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Environmental Implications of Groundwater Quality in Irrigated Agriculture in Kebbi State, Nigeria

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Abstract
The quality of groundwater used for irrigation in Kebbi State, northwestern Nigeria was evaluated. Open-well, tube-well and borehole water samples were collected from various locations in the State. The water samples analyzed had pH values below the normal range for irrigation water and very low to moderate salinity (electrical conductivity 0.05-0.82 $dS.m^{-1}$). The adjusted sodium adsorption ratio values in all the samples were also very low (<0.2), indicating very low sodicity hazards. However, irrigation water of very low salinity (<0.2$dS.m^{-1}$) and low SAR can lead to problems of infiltration into soils. The Ca: Mg ratio (<1) in most of the samples may lead to Ca deficiency in soils after long term use. The nitrate concentration in most of the samples was high ranging from 4.5 to >50mg/L.
Keywords: Ground water quality, irrigation, characteristics, soil drainage, salinity, fadama

1. INTRODUCTION

Irrigation has been practiced since antiquity. Unfortunately, the problems that contributed to the demise of several ancient civilizations are still present today [1]. Eighteen (18) percent of the world's agricultural land is irrigated but it produces 33 percent of the total harvest [2], except for water lost through evapotranspiration, agricultural water is recycled back to surface water and/or groundwater [3]. He also stated that agriculture is both cause and victim of water pollution. It is a cause through its discharge of pollutants and sediment to surface and/or groundwater, through net loss of soil by poor agricultural practices, and through salinization and water logging of irrigated land. It is a victim through use of wastewater and polluted surface and groundwater which contaminate crops and transmit disease to consumers and farm workers.

Salinization of water resources is a major and widespread phenomenon of possibly even greater concern to the sustainability of irrigation than is that of the salinization of soils, per se. [4]

Although irrigation is useful for sustaining/increasing agricultural production, it is imperative that good quality water be used [5] . Conceptually, water quality refers to the characteristics of a water supply that will influence its suitability for a specific use, i.e. how well the quality meets the needs of the user, and is defined by certain physical, chemical and biological characteristics [6]. Regardless of its source, soluble salts are always dissolved in it, which could affect the physical and chemical properties of soils [7]. Excessive use of fertilisers, particularly nitrogen and phosphate fertilisers can lead to the eutrophication of surface waters and excessive concentration of nitrogen compounds in the water. [26] Eutrophication is the enrichment of water bodies with plant nutrients. This leads to an increase in population of aquatic flora. The decomposition processes that occur when it dies cause an excessive oxygen consumption that has detrimental effects on the aquatic fauna. The recommended threshold for eutrofication in freshwater is 0.5-1 $mg.^{-1}$ [27]

The study is aimed at assessing the quality of water from the available sources with respect to their suitability for irrigation purpose in the study area. Irrigation water quality concerns have often been neglected because good quality water supplies have been plentiful and readily available. This situation is now changing in many areas. Intensive use of nearly all good quality supplies means that new irrigation projects and old projects seeking new or supplemental supplies must rely on lower quality and less desirable sources [6] . It is therefore, imperative that irrigation water be monitored on a regular basis, in order to detect any changes in quality so that changes in management can be planned.

OVERVIEW OF IRRIGATION WATER QUALITY STUDIES IN NORTHWESTERN NIGERIA

The criteria used to determine the quality of irrigation water is given in Appendix 1. An earliest reported study of water quality in northwestern Nigeria was made in 1962 which reported that waters from Rima, Sokoto and Zamfara rivers had low to moderate salt content although some of the waters contained principally sodium and bicarbonates [8]. Another study of water samples from open wells in the Sokoto area was conducted. The samples showed moderate levels of salinity [Electrical conductivity (EC) 0.9-1.3 $dS.m^{-1}$]; low sodium adsorption ratio (SAR) with calcium and magnesium being the principal cations and low levels of bicarbonates and no carbonates [9]. Study of irrigation water quality in some irrigation projects in northwestern Nigeria conducted gave water from Kalmalo Lake in Sokoto State had EC 885 $uS.cm^{-1}$, SAR 15, pH 9.0, Na 9.46 mel^{-1} K 0.27 $me.l^{-1}$, Ca 0.44 $me.l^{-1}$, indicating that the water was highly saline and medium in sodium content. The water from Wurno

Irrigation Project (Wurno Lake), had EC 520 $uS.cm^{-1}$, TDS 330 $ug.g^{-1}$, pH 9.0, Na 5.65 $me.l^{-1}$, K 0.18 $me.l^{-1}$ Ca 0.36 $me.l^{-1}$, Mg 0.10 $me.l^{-1}$ and SAR 11.7. The Bakura Irrigation Project (Nato Lake) water had low salt content with EC and TDS values of 100 $uS.cm^{-1}$ and 60 ug/l, respectively. With a pH value of 7.4 SAR was 0.39 while the values for Na, K, Ca and Mg were 0.24, 0.12, 0.49 and 0.26, all in $me.l^{-1}$, respectively [10].

In more recent studies in 1994 and 1996, it was reported that the water used for irrigation in the Wurno Irrigation Project was of low salt content (300 $uS.cm^{-1}$) with an average pH of 7.4, also assessed is the quality of water from the Kandoli Shella stream in Dundaye District of Sokoto State. The water had pH ranging from 7.16 to 7.56, EC from 398 to 541 $uS.cm^{-1}$ TDS 20-170 $ug.g^{-1}$, Ca 2.95-3.35 $me.l^{-1}$, Mg 4.35-5.20 $me.l^{-1}$, Na 0.07-0.22 me.l-¹, K 0.00-0.10 $me.l^{-1}$, Cl 0.46 $me.l^{-1}$, CO_3 and HCO_3 values amounted to zero. The water was found to be safe for irrigation at least as at then [11, 12]. In 1997, a study of irrigation water quality in the Wurno and Bakolori Irrigation Projects was conducted, the water was discovered to have low salinity (EC < 0.1 $ms.cm^{-1}$)/sodicity (SAR <4) and low salinity (<0.1 $mS.cm^{-1}$) and moderate sodicity (mean SAR, 11.3). Na and K were the dominant cations, while the anionic concentrations were within safe limits for irrigation in the areas [13, 14]. Water samples from perennial surface bodies in Sokoto State were evaluated in 2000. They were all of low salinity (EC 0.5-0.64 $mS.cm^{-1}$) and low sodium (SAR 0-1.6), except water from the Sokoto river, which had moderate salinity (EC 1$mS.cm^{-1}$). The water samples in this study showed slightly high NO_3 values, however all the anions were within safe limits for irrigation [15]. Also in 2000, irrigation water quality from mostly tube-wells in Kebbi and Zamfara States were assessed. In Kebbi State, 98% of the waters were rated low to medium salinity and low sodium. However, the other 2% were classified as high salinity, low sodium water. Ca and Mg were the predominant cations with Mg concentrations greater that Ca. In Zamfara State, none of the tube-well waters appeared to have sodicity problems (SAR, 0.04-0.32). However, electrical conductivity (in $mS.cm^{-1}$) for 17% of the samples were 0.42-0.75, for 64%>0.75-2.25 and for the remaining 19% were greater than 2.25 [16]. The quality of tube-well water used for irrigation in the Birnin Kebbi area, which is also within this study area were assessed in 2001. Salinity levels were low (EC 0.12-0.43 $mS.cm^{-1}$) along the Sokoto-Rima river and moderate (0.96-1.2 $mS.cm^{-1}$) along the Shella river, with a mean value of 2.3 SAR for the entire area. Bicarbonate levels were low and no carbonates were reported [17].

2. MATERIALS AND METHODS

The Study Area

The study area lies roughly between latitudes 3 30' to 6 02'E and longitudes 10 30'to 13 17' N, and is drained mainly by the Sokoto-Rima river system. Irrigation is mainly practised non-formally on a small-scale through the use of open-wells, tube-wells and boreholes sunk in *fadama* lands.

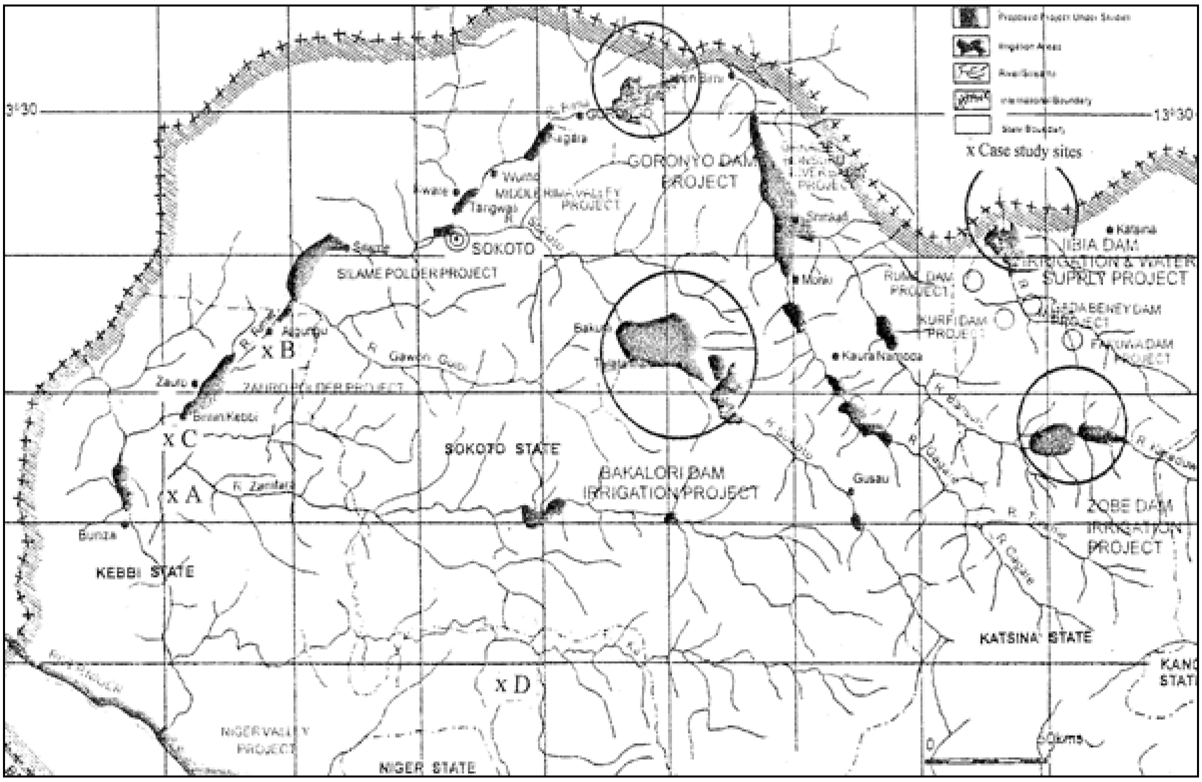
Fadama is a Hausa word which refers to low lying, relatively flat areas either in stream less depression or adjacent to seasonally or perennially flowing streams [18]. The climate ofthe study areaa was classified asSemiaridd Equatorial Tropical, consisting of a long dry (October-May) and a short wet (June-September) season. Mean annual rainfall ranges from 860mm and 853mm at Yauri (10 47'N, 4 50'E) to 690mm and 591mm at Birnin Kebbi (12 32'N, 4 12'E), respectively. These are far exceeded by a potential evapotranspiration of 1770mm [19, 20, 21] The underlying geology of the region was described. The west and north of the state are underlain mainly by sedimentary rocks of the Illo and Gwandu Formations and the Rima Group, the Southeast by Basement Complex Rocks [22].

Sampling Methods

Four sites were selected for sample collection. Jega (A) (4°23'E, 12°15'N) which overlies the Rima Group, Argungu (B) (4°31'E, 12°40'N) and Birnin Kebbi (C) (4°12E 12°32N') overlying the Gwandu Formation and Zuru (D) (5°12'E11°27'N) overlying the Basement Complex. The first three sites are located in the Sudan Savanna, the latter in the Northern Guinea Savanna. At each site, open-wheel, tube-well and borehole water samples were collected in replicating from three different sites located at least 1000m from each other. Samples for laboratory studies were collected in thoroughly cleaned plastic bottles. At each site, approximately 1000ml were taken for analysis. This procedure was undertaken to ensure that the analysed samples were generally representative of the source. The containers used were thoroughly washed and later rinsed with distilled water. Information sought from the water analysis include pH, electrical conductivity (EC), carbonate (CO_3^{2-}), bicarbonate (HCO_3^-) sulphate (SO_4^{2-}), nitrate (NO_3^-), chloride (Cl^-), calcium (Ca^{2+}), magnesium (Mg^{2+}), potassium (K^+) and sodium (Na^+) and Total dissolved solids (TDS). These parameters help to determine the quality of irrigation water in use.

Analytical Methods

The water was analyzed for total dissolved solids (TDS), pH, electrical conductivity (EC), carbonate (CO_3^{2-}), bicarbonate (HCO_3^-) sulphate (SO_4^{2-}), nitrate (NO_3^-), chloride (Cl^-), calcium (Ca^{2+}), magnesium (Mg^{2+}), potassium (K^+) and sodium (Na^+) by the methods described by Chopra and Kanwar (1991). The TDS was determined by the evaporation and drying method. The pH and EC were read on a pH-meter and conductivity -meter, respectively. CO_3^{2-} and HCO3- were estimated by the volumetric titration method. The SO_4^{2-}, NO_3^- and Cl^- were read on a LED photometer (LF200). Ca^{2+} and Mg^{2+} were determined by the EDTA titration method while Na^+ and K^+ by flame photometry. The adjusted sodium adsorption ratio was calculated using the equation [23]:



$$\text{Adj.RNa} = \frac{Na}{\sqrt{\frac{Cax+Mg}{2}}}$$

, Where, Cax = a modified Ca value taken from Table 11 [6].

Fig. 1. Map of the basin indicating case study sites

3. RESULTS AND DISCUSSION

pH is an indicator of the acidity or basicity of water, pH values for the water samples are reported in Table 1. The normal pH range for irrigation water is from 6.5 to 8.4 (Appendix 1). There was a narrow range in pH between all the samples. They all fell within the range 5.7 to 6.1, which is below the normal range in irrigation water. An abnormal pH value is a warning that the water needs further evaluation. Irrigation water with a pH outside the normal range may cause a nutritional imbalance or may contain a toxic ion. They also reported that an adverse pH may need to be corrected, if possible, by the introduction of an amendment (lime for low pH and sulphur for high pH) into the water, but this will only be practical in a few instances. It may be easier to correct the soil pH problem that may develop rather than try to treat the water [6].

Table 1: pH, EC, TDS and adj. RNa obtained for the water samples

SAMPLE	pH	EC (mS/cm)	TDS(mg/l)	Adj. RNa
OPENWELL				
Jega	6.1	0.61	486	0.17
Argungu	5.7	0.48	380	0.12
B/Kebbi	6.0	0.20	164	0.05
Zuru	5.9	0.26	203	0.12
TUBEWELL				
Jega	5.9	0.24	195	0.14
Argungu	5.8	0.09	71.3	0.10
B/Kebbi	5.8	0.82	657	0.12
Zuru	6.0	0.09	75.2	0.03
BOREHOLE				
Jega	5.8	0.19	152	0.13
Argungu	5.9	0.09	70	0.04
B/Kebbi	6.0	0.05	38	0.02
Zuru	6.0	0.25	201	0.11

Open and Tube wells are both shallow with depths not more than 50 metres with high water table, while boreholes are wells with depth greater than 100 metres and are dung in areas with lower water table. Both open and tube wells are prone to surface pollution as reflected in the results in Tables 1,2and 3. The greatest direct hazard of a very low pH in water is the impact on irrigation equipment. As with any acid material, the low pH may cause damage to pipelines, sprinklers and other equipment, and careful choice of resistant materials will be necessary or pH must be carefully controlled [6]. This is particularly important with borehole water used to irrigate orchards in the study area. Table 1, also reports the electrical conductivity (EC) and total dissolved solids obtained, which are indicators of salinity. Except for the tube-well waters in the Birnin Kebbi area (mean EC is 0.82 $dS.m^{-1}$), all the samples were of very low salinity (mean EC 0.05-0.61 $dS.m^{-1}$ and TDS 38-486 $mg.l^{-1}$). This may indicate that they do not have any restrictions to their use for irrigation (Appendix 1). However, low salinity water (<0.5 $dS.m^{-1}$) is corrosive and tends to leach surface soils free of soluble minerals and salts, especially calcium, reducing their strong stabilising influence on soil aggregates and soil structure. Without salts and without calcium, the soil disperses and the dispersed finer soil particles fill many of the smaller pore spaces, sealing the surface and greatly reducing the rate at which water infiltrates the soil surface. Soil crusting and crop emergence problems often result, in addition to a reduction in the amount of water that will enter the soil in a given amount of time and which may ultimately cause water stress between irrigations. In fact, very low salinity water (<0.2 $dS.m^{-1}$) almost invariably results in water infiltration problems, regardless of the relative sodium ratio [6]. This is particularly true for water from tube-wells in Argungu and Zuru and boreholes in Jega, Argungu and Birnin Kebbi.

Table 1, also shows the adjusted sodium adsorption ratio (Adj. RNa), an indicator of the sodium hazards of the water. It is used to predict the potential infiltration problems of high Na (or low Ca) in irrigation water [23, 4]. It is used in place of sodium adsorption ratio (SAR) in Appendix 1 [7]. All the waters sampled gave very low levels of Adj.RNa with a range of 0.02-0.17, and do not pose any hazards with respect to Na build up in the soils. This might indicate that they do not pose any restrictions to their use for irrigation. However, when used in combination with corresponding EC values to determine their effect on infiltration rate of soil's, the tube-well waters in Argungu and Zuru and the borehole waters in Jega, Argungu and Birnin Kebbi indicate severe restrictions to their use for irrigation (Appendix 1). A severe reduction in water infiltration rate due to water quality is usually related to either very low water salinity or to a high sodium adsorption ratio (SAR) [4]. The continuous use of these waters for irrigation often results in a severe water infiltration problem due to soil dispersion and plugging and sealing of the surface pores [6]. This may result in problems such as soil crusting, poor seedling emergence, lack of aeration, plant and root diseases, weed and mosquito control problems caused by the low rate of infiltration which may further complicate crop management.

They also stressed that if the soils become waterlogged and temporarily flooded due to the infiltration rate for even short periods of a few days, and lack good aeration, much of the nitrate-nitrogen present may be quickly denitrified and lost from the soil to the atmosphere as N_2 gas. In such cases, the crop may soon show yellowed areas indicating depleted nitrogen and will benefit from added fertiliser nitrogen. [6]

Effective management of irrigated soils with infiltration problems include: applications of gypsum, which is available in the study area; cultivation and deep tillage; application of organic residues; more frequent irrigation and pre-plant irrigation. [6]

The cationic concentrations in the waters sampled are given in Table 2. In general as reported in earlier studies, Ca and Mg were the predominant cations. With the exception of the borehole waters from Argungu, all the water sample analysed gave very low Ca: Mg ratios (0.2-0.8 mg/L). Use of these waters may pose problems relating to plant nutrition. The ratio of Ca: Mg or calcium to total cations (Ca: TC) in the soil-water may also be used to predict a potential calcium deficiency. There are reports that Ca: Mg ratios less than 1 or Ca: TC less than 0.15 are sometimes associated with calcium deficiencies. [6]

In a magnesium dominated water (ratio of Ca: Mg < 1), the potential effect of sodium may be slightly increased. [6] Research findings show that at a given SAR of the applied water, a higher soil exchangeable sodium percentage (ESP) than normal will result when using water with a Ca: Mg ratio less than one [24] particularly with respect to such crops as wheat and maize [6]. They explained that productivity in Mg rich soils can be low due to a magnesium-induced calcium deficiency caused by high levels of exchangeable magnesium in the soil. Calcium appears to reduce possible toxicities due to other ions (Na, Mg) in the root environment. If the Ca: Mg ratio is near or less than 1, the uptake and translocation of Ca from soil-water to the above-ground parts of the growing crop is diminished due to antagonistic effects of high magnesium or competition for absorption sites to such an extent that less calcium is absorbed.

Table 2: Cationic concentrations (in mg/l) obtained for the water samples

SAMPLE	Na	K	Ca	Mg	Ca:Mg	Ca: T.C.
OPENWELL						
Jega	4.0	4.0	7.2	11.3	0.39	0.23
Argungu	3.8	0.9	5.9	11.2	0.42	0.25
B/Kebbi	1.4	3.3	2.5	2.8	0.57	0.27
Zuru	2.5	0.3	3.3	6.4	0.32	0.21
TUBEWELL						
Jega	2.1	1.1	0.8	1.9	0.2	0.1
Argungu	1.3	0.2	1.3	1.2	0.7	0.3
B/Kebbi	5.1	8.1	9.5	7.5	0.8	0.3
Zuru	0.8	0.2	2.1	2.2	0.6	0.3
BOREHOLE						
Jega	2.5	0.6	2.7	3.3	0.4	0.2
Argungu	1.1	0.2	6.2	1.2	3.1	0.7
B/Kebbi	0.3	0.3	1.4	1.3	0.5	0.4
Zuru	2.7	1.5	5.0	3.7	0.8	0.4

A calcium deficiency may then be experienced at a higher calcium concentration in the applied water or in soil-water than would occur if the Ca: Mg ratio was higher. They went on to state that although not definitely confirmed, it can be anticipated that irrigation water with a similar ratio (Ca: Mg < 1) will produce a similar effect if a readily available source of calcium is not present in the soil. Under such a circumstance, an evaluation may be needed to determine if a readily available source of soluble calcium exists in the soil or whether further studies are needed to determine if calcium should be added as a fertilizer or soil amendment. It was discovered that if the calcium in the soil-water taken up by the crop is less than 2 me/L, there is a strong probability that the crop yield will be reduced due to a calcium deficiency. [4]

The anionic concentrations of the waters sampled are presented in Table 3. Available literature suggest that waters with (mg/L) roughly 300 HCO_3, 3 CO_3, 960 SO_4, 5 NO_3 and 4 Cl are considered safe for irrigation.[4] The mean HCO_3, CO_3, SO_4 and Cl values for all samples all fall within the safe limits (Table 3). As Table 3 shows, of most concern is the nitrate content of the waters. Only borehole water from Jega fell within the safe limits for irrigation. The other samples gave results ranging from 5 to in excess of 50mg/L. In fact tube-well waters from Zuru gave rather excessive (mean 52.8 mg/L) nitrate values. The high nitrogen content of the waters may be attributed to leaching of fertilisers (both organic and inorganic).

Table 3: Anionic concentrations (in mg/L) obtained for the water samples

SAMPLES	NO_3	SO_4	Cl	CO_3	HCO_3
OPENWELL					
Jega	12.2	23.5	3.7	4.4	6.4
Argungu	6.4	11.2	1.9	0.0	8.3
B/Kebbi	8.9	5.5	2.3	0.0	5.4
Zuru	10.2	16.8	2.7	6.0	12.2
TUBEWELL					
Jega	8.3	6.4	3.5	1.2	13.3
Argungu	5.3	6.4	2.0	0.0	24.0
B/Kebbi	13.8	10.3	2.3	3.0	5.3
Zuru	52.8	87.9	2.8	1.7	4.1
BOREHOLE					
Jega	4.5	3.8	3.7	2.1	10.9
Argungu	6.3	18.3	1.7	0.0	8.5
B/Kebbi	5.5	7.7	1.6	0.0	10.3
Zuru	11.3	19.5	2.1	3.5	10.4

If the nitrogen in the irrigation water has much the same effect as soil-applied fertilizer nitrogen and an excess will cause problems, just as too much fertilizer would.[6] If excessive quantities are present or applied, production of several commonly grown crops may be upset because of over-stimulation of growth, delayed maturity or poor quality. Less than 5 mg/L N has little effect, even on nitrogen sensitive crops, but may stimulate nuisance growth of algae and aquatic plants in streams, lakes, canals and drainage ditches [6, 7].It was also reported that nitrogen in water also increases maintenance costs for clearing vegetation from canals and drainage channels. It is generally beneficial to most crops but may cause problems for some. The findings stated that nitrogen in the irrigation water is readily available and if present should be considered as an important part of the fertilizer programme. The result further emphasised that for a few crops, however, the added nitrogen from the water may be too much and result in excessive and vigorous growth, delayed or uneven maturity, and reduced quality Irrigation systems are sources of non-point source pollution from fertilisers [25].

Eutrophication is one of the major causes of Water Hyacinth invasion in rivers and streams. This weed is destructive and costly since it affects ecosystems, food production, energy generation and human health. The plant competes with native plants and fish for oxygen, causing massive die-off. The high nitrate contents of these waters could lead to health problems in humans if the water is consumed. [25] The recommended safe level for nitrates in public drinking water is 10mg/l. [27] Nitrates consumed by humans may be reduced in nitrites in the intestine. Babies below a certain age may not be able to detoxify this nitrite and even for adults, the nitrite produced may be converted into nitrosamines, which could in turn cause hazards to health. [26] Ruminant animals are sensitive to nitrogen and heavy applications to pastures used for direct or indirect livestock feed may cause excessive quantities to accumulate in the forage.[6] This may be hazardous to the animal's health. The recommended safe level for nitrates in water meant for livestock and poultry is 40mg/l [27]. It is therefore imperative that these waters be used with caution and that the farmers make more efficient use of fertilisers.

4. CONCLUSION AND RECOMMENDATIONS.

Irrigation waters sampled in this study showed in most cases are slightly higher pH, low salinity and sodicity, <1 ratio of Ca: Mg and a high level of nitrates. The continued use of such waters for irrigation might lead to nutrient imbalances and infiltration problems in soils. The high nitrate levels can certainly be attributed to anthropogenic causes through excess fertiliser applications. Agriculture exists within a symbiosis of land and water [3] and appropriate steps must be taken to ensure that agricultural activities do not adversely affect water quality so that subsequent uses of water for different purposes are not impaired [28]. In summary, with effective soil and water management such as mulching, application of organic materials and gypsum, the use of the sampled irrigation water can serve as a nitrogen source.

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Appendix 1. Guidelines for interpretation of water quality for irrigation

Potential Irrigation Problem	Units	Degree of Restriction on Use		
		None	Slight to Moderate	Severe
Salinity (affects crop water availability)				
Electrical conductivity	dS/m	< 0.7	0.7 – 3.0	> 3.0
(or)				
TDS	mg/l	< 450	450 – 2000	> 2000
Infiltration (affects infiltration rate of water into the soil. Evaluate using EC_w and SAR together)				
SAR = 0 – 3 And EC_w	=	> 0.7	0.7 – 0.2	< 0.2
= 3 – 6	=	> 1.2	1.2 – 0.3	< 0.3
= 6 – 12	=	> 1.9	1.9 – 0.5	< 0.5
= 12 – 20	=	> 2.9	2.9 – 1.3	< 1.3
= 20 – 40	=	> 5.0	5.0 – 2.9	< 2.9
Specific Ion Toxicity (affects sensitive crops)				
Sodium (Na)				
surface irrigation	SAR	< 3	3 – 9	> 9
sprinkler irrigation	me/l	< 3	> 3	
Chloride (Cl)				
surface irrigation	me/l	< 4	4 – 10	> 10
sprinkler irrigation	me/l	< 3	> 3	
Boron (B)	mg/l	< 0.7	0.7 – 3.0	> 3.0
Miscellaneous Effects (affects susceptible crops)				
Nitrogen (NO_3 - N)	mg/l	< 5	5 – 30	> 30
Bicarbonate (HCO_3)				
(overhead sprinkling only)	me/l	< 1.5	1.5 – 8.5	> 8.5
PH		Normal Range 6.5 – 8.4		

Source: Ayers and Wescot (1985)
Note: 1dS.m^{-1} = 1 mS.cm^{-1} = 1000□S.cm^{-1}

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