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ISOTOPE HYDROLOGY AND HYDROCHEMISTRY OF WATER RESOURCES IN THE BANANA PLAIN (MUNGO-DIVISION) OF THE CAMEROON VOLCANIC LINE

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The isotope hydrology and hydrochemistry of surface and groundwater of the Banana Plain were studied to trace the origin of groundwaters and evaluate the major ion chemistry and geochemical processes controlling water composition. Water samples from rain, streams, lake, springs, wells and boreholes were collected and analyzed for major ions, stable isotopes, tritium and dissolved silica. ^{18}O *and* ^{2}H *data indicate that groundwater has been recharged by meteoric water without significantly being affected by evaporative processes either during or after the recharge process. Evaluation of the groundwater residence time demonstrated that groundwater in the Banana Plain aquifers should be considered as a renewable water resource. In general the waters are* Ca/HCO_3 *and* $Ca\text{-}Mg\text{-}Na/HCO_3$ *dominated. Weathering of silicate minerals controls the concentration of major ions such as calcium, magnesium, sodium and potassium while* NO_3 *and Cl are of anthropogenic origin. Chemical composition of the groundwater in this area is influenced by rock-water interactions.*

INTRODUCTION

Bananas and plantains are major staple foods as well as important source of revenue for a significant proportion of the Cameroonian population. Despite the economic slowdown of the last years, average annual production of banana in Cameroon is above 300,000 tons in 2008, making Cameroon the first producer of banana in Africa (Fogain et al., 1988). Industrial cultivation of banana in Cameroon is concentrated on the foot slopes of Mount Cameroon on volcanic ash, phonolites and basalts at Buea and Molyko, in the Tiko sedimentary and volcanic basin, and in the Littoral Region (Mungo Division) on the Kupe-Maneguba foot-slopes at Mbanga, Njombe, Penja and Loum)(Sama-Lang,2004). Foot slopes of volcanic mountains are known to possess soils that are amongst the best for agriculture (Driessen and Dudal, 1991). Bananas thrive best on the foot-slopes of these mountains because of freely – drained, well-aerated, deep, fertile loam soils (FAO, 1983).

The development of plantation agriculture and the fertility of the soils in the Banana plain (for traditional and modern agriculture) have created a pole of attraction for laborers from Cameroon and beyond. The towns of Mbanga, Njombe, Penja and Loum are all flourishing because of plantation agriculture. Mbanga town has a population of about 140,000 and covers a surface area of about 544 km^2 (population density of 257 inhabitants/km^2) while Njombe and Penja are populated by about 50,800 inhabitants with a surface area of about 260 km^2 (195 inhabitants/km^2) (Mbanga Municipal Council, 2008). The populations of these towns have witnessed rapid increases between 1987 and 2006 (the population of Njombe and Penja increased from 33,000 to 50,000 while that of Loum went from 67,000 to 110, 000 inhabitants) (GTZ, 2006). Unfortunately this rapid increase in population was not accompanied by the development of basic infrastructure (water supply and sanitation). Less than 10% of the population is connected to the potable water network of CAMWATER (national potable water utility) and less than 5 % have adequate sanitation facilities. This situation is accentuated by the breakdown of borehole pumps and drying up of shallow wells and springs during the dry season. The local population therefore fetch their drinking water from the existing deep wells and springs, streams and boreholes and evacuate their wastes in poorly constructed pit toilets or in local streams. Consequently, this region has recorded a series of cholera epidemics in the last years (222 cases in 2004, 1112 cases in 2005, 255 cases in 2006) (GTZ, 2006).

The discovery of hydrogen and oxygen stable isotope natural variations during the thirties, and of tritium, the radioactive hydrogen isotope, in the late forties, together with the establishment of adequate techniques for the routine measurements of these isotopes, led to the birth of a new field of scientific investigation of natural water systems, which was later called isotope hydrology. Environmental hydrogen and oxygen isotopes appeared almost ideal tracers of water, because they are incorporated in the water molecules and therefore their behavior and variations reflect the origin of, and the hydrological and geochemical processes that affect natural water bodies (Gonfiantini, 1998).

Geochemical processes occurring within the groundwater and reactions with aquifer minerals have a profound effect on water quality. These geochemical processes are responsible for the seasonal and spatial variations in groundwater chemistry (Rajmohan and Elango, 2004). The geochemical properties of groundwater depend on the chemistry of water in the recharge area as well as on different geochemical processes that are taking place in the subsurface. The quality of water along the course of its underground movement is therefore dependent on the chemical and physical properties of surrounding rocks, the quantitative and qualitative properties of through-flowing water bodies, and the products of human activity (Matthess, 1982).

The weathering of primary and secondary minerals is brought about by the release of cations and silica (Jacks, 1973; Rajmohan et al., 2000; Mohan et al., 2000). Weathering of pyroxene, amphiboles and calcic feldspar minerals, which are common in basic rocks and are easily weatherable, is an important process controlling the concentration of these ions in surface and groundwaters (Jacks, 1973; Bartarya, 1993). The previous studies explain the influences of geology, hydrogeology, climate and human activities on surface and groundwater chemical composition. Hence, it has become imperative to evaluate their effects on surface and groundwater quality. Such a detailed study has not been attempted before in the Banana Plain of the Mungo Division. Endeley et al. (2001) carried out a preliminary hydrogeochemical baseline study of water resources around Mt. Cameroon. No systematic hydrogeochemical studies have been carried out on the water resources in the Banana Plain of the Mungo Division.

Accordingly, the purpose of this study is to use stable environmental isotopes (^{2}H and ^{18}O), tritium and major ions to characterize the quality of water resources in the Banana Plain and trace the origin, geochemical evolution, and sources of chemical composition (water-rock interactions) of the waters. Data from this study will not only contribute to improve the understanding of the factors that control water quality in agro-industrial catchments, but it will also provide for the first time, water quality data in the study area, thus contributing to the sustainable management of water resources in this agro-industrial area.

MATERIALS AND METHODS

Location, relief and climate of study area

The Banana Plain of the Mungo Division extends from 4°30’-4°53’N and 9°37’-9°50’E between 45 and 520 m altitude between volcanic cones and lava slopes (40-600 m altitude) (Delvaux, 1988) at 70 km north east of Douala, the economic capital of Cameroon (Figure 1). The climate of the Banana Plain is equatorial type influenced by monsoon during summer (July to September) during the rainy season with maximum rainfall in September and with about 175-200 rainfall days per year. There are two distinct seasons, a dry season from November to June and a rainy season from July to October. Five-year (2000-2004) metrological data from the CARBAP metrological station, Njombe show that annual average rainfall is 3000 mm, annual relative humidity 78%, and annual average temperature 28°C (CARBAP, 2009). Ten-year (1985-1994) metrological data from the National Metrological service at Douala, indicate that in Mbanga, annual average rainfall is 1626 mm, Njombe (3197 mm), Penja (2769 mm) and Loum (3230 mm). Temperatures vary between 19°-32°C with an average of 25°C (National Metrological Service, 2008). These climatic conditions have favored the extension of agro-industrial activities since the colonial periods, and the primary forest has been cut down. Large forests reserves now occur in stream beds and on hill tops.

Geomorphology and Geology

The geology and geomorphology of the Mungo is very complex. In the south, after the coastal mangroves of Dibombari in Mbanga, there is a zone made of plateaus and hills with altitude less than 70 m made up of essentially sedimentary rocks of Cretaceous to Quaternary age (from north to south) composed of sands and sandstones (Martin and Sieffermann, 1966). The zone north of Mbanga is characterized by volcanic rocks of diverse origin which according to Geze (1943) can

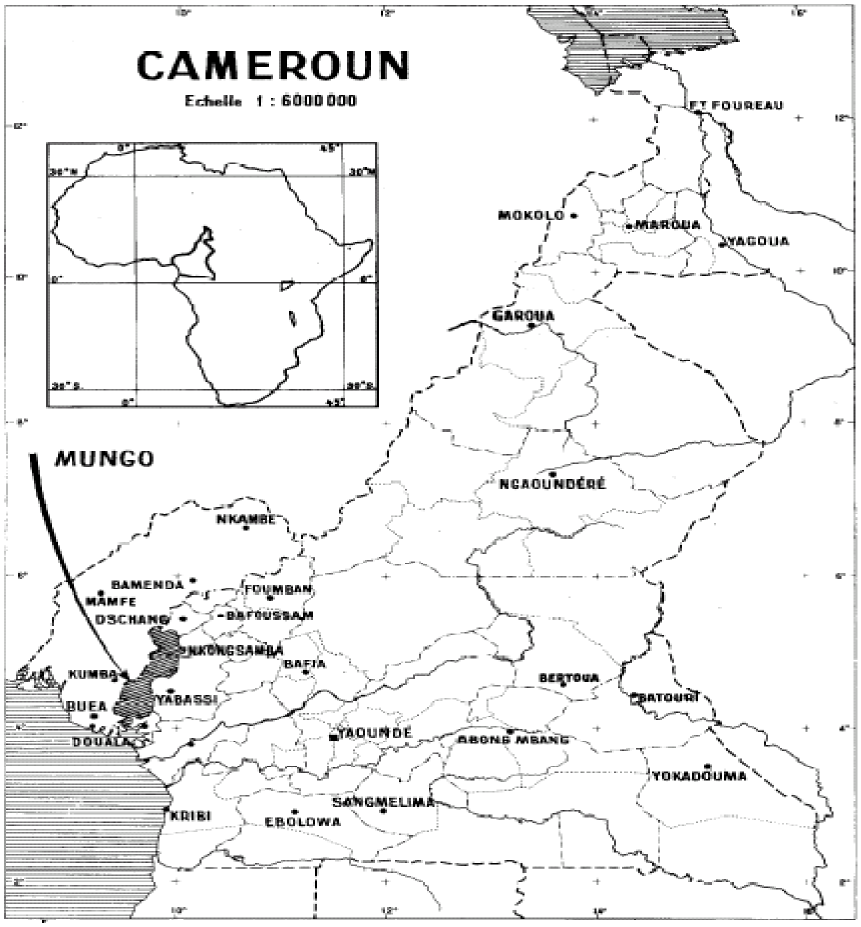

Figure 1. Location of Mungo Division-Cameroon.

be distinguished as follows: an old volcanic series (basalts and andesites), medium age volcanic series (acidic volcanic rocks, trachytes) and young volcanic series (basalts and lapillis). In the south, the soils of the Banana Plain, between Mbanga and Manjo are derived from basalts and lapillis of the young volcanic series. These lava flows rise to heights of 120 m (Mbanga) and 500 m (Mania).

Geologically, the Banana Plain is associated to the Cameroon Volcanic Line (CVL) oriented SSW-NNE is related to the recent (Cretaceous and Quaternary) volcanic activity. Three main eruptive phases can be distinguish: the Lower Black Series (basalt and andesite from Cretaceous to Eocene), the Middle White Series (trachytes, phonolites, rhyolites from Neocene), and the Upper Black Series (exclusively basalt from Quaternary era). The Upper Black Series include e.g. lava flows on the slopes of Mount Cameroon, and ash and pumice deposits from volcanic cones located between Mount Koupe and Mbanga in the Mungo area (around 80 cones on 70 km long and 30 km large) (Dumort, 1968). The Banana Plain is located in this Upper Black Series. The Mungo plain is a graben (Tombel Graben) located between the stratovolcanoes of Mt Cameroon and Mt Manengouba (Nkouathio et al., 2002), part of the N30°E Cameroon Hot Line (Déruelle et al., 2007).

In the Mungo area, a range of well preserved volcanic cones provides gently sloping lava flows (alt 40-600 m) covered by ash and pumice deposits. From these, soils have developed to produce fertile arable lands devoted to intensive banana cropping. These deposits can be up to 20-30 m deep locally (Martin and Sieffermann, 1966).

Hydrogeology

Based on geophysical (resistivity) studies for groundwater prospecting in the region and well logs from boreholes and wells that were constructed in the area (WATER SURVEY, 2007) the stratigraphy of the aquifer is as follows:

0 to 2m: Topsoil rich in organic matter in decomposition

5 to 7m: Lateritic soil

7 to 10m: Sandy clay soil

10 to 50m: Alternation of clays and medium size to fine sands

50 to 85m: Medium to large gain sands

85 to 100m: Large grain sands and gravel

From these studies it was concluded that for sustainable groundwater management, the large grain sand (75 to 90 m) aquifer should be exploited (WATER SURVEY, 2007). Another study at the Djoungo quarry around Lake Mamiwater (Dia-dai) indicates that the piedmont zone of Mt Pele, is covered by a thick, black layer of altered pyroclastic material (cinerites and lapillis) which around the lake is clayey having high resistivities (3000-10000 ohm-m). Most of the wells and boreholes around Djoungo village are tapping their waters from this aquifer. The top of this volcanic cone is composed of scoriaceous (pumice) materials which attain a height of 70 to 80 m and are less altered (GEOBASE, 2008).

Groundwater occurrence in the Banana Plain is controlled mainly by the development of secondary porosity, e.g., fractures, faults and joints. Principally, recharge to the aquifers is by direct percolation of rainfall along the foothills of the volcanic cones. Minor or indirect recharge also occurs mainly in the rainy season when fractures or mega joints intercept ephemeral stream courses. These channels act as conduits that allow water to recharge the aquifer (GEOBASE 2008).

Sampling and analytical methods

Prior to the sampling campaign, sampling sites were selected on 1:50,000 topographic maps of Buea-Douala 2c, 4a (IGNP, 1971, 1972). Sampling was undertaken in April 2009 during which 23 water samples were collected (Figure 2). This study is limited to the functional water sources during the sampling campaign given that most of the springs and shallow wells were dried up (dry season) or the boreholes were out of use due to breakdown. Our sample number was also limited by our quest for uniform sample distribution in the study area. The sources included 8 wells with depths to water ranging from 2.6 to 9.7 m, 6 springs, 4 streams, 1 lake, 2 boreholes, and two rainfall events. Location and altitude of selected sample sites were determined on the field using a Garmin GPS. Water was drawn from the open wells using drawing buckets tied with ropes, while boreholes were pumped for 5–15 min before sampling. The waters were collected into a collector after thorough rinsing with the water to be sampled. Water from the collector was filled into 500 ml capacity plastic bottles after rinsing with the sample and preserved airtight in order to avoid evaporation. Physical parameters like pH, electrical conductivity (EC), water temperature, oxygen reduction potential (ORP) and dissolved oxygen (DO) of sampled water sources were measured in situ using pH/EC/Temperature TOA-DKK meter, TOA-DKK ORP meter and a TOA-DKK DO meter.

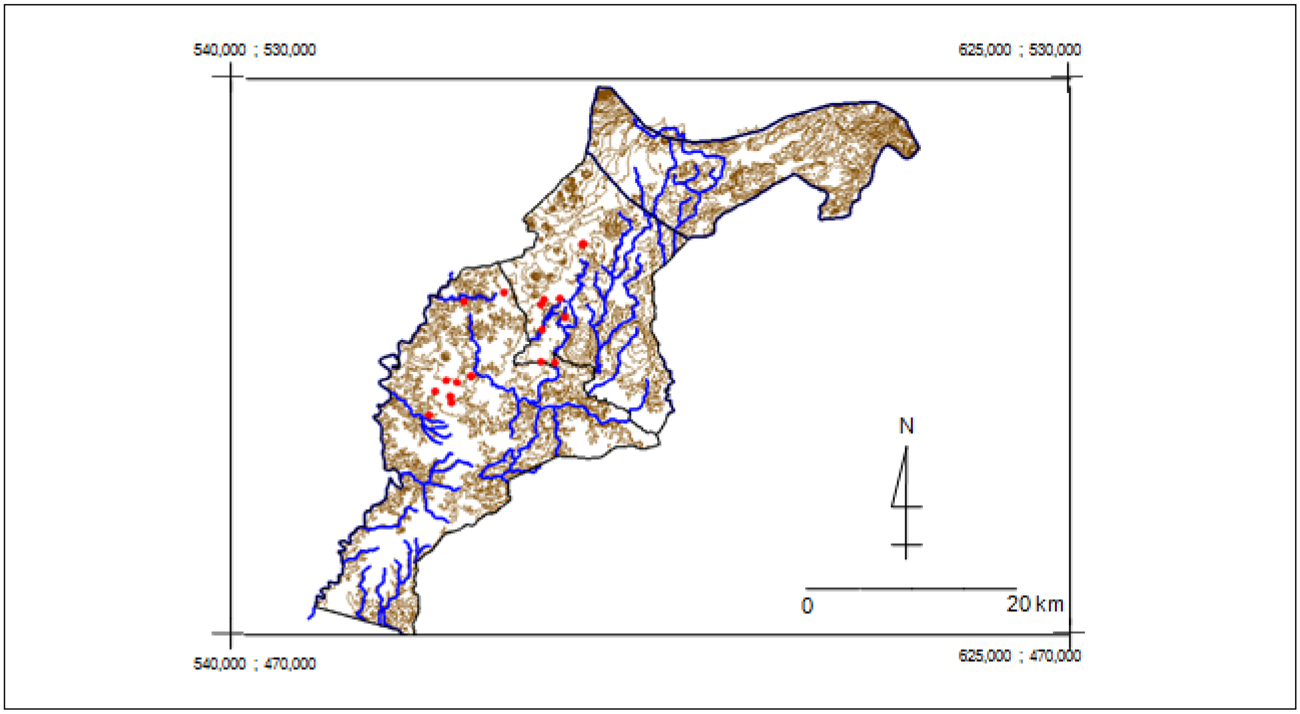

Figure 2. Location of sampling points within the topography and drainage basin of the Banana Plain.

Laboratory analyses were done at the Isotope Hydrology Laboratory of Kumamoto University, Japan and the Kyushu Agriculture Institute, Kumamoto, for silica. Analyses for major chemistry include sodium (Na), potassium (K), calcium (Ca), magnesium (Mg), chloride (Cl), bicarbonate (HCO_3), sulfate (SO_4), nitrate (NO_3) and silica (H_4SiO_4). For stable environmental isotopes, oxygen-18 (^{18}O), and deuterium (D) were analyzed. Na ,K, Ca, Mg, Cl , HCO_3 , SO_4, and NO_3 concentrations were determined by ion chromatography and dissolved silica using ICP Spectrometer .Samples with EC greater than 200µS/cm were subjected to 20 times dilution using distilled water before analyzing for major ions, phosphate and H_4SiO_4. No dilution was done for samples with EC less than 200µS/cm. Both the diluted and undiluted samples were filtered through 0.2 lm filters, prior to major ions, phosphate and dissolved silica determination. The reliability of the chemical measurements was verified by using a charge balance equation (Appelo and Postma, 1999), and it was within a limit of less than ±10% for all samples. Alkalinity measurements were carried out by acid titration from the volume of 0.02 N H_2SO_4 added to the sample to reach the end-point titration, which was marked by a pH of 4.5. Hydrogen and oxygen isotope ratios of all the samples were measured using a mass spectrometer (ThermoQuest Finnigen H/Device for hydrogen and Finnigen mat Delta S for oxygen), after subjecting the samples to a $H_2O–H_2$ equilibration with a hydrophobic platinum catalyst for δD (Coleman et al., 1982) and $H_2O–CO_2$ equilibration for $\delta^{18}O$ (Epstein and Mayeda, 1953). Tritium counting was done using a low background liquid scintillation counter, following electrolytic enrichment of tritium by a factor of about 25 using Fe-Ni electrodes. Stable isotope results were expressed with respect to Vienna standard mean ocean water (VSMOW) in δ units (‰):

$$\delta^{18}O = \{[(^{18}O/^{16}O)_{sample} - (^{18}O/^{16}O)_{standard}]/(^{18}O/^{16}O)_{standard}\} \times 10^3 (‰) \quad (1)$$

$$\delta D = \{[(D/H)_{sample} - (D/H)_{standard}]/(D/H)_{standard}\} \times 10^3 (‰) \quad (2)$$

where oxygen and hydrogen isotope ratios are expressed by $\delta^{18}O$ and δD, respectively. The reproducibility for δD, $\delta^{18}O$ and ^3H were ±1, ±0.1% and ±0.23 TU respectively.

RESULTS AND DISCUSSION

Summary statistic

The physical, chemical, and isotopic data for all the investigated water resources are presented as raw data in Table 1. Statistical summary of physical, hydrochemical and isotopic parameters measured in the water resources of the Banana Plain is presented in Table 2.

Table 2 shows that water resources in the Banana plain are generally fresh (TDS 21.28 - 493.48 mg/l). Fresh waters have total dissolved solids (TDS) < 600 mg/l sufficiently dilute to be potable (Davis and DeWiest, 1966; Freeze and Cherry, 1979). Ca and HCO_3 are the dominant cation and anion, respectively since the median values of both Ca and HCO_3 exceeded 40% of total cations and anions. These are the only ions that exceeded 50% of total cations or anions in all waters. The order of relative abundance of major cations in the waters of the Banana plain is Ca >K > Mg > Na while that of anions is $HCO_3 > NO_3 > SO_4$ and Cl. Water temperatures vary from 27.0°C to 34.3°C with median, mean and standard deviation values of 28.8, 28.8 and 1.5°C, respectively. The small range of values shows the uniformity of water temperatures within the Banana Plain. The pH values are in the range 5.0–7.86 with a mean value of 6.52, median and standard deviation of 6.64 and 0.76 respectively indicating that the waters are generally acidic to slightly alkaline. pH of most samples (74%) is lower than or equal 6. This acidity is probably related to the hydrolysis of silicates and the reaction in the ground with humic acids resulting from the decomposition of organic matter in the infiltration zones. Alkalinity, the essential anion component of water, shows a large range of values (9.8 - 377.7 mg/l). This attests that mineralization is acquired in the unsaturated zone. Conductivity values vary from 23.5 μS/cm to 522 μS/cm with a mean value of 171.6 μS/cm, median and standard deviation of 167.7 μS/cm and 125.8 μS/cm respectively.

Environmental isotopes (^{18}O and ^{2}H)

The δD and $\delta^{18}O$ values of the investigated waters are presented in Tables 1 and 2. The observed values vary from -4.2 to 2.4‰ for $\delta^{18}O$ and from -23.1 to 20.8‰ for $\delta^{2}H$. The interpretation of these data in terms of both origin and recharge mechanisms of groundwaters is generally based upon the comparison of $\delta^{18}O$ and $\delta^{2}H$ in groundwater and rainwater which is the dominant source of recharge for most continental hydrogeological systems. Figure 3 shows a plot of $\delta^{2}H$ versus $\delta^{18}O$ for all the investigated waters. The global meteoric water line (GMWL) is also given as reference. The conventional δD versus $\delta^{18}O$ diagram shows that the springs, shallow and deep groundwaters plot close to the Global Meteoric Water Line of Craig (1961) indicating their meteoric origin. These groundwaters may thus be derived from direct infiltration of local precipitation, in good agreement with the d-excess values close to 10 (Table 2). The isotope contents lie between –3.8 and –2‰ $\delta^{18}O$ and account for 70% of the samples. This reflects the local climatic conditions (cycle evaporation / precipitation close to the coast). The equatorial climate and the closeness of the ocean, induce in the area a "very pure" mechanism of fractional distillation of the vapor masses. This contributes to reducing the annual thermal amplitudes and also reduces variation of the isotopic composition of precipitation. Fontes and Olivry (1976) show that condensations in the area of the Cameroon Mount have the character of a system of fractional distillation which functions in a way very close to the theoretical conditions of Rayleigh, probably exceptional on a worldwide scale. The lake water sample is located below the GMWL with a content of stable isotopes testifying enrichment by evaporation. The deep groundwater sample is also close to the GMWL but more depleted with $\delta^{18}O$ content at –4.2‰. This sample seems to correspond to a recharge carried out under climatic conditions different from the shallow wells

Table 1. Physico-chemical and isotopic data for water resources in the Banana Plain.

Sample	Location	Water source	Elevation (m.a.s.l)	Depth (m)	Temperature (°C)	EC (µs/cm)	Redox (mV)	DO (mg/l)	Ph	Alcalinity meq/l	Ca (mg/l)	Mg (mg/l)	Na (mg/l)	K (mg/l)	Cl (mg/l)	NO3 (mg/l)	SO4 (mg/l)	HCO3 (mg/l)
R/12/08	Mbanga	rain	129		28	27.6			6.52	0.362	5.732	0.120	0.027	0.441	0.384	0.191	0.823	22.077
R13/11/08	Mbanga	rain	129		28	23.5			6.05	0.161	1.644	0.329	0.263	0.764	0.834	6.208	1.226	9.812
Ndom I	Mbanga	bore hole	54.5	59.0m	29	426	-58	28.33	7.14	4.543	46.310	5.664	5.770	2.867	4.037	0.755	6.547	277.189
Ndom II	Mbanga	well	127	9.70m	28.2	66.7	236	19.6	5	0.804	5.702	3.143	2.937	1.701	1.209	1.368	1.413	49.060
Mamiwater	Djoungo	lake	108.1		34.3	73.9	142	41.79	7.02	0.603	5.333	4.169	6.538	2.816	1.385	2.648	0.178	36.795
Mb Q3	Mbanga	well	123	9.45m	27	33.1	247	38.31	5.55	0.523	4.018	2.754	2.415	0.897	2.214	7.085	0.226	31.889
Mb Q9	Mbanga	stream	55.4		28.5	98.1	177	14.56	6.7	0.804	8.108	4.401	6.295	2.005	1.098	1.184	0.813	49.060
Mboale	Njombe	spring	87		28.4	210	186	25.1	6.76	1.608	11.077	7.361	5.469	2.514	4.176	10.188	3.318	98.120
Mb mosque	Mbanga	well	112	9.05m	30.4	133.2	205	31.55	5.88	0.241	9.405	4.859	6.004	2.385	10.660	38.648	0.706	14.718
Boko	Njombe	stream	89		28.4	242	181	34.77	7.25	1.608	14.241	8.590	6.969	2.471	8.371	16.817	5.916	98.120
Zaza	Njombe	spring	103		28.2	195.1	208	35.49	6.83	1.487	16.067	9.637	8.709	3.578	4.910	14.964	4.435	90.761
Mbome	Njombe	stream	155		27.4	211	176	44.41	7.86	1.809	5.054	3.226	2.714	1.074	2.044	3.815	1.587	110.385
Mb Q10	Mbanga	spring	107		29.8	132.6	2.98	15.15	5.15	0.322	9.563	4.842	6.033	2.613	10.651	39.261	0.822	19.624
IMIPHARMA	Mbanga	bore hole	72	105.0m	29.1	522	-11	14.03	6.64	6.191	35.184	6.170	43.007	3.062	2.827	1.356	4.924	377.763
College universel	Njombe	spring	90		29.7	198.2	173	41.71	6.46	1.729	14.489	10.684	10.030	3.961	4.577	12.277	3.993	105.479
Ngouba	Njombe	stream	150		28	167.7	154	36.41	7.8	1.487	13.667	8.416	8.640	3.532	3.345	6.385	3.283	90.761
Chateau	Njombe	spring	89		29.5	190.3	199	33.36	7.03	1.568	15.098	9.741	9.270	3.697	3.940	12.058	3.952	95.667
MbQ4	Mbanga	well	131.2	12.22m	29.4	65.6	195	12.21	5.32	0.523	6.268	2.732	2.712	1.394	1.853	3.488	0.961	31.889
SACAM	Penja	spring	103		27.2	209	199	48.99	6.33	0.402	4.361	1.335	2.088	0.878	2.393	3.869	1.243	24.530
Cacao town II	Penja	well	155	2.60m	28.1	335	152	30.75	6.87	1.849	11.854	4.755	4.206	4.369	3.045	2.199	2.503	112.838
Cacao town I	Penja	well	155	2.66m	28.6	204	178	34.43	6.87	2.774	20.698	7.398	8.686	17.042	6.357	13.786	3.727	169.257
Cacao town I'	Penja	well	121	2.75m	29	148.3	182	46.06	6.57	1.166	11.248	5.529	9.623	4.968	3.323	11.365	4.083	71.137
Mb Q3 sam	Mbanga	well	129	9.30m	28.6	33.6	209	31.07	6.27	2.774	28.049	10.269	13.260	26.461	9.312	20.618	5.335	169.257

Sample	Location	TDS (mg/l)	SiO2 (mg/l)	TH (mg/l CaCO3)	SAR	% Na	δ18O(‰)	δD(‰)	d-excess	Tritium (TU)
R/12/08	Mbanga	30.403	0.608	14.882	0.003	7.400	-0.4	10.6	13.200	
R13/11/08	Mbanga	21.380	0.300	5.459	0.048	34.2	1.2	20.8	11.2	
Ndom I	Mbanga	368.192	19.053	138.997	0.215	14.2	-3.6	-16.4	12.4	1.1
Ndom II	Mbanga	77.618	11.085	27.141	0.246	34.4	-3.3	-10.6	15.8	1.4
Mamiwater	Djoungo	64.302	4.440	30.426	0.52	49.6	2.4	9.5	-9.7	
Mb Q3	Mbanga	59.623	8.125	21.336	0.23	32.8	-3.2	-14.7	10.9	
Mb Q9	Mbanga	92.856	19.892	38.314	0.442	39.9	-3.1	-13.3	11.5	
Mboale	Njombe	167.712	25.489	57.873	0.313	30.2	-3.5	-14.5	13.5	
Mb mosque	Mbanga	97.411	10.026	43.435	0.395	37	-3.0	-15.1	8.9	1
Boko	Njombe	184.745	23.250	70.754	0.361	29.3	-3.0	-13.2	10.8	
Zaza	Njombe	180.786	27.725	79.68	0.426	32.3	-3.1	-15.4	9.4	
Mbome	Njombe	154.594	24.705	25.862	0.231	31.4	-3.3	-14.3	12.1	
Mb Q10	Mbanga	103.356	9.947	43.76	0.397	37.5	-3.1	-14.5	10.3	
IMIPHARMA	Mbanga	493.483	19.190	113.257	1.77	52.7	-4.2	-23.1	10.5	0.8
College universel	Njombe	216.584	25.547	80.027	0.49	35	-3.5	-15.2	12.8	
Ngouba	Njombe	160.392	22.363	68.674	0.45	35.5	-3.2	-15.4	10.2	
Chateau	Njombe	179.981	26.558	77.713	0.458	34.3	-3.3	-15.2	11.2	
MbQ4	Mbanga	61.249	9.952	26.871	0.227	31.3	-2.7	-13.7	7.9	0.8
SACAM	Penja	48.831	8.134	16.377	0.228	34.2	-3.2	-14.6	11	
Cacao town II	Penja	159.319	13.550	49.131	0.261	34.1	-2.1	-6.2	10.6	0.8
Cacao town I	Penja	257.809	10.858	82.077	0.415	47.8	-2.8	-12.4	10	0.7
Cacao town I'	Penja	142.519	21.243	50.789	0.59	46.5	-3.2	-13.5	12.1	1.1
Mb Q3 sam	Mbanga	293.469	10.908	92.792	0.544	50.9	-2.8	-13.5	8.9	0.9

Table 2. Summary statistic of physical, hydrochemical and isotopic parameters measured in the

Parameter	Minimum	Maximum	Median	Average	Standard deviation
Temp (°C)	27	34.3	28.8	28.8	1.5
EC (μS/cm)	23.5	522	167.7	171.6	125.8
Redox potential (mV)	-58	247	181	153.6	88.3
DO (mg/l)	12.2	49	33.4	30.3	11.7
pH	5	7.86	6.64	6.52	0.76
Alkalinity (meq/l)	0.16	6.19	1.49	1.54	1.44
Ca (mg/l)	1.64	46.31	11.08	13.18	10.7
Mg (mg/l)	0.12	10.68	4.86	5.48	3.12
Na (mg/l)	0.44	26.46	2.61	4.15	3.12
K (mg/l)	0.03	43.01	6.03	7.46	8.44
Cl (mg/)	0.38	10.66	3.32	4.01	3.06
NO_3 (mg/l)	0.19	39.26	6.39	10.02	10.8
SO_4 (mg/l)	0.18	6.55	2.5	2.7	1.96
HCO_3 (mg/l)	9.81	377.76	90.76	93.75	88.08
TDS (mg/l)	21.38	493.48	154.59	157.24	113.33
SiO_2 (mg/l)	0.3	27.73	13.55	15.35	8.48
TH (mg/l $CaCO_3$)	5.5	139	49.13	54.59	33.78
SAR (meq/l)	0.003	1.77	0.4	0.4	0.33
%Na	7.4	52.7	34.3	35.33	10.44
$\delta^{18}0$ (‰)	-4.2	2.4	-3.1	-2.6	1.56
$\delta^{2}H$ (‰)	-23.1	20.8	-14.3	-10.6	10.18
d-excess (‰)	-9.7	15.8	10.9	10.21	4.88
Tritium (TU)	0.6	1.4	0.9	0.95	0.25

and springs. The flat topography of the study area does not make it possible to consider it to be the result of the altitude effect. The major part of water samples seem to derive from the infiltration of local precipitation, with significant contribution of another type of water in the deeper part of the aquifer. There exists an obvious relation between the isotopic composition of water and depths (Figure 4). Two points (borehole samples) show isotopic characteristics significantly depleted compared to the other points, in different conditions from the whole group.

These conditions are certainly to be found in natural hydraulic relations or, artificially caused by pumping with lower levels containing older water and recharged under previous conditions different from those prevailing at present. These assumptions will have to be checked by further analyses, including analyses of tritium distribution and the carbon-14 activity, in particular on the water free of tritium.

Groundwater residence time

Tritium (^{3}H) is a commonly used tracer in hydrology for determining relative ages of recent groundwaters. In general, groundwaters with ^{3}H content higher than 2TU represent waters that were

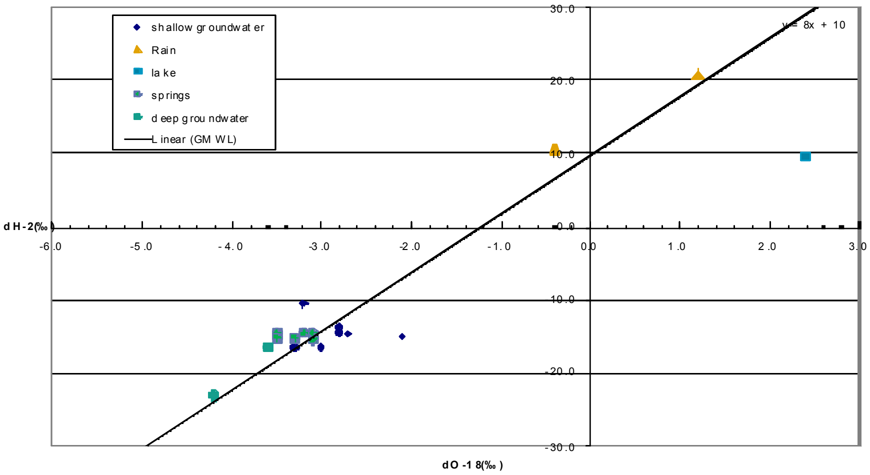

Figure 3. Plot ofδ^2H versusδ^{18}O for waters in the Banana Plain.

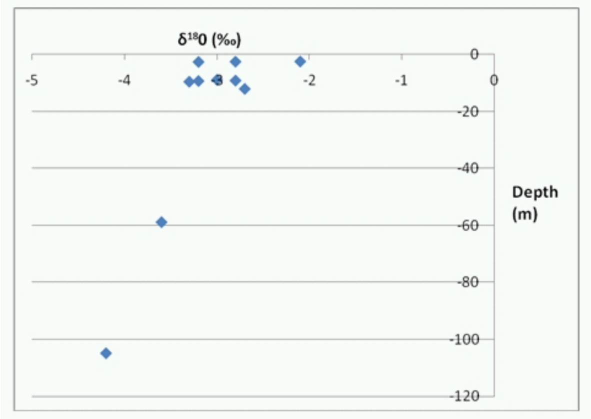

Figure 4. Relationship betweend^{18}O and depth.

recharged during the last 40 years. The tritium concentration measured on 10 samples (wells and boreholes) varies between 0.6 and 1.4 TU with an average of 0.95TU. These low concentrations correspond to the contents expected in tropical areas indicating that generally groundwaters of the Banana Plain have very short residence time. The distribution of tritium concentrations with depth (Figure 5) show an unequivocal relation. Until 20 m depth, tritium concentrations vary between 0.7 and 1.7TU. Deeper waters have lower tritium concentrations (0.6TU at 152 m depth) thereby confirming the ascent of local deeper and older water under the influence of pumping as said above.

Hydrochemistry

On a Piper's diagram (Figure 6) (Piper, 1944) with defined chemical zones, it is evident that about 80% of the waters have a Ca/HCO3 composition and 20% are of the Ca-Mg-Na/HCO3 type.

In volcanic terrains (such as the CVL) the solute composition of waters is principally controlled by the silicate hydrolysis of the rock minerals and the (incongruent) reactions can be generalized as follows (Tanyileke et al., 1996):

$$\text{Rocks} + H_2CO_3 \text{ ? cations} + H_4SiO_4 + HCO_3^- + \text{solids} \quad (1)$$

The major ion chemistry of the aquatic system was mainly controlled by weathering of rock forming minerals with minor contribution from atmospheric and anthropogenic sources (Berner and Berner, 1987; Singh and Hasnain, 2002). The dissolution of CO_2 and oxidation of sulfides are the two major reactions providing the bulk of the protons used to chemically weather carbonates,

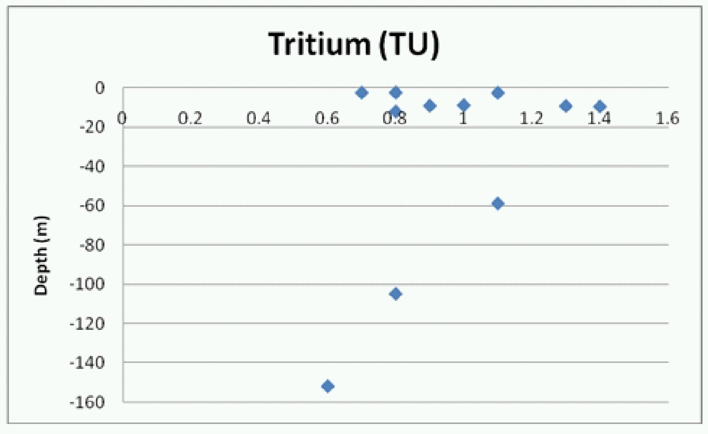

Figure 5. Relationship between ^{3}H and depth.

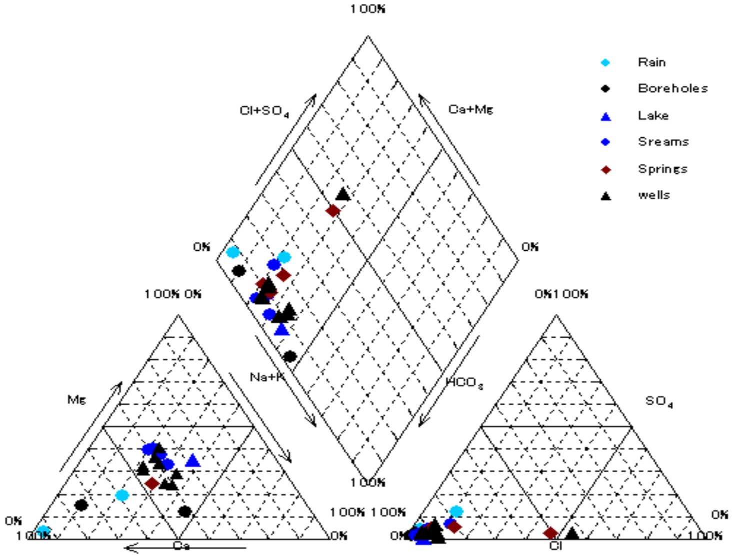

Figure 6. Piper diagram showing water types in study area.

silicates and aluminosilicate minerals. The dissolution of carbonate rocks proceeds more rapidly than silicate breakdown and was the likely mechanism of solute acquisition in aquatic systems. However, the solution products of silicate weathering are difficult to quantify because the degradation of silicates incongruently generates a variety of solid phases (mostly clays) along with dissolved species. The relative proportions of the various ions in solution depend on their relative abundance in the host rock as well as on their solubility. The abundance of various ions can be modeled in terms of weathering of various rock forming minerals (Singh and Hasnain, 2002; Pandey et al., 1999). The proportion of HCO_3 and SO_4 in the water reflects the relative dominance of the two major sources of protons, i.e., carbonation and sulfide oxidation, during chemical weathering. The ternary anion diagram relating HCO_3, SO_4 and Cl shows that most of the samples of groundwater and surface water contain a high amount of HCO_3 and plotted points cluster towards the alkalinity apex with very minimal secondary trends towards Cl and SO_4 (Figure 6). The relative high ratio of HCO3/(HCO3 + SO4) in most of the surface and subsurface waters (~0.9) (Table 3) signified that carbonic acid weathering was the major proton producer in these waters (Pandey et al., 1999). The bicarbonates are derived mainly from the soil zone CO_2 and weathering of parent minerals.

Since most of the chemical parameters were not normally distributed, correlations between major ions were carried out using Spearman's correlation analysis. The results are shown in Table 4.

High positive correlations were found among the cations (r = 0.84 was found between Ca and Mg, Na and K, r = 0.87 between Mg and Na, r = 0.8 between Ca and K, r = 0.81 between Mg and K). Among the anions, high positive correlations exist between SO_4 and HCO_3 (r = 0.78), r = 0.82 between NO_3 and Cl. Since the correlation coefficient between the cation and anion pairs is positively high, it can also be deduced that most of the water samples (minus the rain samples) originate from a common source. Very high positive correlations exist between total dissolved solids (TDS) and Ca , Mg and HCO_3, respectively r = 0.93, 0.87 and 0.88. The correlation between TDS and SO_4 (r = 0.84) is also high and significant (r = 0.3) at a 1% level. On the other hand, correlations between other ions and TDS and among themselves though positive are significantly lower suggesting that TDS is derived mainly from Ca, Mg and HCO_3. Chemical composition of water indicates that there is a very weak mineralization in the whole Banana Plain. The most common water type is the calcic and sodic bicarbonate type. The most abundant cation changes according to the sectors of aquifer, which reflects the variety of the mineralogical groups subjected to alteration (Ketchemen et al., 2007). The relative weakness of the ions of meteoric origin such as chloride suggests that the evaporative process does not affect mineralization. These results show that infiltration is relatively fast on the whole area.

Table 3. Ratios of some chemical constituents in surface and groundwaters in the study area.

	meq ratio		
Name of sample	Mg+Ca/HCO_3	HCO_3/HCO_3+SO_4	HCO_3/? Anions
Ndom I borehole	0.6	1	1
Ndom II well	0.7	1	0.9
Mamiwater lake	1	1	0.9
Mbanga Q3 well	0.8	1	0.7
Mbanga Q9 stream	1	1	0.9
Mboale spring NJ	0.7	1	0.8
Mbanga mosque well	4	0.9	0.2
Boko stream NJ	0.9	0.9	0.7
Zaza spring NJ	1.1	0.9	0.8
Mbome stream NJ	0.3	1	0.9
Mbanga Q10 spring	2.7	1	0.3
IMIPHARMA borehole	0.4	1	1
College universel sp	0.9	1	0.8
Ngouba stream NJ	0.9	1	0.8
Chateau spring NJ	1	1	0.8
Mbanga Q4 well	1	1	0.8
SACAM spring	0.8	0.9	0.7
Cacao town II well PJ	0.5	1	0.9
Cacao town I well PJ	0.6	1	0.9
Cacao town I' well PJ	0.9	0.9	0.8
Mbanga Q3 well sam	0.8	1	0.8

Table 4. Spearman rank correlation coefficients of major ions concentration in the water resources of the Banana Plain.

	Ca	Mg	Na	K	HCO_3	SO_4	Cl	NO_3	pH	TDI
Mg	0.84									
Na	0.78	0.87								
K	0.8	0.81	0.84							
HCO_3	0.76	0.64	0.57	0.66						
SO_4	0.81	0.71	0.6	0.61	0.78					
Cl	0.64	0.76	0.56	0.6	0.32^*	0.46^*				
NO_3	0.24	0.56	0.42^*	0.39^*	-0.61	0.18	0.82			
pH	0.38^*	0.4	0.28	0.32	0.58	0.43^*	0.1	-0.11		
TDS	0.93	0.87	0.77	0.76	0.88	0.84	0.66	0.28	0.48^*	
SiO_2	0.56	0.73	0.58	0.49	0.59	0.64	0.38^*	0.22	0.54	0.66

Water - rock interactions

As it is generally observed in many continental basins chiefly recharged by meteoric water, the chemical composition of waters in the Banana Plain of the Mungo Division can be explained by water-rock interaction processes (Njitchoua and Ngonou Ngatcha, 1997). Based on thermodynamic calculations (Karpov and Kaz'min, 1972; Morel and Morgan, 1972; Plummer et al., 1976), this method generally gives some information about the mineral assemblage involved in the interaction processes. This procedure has been applied in this study to assess the geochemical processes that may have occurred within the Banana Plain. Special attention will be given to some selected chemical parameters such as partial pressure of carbon dioxide (P_{CO2}) and saturation index (SI) of waters with respect to selected minerals. These parameters were calculated using the computer geochemical program PHREEQC for Windows version 2.1 (Parkhurst and Appelo, 1999). Thermodynamic data used for these calculations are from Fritz (1976).

By using the saturation index (SI) and activity diagrams, it is possible to predict the reactive mineralogy of the subsurface from groundwater data without collecting the samples of the solid phase and analyzing the mineralogy (Deutsch, 1997). The saturation index (SI) of a given mineral is defined in Equation (2) (Garrels and Mackenzie, 1967).

$$SI = \log_{10} (IAP/K_{sp}) \qquad (2)$$

where IAP is the ion activity product of the solution and K_{sp} is the solubility product at a given temperature (the thermodynamic equilibrium constant adjusted to the temperature of a given sample).

An index (SI), less than zero, indicates that the groundwater is undersaturated with respect to that particular mineral. Such a value could reflect the character of water from a formation with insufficient amount of the mineral for solution or short residence time. An index (SI), greater than zero, specifies that the groundwater is being supersaturated with respect to the particular mineral phase and therefore is incapable of dissolving more of the mineral. Such an index value reflects groundwater discharging from an aquifer containing ample amount of the mineral with sufficient residence time to reach equilibrium. Nonetheless, super saturation can also be produced by other factors that include incongruent dissolution, common ion effect, evaporation, rapid increase in temperature and CO_2 exsolution (Langmuir, 1997). The computed values of SI of the studied waters with respect to partial pressure of carbon dioxide (P_{CO2}) and selected carbonate, gypsum and siliceous minerals are summarized in Table 5.

Table 5. Saturation indices and partial pressure of CO2 of surface and groundwaters in the study area.

Sample	Location	Source	Satuaration index=log(IAP/K_{sp})											log (P_{CO2})
			Anhydrite	Aragonite	Calcite	Dolomite	Gypsum	Chalcedony	Chrysotile	Quartz	Sepiolite	Amorphous silica	Talc	(atm)
Boko	Njombe	stream	-3.55	-0.97	-0.83	-1.48	-3.35	0.08	-5.58	0.46	-4	-0.74	-1.66	-2.13
Cacao town II	Penja	well	-3.97	-1.39	-1.25	-2.52	-3.76	-0.12	-9.42	0.28	-6.77	-0.95	-5.93	-1.71
Chateau	Njombe	spring	-3.71	-1.21	-1.07	-1.94	-3.5	0.16	-6.91	0.56	-4.65	-0.67	-2.84	-1.94
College universel	Njombe	spring	-3.72	-1.74	-1.6	-2.94	-3.52	0.13	-10.11	0.52	-6.88	-0.69	-6.09	-1.32
IMIPHARMI	Mbanga	borehole	-3.35	-0.69	-0.54	-1.44	-3.15	0	-10.08	0.39	-7.1	-0.82	-6.31	-0.95
Mbanga mosque	Mbanga	well	-4.62	-3.43	-3.29	-6.47	-4.41	-0.27	-15.92	0.13	-11.4	-1.09	-12.71	-1.51
Mboale	Njombe	spring	-3.89	-1.64	-1.5	-2.79	-3.68	0.14	-9.19	0.53	-6.23	-0.69	-5.17	-1.59
Mbome	Njombe	stream	-4.52	-0.76	-0.62	-1.06	-4.32	0.12	-3.36	0.52	-2.36	0.71	0.63	-2.7
Q10	Mbanga	spring	-4.55	-3.95	-3.81	-7.55	-4.34	-0.26	-19.98	0.14	-14.05	-1.09	-16.77	-0.74
Mbanga Q3 samuel	Mbanga	well	-3.37	-1.48	-1.34	-2.73	-3.17	-0.23	-12.18	0.16	-8.85	-1.06	-8.9	-0.94
Mbanga Q3	Mbanga	well	-5.38	-3.59	-3.45	-6.61	-5.2	-0.42	-17.54	-0.05	-12.94	-1.23	-14.56	-0.88
Mbanga Q4	Mbanga	well	-4.57	-3.69	-3.55	-7.06	-4.37	-0.28	-19.36	0.11	-13.75	-1.11	-16.16	-0.68
Mbanga Q9	Mbanga	stream	-4.58	-2.07	-1.92	-3.74	-4.37	0.05	-10.17	0.45	-6.98	-0.78	-6.35	-1.9
Mamiwater lake	Djoungou	lake	-5.39	-2.03	-1.89	-3.49	-5.19	-0.62	-9.46	-0.23	-7.67	-1.45	-6.96	-2.33
Ndom I	Mbanga	borehole	-3.09	-0.19	-0.05	-0.62	-2.89	0.01	-7.24	0.4	-5.17	-0.82	-3.47	-1.59
Ngouba	Njombe	stream	-3.8	-0.48	-0.34	-0.49	-3.6	0.06	-2.41	0.45	-1.88	-0.76	1.48	-2.73
Ndom II	Mbanga	well	-4.46	-3.88	-3.74	-7.34	-4.26	-0.2	-21.03	0.19	-14.71	-1.03	-17.68	-0.18
SACAM	Penja	spring	-4.59	-2.94	-2.8	-5.73	-4.39	-0.37	-14.41	0.02	-10.59	-1.19	-11.39	-1.81
Zaza	Njombe	spring	-3.63	-1.4	-1.26	-2.35	-3.43	0.18	-8.04	0.57	-5.4	-0.65	-3.94	-1.76
Cacao town I'	Penja	well	-3.63	-1	-0.86	-1.77	-3.42	-0.23	-8.98	0.16	-6.71	-1.06	-5.69	-1.53
Cacao town I	Penja	well	-3.77	-1.89	-1.75	-3.42	-3.57	0.05	-10.43	0.44	-7.22	-0.77	-6.57	-1.6

The computed values of P_{CO2} vary between $10^{-2.73}$ and $10^{-1.32}$ atm, being significantly higher than that of the atmosphere ($10^{-3.5}$ atm). Such elevated values suggest that the groundwater system is open to the soil CO_2. The origin of CO_2 can be primarily attributed to the root respiration and/or decomposition of organic matter within the soil horizon. This also indicates a low temperature water—rock interaction for the groundwater system, which is supported by high HCO3/Σanions ratios (0.2–1.0) (Table 3), as suggested by Kortatsi et al. (2008). Calcium to Mg ratios ranging from 0.8 to 4.9 and Mg + Ca/HCO3 ratio of most of the waters are less than 1 (Table 3), suggest that the possibility of calcite and dolomite contributing to the presence of Ca and Mg is totally eliminated. The soil zone in the subsurface contains elevated CO_2 pressure (produced by decay of organic matter and root respiration), which in turn combines with rainwater to form bicarbonate (Drever, 1988).

$$CO_2 + H_2O = H_2CO_3$$

$$H_2CO_3 = H^+ + HCO_3^- \tag{3}$$

Bicarbonate may also be derived from the dissolution of carbonates and/or silicate minerals (Equation 4) by carbonic acid:

$$CaCO_3 + H_2CO_3 = Ca + 2HCO3 \tag{4}$$

Limestone

$CaMg\ (CO_3)_2 + 2H_2CO_3 + Ca + Mg + 4HCO3$ (5)

Dolomite

CO_2 induces interactions of water with silicate rocks (Mazor, 2004):

$2KAlSi_3O_8 + 6H_2O + CO_2 \rightarrow Al_2Si_2O_5(OH)_4 + 4SiO(OH)_2 + K_2CO_3$
(6)

K-feldspar clay soluble soluble

$(Ca,Fe,Mg)\ (SiO_3) + 2H_2O + 2\ CO_2 \rightarrow (Ca,Fe,Mg)\ (HCO_3)_2 + SiO(OH)_2$ (7)

Pyroxene soluble soluble

All the above weathering reactions are governed by a CO_2 gas phase and by the relatively high partial pressure of soil CO_2 (Njitchoua and Ngounou-Ngatcha, 1997). Thus, water containing HCO_3 indicates CO_2 induced interactions with rocks, and the balancing cations may indicate the type of rocks passed: Ca and Mg together come from interaction with dolomite; K and even more often, Na in bicarbonate come from silicate rocks, rich in K or Na feldspars (Mazor, 2004).

Mazor (2004) indicates that bicarbonate-dominated water with TDS of up to about 600 mg/l has not passed evaporates, and the nature of rocks interacted with can be deduced from the cations: Ca dominated water has passed limestone; Ca + Mg dominated HCO_3 water is produced by contact with dolomite, Na dominated and K rich HCO_3 waters have interacted with feldspar, plagioclase and pyroxene, contained in igneous and volcanic rocks. In this study area, major cation chemistry is dominated by Ca and K and this can be attributed to the reactions of Equations (6) and (7). Endeley et al. (2001) revealed that waters around Mt. Cameroon have a major cation chemistry dominated by the presence of Na (and K). They attributed this to the dominance of alkali feldspars as the major source of mineralization of the waters around this area.

Plots of the obtained SI against TDS for important carbonate minerals (calcite and dolomite) gypsum and siliceous minerals (chalcedony, quartz and amorphous silica) are illustrated in Figure 7. 100 % of the analyzed surface and groundwater samples are undersaturated with the carbonate minerals (anhydrite, aragonite, calcite and dolomite) and gypsum. This represents water that has come from an environment where carbonate and sulfate minerals are impoverished or where Ca and Mg exist in other forms. Waters of this type will dissolve carbonate minerals and/or sulfate minerals if the water comes in contact with source rocks. For the silicate minerals 100% of the analyzed water samples are undersaturated with chrysotile, sepiolite, amorphous silica and talc, 48% are both supersaturated and undersaturated with chalcedony with one sample (IMIPHARMI) is saturated or at equilibrium with chalcedony. 90% of the samples are supersaturated with quartz and 10% (2 samples) are undersaturated.

Based on partial pressure of carbon dioxide (P_{CO2}) and saturation index (SI), waters of the study area are all undersaturated to carbonate (calcite and dolomite), sulphate and some silicate (chalcedony and amorphous silica) minerals and supersaturated with respect to quartz. Thus these waters come from environment where calcite, dolomite, gypsum, anhydrite are impoverished or where Ca and Mg exist in other forms. Dissolved silica concentration of 0.30- 27.73 mg/l which are greater than the average concentration of silica in groundwater (17 mg/l) given by Hem (1991). This suggests that dissolution of aluminosilicates is responsible for the release of Ca, K and Mg leading to the formation secondary minerals (Dobrzynski, 2005).

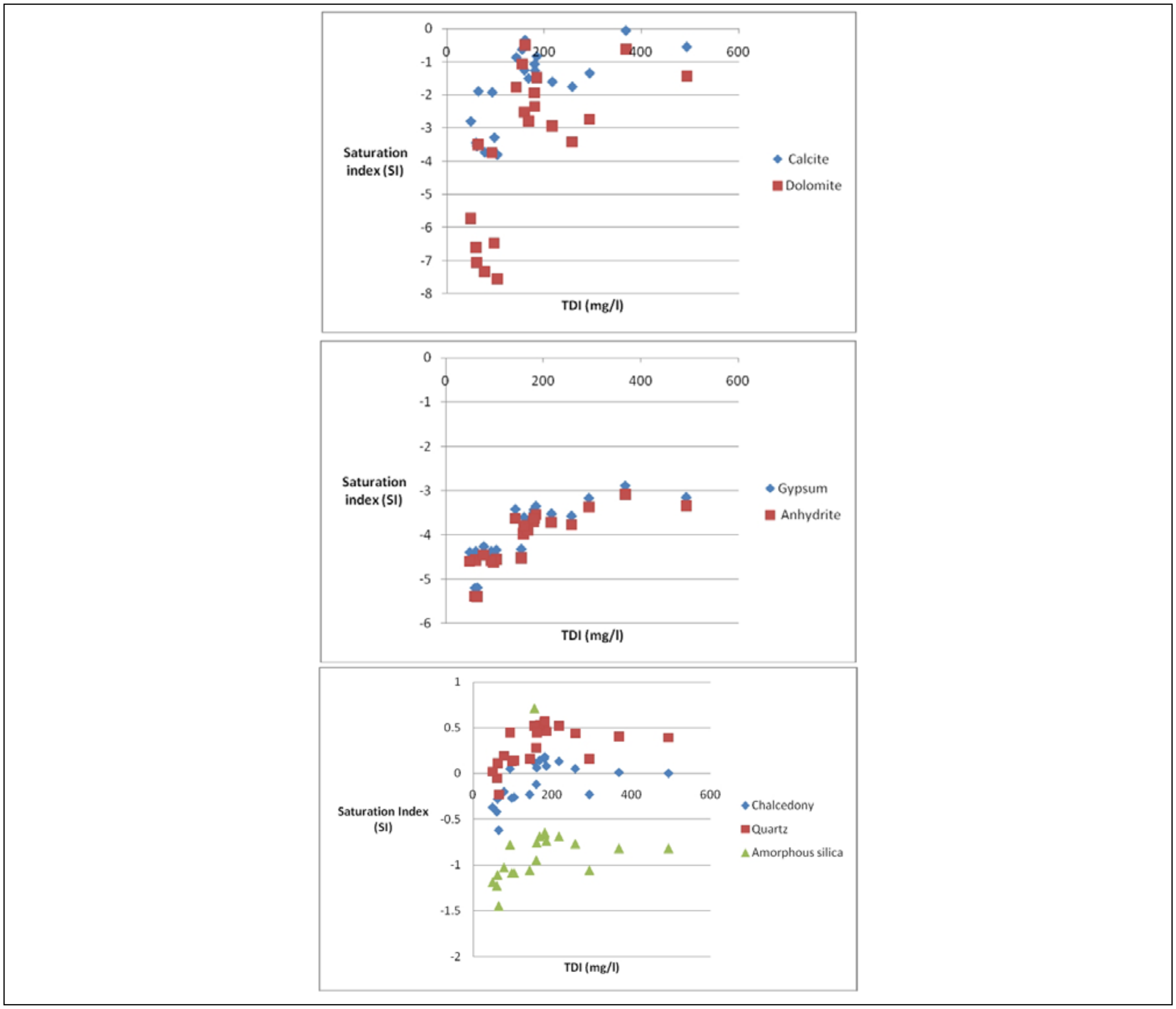

Figure 7. Graph showing the relationship between the Saturation index (SI) and TDI values for surface and groundwaters from the Banana Plain.

Anthropogenic contamination

There are three major sources of nitrogen in groundwater — biological fixation, precipitation, and the application of fertilizers (Berner and Berner, 1987). Human activities have also influenced the nitrogen load considerably. Anthropogenic sources of nitrogen include (1) point sources including industrial sewage, refuse dumps etc, discharged directly into the surface water, (2) diffuse sources including runoff and leaching from rural and urban land and (3) precipitation (Kumar and Anderson, 1993).

Nitrate concentrations of water samples are in the range 0.19-39.26 mg/l with 10 of the 23 samples (43.5%) having nitrate concentrations greater than 10 mg/l, exceeding the WHO (2004) drinking water limit. Demlie et al. (2007) illustrate that a positive correlation of NO_3 and Cl, is a diagnostic indicator of anthropogenic activity. In this study, a correlation matrix (Table 4) shows a strong positive correlation between NO_3 and Cl (R = 0.82) and is a diagnostic indicator of anthropogenic activity on water quality.

Figure 8 shows a plot of NO_3 against depth. It can be seen that the amounts of nitrates are significantly higher in the first 20 m of the aquifers and decrease with depth. Such a distribution clearly indicates that nitrate species in most of the considered groundwaters are of superficial origin (anthropogenic). The significant concentrations of NO_3 in groundwater is indicative of the unconfined nature of the system. This assumption would be verified by the tritium contents of the groundwaters. Figure 9 shows a stream in the study area in advanced state of eutrophication due to nitrates from anthropogenic activities.

In the Banana Plain, the most common land use is agro-industrial cultivation of bananas, coffee, cocoa accompanied by large applications of fertilizers and pesticides. Another contributing factor is the large population density with little access to sanitation facilities. These all contribute to the high nitrate concentration in the water resources of the area. The high fertility of the soils in the area is a probable source of nitrates due to natural N-fixing under aerobic conditions.

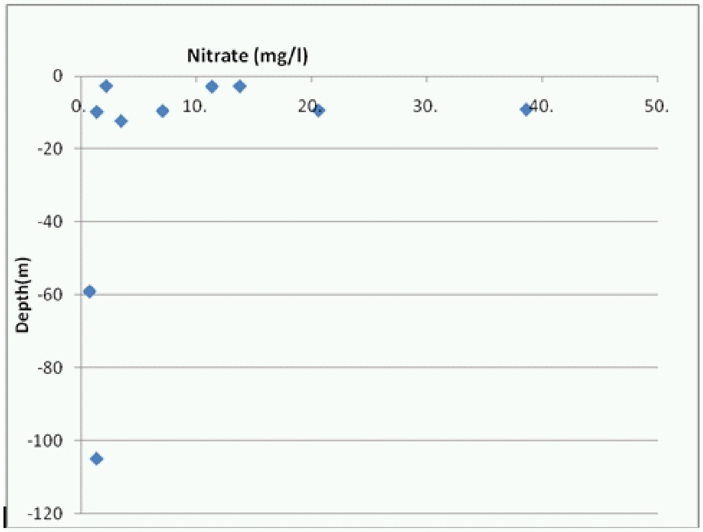

Figure 8. Plot of depth of wells and boreholes versus nitrate concentrations in water.

Figure 9. Eutrophication of surface water (Boko stream, Njombe) due to anthropogenic activities in the Banana Plain.

CONCLUSIONS

Application of environmental isotopes in the Banana Plain has provided valuable information on the hydrology in this agro-industrial area. ^{18}O and ^{2}H data for water from the Banana Plain indicate that groundwaters have been recharged by meteoric water without significantly being affected by evaporative processes either during or after the recharge. It seems therefore likely that the infiltration is fast and direct. Evaluation of the groundwater residence time in conjunction with hydrochemical data demonstrated that the groundwater in the Banana Plain aquifers should be considered renewable water resource. Geochemical studies have shown that groundwaters are fresh, TDS (< 600 mg/l). The investigated waters evolve between the Ca/HCO_3 and Ca-Mg-Na/HCO_3 chemical types. The chemical content of waters is chiefly controlled by low temperature water-rock interaction, including the following reactions: (1) acid weathering of silicate minerals; (2) anthropogenic activities. These reactions are governed in most cases by a CO_2 gas phase of biogenic origin. Dissolved silica is controlled by the weathering of silicate minerals and also by the solubility of some siliceous minerals, such as quartz.

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