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Full Length Research Paper

Hydrochemical Characteristics of Ground and Surface water under the influence of Climate variability in Pallisa District, eastern Uganda

Jacob Nyende[1, 2*], van Tonder G[2] and Danie Vermeulen[2]

[1]*Department of Civil & Building Engineering, Faculty of Engineering, Kyambogo University, P.O. Box 1, Kyambogo-Kampala, Uganda*
[2]*University of the Free State, Institute for Groundwater Studies, Faculty of Natural and Agricultural Sciences, P.O. Box 339, Bloemfontein 9300, South Africa*

Abstract

Hydrochemical investigations of ground and surface (G-S) water were carried out with the objectives of evaluating groundwater quality and sustainability. The increasing population combined with environmental degradation and extreme poverty is affecting the quantity and quality of groundwater. This paper therefore presents the hydrochemical characteristic of mainly groundwater and a few surface water points in the Pallisa District, eastern Uganda under the impact of climate variability. The approaches followed in the study include the chemical analyses for major ions chemistry and production of hydrochemical Durov, Piper plots and graphs of total dissolved solids (TDS), sodium (Na^+), bicarbonate (HCO_3^-), Total alkalinity (Talk) and chloride (Cl^-) ions. The hydrochemical characteristics of basically groundwater in the fractured bedrock aquifer, development and management considerations are discussed. The results of the different waters analysed show the regime of calcium/magnesium - bicarbonates. High concentrations of calcrete ($CaCO_3$) with magnesium and aluminium in the upper and lower aquifers suggest along history of hydraulic interactions within the regolith and the granitic fractured bedrock.

Keywords: Hydrochemical, Climate variability, geology and Soils, G-S water, fractured-bedrock, Pallisa District, eastern Uganda.

INTRODUCTION

The change in climate in the tropical part of eastern Uganda has affected the use of groundwater. Variations in natural and human activities reflect spatial variations in the hydrochemical parameters of the groundwater. The difference of dissolved ions concentration in groundwater are generally, governed by lithology, velocity and quantity of groundwater flow, nature of geochemical reactions, solubility of salts and human activities. Pallisa District is located in the arid region of Kyoga basin, eastern Uganda and intensively inhabited during the last decenniums, leading to expansion of the residential areas from the surface water courses. Suitable quantity and quality of groundwater become a more crucial alternative resource to meet the drastic increase in social, agricultural, and industrial development and to avoid the expected deterioration of groundwater quality due to heavy abstraction for miscellaneous uses (Gupta and Onta, 1982). Hence, hydrochemical investigations are the main objectives of study for the surface and groundwater system in Pallisa. In this paper, results of preliminary investigation that were conducted are in form of table and hydrochemical graphs that evaluate the variations in groundwater chemistry, which was more related to ionic exchange, with often high bacteria counts and salinity hazards. Annual rainfall varies from over 2000 mm over Lake Victoria and Mt. Elgon, to less than 700 mm in the north-eastern parts of the country which presupposes high infiltration rate. Average daily temperatures vary from

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*Corresponding Author Email: jmnyende@yahoo.com

18^0 C in March to January to 30^0 C in July. Much of the land area of Pallisa District is rural, with 43% of the land use being arable, pasture and permanent crops and 28% being forested. Agriculture is the most important sector of the national economy. Despite the importance of agriculture nationally, the use of fertiliser and agricultural pesticides is apparently limited (DWD, 1994).

General geological setting

The geology of Uganda and especially that of the Kyoga catchment is dominated by ancient (Precambrian) crystalline rocks (including granites), which constitute around 90% of the land area. The remaining rock types are dominantly younger volcanic and sedimentary rocks. In this area, volcanic rocks outcrop around the town of Mbale and form the highlands of Mounts Elgon and Moroto. However, in Kyoga catchment, the geology can be described as undifferentiated gneisses including elements of partly granitised and metamorphosed formations. It consists of however, a gneissic complex formation. Gneiss and granitic formations of the Pre-Cambrian predominates which are usually referred to as gneiss complex. The northern part is largely underlain by older, wholly granitised or medium to high-grade metamorphic formations. The hillier region of the east is underlain by young cover formations comprising of partly granitised to relatively unmetamorphosed argillite and arenites. The various formations of the Gneiss Complex show a different response to weathering and fracturing, which have important consequences in terms of groundwater occurrence, flow and quality (Nyende, 2007).

Location and Geology of the Study Area

Site Description

Pallisa District within the Kyoga Basin is the area under investigation and is located in the eastern part of Uganda. It has approximately 1 585 km^2 in area and is bordered by Kumi District to the north, Budaka District to the east, Butaleja District to the south - east, Namutumba District to the south, Kaliro District to the west, to the north - west lies both Kamuli District and Soroti District. The chief town is Pallisa and its coordinates are 01^o 1’’N, 33^o 43’’E (http://www.pallisa.go.ug/). Pallisa District is located between latitude 33^o 25’’E and 34^o 09’’E and Longitude 0^o 50’’N and 01^o 25’’N. There are small towns of Kabwangasi, Kamuge, Kibuku and Butebo within Pallisa district (Figure 1B). The topography slopes gently from east to west with land surface elevations from 1 200 mamsl in the eastern part to near 1 000 mamsl in the south - western part. Most of the land is used in small scale agricultural farming while wetlands, woodland, bush land, grassland, deciduous plantations and urban areas represent about 30% of the land surface. The average temperatures range between 20 - 30 ^{o}C, with minor daily temperature variations. Mean annual minimum temperature is 18 ^{o}C and the mean annual maximum temperature is 32 ^{o}C. The weather conditions are characterised with bi - modal rainfall system controlled by the Inter - Tropical Convergence Zones (ITCZ) (Nyende, 2007). The mean annual precipitation is about 1 250 mm/year.

Local geology

The structural geological history is complex. Major structural features include the northwest and eastern areas and the step or en-echelon faulting associated with the western and eastern rift valleys. The crystalline rocks of Pallisa are generally covered by ‘regolith’, a layer of weathered material which varies from rock fragments near the interface with the bedrock, to well-weathered soil and sometimes hardened laterite at the ground surface (Carter, 1999; Omorinbola, 1984 and Ruwasa, 1996). Sedimentary deposits of Paleozoic to early Tertiary are absent, except for minor fault - bounded outliers of the ecca shales (Karoo, Mesozoic). In mid to late Tertiary, up to 3 000 m of mainly lacustrine deposits (Elgon beds) accumulated in the eastern rift valley and along the river valleys which are recent accumulation and depositions (Figure 1D).

Hydrogeology

Groundwater is the most important source of potable water in Uganda, especially in the rural areas, and provides 80% or more of the water supply. Water is abstracted from both the fractured bedrocks and from the overlying weathered regolith (BH1). The regolith aquifer is seen increasingly as a usable resource which aid agencies are seeking to develop on grounds of favourable yields and lower cost than the deeper groundwaters from the basement (BH2) (Clerk, 1985; Acworth, 1987). Figure 2

The regolith layer typically has an upper horizon of clayey sediment which is effective at filtering out some surface-derived pollutants (e.g. bacteria) and in restricting entry of air to the underlying aquifers (R. Oppong-Boateng 2001, M.Sc. Thesis, International Institute for Aerospace Survey and Earth Sciences, Enschede (ITC)). This has some implications for the degree of aeration of the aquifers and of the resulting groundwater chemistry. The basement aquifer has poor permeability but is variably fractured. The development of fractures is crucial for the availability and yield of groundwater; hence the productivity of the aquifer is

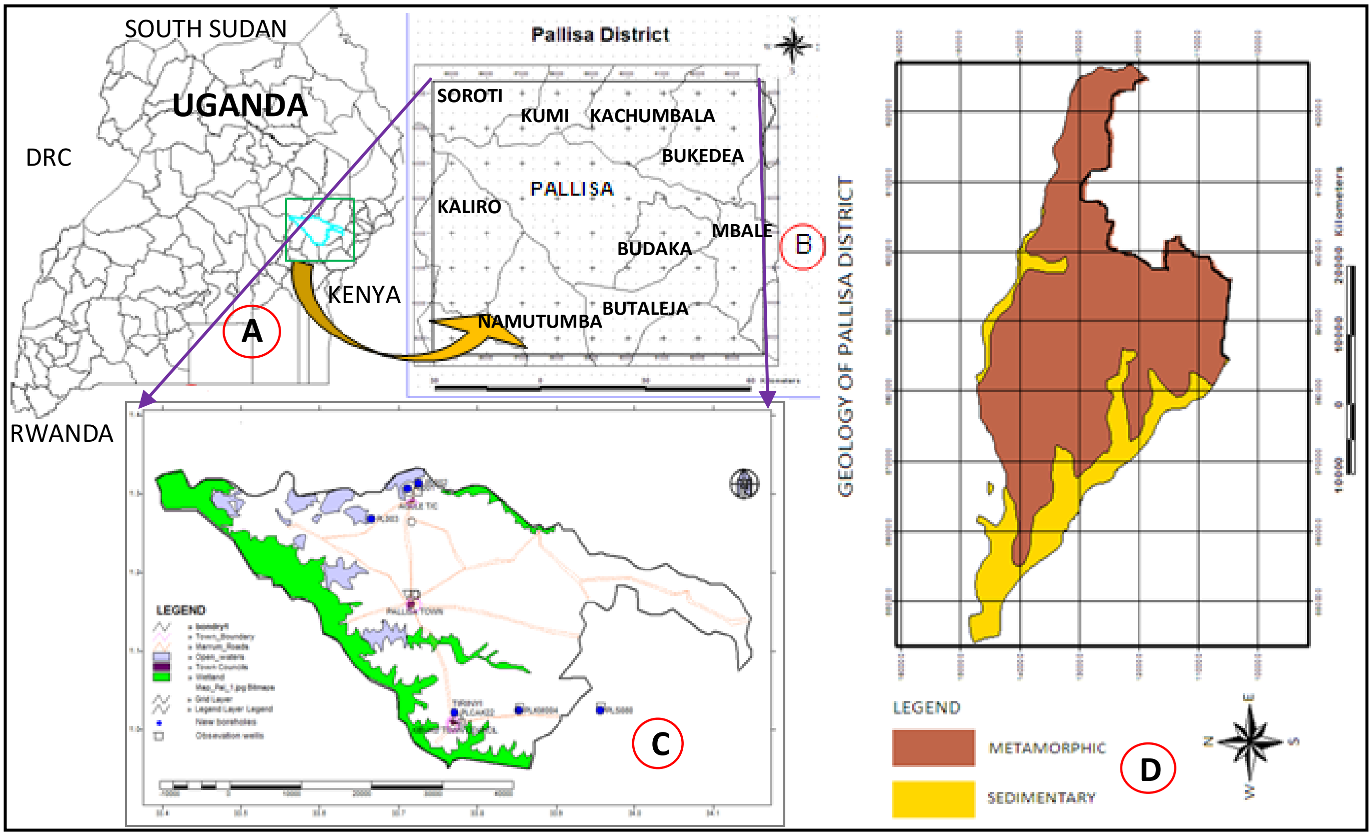

Figure 1. Location and Geology of Pallisa District in the Kyoga basin

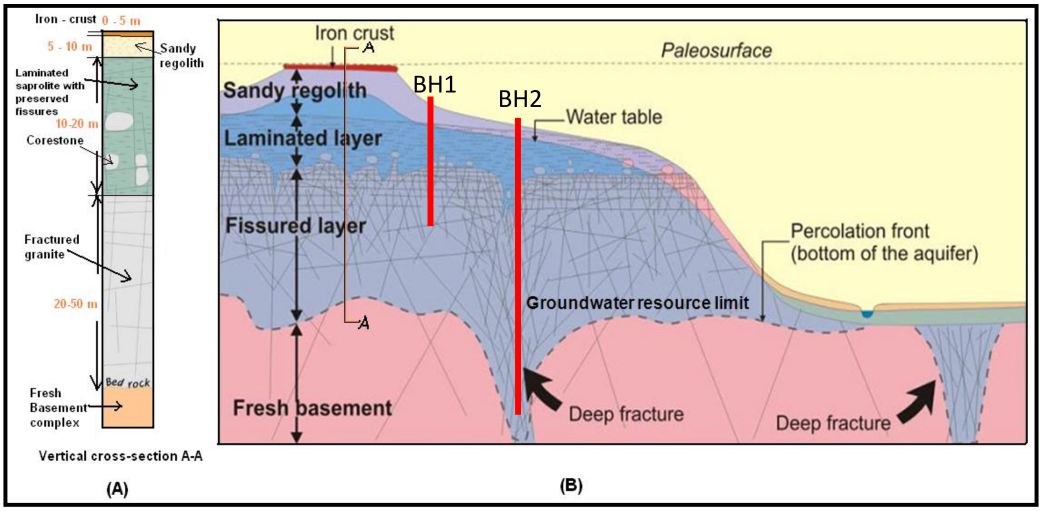

Figure 2. Schematic weathering vertical cross - section profile of Pallisa area (A) and (B) an idealised single phase weathering palaeo - profile in hard - rock aquifers, cross - cut by the current topography (adapted and modified from Dewandel et al., 2006 and cited by Wyns et al., 2004).

highest at the shallowest levels. According to Morgan (M.Sc. Thesis, International Institute for Aerospace Survey and Earth Sciences, Enschede (ITC), 1998) and Nyende (2003), the high rainfall and temperature of tropical climates serve to increase the rate at which chemical weathering processes occur as a result of hydrolysis, oxidation and dissolution. The geopetal imprint of long-term deep weathering and erosional unloading was identified in the vertical heterogeneity of the fractured-bedrock and weathered-mantle aquifers; the horizontal heterogeneity is lithologically controlled. The two units form an integrated aquifer system in which the more transmissive (5-20 m^2/d) (Nyende, 2003) and porous weathered mantle provides storage to underlying bedrock fractures (T = 1 m^2/d). The thickness and extent of the more productive weathered-mantle aquifer are functions of contemporary geomorphic processes.

METHODS

Collection of water samples

The present groundwater study is primarily based on the water sampling carried out in 2010 - 2011. In order to study the variation of groundwater quality in the study area, groundwater and soil samples were collected from the study area twice a year during wet and dry periods, from July - October 2010 and December 2010 - March 2011. Samples were collected during the driest part of the year to avoid dilution by infiltration and the wettest part when dilution had taken place under the recharge activity. A total of 176 groundwater samples were collected from existing 56 sampling stations that included two newly drilled deep and four shallow wells. Plastic sampling bottles were rinsed with distilled water before being used to sample. The bottles were tightly sealed, stored in ice box in the field (at 4 °C) and taken to the Government laboratory at Wandegeya in Kampala for analysis. The sample preservation and analysing techniques were in accordance with the standard test procedures. The collected groundwater samples were analysed for major ions such as Ca^{2+}, Mg^{2+}, Na^+, K^+, HCO_3^-, Cl^- and SO_4^{2-}using the computer aided WISH program. Sensors were used for on-the-spot field water quality measurement of TDS, electrical conductivity (EC), pH and temperature. Alkalinity was measured (by Gran-titration) within 12 hours at a field laboratory and some minor constituents (nitrate, fluoride, aluminium and iron). Trace elements such as lead and arsenic were not analysed, due to limitations of standards and reagents. Water samples were also collected in yellow high density polyethylene bottles except for samples for the analyses of hydrogen and oxygen isotope ratios. In the field, two filtered (0.45 µm cellulose nitrate membrane filter) samples (one part was acidified to pH = 1 with ultra-pure HNO_3 in new pre - flushed PE bottles and the other not acidified) were then taken for laboratory analysis for the determination of cations as described by Edmunds (1996b). Concentrations of cations in water and the rock samples were determined by Atomic Absorption Spectroscopy (AAS); following dissolution of the rock sample powders in 2NHCl. Analyses of anions were carried out on a Dionex DX120 ion chromatograph. The detailed hydrochemical characteristics of potable groundwater, including variations in concentrations of major cations and anions, are described in US 201 (1994) and US 43 (1999) for drinking water quality.

RESULTS AND DISCUSSIONS

Results

Table 1, provides the major water quality constituents of water samples collected from Lake Kyoga reservoirs and nearby boreholes at Agule and Chelekula (Figure 3). The results are presented in bar diagrams, respectively in Figure 4.

The difference observed between the water samples collected from the boreholes and reservoirs in the two marked areas is that the levels of most Physico - chemical parameters like EC, HCO_3^-, Ca^{2+}, Mg^{2+}, Cl^-, K^+, Na^+, TDS, Colour, Turbidity and SO_4^{2-} are generally higher for samples from Chelekula than those from Obwanai in Pallisa. These differences could be attributed to, among others, the depth and type of aquifers of the wells themselves, relationship to geological characteristics of the catchments (natural weathering of the aquifer matrix) and the groundwater residence time.

Very low concentration of other ions in groundwater compared to the lake water at Pallisa town indicates that groundwater recharge is highly localised with less accumulation of ions from animal grazing, while the lake receives these ions from all over the catchment through surface runoff. Overall, surface and groundwater in Pallisa area are more similar to each other than those of the Kibuku area. It is also worth noting that the concentration levels of most of the chemical parameters in Pallisa area are lower for the lake water than for the groundwater (Figure 4), which usually is the reverse for most natural conditions. Moreover, one can conclude that all waters are rather recent, because they are dominated by BCO_3, MALK, TALK and Ca.

Analysis and evaluation of groundwater samples

Groundwater quality defined in terms of aesthetic and health related guidelines furnished by the World Health Organisation (WHO, 2004 guidelines) were compared to the values obtained from the existing sources in Pallisa District, eastern Uganda. The results of the analyses are indicated in Table 2.

There are significant differences that emerge reflecting the variations in both the construction mode and the geological environment in which the water sources exist. From Table 2, it appears that the boreholes show the lowest frequency of bacteriological (E.Coli) and dug up wells the highest, but generally a presence of very high coli form counts in protected springs and open dug up shallow wells is an indication of contamination.

Table 1. Physico - chemical composition of water samples from boreholes and Lake Kyoga reservoirs in Pallisa District

	AGULE		CHELEKULA	
Parameter	**PL001**	**reservoir-1**	**PL003**	**reservoir-2**
Turbidity	4.4	12	13.4	9.8
Colour	18	16	27	19
pH	5.94	7.2	6.90	7.3
EC (µS/cm)	34.2	200	338	181
Na (mg/l)	29	9.9	72	5.92
K (mg/l)	6.90	3.75	21	1.66
Ca (mg/l)	85	26.8	155	26.5
Mg (mg/l)	11	9.45	11	5.38
T/Fe (mg/l)	0.9	0.11	0.3	0.11
Mn (mg/l)	0.342	0.01	0.055	0.01
N-NH_4 (mg/l)	0.70	0.21	0.70	0.17
Cl (mg/l)	3.0	13.92	45	7.95
SO_4 (mg/l)	2	33.11	36	9.28
N-NO_3 (mg/l)	3.1	0.38	7.7	0.2
NO_2 (mg/l)	0.02	0.14	0.02	0.02
BCO_3 (mg/l)	201.2	128	185.9	99.43
Al (mg/l)	1.76	0.20	0.10	0.00
TDS (mg/l)	176	122	337	161
Fluoride (mg/l)	0.09	0.01	0.00	0.00

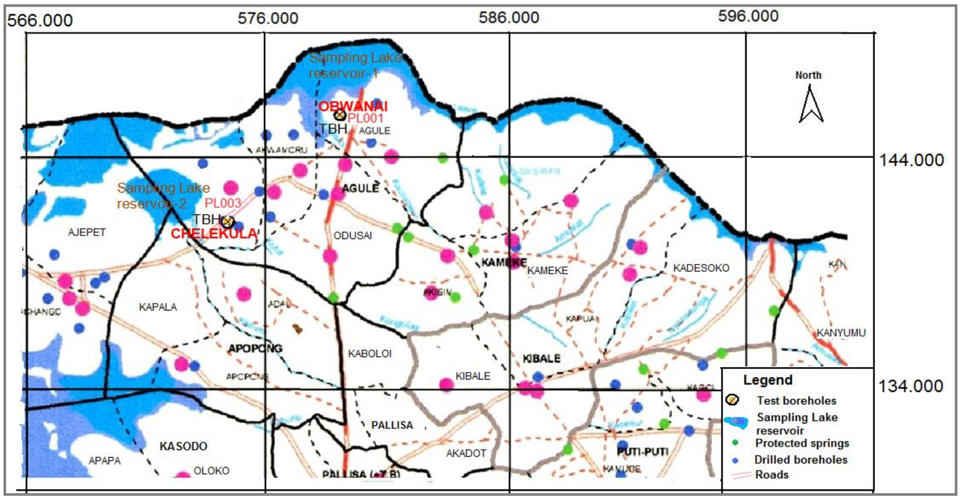

Figure 3. Positions of test wells and sampling stations at Lake Kyoga reservoirs within Pallisa District.

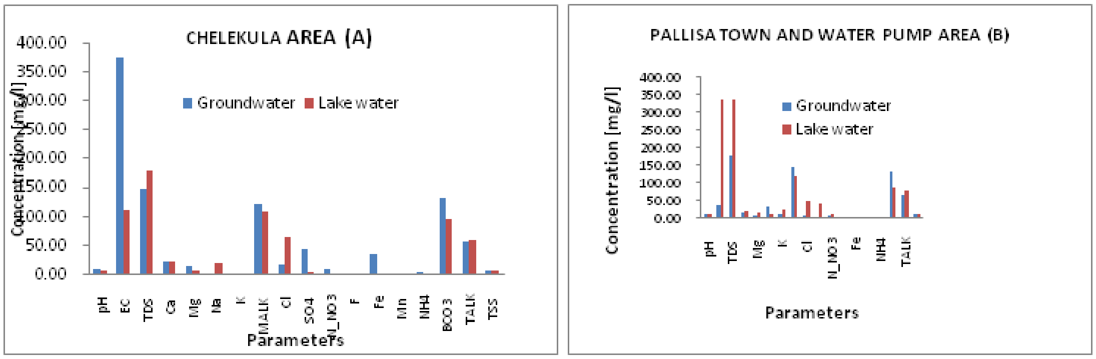

Figure 4. A comparison of surface water and groundwater quality in Chelekula area (**A**), and Pallisa town and the main water pump area (**B**).

Table 2. Average values for water quality parameters from dug-up wells, protected springs and existing boreholes in Pallisa District.

PARAMETER	AVERAGE VALUES OF DUG-UP WELLS (30 No.)	AVERAGE VALUES OF PROTECTED SPRINGS (45 No.)	AVERAGE VALUES OF EXISTING BOREHOLES (38 No.)	WHO 2004 GUIDELINES
Manganese, mg/l Mn^{2+}	0.10	0.05	0.07	0.1
Alkalinity, mg/l $CaCo_3$	119.5	48.7	196.6	-
T-Hardness, mg/l $CaCo_3$	124.6	48.4	229.8	500
Conductivity, µS/cm	410	124	766	1000
Calcium, mg/l Ca^{2+}	51.2	35.7	105.1	75
Carbon dioxide, mg/l CO_2	100.5	136.3	175.9	-
Sodium, mg/l Na^+	45.2	7.4	70.4	200
Potassium, mg/l K^+	5.54	1.76	5.23	-
Chloride, mg/l Cl-	22.1	9.3	73.4	250
Sulphate, mg/l SO_4^{2-}	27.8	12.8	57.5	400
Phosphate, mg/l PO_4^{2-}	1.6	0.9	1.2	-
Nitrate, mg/l NO_3^-	2.26	2.36	3.48	10
TAlk, mg/l	166	186	222	-
% Water points with E.Coli count > 0	46*	22*	9*	0
Aluminium, mg/l	0.46*	0.35*	0.5*	0.2
Turbidity, NTU	0.9	0.35	0.45	5.0
TDS, mg/l	1502*	353	475	1000
PH	6.79	5.67	6.49	6.5-8.5
Fluoride, mg/l F^-	1.8*	0.24	0.79	1.5
Total iron, mg/l $Fe^{2+} + Fe^{3+}$	0.37*	0.3	0.56*	0.3
Magnesium, mg/l Mg^{2+}	9.1*	5.2*	22.1*	-
Bicarbonate, mg/l HCO_3	140.5	81.6	216.3	-

The figures in with esterisk indicate the value not in accordance with WHO (2004) guidelines.

This perhaps may be caused by the difficulties in construction and maintenance of proper sealing on large diameter, usually shallow hand - dug wells, where seepage of surface runoff into the wells may occur. If the hand dug wells were not adequately covered/protected, introduction of foreign materials, lifting devices, etc, could be major sources of contamination. Boreholes on the other hand tap water from relatively deeper aquifer horizons and the top layers are sealed with cement slurry or bentonite and backfilled to prevent surface flows or interflows from entering the well.

In terms of mineralization, it is important to note that conductivity values are significantly lower for springs than for hand dug wells and comparatively much lower in boreholes. This is due to the extensive leaching of spring water trajectories that occurs through many years of groundwater flow. In addition, the water in these aquifers shows relatively minor enrichment in organic substances. From the tests carried out, spring water shows the lowest pH values, which again demonstrates that this water, in spite of the low pH, has caused limited decomposition of aquifer minerals. Boreholes on the other hand, show the highest degree of mineralization with relative enrichment of nearly all elements tested. This may be due to the residence time of groundwater flows, temperature variations, recharge/discharge, fracture disposition, geology or the ability of aggressive groundwater to decompose the relatively fresh minerals in the bedrock fractures.

Water from dug wells shows an immediate enrichment in organic constituents, in accordance with the aquifers' geological setting. The ions, Ca^{2+}, Mg^{2+}, Na^+, K^+, Cl^-, SO_4^{2-}, and HCO_3^-, are naturally very variable in groundwater due to local geological, climatic, and geographic conditions. Table 3 shows the maximum allowable concentration of selected water quality variables for drinking water according to guidelines of the World Health Organisation (WHO, 2004), European Union (EU), Canada, USA and Uganda [Uganda National Bureau of Standards (UNBS)], and average values of the water samples taken from Pallisa District within the Kyoga catchment.

The summary statistics of the measured water quality parameter are given in Table 3. The main lithology in these localities is the laterite, which in one of the boreholes is inter - layered with a gypsum related horizon and is the main sources of sulphate in that borehole (PL003). The occurrences of high nitrate concentrations in the water samples could not be correlated with the distribution of major lithological units.

These wells or springs are found on areas with lateritic, metamorphic, sandstone or dolerite rocks.

Table 3. Maximum allowable concentrations of major ions for drinking water (UNBS, 1999 & 2008), and average values for Pallisa District within the Kyoga basin

Variable	WHO	EU	Canada	USA	(UNBS)	Pallisa District
pH	<8	6.5-8.5	6.5-8.5	6.5-8.5	6.5-8.5	5.0-9.2
Ammonium (mg/l)	-	0.5	-	-	-	-
Nitrate as N (mg/l)	-	-	10	10	10	-
Nitrate (mg/l)	50	50	-	-	5.0	0.10
Turbidity (NTU)	5	4JTU	5	0.1-1.0	5	13.4
Total dissolved solids (TDS) (mg/l)	1000	-	500	500	700	101-690
Colour (TCU)	15	20	15	15	15	70
Chloride (mg/l)	250	150	250	250	250	7.7
Sodium (mg/l)	250	150	-	-	-	-
Total suspended solids (mg/l)	-	-	-	-	0.0	3.0-12.0
Manganese	0.5	0.05	0.05	0.05	0.5	0.7
Iron (mg/l)	0.3	0.2	0.3	0.3	0.3	-
Bicarbonates (mg/l)	-	-	-	-	500	-
Fluoride (mg/l)	-	-	-	-	1.0	0.10-1.1
Total Alkalinity (mg/l)	-	-	-	-	500	-
Sulphates (mg/l)	250	250	250	250	200	0.0-670
Total Iron (mg/l)	-	-	-	-	0.30	0.11-0.35
Total Hardness (mg/l)	-	-	-	-	500	38.9-501
Calcium (mg/l)	-	-	-	-	75	-
Electrical conductivity (µS/cm)	-	-	-	1000	-	-
SAR	-	-	-	-	-	-

***N.B.** The physical - chemical characteristics for colour, turbidity and TSS are higher than the National standards and these could be reduced by settlement and simple infiltration.*

Table 4. Fluoride concentrations observed at four wells during the dry and wet seasons from August 2009 to February 2011.

Sample Location	dry season 2009	wet season 2009	dry season 2010	wet season 2010	dry season 2011
PL001	1.0	1.2	<1	<1	<1
PLS080		<1	<1	<1	<1
PLKM004		<1	<1	<1	<1
PLCAK22	1.1	1.1	1.1	<1	<1

Hence, the most probable source could be agricultural inputs, like manure, chemical fertilizer and animal grazing in the low-lying areas. The range of concentration for most ions is high, indicating a marked difference of geochemical characteristics of the rocks and possibly also differences in recharge and discharge conditions. Water in boreholes shows the highest variation for most ions, while hand dug wells show the lowest (Table 3).

Fluoride in the Study area

The results of the two field campaigns in 2009 showed increased concentration values due to solubility constant of 0.2 for the borehole PL001 in Agule and constant values for borehole PLCAK22 around Tirinyi Trading Centre (Table 4). Later field tests on these boreholes showed no fluoride content above the detection limits. This effect might be due to a change in the well by dilution or strict laboratory tests.

The distribution of the major ion composition in Pallisa District is shown in Figures 5 and 6 by Piper Tri - linear diagrams, where groundwater samples in the district have been presented by the measured and tested groundwater from the different sampling locations. The pH value for the groundwater in Pallisa District ranges from four to 10 with an average value of 6.90 during the dry season (Figures 7 and 8). In the Piper diagrams, major ions are plotted as cation and anion

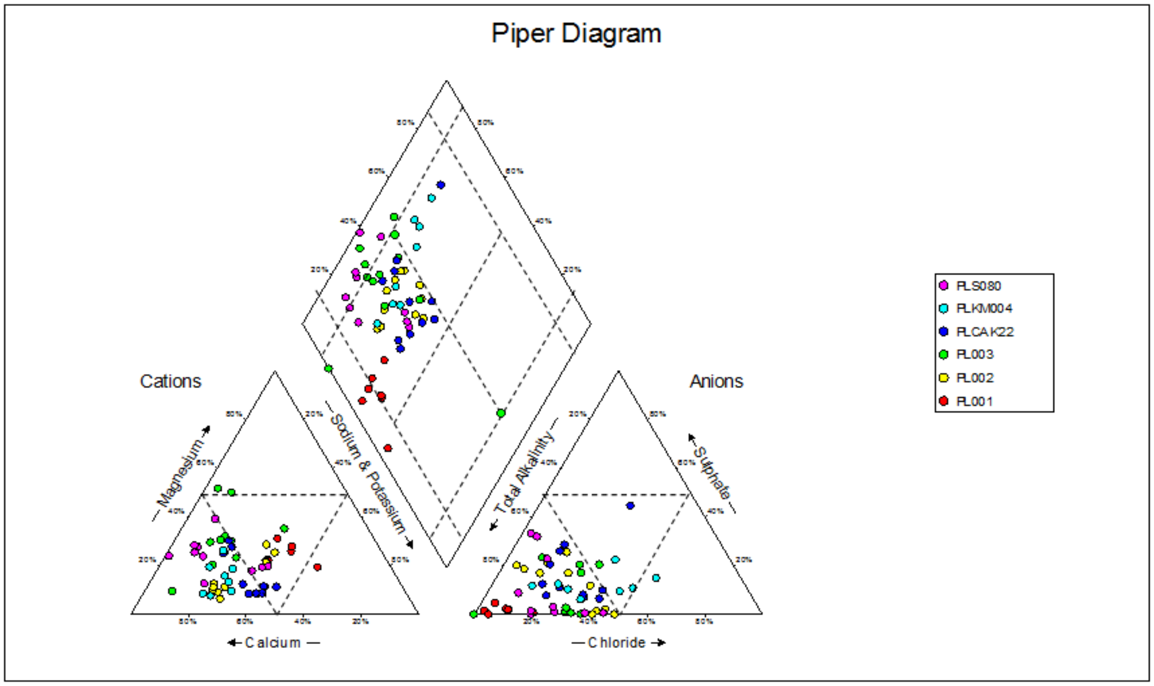

Figure 5. Piper Tri - linear diagrams showing hydrochemical facies of groundwater during the wet season in the different boreholes of Pallisa District in eastern Uganda.

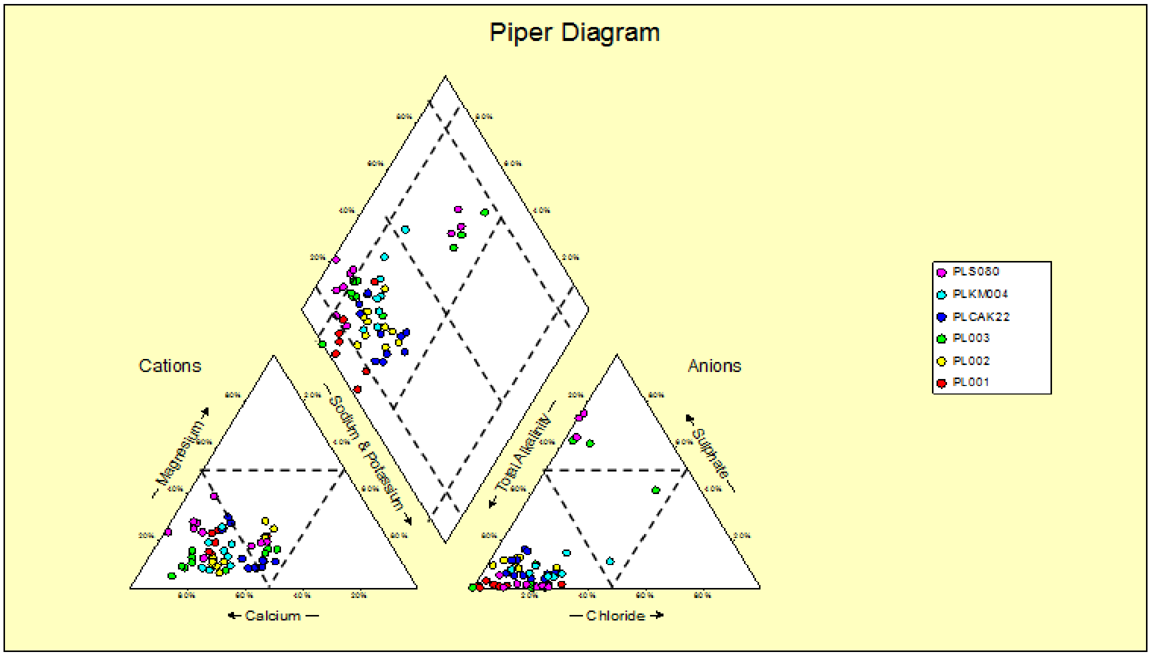

Figure 6. Piper Tri - linear diagrams showing hydrochemical facies of groundwater during the dry season in the different boreholes of Pallisa District in eastern Uganda.

percentages in mill-equivalent (meq) in two base triangles.

From Figures 5 and 6, it can be seen that most wells in saprolite, fractured and granite layers are mainly dominated by Ca+Mg, Na+K, CO_3+HCO_3, Ca-HCO_3^--SO_4 or HCO_3-Cl+SO_4 - waters. Water samples from the basement rocks are typically low in Mg, Cl, SO_4, and high in Ca. Hence, they are of Ca-HCO_3, or Ca-HCO_3 - type, with a few of Mg-Ca-HCO_3 type. Water samples from sandstone are NaCa-Mg-HCO_3, Mg-Ca-HCO_3 and

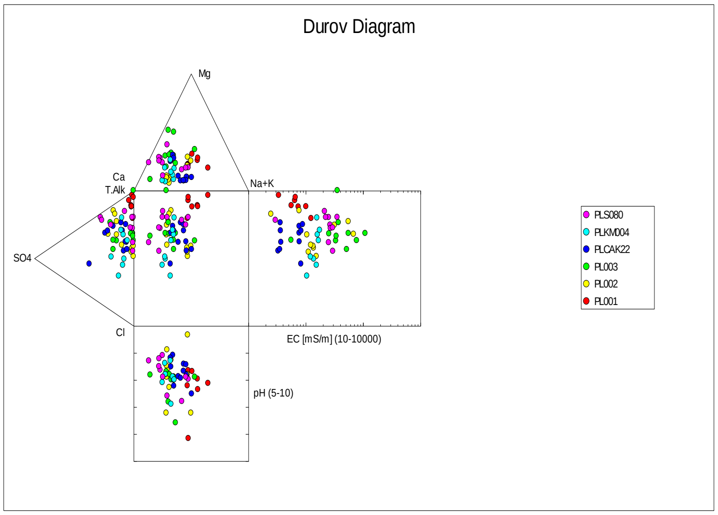

Figure 7. Durov diagram showing the distribution of the chemical constituents in the boreholes tested in Pallisa District during the wet season.

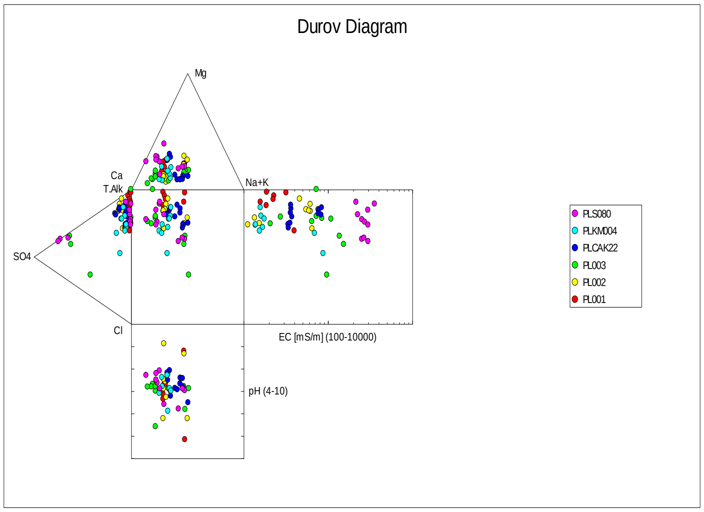

Figure 8. Durov diagram showing the distribution of chemical constituents in the boreholes tested in Pallisa District during the dry season.

Na-HCO_3 - types. Others have Ca-Mg-Na+K and are not dominant in any type. The Piper diagrams also show overlapping hydrochemical characteristics of borehole water for the dry and wet seasons. Groundwater in Pallisa is generally of Ca-[Mg]-HCO_3 - type. This type of water is typical of shallow groundwater systems in crystalline areas. With increasing depth an increase in magnesium is observed.

The Durov diagrams in Figures 7 and 8 show the distribution of the water types in the boreholes for the two seasons during which the tests were carried out. There were two distinct disparities that can be observed in these figures in terms of pH for borehole PL002 and EC for borehole PLS080 in both seasons.

It can be concluded from the diagram that the water samples in fractured aquifer of Pallisa district belong to the bicarbonate group with significant amounts of magnesium and calcium cations. The slight sodium content in borehole PL001 may be attributed to the presence of clay and possible shale intercalations within the regolith layers. This may be due to a slight release of sodium and potassium ions from the argillaceous materials through the ion-exchange process between the formation waters and clay minerals. The dominant ion concentrations of Ca and HCO_3 with respect to the significant amount of Na and Mg are well - indicated in the Durov's Diagrams. This dominance indicates recharging waters in limestone aquifers.

From Figure 10, show all the boreholes have high values of bicarbonate (alkalinity) whose amount is directly dependant on the availability of organic substances and pH of the precipitation water. The ions Ca, Mg, Na, and SO4 show considerable variations. The different patterns may reflect the evolutionary stages of water in the fractured aquifer of Pallisa or mixed waters. The analysis of how major ions compounds are distributed in the fractured aquifer helps to interpret the aquifer mechanics and reveals flow paths and potential recharge areas.

The WISH program analyses the different boreholes and places them in the following categories as in the stiff diagrams (Figure 11): PL001 is of Ca-Na+K-HCO_3, PL002 of Ca-Na+K-HCO_3, PL003 of Mg-Ca-Cl-SO_4-HCO_3, PLCAK22 of Ca-Na+K-HCO_3, PLKM004 of Ca-Mg-Na+K-HCO_3 and PLS080 of Ca-HCO_3 water type. Therefore, calcium bicarbonate and magnesium bicarbonate type of waters indicated above show fresh recharge or that the recharged water has not moved a long distance from the source area. Occurrence of some magnesium bicarbonate type of groundwaters (PL003 in Figure 11) indicates the presence of dolomite mineral in the reservoirs formations.

Graphs of BCO_3^-, electric conductivity and pH along the bore wells, at the time of the hydrochemical logging, are presented in Figures 12 to 13.

Figure 13 shows the graphical distribution of the groundwater quality with depth in Pallisa District. Samples with the lowest EC are mainly those from sandstone aquifers in the northern part of the catchment and a few in the south -west. Boreholes with the highest EC and thus highest concentrations of ions (especially SO_4), are from the limestone -shale -gypsum intercalations in the vicinity of Chelekula. The relatively low EC samples from in and around Kibuku, Tirinyi, Saala, Kadama, Bulangira and Butebo areas can best be explained by the depth of well sampling, the discontinuous nature of layers such as clay, and the topography at each location. Water samples were also

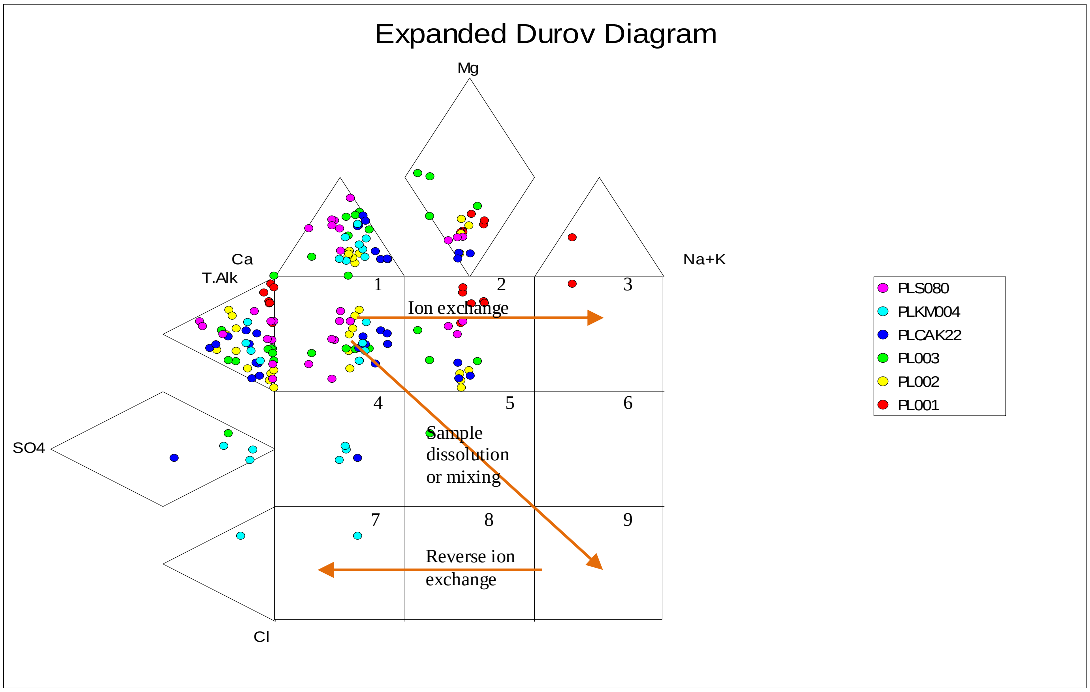

Figure 9. Durov's modified diagram of all the boreholes tested in Pallisa.

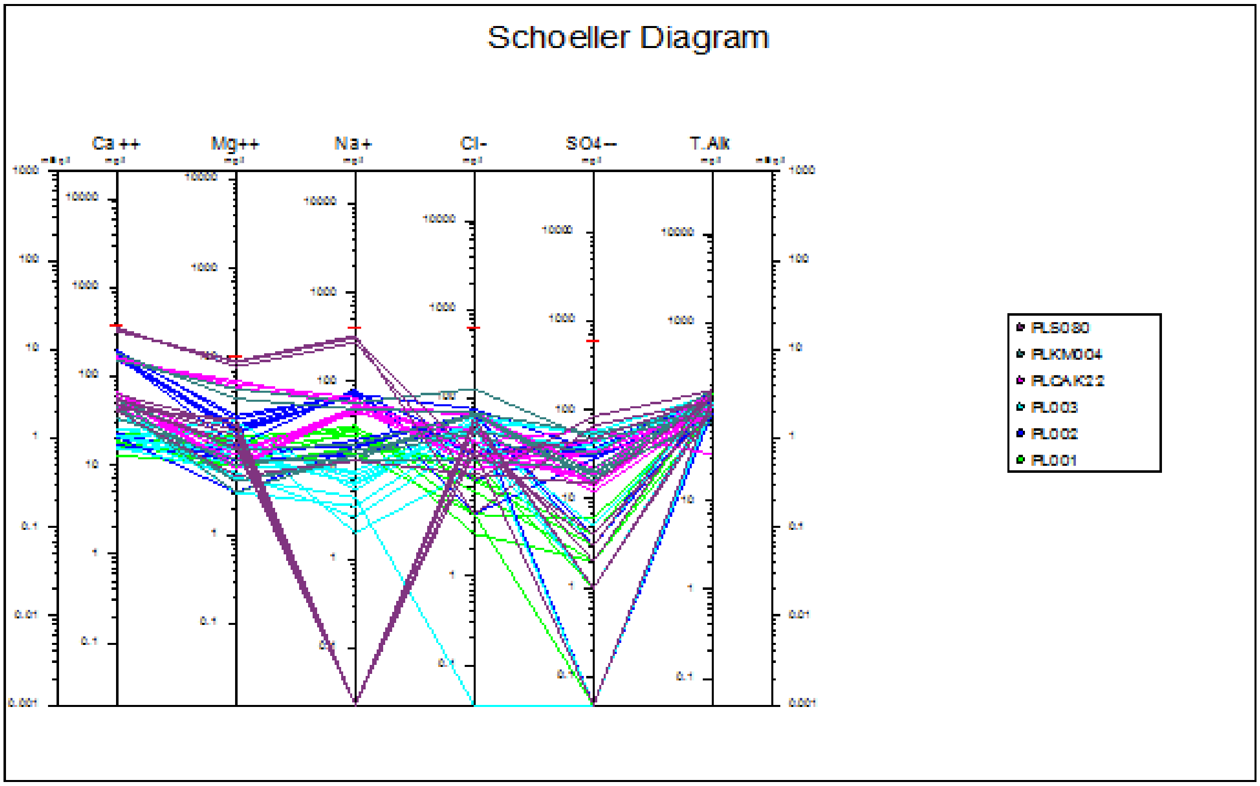

Figure 10. Schoeller diagram showing the different ion concentrations for the drilled boreholes in Pallisa District.

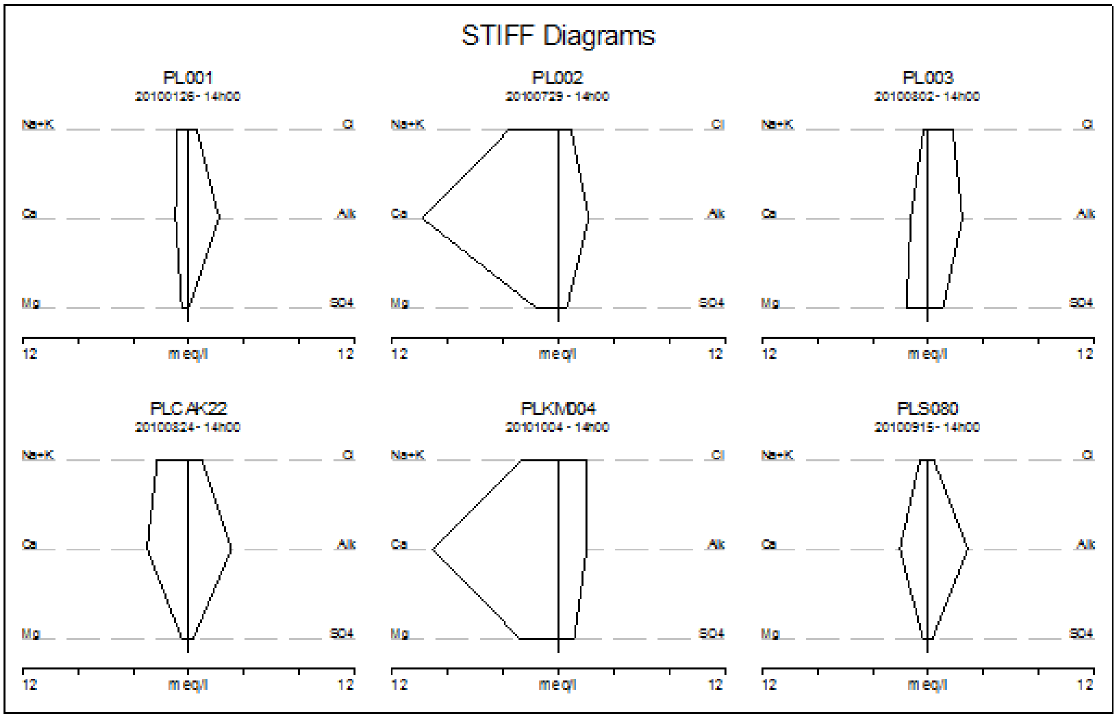

Figure 11. Stiff pattern diagrams of six borehole samples in Pallisa District, eastern Uganda.

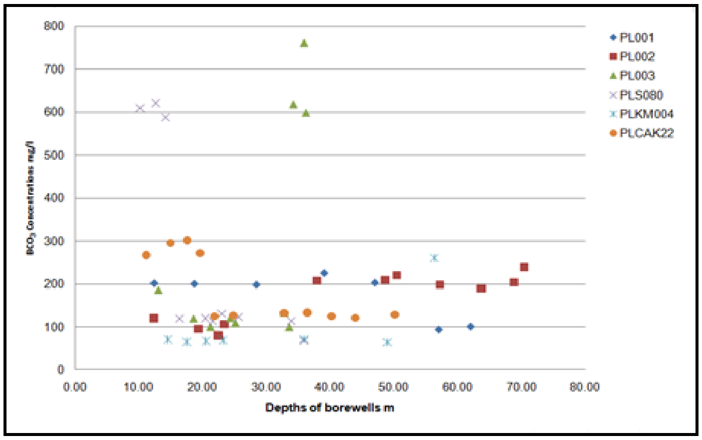

Figure 12. Results from analysis of bicarbonate (BCO$_3^-$) in groundwater samples obtained from the hydrochemical logging in boreholes PL001, PL002, PL003, PLS080, PLKM004 and PLCAK22 Pallisa District.

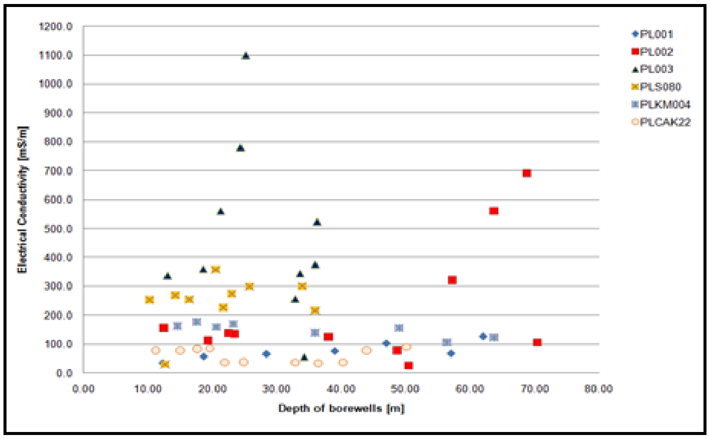

Figure 13. Electrical conductivity values along the boreholes PL001, PL002, PL003, PLS080, PLKM004 and PLCAK22 obtained from the hydrochemical logging in Pallisa District.

collected from the Lake Kyoga reservoirs (Figure 14) and the nearby drilled boreholes to investigate the hydrochemical relationship. The hydrochemical data was graphically tested for charge balance.

The evaluation is based on:

- Comparison of the results from different laboratories and/or methods. The analyses are repeated where a large disparity is noted (generally more than ± 10%).
- Calculation of charge balance errors. Recommended relative errors to lie within ±5% and are considered acceptable (and for surface waters ± 10%).
- General judgments of plausibility based on earlier results and experiences.

Accordingly, the charge balance error for the groundwater samples are reflected in Figure 15 for the different drilled boreholes between percentiles at 50 - 95%:

The charge balance error, giving an indication of the

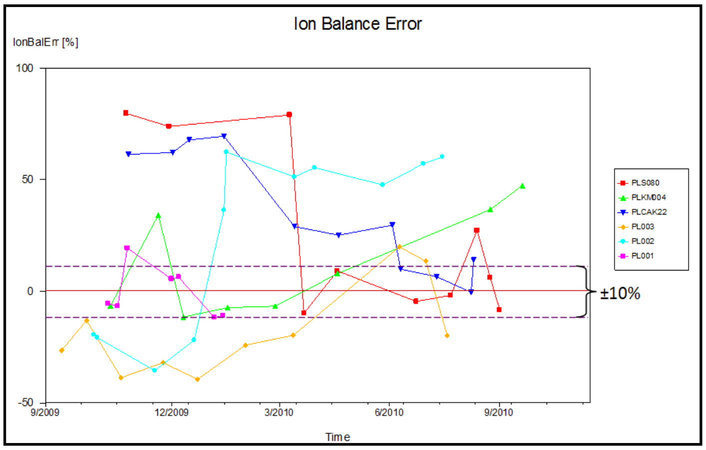

Figure 14. Graph of Ion Balance Error for the drilled boreholes in Pallisa District, eastern Uganda during the wet season.

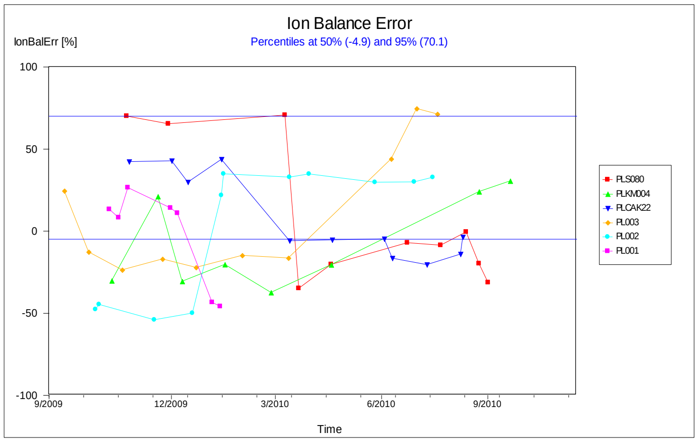

Figure 15. Drill water content at different times of the hydrochemical logging in PL001, PL002, PL003, PLS080, PLKM004 and PLCAK22 boreholes, Pallisa District in the dry season.

quality and uncertainty of the analyses, did exceed ± 5% in almost all the six cases sampled at any one of the drilled boreholes in Figure 14. All the results were considered unconfident, based on general trends. The quality of the analyses seems to be unsatisfactory, and there are obvious reasons to discard some of the results from September 2009 to nearly end of January 2010 for all the boreholes at various depths. No other samples were sent to different laboratories due to lack of organized transport and safety mechanism for the sampled waters.

The main conclusions that could be drawn from the hydrochemical logging include the following:

- The amount of drilled water at the time of the hydrochemical logging was either above or below ± 10% of Ion Balance Error for almost all through the sampled boreholes. Therefore these results in Figure 15 cannot be considered representative of the groundwater chemistry in the boreholes within the water - bearing fractures.
- The electric conductivity and chloride concentration increased with depth up to 30 m. From 35 m and below the concentration decreased in some boreholes. The values of EC and Cl are much higher than in the samples at corresponding depth in the boreholes PL002, PL003 and PLKM004, PL003, where the conductivity and chloride concentrations were 700, 790 mS/m and 125, 380 mg/l, respectively. Looking at the ion balance error graphs, the results imply that these boreholes are most likely intersecting different water-bearing structures.

Spatial Distribution of Groundwater quality parameters

Pallisa District is quite extensive and contains possibly confined and unconfined aquifers, interconnected or disconnected by geological structures like fractures, faults and in some areas suspected presence of dykes. The greater part of the study area is covered by low hydraulic conductivity in the laterite, saprolite and granitic fractured layers with occasional gneissic rock, and hence, the age of groundwater in this area is not expected to increase significantly with depth, resulting in low EC values and ion concentrations. Maps showing the spatial distribution of the major ions, pH and EC are prepared using the WISH program. Contour lines are drawn to reveal spatial distribution of parameters for each case in Figures 16 to 18.

The interpolated spatial distribution map (Figure 16) shows that the highest levels are observed in borehole PL003 at Chelekula where there are exposures of laterite, clay and micaceous clay with sometimes traces of gypsum. The north-eastern and south - eastern parts Pallisa District which are covered by saprolite and basement rocks, show low levels of EC in boreholes PL001, PL002, PLCAK22 and PLKM004 and low pH especially in borehole PLKM004. PH values are high in the western part of the Pallisa where carbonate rocks are common, which results in more alkaline conditions, while the pH is lowest in the northern part of the basin around Obwanai where there are less carbonate rocks. The concentration of nitrate is high in the south western part of Pallisa around Tirinyi trading centre. The north eastern and eastern parts of Pallisa are observed to have low nitrate concentrations (Figure 18(m)). Sulphate concentration is high around Chelekula and Kadama areas which are known for the occurrence of thick clay and thin gypsum like layers. The eastern and western parts of Pallisa have low sulphate concentrations (Figure 18(d)).The concentration of bicarbonate is highest around Agule and Kadama (Figure 18(h)), while it is lowest in the eastern part of the catchment. The concentration of sodium is high in the northern part of Pallisa around Agule. Low sodium

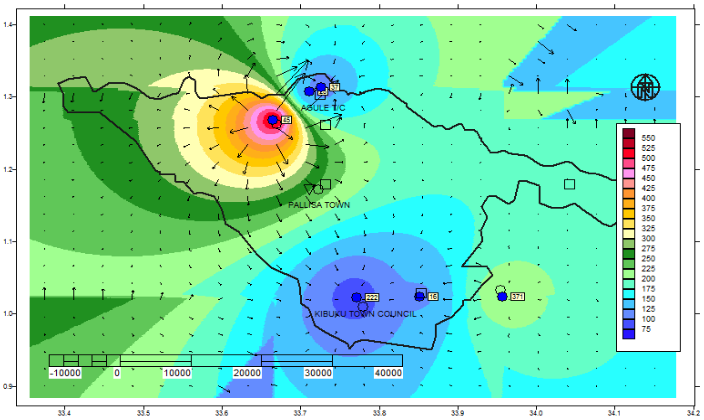

Figure 16. Electrical conductivity (µS/m) distribution in the tested boreholes within Pallisa District, eastern Uganda.

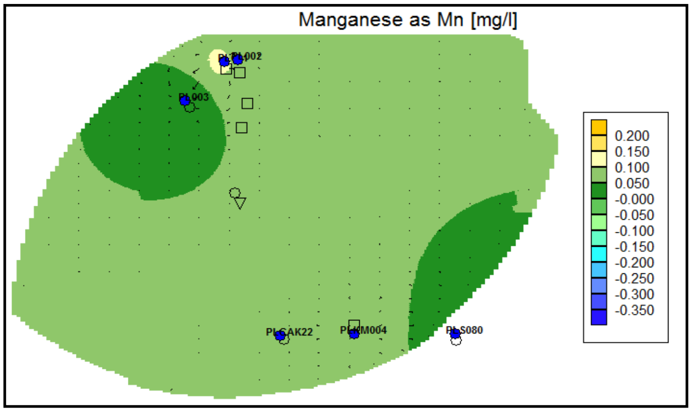

Figure 17. Manganese ion concentration (mg/l) distribution in tested boreholes of Pallisa District, eastern Uganda.

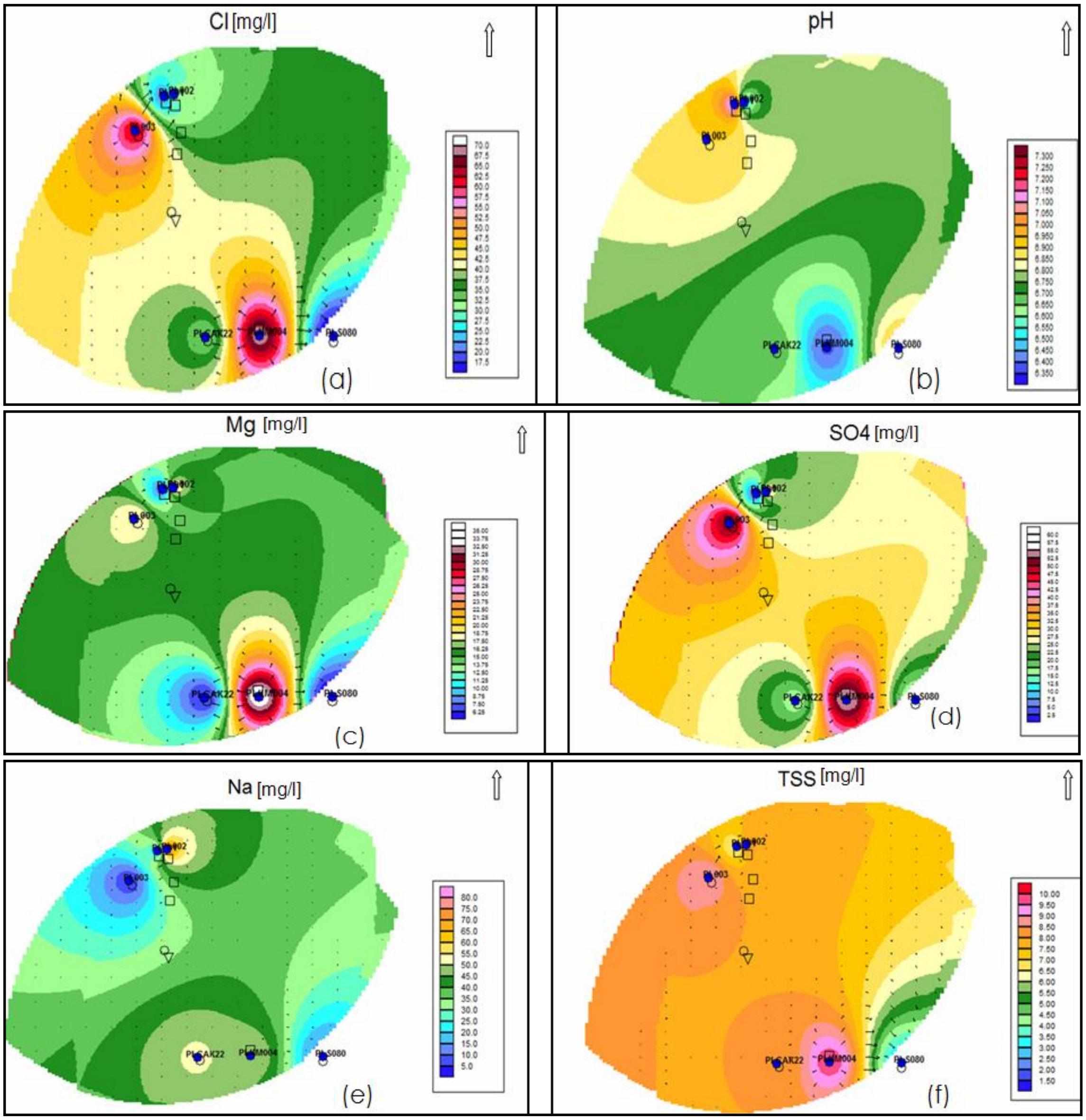

Figure 18. Spatial distribution of chemical constituent concentrations (mg/l) and pH distributions in tested boreholes of Pallisa District, eastern Uganda.

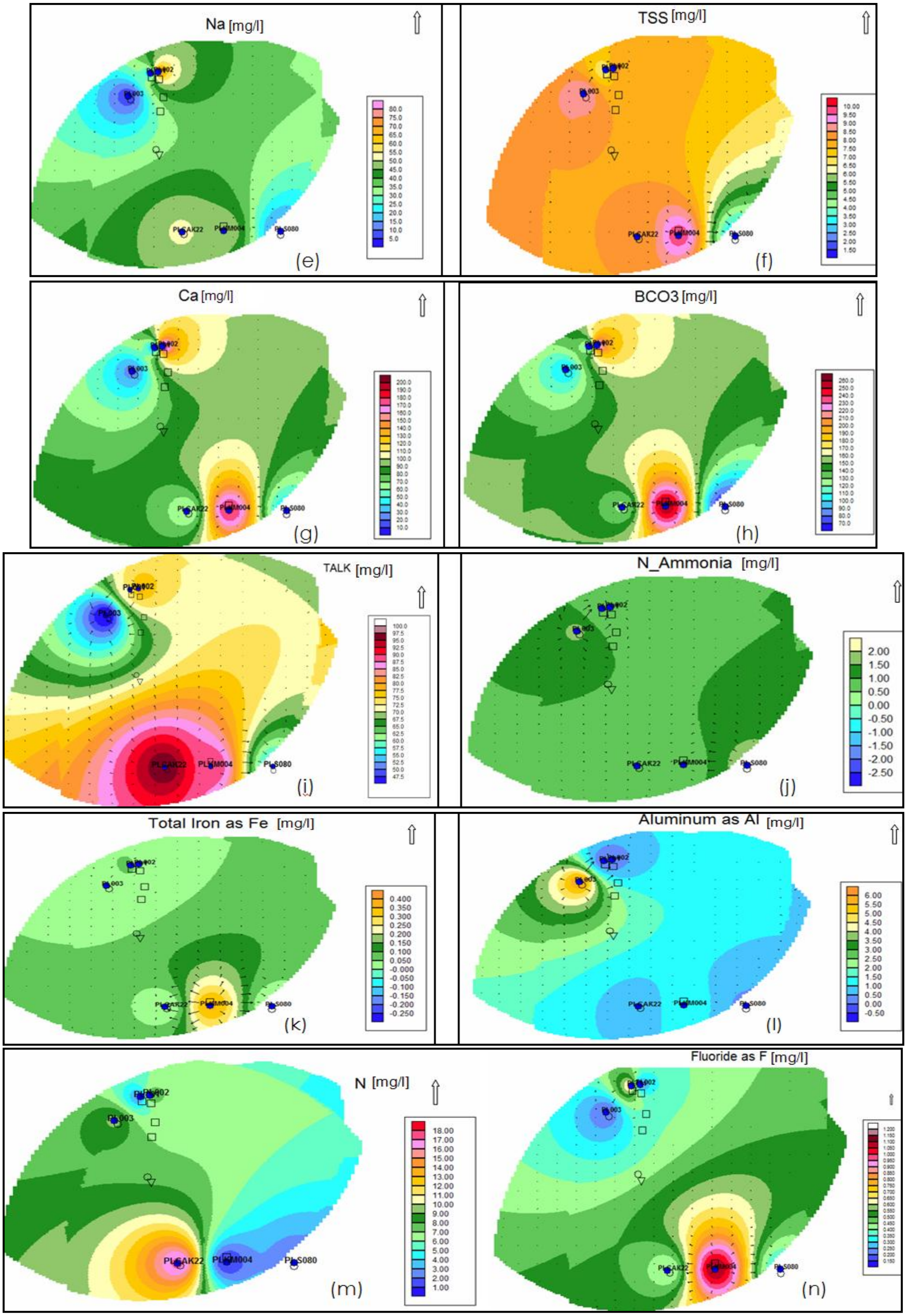

Figure 18. Continue

concentrations are observed in eastern part of Pallisa (Figure 18(e)). Magnesium concentration is high in the southern part east of Tirinyi trading centre (Figure 18(c)). Low magnesium concentrations are noted in the south western part of Pallisa District and in areas north of Chelekula and Agule. High chloride concentration is observed in Chelekula and Kadama areas (Figure 18(a)). Low concentrations are noted in Agule and south eastern parts of the district, while most central and north - eastern parts of Pallisa have an intermediate concentration of chloride.

Concentration of calcium is high in the northern part of Pallisa around Agule and Kadama, while the eastern and western parts concentrations are low (Figure 18(g)). From the hydrochemical observation no typical hint can be deduced to say whether or not rainfall may flush surface deposits and faeces directly into a well or into a badly cased borehole. One point of interest was the pump located at PLCAK22, where all measurements were done in both the wet and dry seasons due to its good accessibility details. The analyses showed that sample of this borehole has a higher anion charge, principally in nitrate as indicator for faecal contamination was highly detected but low in chloride. The bacteriological critical wells of Tirinyi show no seasonal fluctuations.

Note that whereas the spatial distribution of these ions are indicated in form of contours it does not necessarily mean the different chemical concentrations lie within or to exact position along the contours, but varies. Due to a small number of drilled boreholes a representation to that effect was done, but a lot more data collection require further research to be conducted.

Table 3 shows that very few of the parameters exceed the maximum permissible limits of WHO (2004) except turbidity of NTU for Pallisa compared to 5 NTU for WHO, 70 TCU for Pallisa in comparison to 15 TCU for WHO and others like Magnesium (3.0 - 90.0 mg/l), Fluoride (0.10 - 1.10 mg/l), Total iron (0.11 - 0.35 mg/l), Total hardness (38.9 - 501 mg/l) for Pallisa with no specified concentrations for WHO. The recommended limit for sodium concentration in drinking water is 200 mg/l. A higher sodium intake may cause hypertension, congenial heart diseases and kidney problems. Concentrations of sodium are within the prescribed limit of 200 mg/l in 46% of the analysed groundwater samples.

The conductivity values ranges from 150 - 370 mS/m. The large variation in EC is mainly attributed to lithologic composition and anthropogenic activities prevailing in this region. Based on the WISH classification for South African Drinking waters (2005) and the US Laboratory classification (modified after Richards (1954)) (see Figure 19-20) the salinity hazard for water samples in Pallisa District is low (2.2%), medium (21.7%), high (34.8%) and very high (41.3%). Most of the groundwater samples belong to high salinity hazard (C3) as per the salinity hazard classification in the study area. Nineteen samples fall in very high salinity (C4), sixteen samples fall in the high salinity hazard category (C3) while ten of the samples belong to the medium salinity hazard category (C2) and one in low salinity zone (C1).

Figure 16 shows spatial distribution of EC in ground waters. Only small parts in the north and south west of studied area have medium salinity hazard while the samples from south - east have very high salinity and are thus unsuitable for irrigation. Increasing soluble mineral materials along flow paths might be the major causes of Stalinization in south eastern zones of Pallisa District plains.

The SAR values plotted on the WISH salinity diagram as alkalinity hazard shows that alkali or sodium hazard for water samples in Pallisa District is classified as low (100%), medium (0%), high (0%) and very high (0%). As per Richard (1954) classification based on SAR values, 56 samples fall in the excellent category because none of the samples exceeded the value of SAR = 10 (Table 4).

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+} causes deflocculation (dispersion). The sodium hazard is typically expressed as the sodium adsorption ratio (SAR). The general classifications of groundwater samples in the study area for irrigation were based on SAR values as described by Bauder et al. (2007) that generally showed low SAR. Figure 21

The increase in concentration of aluminium is observed highest in borehole PLKM004; high in PL003 borehole and slightly low in borehole PLS080 (Figure 21). A high concentration of aluminium and the increased acidity has over time reduced the fish diversity in and around Lake Kyoga plus the complaint of bad taste of groundwater from the rural poor.

DISCUSSION

The discussion is based on the study done that made it possible to collate available groundwater data and information in Pallisa District. This information has been used to assess the groundwater resources in the Kyoga basin. The boreholes within the interior of Pallisa District and the groundwater sampled from shallower depth are of a much better quality. No microbiological analyses were performed on the samples, but a H_2S test was used in the field and it gave an indication that some forms of bacteria are present. The shallow aquifer has modern age waters, and is rapidly recharged by precipitation that is prone to contamination by activities on the ground surface such as poor sanitation practices, overgrazing and farming practices including application of fertilizers.

The source for this could be probably the extensive use of on-site sanitation systems (mostly the pit latrines)

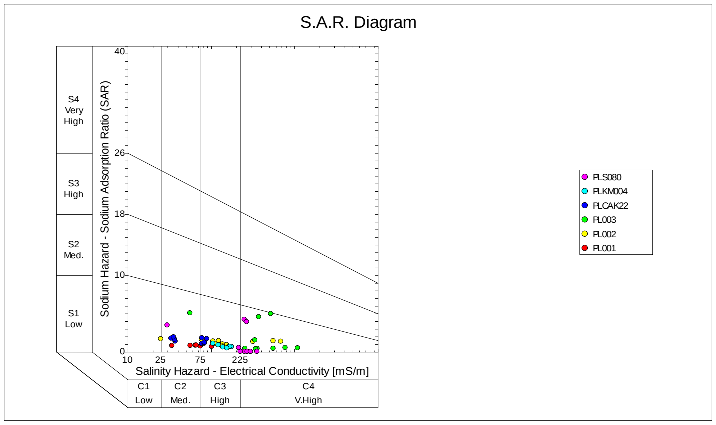

Figure 19. Groundwater classification for the different boreholes sampled during the wet and dry seasons in Pallisa District.

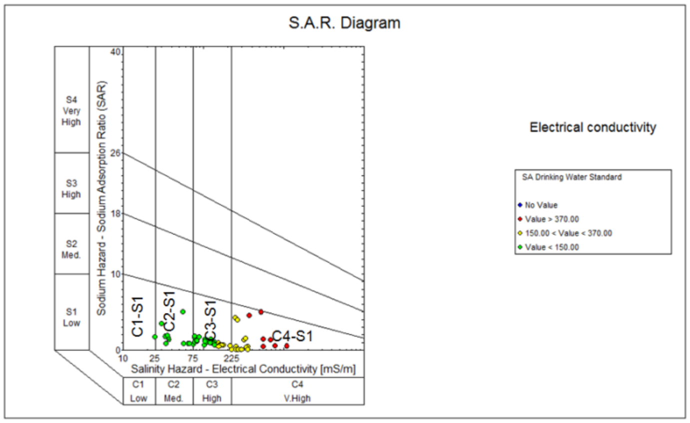

Figure 20. Salinity diagram for classification of irrigation waters (after Lukas, 2003; modified and adapted from Richard, 1954; Wilcox, 1948; 1995).

Table 4. Salinity and Alkali Hazard classes after Lukas (2003) and Richard (1954).

Quality of water	Electrical conductivity (µS/m)	Sodium Adsorption Ratio (equivalent per mole)
Excellent	<25	<10
Good	25 - 75	10 - 18
Doubtful	75 - 225	18 - 26
Unsuitable	>225	>26

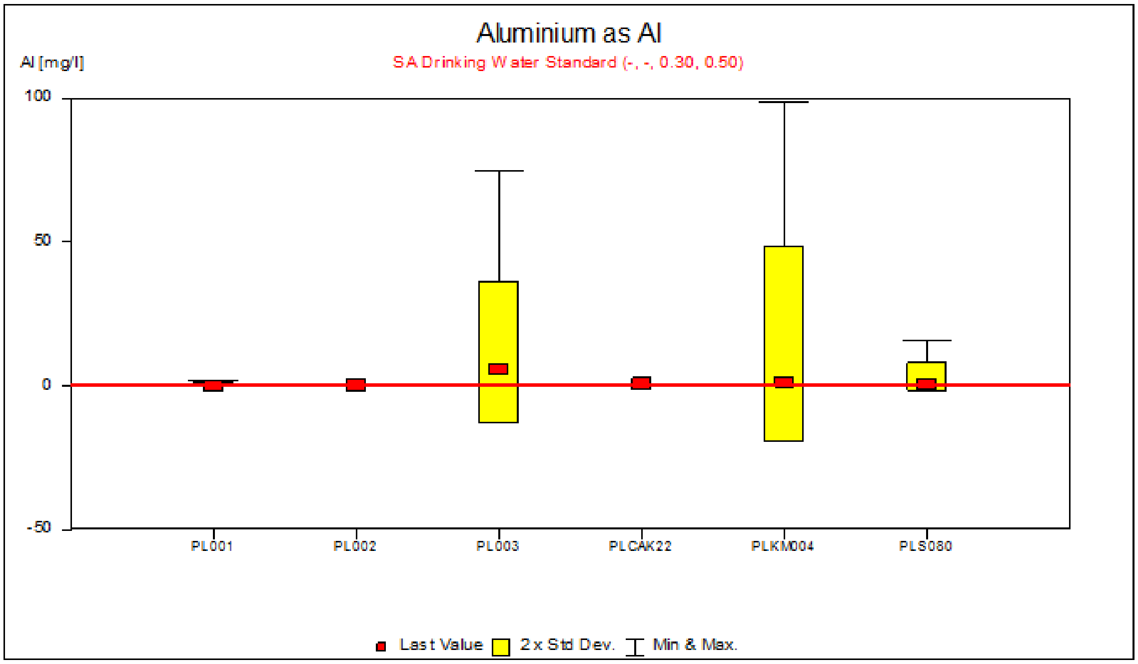

Figure 21. Box and Whiskers plot of aluminium for the drilled boreholes in Pallisa District, eastern Uganda.

in many parts of the rural areas of Pallisa district. The investigation indicates that among major cations, Ca^+ is generally dominant representing on average 64.11% of all the cations. The order of anions abundance is HCO_3^- > Cl^- > SO_4^{2-}.

Based on TDS, 46% of water samples are suitable for drinking purposes. Salinity diagrams reveal that except for the southern parts of study area; most of the groundwater samples are not suitable for irrigation purposes under normal condition. The salinity hazard for water wells is classified as medium, high and some show very high salinity. Alkali hazard also is classified from low hazard to very high. Therefore, salinity is the principal concern in irrigated agriculture in Pallisa area. The fluoride levels reflect the distribution of granite rather than the contamination sources. Geochemical data in Pallisa area indicates that the polluted sources degrade the groundwater quality along the downgrading zone. Stiff diagrams suggest that mixing of the slightly polluted water with fresh groundwater occurs.

CONCLUSIONS

The main results are summarised below:

1. By human health standards, most of the groundwaters are generally acceptable in terms of their inorganic water quality. Aesthetically, however, many groundwaters show excessive levels of aluminium, chloride, iron, manganese, zinc and hardness in a limited number of wells, thus substantiating concerns raised by the consumers nearby some of these wells.
2. The water that predominates in the study area is Ca-HCO_3 type during both wet and dry seasons of the year 2010 - 2011 and based on hydrochemical facies,
3. The boreholes appearing in the “mixed” region have a $Na^+/Ca^{2+}/Mg^{2+}$-Cl^- major ion composition. A major ion composition of this nature is characteristic of stagnant groundwater zones or of groundwater at some distance along a flow path,
4. The boreholes plotting in the freshwater region have a Ca^{2+}/Mg^{2+}-HCO_3^- major ion composition. This is characteristic of freshly recharged groundwater that has equilibrated with CO_2 and soluble carbonate minerals under open system conditions in the soil zone.
5. The water from boreholes located in the area of recharge (boreholes located inland) is fresher than the ones located in the area of discharge (boreholes near Lake Kyoga).
6. Evidence of groundwater quality deterioration is associated with the corrosion of the borehole casings and the raising mains, or the seepage of the wastewater into shallow wells from domestic wastes due to insufficient sanitary practices by humans and livestock. Wastewaters are generally responsible for elevated concentrations of chlorides and nitrates, while corroded pipe work increases the contents of iron, zinc and manganese. However, elevated aluminium, iron, and manganese and to some extent chromium, are also associated with natural weathering of the aquifer matrix.

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