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Assessment of the Quality of Shallow Groundwater for Irrigation in the Atankwidi Sub-Basin of the White Volta Basin, Ghana

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Abstract

The potential use of shallow groundwater for small-scale dry season irrigation is a key issue for irrigation development in the arid zone of Ghana. Farmers within the Atankwidi sub-basin of the White Volta Basin are increasingly adopting groundwater as a source of irrigation water due to the unavailability of surface water during the dry season. However the quality of the groundwater and its suitability for irrigation is not known, hence the need to assess the quality and its suitability in order to ensure sustainability in the application and possible expansion of groundwater irrigation in the area. Two main water types (Ca-Mg-HCO_3 and Na-Mg-Ca-HCO_3) have been determined using the Piper diagram. The relative abundance of cations in the groundwater was found to be in the decreasing order of $Na^+ > Ca^{2+} > K^+ > Mg^{2+} > Fe^{2+}$. Similarly, that of anions was found to have a decreasing order of $HCO_3^- > SO_4^{2-} > Cl^- > PO_4^{2-} > NO_3^- > F^-$. Groundwater in the area had low SAR and low to medium salinity hazard. However, magnesium hazard and alkalinity problems are likely to limit its use for irrigation.

Keywords: Shallow Groundwater, Hydrochemical facies, Irrigation Water Quality.

1. Introduction

Globally there is a strong positive relationship between higher density of irrigation and lower poverty rates, as Lipton *et al.* (2003) indicates. In Africa, only 3% of cropland is irrigated and the region has experienced very little reduction in poverty in the 1990s (World Bank, 2000). In contrast, those regions that have the greatest proportion of cultivated area irrigated (namely East Asia, Pacific, North Africa and Middle East) have experienced the greatest poverty reduction. That of Ghana is put at 0.02 % as at the end of 2008. Irrigation of some of these arable lands could not materialise due to the projected capital involvement in channeling surface water over long distances to the irrigable lands.

The use of hand-dug wells enables the utilization of shallow groundwater for irrigated production of vegetables and cash crops during the dry season and, therefore, provides an alternative source of income for farmers and poor households. For instance, the large scale production of shallot and other vegetables using shallow groundwater in the Keta Strip has provided enormous income to the indigenous inhabitants (Kortatsi and Agyekum, 2000). In most cases, Shallow Groundwater Irrigation (SGI) has developed without any government or donor involvement.

Farmers in the White Volta Basin and the Atankwidi sub-basin to be specific where this study focuses heavily rely on shallow groundwater as a source of irrigation water due to the unavailability of surface water in the dry season. As this is farmer driven, little is known about the quality of water used for the production of vegetables which crucial so far as farming is concern. This is because, besides affecting crop yield and soil physical conditions, irrigation water quality can affect fertility needs, irrigation system performance and how the water can be applied. Therefore, knowledge of irrigation water quality is critical to understanding what management changes are necessary for long-term productivity. Above all, water quality analysis in general, and not limited to irrigation water, is one of the most important issues in groundwater studies. It reveals the suitability of the water for different purposes and also helps to understand the possible change in quality probably due to rock-water interaction or anthropogenic effects. The main objective of this paper is therefore to assess the shallow groundwater quality for irrigation in the study area which will inform both policy and decision makers so far as SGI in the area is concern.

2. Study Area

2.1 Location and Size

The Atankwidi sub-basin is located between latitudes 10°49’47 N and 10°55’35 N and longitudinal 0°55’27 W and 0°59’27 W, a tributary of the White Volta located in the Upper East Region of Ghana between Navrongo and Bolgatanga (Kassena Nankana District) with its upper reach in Burkina Faso as shown in Figure 1. The sub-basin is located in one of the areas with the highest groundwater use per km² in the Volta River basin (Martin 2006). The sub-basin covers an area of about 275 km^2 of the White Volta basin.

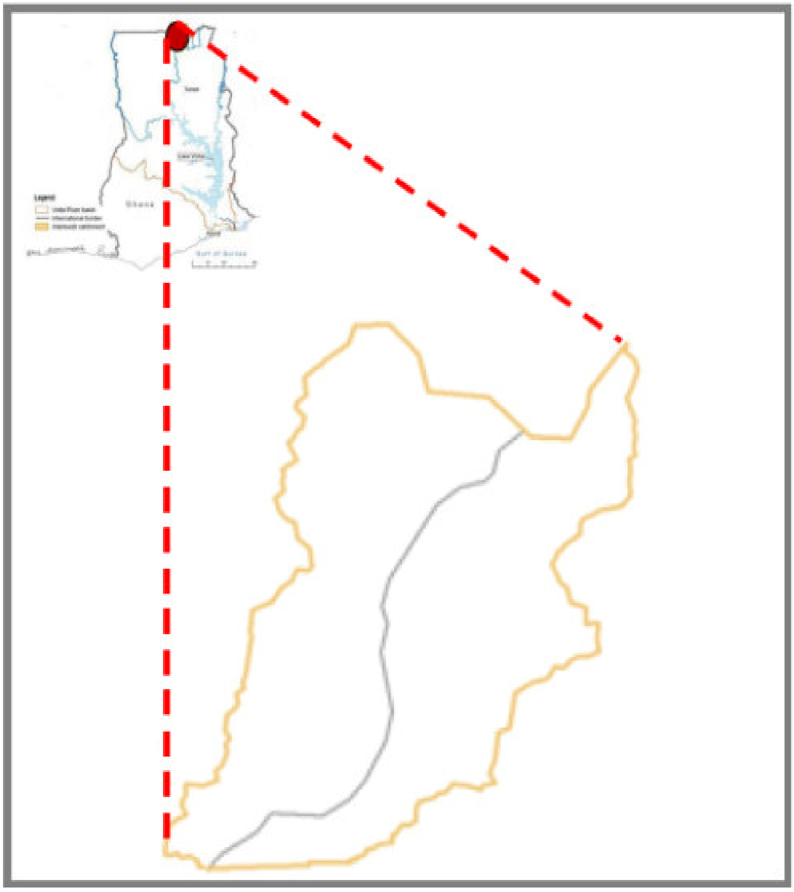

Figure 1. Map of the Atankwidi sub-basin

2.2 Climate and Vegetation

The study area falls within the Sudan-Savanna climate zone, which is characterised by high temperatures and a uni-modal rainfall distribution with a distinct rainy season lasting approximately from May to September. The mean annual rainfall in Navrongo is approximately 980mm. The spatio-temporal distributions of precipitation and evaporation have a large impact on the water regime including the groundwater variability. In the rainy season daily rainfall may exceed 50 mm, this falls in less than one hour. Monthly rainfall only exceeds potential evaporation in the three wettest months, July, August and September. The total potential evaporation is 2050 mm, which is twice the annual rainfall. The average annual temperature is 29 ^{o}C. The mean daily minimum temperature is 25 ^{o}C, coinciding with the peak of the rainy season, and rises to a maximum of 34 ^{o}C in April. Relative humidity is highest during the rainy season with 65 %. It drops quickly after the end of the rainy season in October, reaching a low of less than 10 % during the harmattan period in December and January (Martin, 2006).

2.3 Land Use

Open tree-savanna forms the natural vegetation in the Upper East Region. Trees show a large spacing and the area is largely covered with grass and shrubs. The most common economic trees are the sheanut, dawadawa, boabab and acacia. Common grasses include *Andropogen gayyanus* in the less eroded areas and *Hyperrhenia spp*., *Aristida spp*. and *Heteropogen spp.* in the severely eroded areas. Most of the area is used for small-scale agriculture. During the rainy season, almost 70 % of the area is covered with small plots of rainfed agriculture (Martin, 2006). Other parts of the area are used for livestock grazing and drinking. In the dry season, the amount of agriculture is substantially lower, approximately 1 % of the area (Unofficial report, GVP, 2007). The other parts of agricultural land remain as bare soil until the next rainy season starts. Land not used for agriculture is either sparse vegetation on shallow soils in stony areas or land used for the grazing of livestock, which is covered by grass, shrubs and trees.

2.4 Relief and Drainage

The relief of the sub-basin is generally flat, gently undulating with slopes ranging from 1% to 5% except in a few uplands where slopes are about 10%. According to Adu (1969), the relief of the UER is related to the geology, where a range of Birimian greenstone hills rising up to 457m above sea level dominate north of Bawku and Zebilla along the border with Burkina Faso and in the southwest along the White Volta River (WVR). The granite areas are generally of low, gently rolling relief ranging from 122 m to 260 m above sea level. The relief under Voltain rocks has similar characteristics to granites, with few escarpments rising above 518 m near the border with Togo in the east. The mean elevation for the area is 197 m above sea level (Liebe, 2002).

2.5 Geological setting

Three formations of the Birimian domain can be distinguished in the study area (Figure 2) from the geological map 1:125,000, sheets Navrongo (Van den Berg *et al.,* 1963) and Zuarungo (Murray and Mitchell, 1960). These are: Birimian metasediments; Granitoids (granodiorites, granite and gneiss) associated with the Birimian; Intrusive Bongo granite. Paleoproterozoic granitoids consisting of hornblende - biotite granodiorite, biotite granite and biotite gneiss make up the largest part of the study area and form the slightly undulating south-western part of the Atankwidi sub-basin. Birimian metasediments made up of phyllite, schist and quartzite are found in small patches among the granitoids.

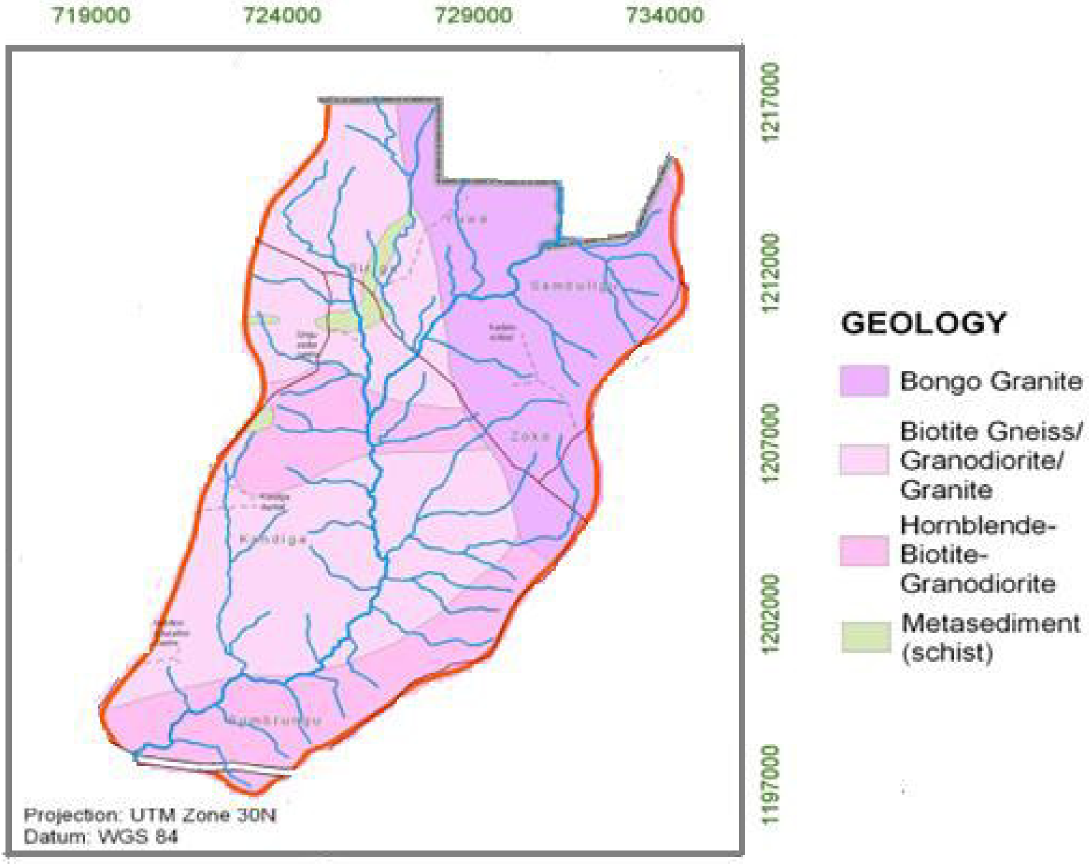

Figure 2. Geological and drainage map of the study area.

3. Materials and Methods

Groundwater samples were collected from 40 wells in March 2009 for major and minor ions analyses. Sampling protocols according to Wood (1981), Claasen (1982), and Barcelona *et al* (1985) were followed. The map of groundwater sampling points is shown in Figure 3. Water samples according to standards were collected after pumping the well for about 5 minutes in order to purge the well of stagnant water. The purging was done to stabilized temperature, pH and electrical conductivity readings.For metal analysis, samples were filtered through 0.45µm filters and preserved with 5ml 6 N HNO_3 in laboratory treated 100ml high density linear polyethylene bottles. However, samples for anion analyses were without preservation. The Universal Conductivity Meter Multiline P4 set that had an in-built temperature compensation probe was used to measure electrical conductivity and temperature simultaneously. For the determination of total alkalinity (as HCO_3^-), field titration with 1.6 N H_2SO_4 to pH ~4.5 using HACH Digital Multi Sampler Model 1690 was done.

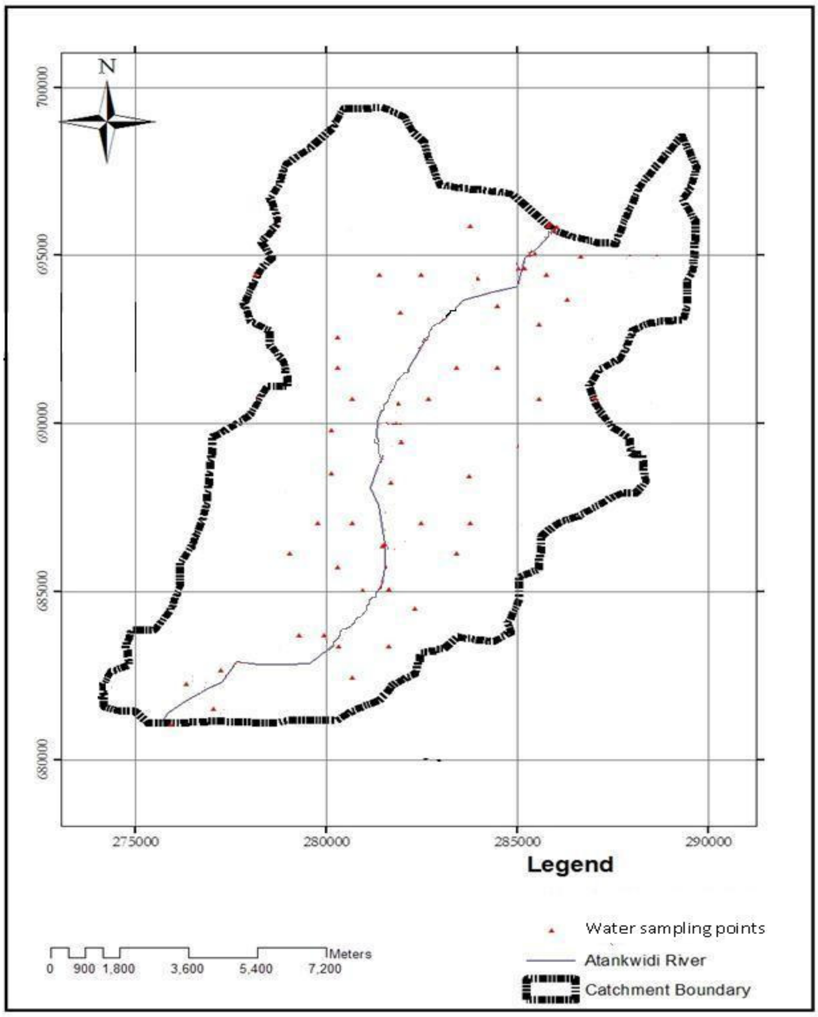

Figure 3. Map of Groundwater sampling locations

Chemical analyses for all major ions (Na^+, Ca^2, Mg^{2+}, HCO_3^-, Cl^-, SO_4^{2-}) as well as some minor ions (K^+, NO_3^-, F^-, PO_4^{2-}) were carried out with the Dionex DX-120 ion chromatograph at the Environmental Chemistry Laboratory at the Water Research Institute of Ghana. Manganese (Mn) and Iron (Fe) were also determined with mass spectrometer UNICAM 386 in the same laboratory. In accordance with international standards, results with ionic balance more than 5% were rejected.

4. Results and Discussion

4.1Physico-chemical Analysis of Water samples

The results of physico-chemical analysis of groundwater samples from the Atankwidi sub-basin are summarised in Table 1

Table 1: Summary of physico-chemical water quality parameters in the Atankwidi sub-basin

Parameter	**Minimum**	**Maximum**	**Mean**	**Median**	**STD**
Temp	26.40	34.00	29.94	29.90	1.92
pH	6.73	7.93	7.24	7.21	0.33
EC	100.00	484.00	236.25	217.5	99.88
TDS	55.00	266.20	129.94	119.63	54.93
TSS	1.00	294.00	55.19	31.50	69.79
Turb	1.75	316	69.23	36.25	81.53
Br_2	0.00	1.98	0.47	0.34	0.47
Ca	5.60	40.9	15.27	13.2	8.36
Cl	3.00	44.00	15.54	12.90	9.28
NO_2	0.001	0.12	0.02	0.02	0.03
NO_3	0.001	10.10	1.06	0.43	1.89
PO_4	0.01	14.30	3.52	2.95	2.42
SO_4	4.00	84.00	23.42	20.00	16.95
Na	7.80	70.90	24.79	20.15	16.16
K	1.4	25.30	9.76	10.65	5.12
F	0.03	0.65	0.33	0.35	0.18
HCO_3	12.20	258.64	117.97	117.12	62.98
CaH	14.00	102.00	37.56	33.10	20.51
MgH	3.9	77.8	26.99	25.85	14.65
Mg	0.90	18.90	6.57	6.25	3.36
Mn	0.005	0.65	0.12	0.04	0.18
Fe	0.02	13.1	2.25	0.99	3.00
Zn	0.005	0.06	0.02	0.01	0.01

All concentrations are measured in mg/l, pH in pH unit, Turbidity in NTU, electrical conductivity in µS/cm and temperature in °C.

Generally, the chemical constituents of the groundwater samples are low as shown in Figure 4, with HCO_3^- as the predominant anion which is known to be very consistent with the chemistry of most natural waters in granitic formations (Freeze and Cherry, 1979). NO_3^- and F^- occur in minor concentrations compared with the other anions. The decreasing order of cations in the groundwater samples is in order of $Na^+ > Ca^{2+} > K^+ > Mg^{2+} > Fe^{2+}$ and that of anions is $HCO_3^- > SO_4^{2-} > Cl^- > PO_4^{2-} > NO_3^- > F^-$.

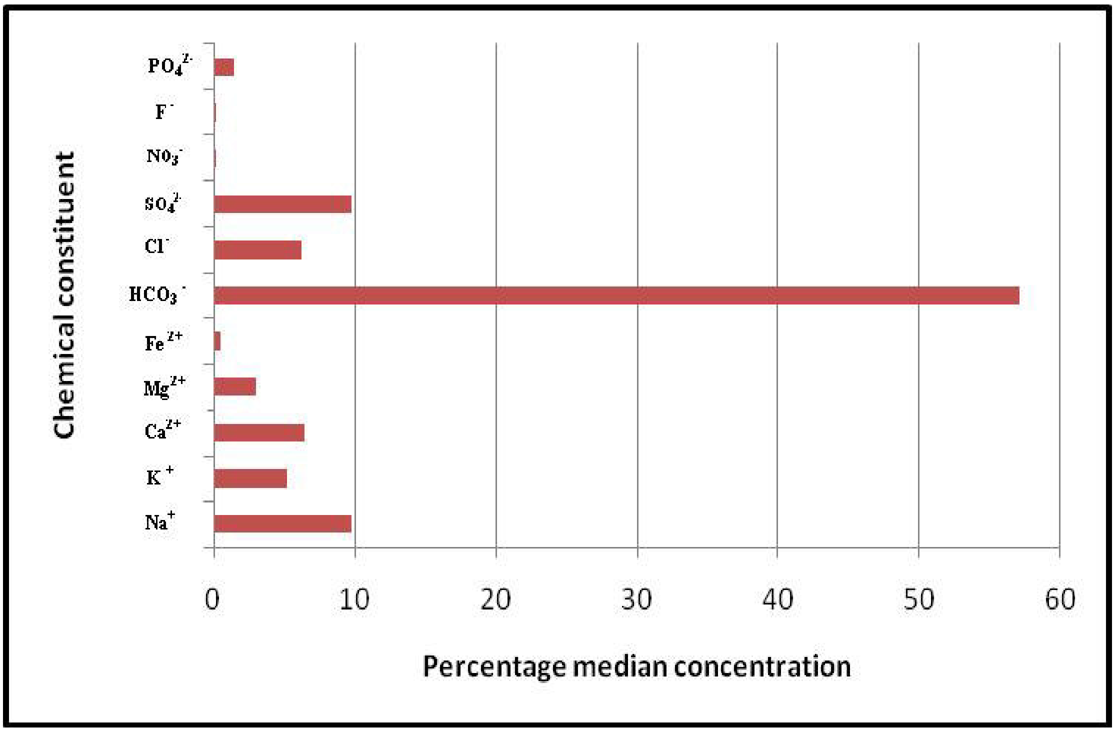

Figure 4. Median concentration of chemical constituents in the Atankwidi sub-basin

4.2 Hydrochemical facies of groundwater samples

Hydrochemical facies are distinct zones that possess cation and anion concentration categories (Sadashivaiah *et al.*, 2008). The chemical analysis results of the groundwater samples in the Atankwidi sub-basin has been presented by plotting them on a Piper tri-linear diagram (Piper, 1944) in Figure 5 which reveals the analogies, dissimilarities and different types of waters in the sub-basin.

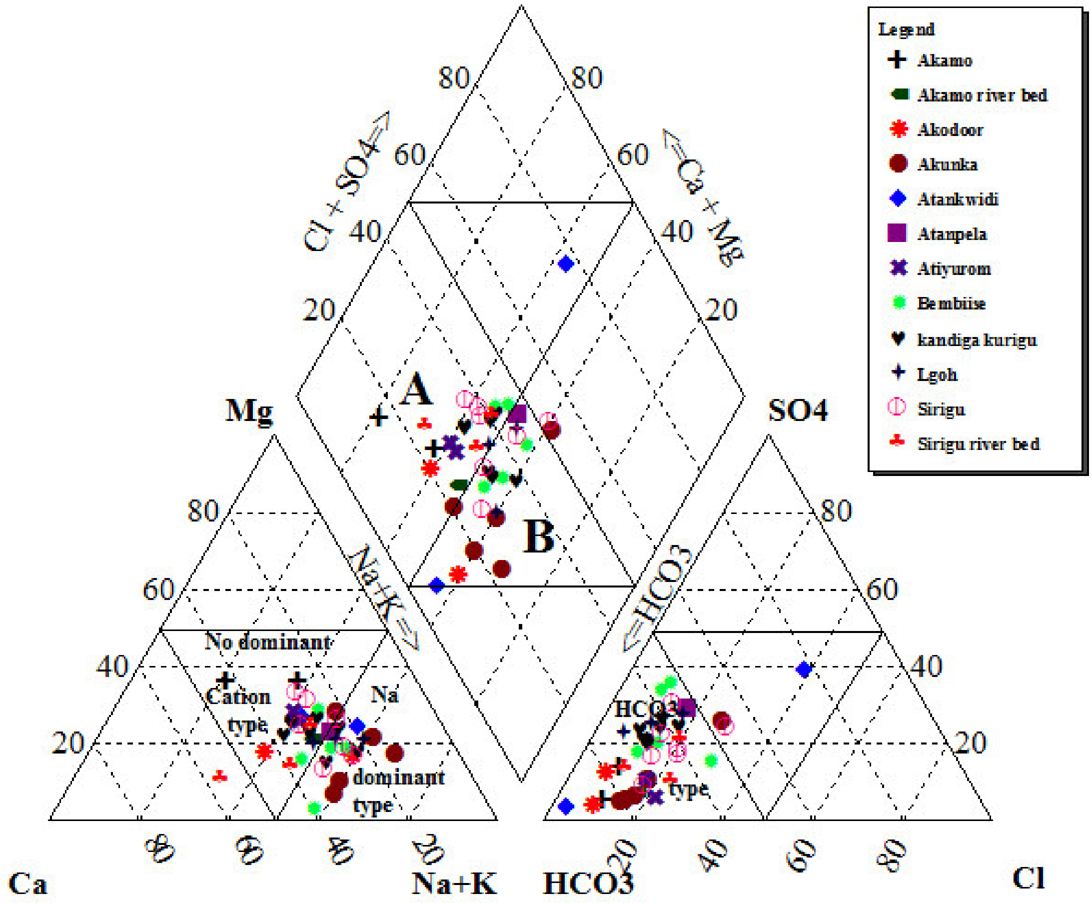

Figure 5. Piper diagram of groundwater samples from the Atankwidi sub-basin

In the cation plot field (triangle on the left) of the Piper tri-linear diagram, 50% of the groundwater samples plot mainly in the middle which suggests mixed cations with no dominant cation type whiles the other 50% of the samples depicts Na-K as the predominant cation type. However, in the anion plot field (triangle on the right), almost all the samples plotted are towards the HCO_3^- corner which again suggests HCO_3^- as the predominant anion.

The groundwater samples plotted in the Ca-Mg-HCO_3 dominant of the diamond field (section A) suggests active recharge, short residence time and temporary hardness (Kortatsi *et al.*, 2008). This type of waters usually has chemical properties which are dominated by alkaline earths and weak acids (Karanth, 1994), and apparently not associated with a particular geological formation (Kortatsi *et al.*, 2008) but may have emanated from either dolomite ($CaMg(CO_3)_2$) or calcite ($CaCO_3$) in rock matrix. Some (35 %) of the groundwater samples (section B) also showed mixed type of water with no cation-anion exceeding 50 %. This water specifically is more of the Na-Mg-Ca-HCO_3 mixed type of water.

4.3 Irrigation Water Quality

The evaluation of groundwater quality for irrigation in this study was based on the following factors:

i. Salinity (total amount of dissolved salts in water),
ii. Sodium hazard (the amount of sodium in the water compared to calcium plus magnesium),
iii. Magnesium hazard (MH), and
iv. pH and total alkalinity.

4.3.1 Salinity Hazard

The most influential water quality guideline on crop productivity is the water salinity hazard as measured by electrical conductance (Bauder *et al.*, 2007). High concentration of salinity (electrical conductivity) in irrigation water affect crop yield through the inability of the plant to compete with ions in the soil solution for water (osmotic effect or physiological drought). The severity of the osmotic effect may vary with the plants growth stage and in some cases may go unnoticed because of a uniform yield decline over the whole crop (George, 1979). Table 2 shows the classification of groundwater samples for irrigation water use based upon electrical conductivity.

Table 2: Classification of groundwater samples in Atankwidi sub-basin for Irrigation water use based on electrical conductivity (Bauder *et al*, 2007)

Number of samples	**Percentage**	**Electrical Conductivity (µS/cm)**	**Classes of Water**
26	65	≤250	Class 1: Excellent
14	35	250 – 750	Class 2: Good
0	0	750 – 2000	Class 3: Permissible
0	0	2000 – 3000	Class 4: Doubtful
0	0	≥3000	Class 5: Unsuitable

4.3.2 Sodium Hazard

According to Karanth (1994), excessive Na^+ content of irrigation water renders it unsuitable for soils containing exchangeable Ca^{2+} and Mg^{2+} ions as the soil take up Na^+ in exchange for Ca^{2+} and Mg^{2+} causing deflocculation (dispersion) and impairment of the tilth and permeability of soils. The sodium hazard is typically expressed as the sodium adsorption ratio (SAR). The general classifications of groundwater samples in the study area for irrigation based on SAR values according to Bauder *et al*, (2007) generally showed low SAR.

4.3.3 Classification of Irrigation Water Quality

When the salinity and sodium absorption ratio (SAR) of water are known, the classification of irrigation waters can be determined by graphically plotting these values on the Wilcox diagram (Wilcox and Durum, 1967). The diagram expresses the relationship between sodium (SAR) and salinity (EC) hazards, in other words, it expresses the integrated effect of both sodium and salinity hazards of irrigation waters. That for the Atankwidi sub-basin was therefore plotted as shown in Figure 6.

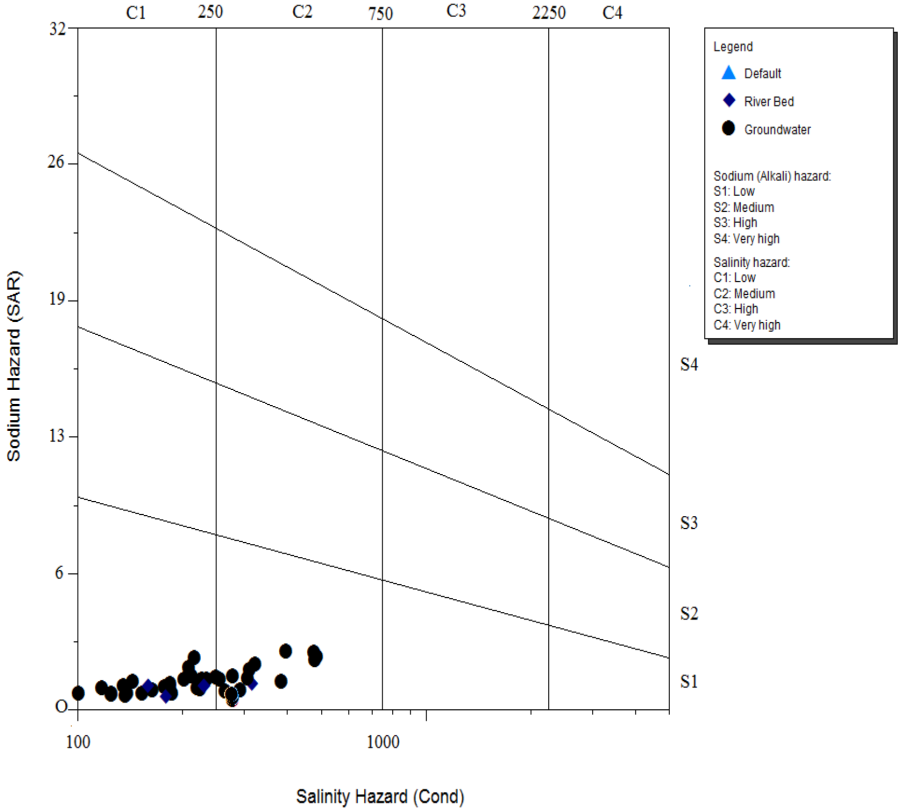

Figure 6. Classification of irrigation waters in the Atankwidi sub-basin

4.3.4 Magnesium Hazard

Magnesium is believed to be injurious to plants, but the harmful effect is greatly reduced by the presence of calcium. The magnesium hazard (MH) is defined as $100Mg\ (Ca + Mg)^{-1}$ with the chemical constituents expressed as meq/l. The classification of groundwater samples according to Szabolcs and Darab (1964) based on magnesium hazard is shown in Table 3

Table 3: Classification of groundwater samples in Atankwidi sub-basin based on Magnesium hazard (Szabolcs and Darab, 1964).

Number of wells	**Percentage**	**Magnesium hazard $[100Mg(Ca + Mg)^{-1}]$**	**Water classification**
29	72.5	<50	Desirable
11	27.5	>50	Undesirable (deleterious to most crops)

The groundwater sampled had 27.5% of them with MH above 50 implying that, magnesium hazard is a potential problem associated with the groundwater in the study area should it be used for irrigation.

4.3.5 pH and Alkalinity

Alkalinity is related to pH, because water with high alkalinity has a high “buffering capacity” or capacity for neutralising added acids. The major chemicals responsible for alkalinity in water are the dissolved carbonates and bicarbonates from the geologic materials of the aquifer from which the water is drawn. The dissolved carbonates and bicarbonates increase the media pH over time by neutralising H^+ ions in the media solution. Although there are no established optimum or toxic levels for alkalinity, typical recommendations range from 37.5 – 130 mg/l $CaCO_3$ (Will and Faust, 1999). The concentration of alkalinity varied from 10 – 216 mg/l with the mean, median and standard deviation of 96.7, 96 and 51.62 mg/l respectively. 22.5% of the total groundwater samples had their concentrations above this desirable range probably due to the relatively high concentrations of bicarbonate (HCO_3^-) in the samples. Nonetheless, 5 % of the groundwater samples had low alkalinity concentrations. Low alkalinity of irrigation water provides no buffering capacity against pH changes which leads to the decline of media solution pH when acid-residue fertilisers are used (Will and Faust, 1999).

4.3.6 Assessment of Irrigation water quality based MH and Total Alkalinity

The irrigation water quality was assessed based on all the criteria used (SAR, salinity hazard, magnesium hazard and alkalinity) to know the percentage of groundwater samples that fell within the recommended ranges.

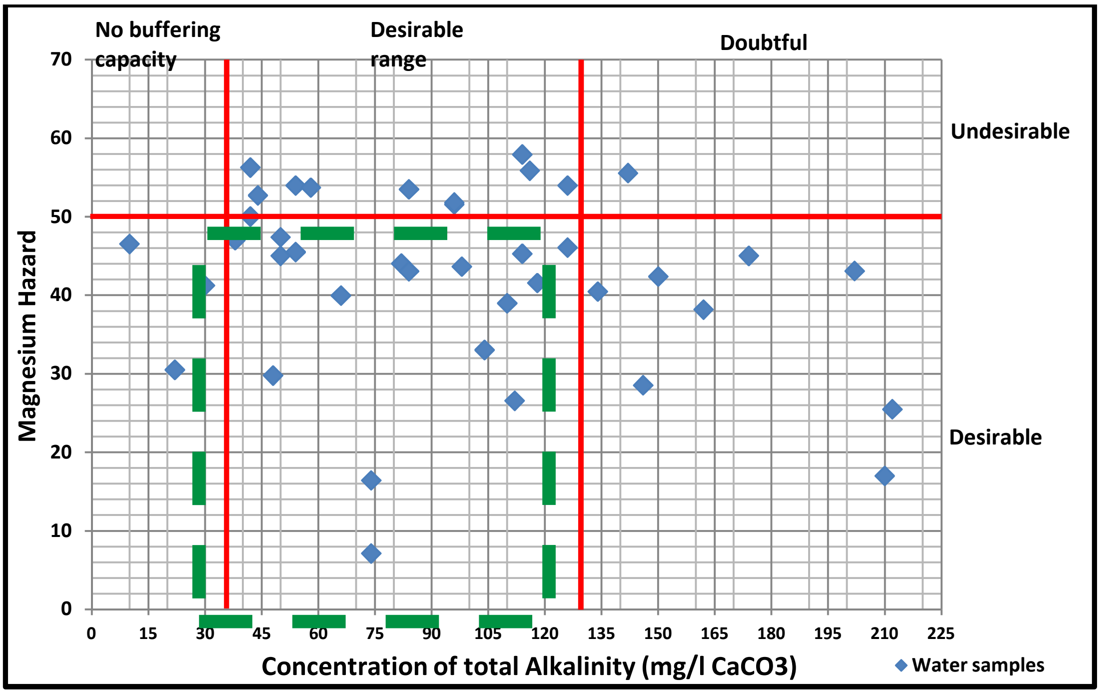

Figure 7. Assessment of irrigation water quality based on MH and alkalinity

Figure 7 shows the assessment of groundwater samples based on both magnesium hazard and total alkalinity. Since all the groundwater samples fell within the recommended ranges of both sodium (SAR) and salinity hazards at the same time, the only limitations will be from magnesium hazard and alkalinity. Therefore the percentages of samples that fall within the desirable ranges of both magnesium hazard and alkalinity at the same time are considered to be the percentage of samples with absolutely no limitation. With this assumption, the percentage of samples that fall within the recommended region of the Figure above is 52.5 % with 25 % and 22.5 % of the samples with magnesium hazard and alkalinity problems respectively.

It is however worth mentioning that the potential problems identified were not area specific so far as the study area is concern which literature suggests that, it may due to the different recharge patterns of the aquifer system.

5. Conclusion

Two main water types (Ca-Mg-HCO_3 and Na-Mg-Ca-HCO_3) have been delineated using the Piper diagram. Furthermore, the relative abundance of cations in the groundwater is in the order of $Na^+ > Ca^{2+} > K^+ > Mg^{2+} > Fe^{2+}$. HCO_3^- was however the predominant anion which also had a decreasing order of $HCO_3^- > SO_4^{2-} > Cl^- > PO_4^{2-} > NO_3^- > F^-$. The suitability of groundwater for irrigation evaluated based on sodium (SAR), salinity and magnesium hazards, pH and alkalinity showed low SAR and low to medium salinity hazard and is therefore good for irrigation but with some potential magnesium hazard and alkalinity problems which partially limits its use for irrigation by developing sodic soil conditions with continuous use. Due to the magnesium hazard problems that were recorded in some of the areas which also actually increase slightly the potential effect of sodium on soils, soil conditions should also be monitored with time to ascertain any problem of sodicity and if necessary leach the soil. Groundwater quality in the sub-basin should also be monitored regularly to ensure early detection and intervention of any pollution or contamination that may occur due to the susceptibility of the regional aquifer system to pollution (weedicides, pesticides etc.).

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