GROUNDWATER QUALITY ASSESSMENT AND WATER QUALITY INDEXING: CASE STUDY OF MAKUENI COUNTY, EASTERN KENYA

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Abstract

Makueni falls in South Eastern, semi-arid region of Kenya, that is characterised by erratic rainfall and inadequate surface water from a few rivers. One of the options to supply both human and animal population is groundwater. Occurrence of groundwater in the basement complex terrain of this study area is controlled by secondary porosity developed through weathering, fracturing and cracking of the bed rocks. However, the quality of groundwater is more often than not found to be above the WHO limits. The objectives of this study were to analyse the geochemistry of the groundwater for major and minor elements and heavy metals, develop a water quality index (WQI) and then develop a water quality potential map for Makueni County. Groundwater samples from 61 boreholes spread across the county were analysed using the standard methods of water and wastewater while the index was developed through comparison of water quality parameters with respect to WHO standards to provide a single number that expresses the overall water quality. The water quality potential map on the other hand was developed using thematic layers selected for water quality potential map based on literature, geophysical investigations and data appropriately weighted in a modified DRASTIC model based overlay scheme. The results of the study showed that major anions and cations concentrations are beyond the limits recommended by WHO. Iron (Fe) was found to be more than 4.5 mg/L well beyond the allowable 0.3 mg/L. while electrical conductivity was found to be more than 1000 mg/L. The water quality index (WQI) for most of the areas of the County were greater than 180, which means that groundwater from most areas of Makueni is not potable.

Keywords: Groundwater, DRASTIC modelling, WHO Standards, Water Quality Index (WQI) Water Quality Potential Map, Geochemistry, Makueni County.

Introduction

Groundwater constitutes 30.1 % of all world water and over 90 % of the readily available fresh water[8,4]. Groundwater is a comparatively safe and reliable source of water when compared to surface water. It is generally not polluted, however, when polluted it becomes very difficult to treat to acceptable levels. On the other hand, availability of surface water is dwindling by the day mainly because of climate change, population increase and anthropogenic changes such as land use and land cover patterns which has led to groundwater gaining in prominence as a source of water supply. However, the quality of groundwater which is also dictated by the geology and the geochemistry of a given locality is gradually changing. Figure 1 shows the digitized geological map showing 12 different geological materials that are exposed on the surface or encountered in boreholes and at sampling sites within the study area

Large areas of the eastern, north eastern, and north-central parts of the county are underlain by crystalline Precambrian basement rocks that dominate South Eastern Kenya. These rocks belong to the Kasigau series[18,6]. Parts of the area are underlaid by Basement rocks of the Semi- Calcerous group while others are underlaid by the Basement system of the middle, Semi Pelitic group[24]. According to Saggerson (1963) these Precambrian crystalline rocks are geologically complex with the spaces between their mineral crystals being microscopically small, few and generally unconnected and consequently their porosity is low. These metamorphic rocks are only permeable where they are fractured and their yields are low but because they extend over large areas large volumes of water are withdrawn from them. In areas dominated by the basement system the main water stuck levels (WSL) range from 15 to 25 M for the first aquifer, between 35 and 45M for the second aquifer and from 85 to 140M for the 3rd aquifer.

The South-Eastern part of this County is dominated by a Volcanic over Basement rock system. These Volcanic rocks have a wide range of chemical, mineralogic, structural, and hydraulic properties, due mostly to variations in rock type and the way the rock was ejected and deposited. Unaltered pyroclastic rocks, have porosity and permeability similar to poorly sorted sediments while hot pyroclastic material became welded as it settled and is therefore almost impermeable[3].

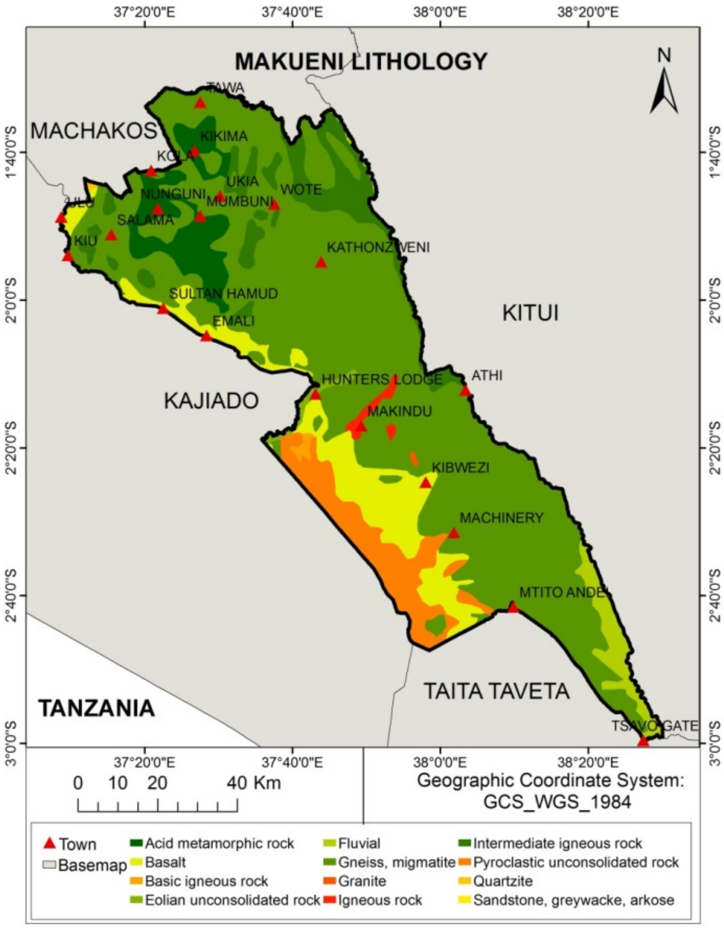


Figure 1 showing the main geological features of Makueni county[21]

Silicic lavas tended to be extruded as thick, dense flows, and has low permeability except where they are fractured. Basaltic lavas tended to be fluid and formed thin flow that has considerable pore space at the tops and bottoms of the flows. Numerous basalt flows commonly overlapped and the flows were separated by soil zones or alluvial material that formed permeable zones. Columnar joints developed in the central parts of basalt flows creating passages that allowed water to move vertically through the basalt. Basaltic rocks are characterized by very productive aquifers in volcanic rocks. These type of aquifer is found along the western side of the Nairobi-Mombasa Highway. Along the Highway itself the aquifer is found between the contact zone of the Chyulu Volcanics and the Basement system while further westwards the aquifers are found between the contact zones of the various lava flow episodes.

Spread throughout the County are seasonal langas that are filled with recent alluvium deposits on sand and soil. These langas are shallow and unconfined and their yields depend on recharge.

The water quality in the basement system is described as saline[13,6,9,20]. The water quality has led to the abandoning of already sunk boreholes even where such boreholes have adequate yield. The water is said to have excess flourides, excess iron as evidenced by rusting of metal components of plumbing accessories among other compounds. According to Maina (1982), Nanyaro et al., (1984) and Gaciri and Davies (1993) the major source of fluoride and other compounds in groundwater particularly in the volcanic Chyulu hills is traced to volcanic activity and chemical weathering of the volcanic rocks.

Groundwater in some areas is fresh depending on the chemical composition of the host rock and the retention time of the water in the aquifer[22]. The water quality in the langas comprising alluvium deposits is good where the aquifer lies between lava flow episodes but may be hard where the aquifer is along the contact zone of the basement system or along ancient river valleys which were by carbonaceous rocks[23].

Until recently, groundwater assessment has been based on laboratory testing and field incursions but the advent of Satellite technology and Geographical Information system (GIS) has made it easy to integrate various database[11,14,21]. Where large quantities of data are available water quality indexing has been developed that results in a water quality index (WQI) for a given area. This analysis allows good and bad water quality data to be quantified by reducing data on physical, chemical and biological variables into a single number in as simple, objective and reproducible manner[7,15]. The WQI concept is based on the comparison of the water quality parameter with respective regulatory standards[12] and provides a single number that express overall water quality at certain location based on several water quality parameters[26].

For computing WQI, three steps are followed. In the first step, each of the 10 parameters (pH, Turbidity, Ec, Mn, Mg, Ca, Fe, K, Na, and TDS) is assigned a weight (wi) based on their perceived effects on primary health. The maximum weight of 5 is assigned to parameters like total dissolved solids, iron and electrical conductivity due to their major importance in water quality assessment. Manganese and potassium are assigned minimum weight of 1 as they play an insignificant role in water quality assessment. Other parameters are assigned a weight between 1 and 5 based on their importance in the overall quality of water for drinking purposes.

The second step, the relative weight (Wi) of each parameter was computed using the equation (i).

$$Wi = \frac{wi}{\sum_{i=1}^{n} wi} \qquad \text{(i)}$$

Where, wi is the weight of each parameter, n is the number of parameters and Wi is the relative weight.

In the third step, quality rating scale (qi) was calculated for each parameter using the equation (ii)

$$qi = \frac{Ci}{Si} * 100 \qquad \text{(ii)}$$

Table 1. Drinking water standards and proposed relative weights of various parameters.

Chemical Parameters	WHO Standard (Si)	Weight (wi)	Relative Weight (Wi)
Ph	8.5	3	0.0967
Turbidity	5	4	0.129
E. Conductivity	500	5	0.1612
Manganese	0.1	1	0.0322
Magnesium	50	2	0.0645
Calcium	75	2	0.0645
Iron	0.3	5	0.1612
Potassium	12	1	0.0322
Sodium	200	3	0.0967
TDS	1000	5	0.1612
		∑wi 31	∑Wi 0.9994

Where, qi is the quality rating, Ci is the concentration of each chemical parameter in each water sample in mg/l and Si is the WHO standard for each chemical parameter in mg/L.

To compute the WQI, the SI is first determined for each chemical parameter using equation (iii)

$$Sii = Wi * qi \qquad \text{(iii)}$$

WQI was then computed using the equation (iv)

$$WQI = \sum Sii \qquad \text{(iv)}$$

Where, Sii is the sub-index of ith parameter, qi is the rating based on concentration of i parameter and n is the number of parameters.

GIS is a powerful tool to assess the water quality parameter, determining water availability of water, preventing flooding, understanding the natural environment, and managing water resources on a local regional scale[2]. Spatial analysis extension of GIS allows interpolation of the water quality parameter at unknown location from known values to create a continuous surface which will help us to understand the scenarios of water quality parameter of the study area. There are various Interpolation Techniques such as Inverse Distance weighted (IDW), Spline, Trend surface Analysis and Kriging available in Arc GIS Spatial Analysis extension. In the present study IDW technique was adopted to create the spatial distribution maps of water quality parameters and WQI.

MATERIAL AND METHODS

A field survey was conducted and water samples were collected from 61 boreholes. These water samples were analysed in the laboratory for different physical chemical parameters. The parameters included pH, turbidity, electrical conductivity (Ec), Total dissolved solids (TDS), clour, Iron (Fe), Manganese (Mn), Magnesium (Mg), Calcium (Ca), Sodium (Na), Potassium (K), Flourides (F), chlorides (Cl-). The alkalinity as well as hardness and the concentration of nitrates were determined.

The parameters were expressed as Mg/L except for the pH, Electrical Conductivity (μs/cm), turbidity (NTU) and colour (TCU). Sampling, preservation, transportation and the analysis of the samples was carried out according to methods described in water and wastewater analysis. (1998). The sampling bottles were rinsed with the groundwater being sampled and then completely filed up and air-tightly capped. The samples for chemical analysis were preserved and analysed within the holding period[28]. The Atomic Absorption Spectrophotometer (AAS) was used for in the analysis of heavy metals. This spectrophotometry is based on the phenomenon that an atom in the ground state absorbs light of wavelengths that are characteristic of each element when light is passed through the atoms in the vapour state. The absorption of light depends on the concentration of atoms in the vapour, the concentration of the target element in the water sample is determined from the measured absorbance[16]. A more sensitive spectrophotometry, flame atomic absorption spectrophotometry.

To develop the Water Quality Index map a spatial distribution map of the WQI computed was developed using the IDW (Geostatisical Analyst) tool in Arc Map software.

RESULTS AND DISCUSSION

The results of the physical chemical tests that were carried out are shown in Table 2 (a) and Table 2 (b). The lowest pH was recorded at a borehole owned by Teresia Ndumia while the highest pH of 8.23, this value being a measure of ions in the sample. All the water from boreholes in the study area had pH values that fall within the WHO as well as KEBS permissible range of between 6.5 and 8.5 for drinking water.

Table 2 a. Physicochemical parameters of groundwater from representative boreholes.

	Name of Borehole	UTMX	UTMY	Water Quality Parameters						
				pH	Turbidity	Ec	TDS	Colour	Fe	Mn
1	Kivaani	319087	9809581	6.91	1	795	508.8	7.5	5.4636	0.0000
2	Emali BH	329893	9770031	7.36	4	1245	796.8	10	5.3616	0.1802
3	Makindu Sisters	369826	9749031	6.75	8	9520	6093	7.5	5.3723	0.1019
4	Mwaani BH	352531	9805210	7.68	1	1466	938.2	25	5.3370	0.1521
5	Kithunzi	339485	9804956	6.84	63	2310	1478	15	5.3357	0.6883
6	Makindu Hosp.	369261	9747647	6.89	<1	6900	4416	15	5.3349	0.1201
7	Kee BH	316848	9809031	7.08	<1	1558	997.1	10	5.3335	0.0965
8	Kibwezi	390789	9722224	7.75	1.5	484	310	5	1.72	0.05
9	C-4309 – Tawa	329344	9830495	6.90	4.6	1000	600	5	4.89	0.74
10	C-5054 - Masongaleni	403602	9738454	8.20	25.0	1900	1140	5	4.7	0.4
11	Kyandumbi Water Project	329250	9806158	7.75	47	1013	648.2	7.2	5.12	8.36
12	Komboyoo Water project	389206	9712346	7.56	10	1680	1075	5.3	4.8	33.6
13	David Mutangili	302519	9803195	7.93	41	2540	1626	0.120	4.6	0.92
14	Teresia Ndunda	305954	9834852	6.58	1	655	419.2	0.9	5.12	13
15	Wadi Wa Mitila	299332	9821774	8.23	8	1411	903.04	0.010	7.6	28.7
16	Muli Ndambuki	305615	9806203	8.1	61	762	487.68	0.080	1.8	26.7

This range of pH; slightly acidic to moderately high alkaline was also reported by British Geological Survey (BGS) (2000) for groundwater quality for boreholes in the region. Figure 2 (a) and 2(b) show the pH map and the Turbidity map of the study area. Turbidity values varied from low values of <1 NTU to a high value of 63 NTU recorded from a borehole at Kithunzi. Several other boreholes had values greater than 5 NTU which is the upper limit for domestic water. Boreholes such as Muli Ndabuki (61 NTU), Kyandumbi (47 NTU), Mutangili's borehole (41 NTU), Masongaleni borehole with a turbidity of 25 NTU all show boreholes that are turbid. Some of these boreholes are only used during prolonged drought because of their high turbidity.

The electrical conductivity (EC) was highest in areas around Kibwezi and was lowest in high rise areas along the Machakos/Makueni border near Kola, Mukuyuni. For example Kee borehole had an Ec value of 1558 µS/cm while the EC value for Komboyoo borehole was 1680 µS/cm. Figure 3 (a) is a map showing the expected electrical conductivity in a given area of the study area while Figure 3 (b) shows the total dissolved map of the study area.

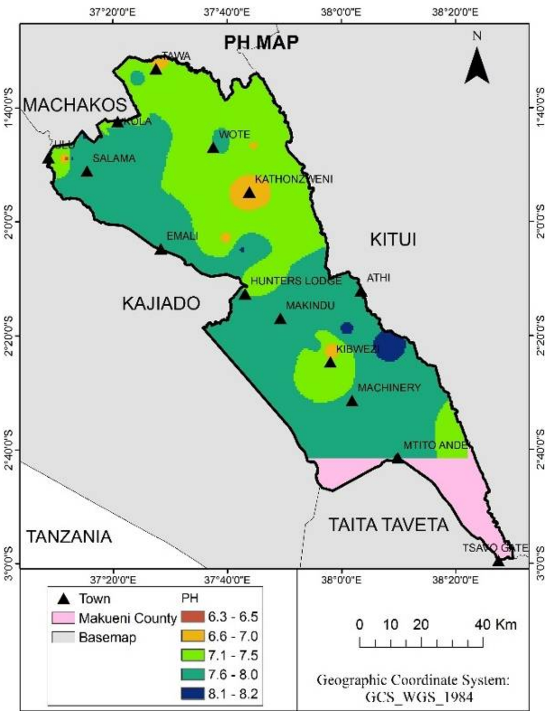


Figure 2 (a). The pH map of the of the study. area

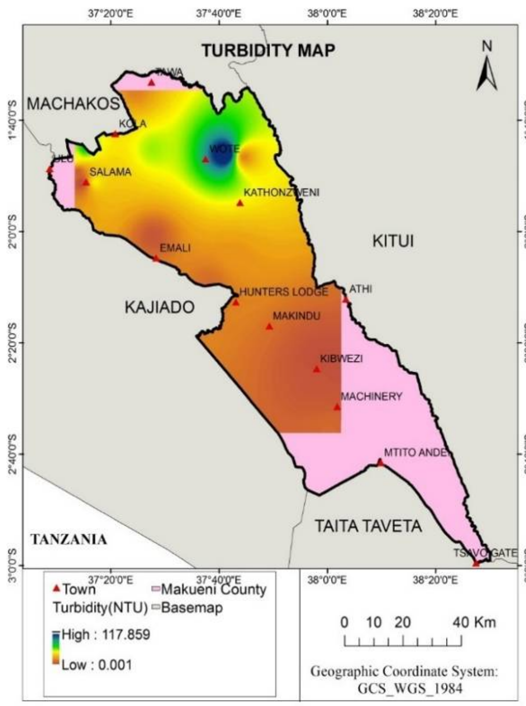


Figure 2 (b). The turbidity map of the study area

A variety of calcium and magnesium compounds in water cause it to be hard. For example magnesium sulphate (Epson salt), Calcium sulphate, magnesium hydrogencarbonate and calcium hydrogencarbonate among other salts cause both permanent and temporary hardness. Temporary hardness is removed by boiling but permanent hardness cannot be removed by boiling. Equation 1 shows the chemical reaction when aqueous calcium hydrogen carbonate is boiled thereby making water soft.

$$Ca(HCO_3)_{2\,(aq)} \rightarrow CaCO_{3(s)} + H_2O_{(l)} + CO_{2\,(gas)} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(v)}$$

The total hardness of groundwater from most of the borehole had hardness values greater than the allowable 500 mg/ $CaCO_3$/ L. It means groundwater of most of Makueni boreholes is hard. Indeed, the alkalinity, which is a measure of the capacity of the water to neutralize acidity was also high. The ability of water to act as a buffer is controlled by the amount of calcium and carbonates ions in solution. Localities that have limestone such as Makueni are likely to contain high levels of Ca^{++} and CO_3^{2-} ion and consequently elevated hardness as well high alkalinity.

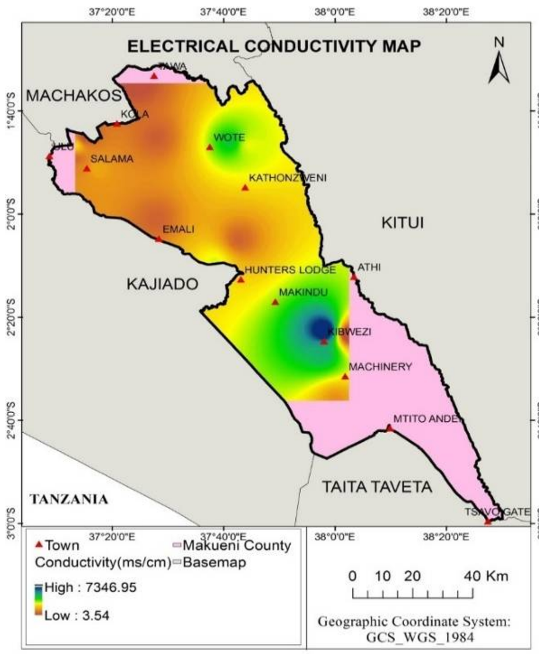


Figure 3 (a). The electrical conductivity map of the study area.

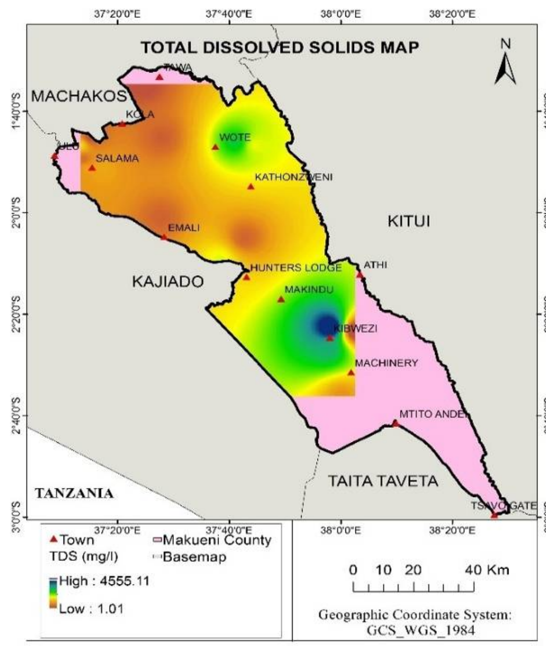


Figure 3 (b). The total dissolved solids map the study area.

Highly alkaline ions react with cations in water resulting in a precipitate that corrode pipes and other accessories in the water distribution systems.

Table 2 b. Physicochemical parameters of groundwater from representative boreholes

		Water Quality Parameters							
		Mg	Ca	Na	K	Flouride	Chloride	Alkalinity	Hardness
1	Kivaani	1.6511	12.8272	49.589	8.56	2.9	16.0	356	2850
2	Emali BH	1.8636	9.9489	86.08	10.96	1.23	19	326	1298
3	Makindu Sisters	1.9413	40.7460	399.50	16.99	8.2	42.87	404	1550
4	Mwaani BH	1.7830	21.8757	137.73	11.62	3.1	22	325	880
5	Kithunzi	1.8317	31.3201	201.37	5.25	6.5	50.02	401	876
6	Makindu Hosp.	1.9299	32.8360	361.97	4.60	5.1	41	324	1180
7	Kee BH	1.8026	17.3413	99.63	11.29	3.1	37.02	330	980
8	Kibwezi	1.6958	25.175	30.31	83.23	1.79	0.56	94	8
9	C-4309 – Tawa	0	0	0	0	1.3	234	400	760
10	C-5054 - Masongaleni	100	133	1020	15	4.5	167	112	690
11	Kyandumbi Water Project	162.4	1.03	25.7	7.6	1.79	0.29	358	656
12	Komboyoo Water project	150.4	0.8	144.2	8.2	2.43	3.063	172	. 29
13	David Mutangili	152	0.77	220.5	20	3.50	192	358	160
14	Teresia Ndunda	83	0.02	95.9	-	1.79	180	192	585
15	Wadi Wa Mitila	43.2	0.729	201	32	4.6	244.90	358	675
16	Muli Ndambuki	24.8	0.72	1.8	94.5	4.1	60.02	340	560

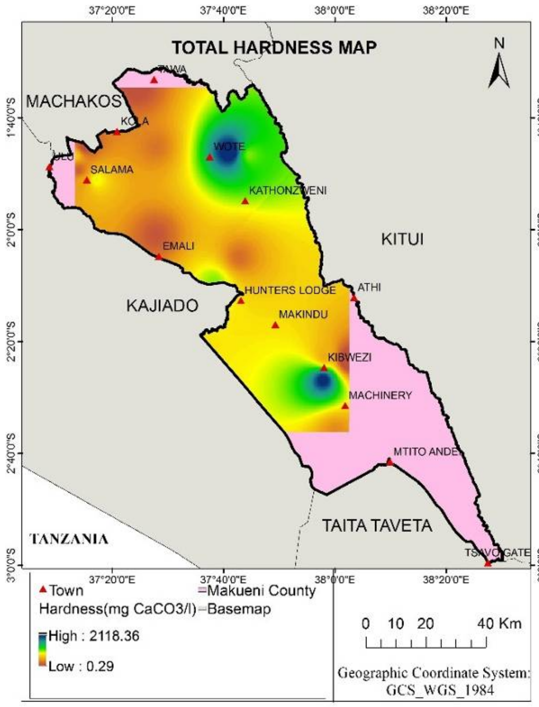


Figure 4(a). The total hardness map of the study area

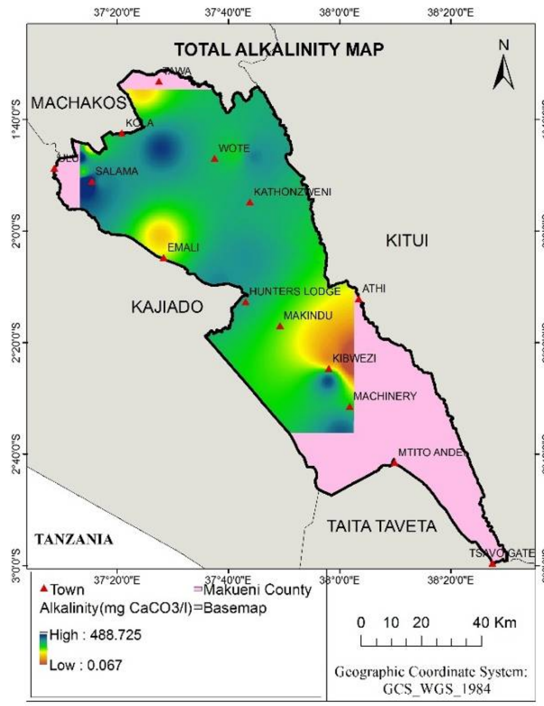


Figure 4(b). The total alkalinity map of the study area

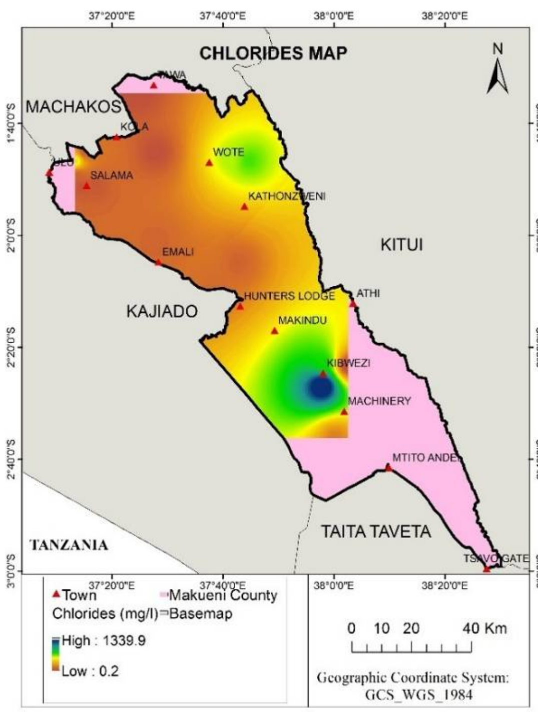


Figure 5 (a). The chloride map of the study area.

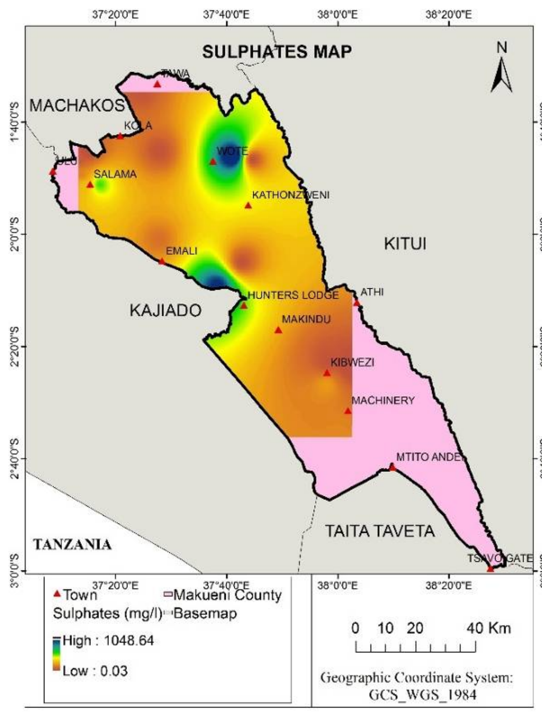
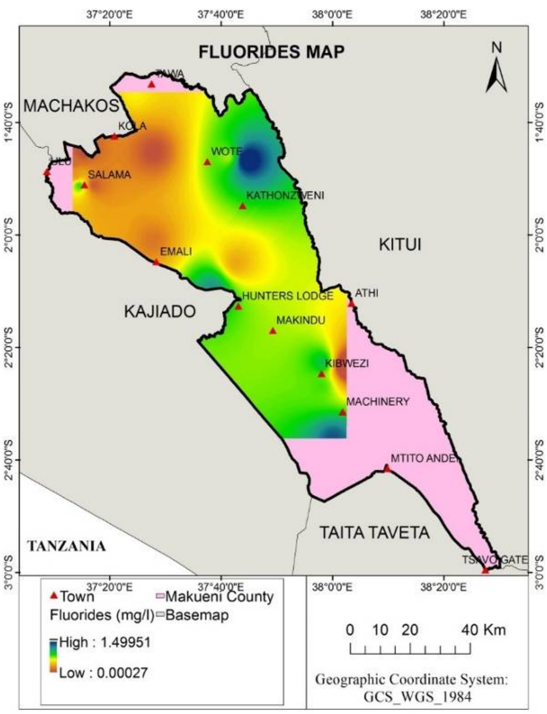


Figure 5 (b). The sulphate map of the study area

But all boreholes along the Nairobi – Mombasa Highway such as Emali and makindu had lower chloride ion concentrations.

The average flouride concentration in borebole in Makueni was found to be higher than the allowable 1.5 mg/L. High fluoride concentrations values were noted around Wote / Kathonzweni area and also in Makindu. Boreholes in Chyullu Hill had high fluoride values also. Groundwater from boreholes located near Kibwezi had relatively high values of Flouride. A study by Francisca et al. (2017) in Makindu area has reported values > 4.2 mg/L. which has precipitated a crisis in dental health care.

According to Pauling (1960) and Gaciri and Davies (1993) fluorine is the most electronegative of all known elements with an electronegativity of 4. It is also the most reactive element and rarely occurs free in nature. It combines chemically to form flourides and occurs as fluoride ion (F-). Flourides ions in drinking water increase skeletal abnormalities and dental fluorosis[25,1,6]. conditions that are common in Makueni. the spread of dental caries and dental fluorosis is related to the amount of flourides consumed from borehole water.



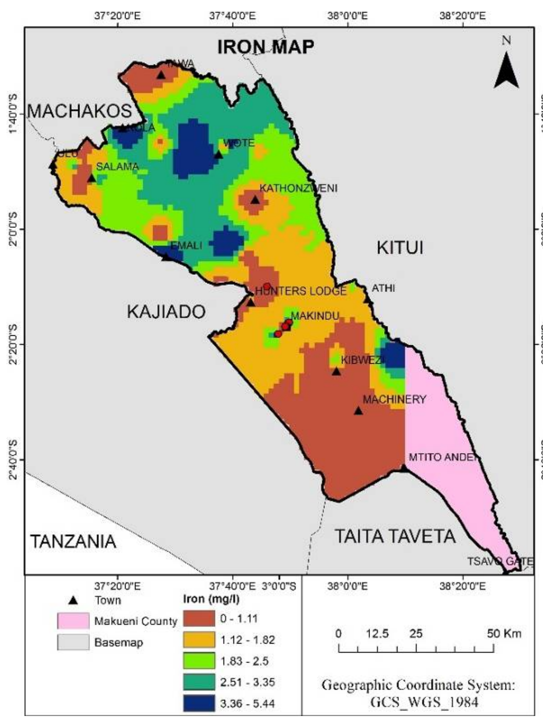


Figure 6 (a). The Flouride map of the study area. Figure 6 (b). The Iron map of the study area.

The turbidity of Kithunzi borehole increased upon storage in a tank leading to rapid deterioration of the of the tank. This was attributed to oxidation of ferrous ions (Fe^{2+}) to ferric ions (Fe^{3+}). Similar behaviour was reported in other localities where the groundwater had high iron content. Iron and manganese data has not reported in published water quality investigations and the two elements have been thought not to represent serious water problems but high concentrations > 5 mg/L are causing rusting of steel storage tanks as well as syringes in health facilities[22].

Excess iron may cause conjunctivitis, choroiditis and retinis if it remained in body tissues for long while chronic inhalation of high concentrations of iron oxide fumes or dusts results in development of benign pneumoconiosis. If also enhances the risk of lung cancer development in workers exposed to pulmonary carcinogens.

The water quality index (WQI) values in this county are very high; greater than 41 and rising to very high values of 696. Areas such as Wote, the County Headquarters have vey y high values of WQI which means the groundwater quality is very low. The town of Wote does not have a permanent surface supply but rely on borehole spread within a radius of 4 Kilometers. Kaiti river which passes adjacent to the town is ephemeral.

Makindu Town located on the on the South Eastern side of this County also has very high WQI. This locality has several boreholes but the main source of domestic water supply is Makindu spring where the water levels are dwindling very fast. The borehole water on the other hand is adequate but the quality is wanting for example the fluoride concentration in the Makindu Hospital borehole is 5.1 mg/L while that of a borehole at the Catholic Mission still in the Town is 7.3 Mg/L. These high levels of flourides in these areas are due to the proximity of the volcanic Chyullu hills that are several kilometres to the South of Makindu Hospotal. Other important locations such as Kothonzweni, Emali and Mtito Andei also show that groundwater in Makueni is of low quality. For example Makindu Sisters' borehole has Sodium concentration of 399.50 mg/L is way above the permissible value of 200 mg/L (WHO, 1996).

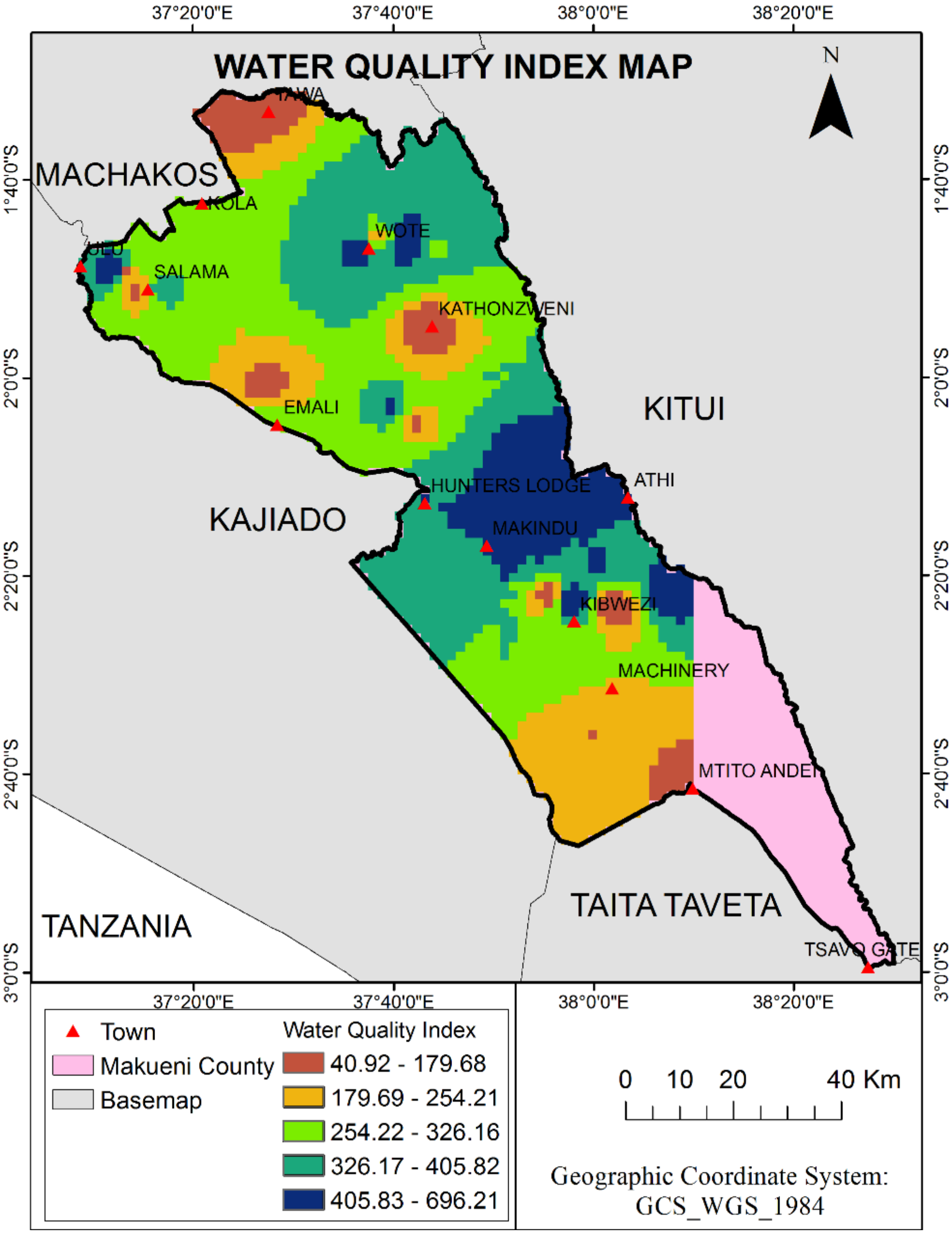


Figure 7. The water quality index (WQI) of the study area.

CONCLUSION AND RECOMMENDATIONS.

Groundwater abstracted from boreholes in most of Makueni, on account of their high fluoride content > 1.5 mg/L would require deflouridation in order to reduce the number of cases of fluorosis in these areas that are dependent of Groundwater. The concentration of iron was also found to be way above the allowable limit of 0.3 Mg/L which lead to rusting of pipes, tanks and other metal plumbing appliances. To reduce the concentration of iron in the groundwater it is recommended that a non-motorized aeration/ filtration unit be introduced in the water supply system to lower the iron content in the water.

Trace elements that endanger life if they occur in drinking water such as arsenic with a limit of 0.2 mg/L, chromium with a limit of 0.05 mg/L, selenium with a limit of 0.05 Mg/L and cyanide with a limit of 0.01 mg/L have not been investigated. Future analysis of these elements is desirable.

10 % of the borehole under investigation had turbidity values above the allowable 5 NTU. The turbidity of water can be reduced through use of natural coagulants such a Moringa Oleifera which is readily available in the study. However, the effectiveness of this natural coagulant in reducing turbidity of groundwater has not be tested. It is recommended that the effectiveness of this coagulant be tested in a future research.

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