season raises solute concentrations, particularly salinity and electrical conductivity. Moreover, the seasonal variations in sulphates and chlorides, which were more pronounced during the wet season due to agricultural runoff, support theoretical frameworks emphasising the impact of anthropogenic activities, such as fertiliser application and surface runoff, on groundwater chemistry. Additionally, the increased levels of calcium carbonate and other ions during the rainy season align with theories on water-rock interactions, where mineral dissolution and leaching processes during groundwater recharge lead to higher concentrations of certain ions. Finally the study offers valuable theoretical contributions to the field of groundwater quality assessment. Theoretically, it enhances the understanding of hydrogeochemical processes by confirming significant correlations among key water quality parameters such as calcium, magnesium, TDS, sulphates, and chlorides. These findings support existing theories related to water hardness, mineral dissolution, and the interplay between geogenic and anthropogenic factors in shaping groundwater chemistry.

Practical Applications of the Study

The study highlights the need for regular monitoring of shallow groundwater, especially during different seasons, to detect contamination trends and ensure water safety for human consumption. Given that some wells exceed safe limits for nitrates, sulphates, and turbidity, local health authorities can use this data to issue advisories, provide alternative safe water sources, or promote point-of-use water treatment methods like filtration or boiling. The study suggests a correlation between farm inputs and water contamination. This supports the need to train farmers on proper fertiliser and pesticide use to reduce leaching into groundwater. Findings on geologic and human activity impacts can inform land use policies, encouraging buffer zones around wells and zoning regulations that prevent contamination from agriculture or development. The results can also support community-based awareness campaigns to educate locals on the importance of protecting groundwater sources through proper sanitation, waste disposal, and controlled land use. The study also provides

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evidence that can be used by policymakers to update or enforce groundwater quality standards, especially in arid and semi-arid regions like Kitui County. Finally Local governments or NGOs can use the findings to prioritise infrastructure investments, such as installing wellhead protection systems, improved drainage, or sealed well covers.

CONCLUSION AND RECOMMENDATIONS

The study concluded that geological differences, land use practices, and anthropogenic activities were the key contributors to spatial variations in water quality. The temporal variations were primarily influenced by factors such as rainfall, evaporation and groundwater recharge during the wet season. Finally, the correlation between water quality parameters indicated significant associations between certain ions and compounds, implying that controlling one parameter could help manage others. To ensure the sustainability and quality of shallow wells, protection should be prioritised to prevent contamination. This can be achieved through well lining and covering, fencing off the surrounding area to restrict access by grazing animals and using appropriate water withdrawal means. Secondly, training programs for farmers on applying the right quantities of farm inputs as part of their crop production system. Regular groundwater quality monitoring is a necessity to provide information on water quality changes and offer early identification of contamination and consequent solutions prescriptions.

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Conflict of Interest

The authors declare no conflict of interest in the study.

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