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Hydrochemistry of shallow groundwater and surface water in the Ndop plain, North West Cameroon

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This study was conducted on the hydrochemistry of shallow groundwater and surface water in the Ndop plain, North West Cameroon. The objectives were to determine the physico-chemical characteristics of water, controls on water chemistry and suitability for drinking and irrigation. Forty-six shallow groundwater and 26 surface water samples were investigated. Field measurements of physical parameters were preceded by chemical analyses of the samples for major ions and F⁻. About 69% of the water sources had pH values below 6.5, classifying the water as barely acidic. Electrical conductivity (<282 µS/cm) and total dissolved solids (<183 mg/l) were low suggesting low-mineralised and freshwater. The relative abundance of major ions (meq/l) was Na²⁺>Ca²⁺>Mg²⁺>K⁺ for cations and HCO₃⁻>>NO₃⁻≥Cl⁻>SO₄²⁻ for anions. Major ion concentrations were low, and within the WHO guidelines for drinking water, but F⁻ concentrations were much lower (<0.39 mg/l) and below guideline value. Main water types and proportions were Na-HCO₃ (53 %), Ca-HCO₃ (35 %) and a mixed Na-Ca-HCO₃ (11%). Predominant processes influencing water chemistry were incongruent dissolution of silicate minerals and cation-exchange of Na⁺ in rocks for Ca²⁺ in water. The low major ion concentrations indicated low water-rock interactions and short residence time. The analysed water was suitable for irrigation.

Key words: Water chemistry, hydrochemical controls, drinking-irrigation quality, Ndop plain, Cameroon.

INTRODUCTION

Groundwater and surface water geochemical studies can provide a better understanding of potential water quality variations due to geology and land use practices (Edmunds and Smedley, 1996; Deutsch, 1997; Appelo and Postma, 2005; Ramesh and Elango, 2012). In Africa, groundwater is a vital resource with nearly 80% of the continent's population relying on it as a main source of drinking water. However, in many parts of the continent, reaching basic health requirements is still a concern (Adelana and MacDonald, 2008; Adelana et al., 2011; Edet et al., 2011; Tay, 2012).

Cameroon is endowed with numerous water resources (Katte et al., 2003; Molua and Lambi, 2006), but an assessment of these resources, including their reliability, quality and sustainability has not been systematically carried out (Katte et al., 2003). Improved drinking water sanitation in semi-urban and rural communities is nearly the same from 37% in 1990 to 36% in 2010 (WHO/UNICEF, 2012). With increasing population, the high demand for water, especially in most poor rural communities, is met by shallow groundwater of generally unknown quality. This is usually the best option all year

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round as most surface water sources and springs are unreliable and run dry or reduce in size during the dry season, or become polluted by heavy floods in the rainy season.

Only few hydrochemical studies have been carried out to assess the geochemical characteristics of groundwater and its suitability for use in Cameroon (example, Njitchoua and Ngounou-Ngatcha, 1997; Katte et al., 2003; Fantong et al., 2009; Eneke et al., 2011; Ako et al., 2012). The Ndop plain is a semi-urban community where groundwater, as well as surface water, is a critical resource for human livelihood. The plain has an estimated population of over 200,000 people with ca. 70% involved in subsistence farming. Many ethnic groups have been attracted to the area as a result of fertile soils (Ndzeidze, 2008; Fonge et al., 2012). This has been followed by high demand for water and other natural resources (Fonge et al., 2012). Over 70% of the population depends solely on shallow groundwater, as well as surface water of poor microbial quality for drinking and other domestic purposes (Wirmvem et al., 2013). A hydrochemical study of water quality based on major ion composition has not been carried out. Since the development of the Bamendjin dam in the area in the 1970s, rice cultivation is the main cash crop using the dam and river waters. Unfortunately, there is no information on the suitability of the water sources for irrigation despite the on-going programme by the Cameroon government to revamp rice cultivation in the area. The chemical composition of water and its mineralization process are imperative in classifying and assessing drinking water quality (Deutsch, 1997; WHO, 2004; Kozisek, 2005) while irrigation water quality criteria can be used as a guideline by farmers for selecting appropriate management practice to overcome potential salinity hazard (Gupta et al., 2009; Ramesh and Elango, 2012).

The present study, therefore, presents the first hydrochemical baseline dataset of groundwater and surface water in the Ndop plain. The objectives were to (1) determine the physico-chemical characteristics of the water, (2) define the factors that control major ion chemistry, and (3) evaluate their suitability for drinking and irrigation. The data will provide a hydrochemical baseline data for water quality assessment, management, and monitoring of changes in the hydrochemical system from the prevailing human activities in the area. The study will also contribute to the limited knowledge on natural water composition in North West Cameroon. With the on-going programme to revamp rice cultivation in the area, an assessment of the suitability of the water sources for irrigation is invaluable.

The study area

The study area (Figure 1) is an inter-mountain basin (ca. 1,100 km²) in the Western Highlands of Cameroon (WHC),

along the Cameroon Volcanic Line (CVL). From the surrounding CVL ranges, the relief drops steeply from an average altitude of ca. 1,899 m to ca. 1,200 m at the margins of the plain, and then gently to ca. 1,180 m above sea level in the south central portion. The flanks of the mountain chain are discharge points for numerous rivers and streams flowing dendritically into the plain and recharging the Bamendjin dam (Figure 1). Details on the drainage are described by Ndzeidze (2008). According to Neba (1999), the area has an Equatorial monsoon climate type characterized by high rainfall and relative humidity. This is attributed to the effect of the mountainous relief that characterises much of the WHC (Neba, 1999; Molua and Lambi, 2006). Two distinct seasons are differentiated, a long rainy season (mid-March to mid-November) and a short dry season (mid-November to mid-March). Mean annual rainfall and temperature, in 2012, were 1,540 mm and 26°C, respectively (Wirmvem et al., unpublished data), but with cooler climate in adjacent high elevations (Ndzeidze, 2008; Ndenecho, 2009). The heaviest rainfall occurs from July to September and often results in floods due to the poor drainage (Ndzeidze, 2008).

Geologically, the area is a shallow Cenozoic 'sedimentary' basin, underlain mainly by a consistent Precambrian granitic basement (Figure 1). This basement forms part of the tectonically inactive African shield consisting mostly of Precambrian Basement Complex rocks (Neba, 1999; Marzoli et al., 1999). Chemical weathering of the basement and surrounding volcanic rocks has produced thick unconsolidated sediments, mainly of clay to sand sizes. The basement is largely covered with these sediments, but outcrops in certain areas. The surrounding volcanoes are represented by voluminous Q-trachytes and minor rhyolitic ignimbrites with slight to moderate alkaline basalts and minor basanites (Marzoli et al., 1999). The voluminous Q-trachytes are enriched in alkali feldspars (Na₂O+K₂O). *In-situ* weathered basement and alkali-rich fluvial sediments constitute the aquifer material in the plain. From the margins of the plain towards the south-central portion, there is a progressive change from sandy to clayey sediments. The unconsolidated sandy-sediments form the groundwater aquifer system. This explains the concentric model of human settlement around the dam water (Ndzeidze, 2008) tapping groundwater through wells from this aquifer. The poor microbial quality of water with consequent water-borne infections (Wirmvem et al., 2013) has prompted the chlorination of water in wells by some members of the community.

MATERIALS AND METHODS

Water sampling and physico-chemical measurements

Water was collected from 72 water sources in January 2012 (dry season) within 13 communities (Figure 1). The sources comprised 32 open wells and 14 'boreholes' (hereafter termed groundwater); and 14 streams, 4 rivers, 5 dam waters, and 3 lakes (Lakes Bambili,

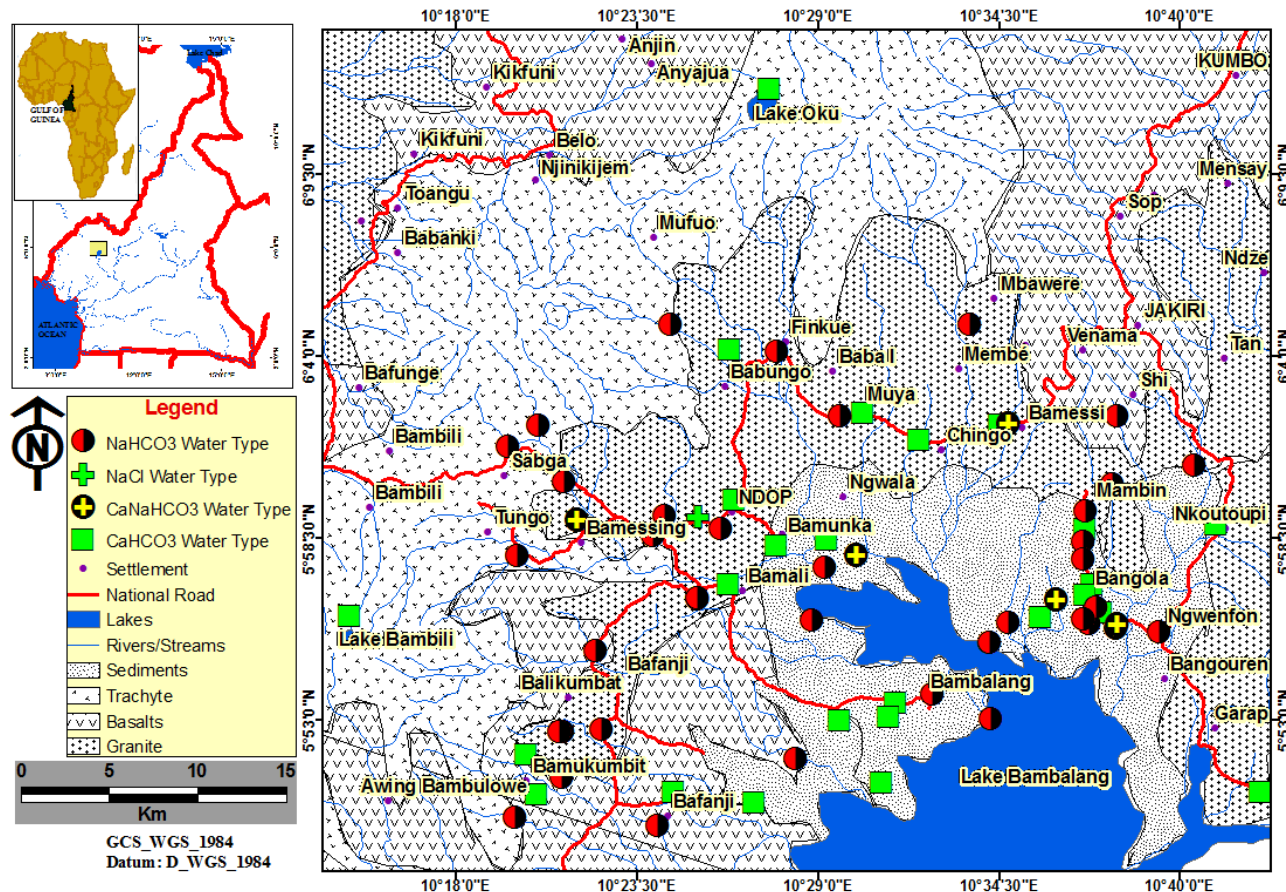


Figure 1. The geology and drainage map of Ndop Plain (modified after Ndzeidze, 2008) showing sample points/spatial distribution of water types.

Oku, and Ber) (hereafter called surface water). The sample location points (Figure 1) and altitudes were noted in the field by using a Garmin Vista CX GPS. Four sporadic rainfall events in the plain and its environs were also sampled. Field measurements and water sampling followed methods described by Karklins (1996). New 100 ml narrow mouth and low-density polyethylene (LDPE) bottles were properly rinsed with distilled water and dried in the Laboratory (in order to avoid contamination) and used for sampling the water. At each site, water was collected into a plastic bucket after thorough rinsing with water to be sampled. Groundwater from active wells was collected using a rope tied to a bucket and/or permanently installed hand-pumps (after several minutes of pumping). Surface water was sampled as far as possible from the edges of the water bodies and as deep as possible along the flow path. The water collected was then filtered directly into 2 LDPE bottles using a plastic syringe, fitted with a 0.20 μm filter after thorough rinsing with the same water that was sampled. Collected samples were properly capped and preserved in a cooler container containing ice blocks. Water for major ion analyses was put in one bottle and water for alkalinity determination in a separate bottle. The following physical parameters: activity of hydrogen ion (pH), electrical conductivity (EC), total dissolved solids (TDS), and water temperature were measured immediately from the remaining collected water using a multipurpose HI991300 hand held pH/EC/TDS/C Hanna Meter. The meter was calibrated before and during the field campaign using buffer solutions recommended by the manufacturer. The depths to standing water level and total depth of water column were determined with a water level indicator. Alkalinity/bicarbonate (HCO_3^-)

was determined within 8 hours of sampling by acid titration from a volume of 0.02 M HCl, added to the sample and stirred with an automatic stirrer until the end-point, marked by a pH of 4.5.

Chemical analyses

Chemical analyses were carried out at Tokai University, Japan within two weeks of sample collection. Major cations: Na^+ , K^+ , Mg^{2+} and Ca^{2+} were determined by a Flame Technique in a High Resolution Continuum Source AAS (ContrAA 700) as described by Welz et al. (2006). Samples with EC values $>100 \mu\text{S}/\text{cm}$ were diluted 5 or 10 times to acquire an absorbance within the range of the used standards for Na^+ , K^+ and Ca^{2+} . The anions: F^- , Cl^- , NO_3^- , SO_4^{2-} , PO_4^{3-} , NO_2^- and Br^- were determined by using an Ion Chromatography (Dionex ICS-900) while dissolved Silica ($\text{Si}(\text{OH})_4$), hereafter considered as SiO_2 , was determined by using an ICP-AES. The reliability of the chemical analyses was verified by using an ionic balance error (IBE) equation (Appelo and Postma, 2005). The values were within $\pm 5\%$; hence, suitable for geochemical interpretations.

RESULTS AND DISCUSSION

Physico-chemical composition of groundwater and surface water

Table 1 presents results of the 72 water samples with a statistical summary shown in Table 2. A statistical summary

of rain data is presented in Table 3. Mean depth to the water table (<27 m) and depth of the water column (<8.4 m) were low, suggesting a shallow aquifer system. The mean temperature of the water was closer to the mean atmospheric temperature of 26°C, suggesting present day climatic influence and recharge. Ground-water had a lower and narrow range in pH with a mean of 5.9, moderately acidic, while surface water had a relatively higher and wider range in pH with a mean of 6.8, slightly acidic. About 88% of the 72 samples had pH<7, suggesting an acidic aquifer system. The EC and TDS values of all water sources were low with mean values of 60 $\mu\text{S}/\text{cm}$ and 39 mg/l, respectively suggesting low-mineralised and freshwater. Major ion concentrations, like TDS, were low (Table 2) and in the order (meq/l) $\text{Na}^{2+} > \text{Ca}^{2+} > \text{Mg}^{2+} > \text{K}^+$ for cations and $\text{HCO}_3^- > \text{NO}_3^- \geq \text{Cl}^- > \text{SO}_4^{2-}$ for anions. The small range in their concentrations and higher dispersions around their respective mean values as reflected by the small STD values, except for NO_3^- and Cl^- (Table 2), suggests a unique source of most ions and a single aquifer system. Mean concentration of SiO_2 was higher than that of individual cations but less than the mean of HCO_3^- (Table 2). This suggests that SiO_2 was released more than the cations into solution. The high SiO_2 suggests the abundance of silicate minerals (Srinivasamoorthy et al., 2008) in agreement with the dominant granitic basement (Figure 1) and as observed in similar terrains by Njitchoua and Ngounou-Ngatcha (1997) and Fantong et al. (2009).

As expected, the mean TDS increased progressively from a minimum in rainwater (20 mg/l) to surface water (30 mg/l) and a maximum in groundwater (44 mg/l). Similarly, mean relative concentrations of dissolved ions showed a progressive increase from the lowest in rainwater, to surface water, and the highest in groundwater (Figure 2a). These results suggest chemical evolution from rain to surface water and groundwater. The relatively high TDS in groundwater indicated the influence of the unconsolidated sediments and granitic bedrock material in chemically enriching the water as it percolates through the under-saturated zone (or flows through the aquifer). The small difference in mean TDS of groundwater and rainwater by only 53 % is likely because these are early rains, usually enriched in dissolved ions (Takounjou et al., 2011). The low major ion concentrations in groundwater depict low water-rock interactions in the granitic basement, short residence time, the shallow nature of the aquifer and its acidic nature (Edmunds and Smedley, 1996). Similar low pH and major ions have been reported from granitic basement complex aquifers in Ghana (Adomako et al., 2011) and Nigeria (Edet et al., 2011).

Hydrochemical facies

The meq/l concentrations of major ions plotted on a pie chart (Figure 2b), showed that Na^+ , HCO_3^- and to some extent Ca^{2+} were the major ionic species. Low K^+ may be

due to its low geochemical mobility (Hem, 1989; Srinivasamoorthy et al., 2008) while low Mg^{2+} is possibly due its to low content in rocks of the study area. On a Piper diagram (computed using GW_Chart Version 1.23.7.0), most samples plotted in the field of alkali metals (Na+K) (Figure 3). This indicates the dominance of alkali metals in the groundwater aquifer system. The water types and their proportions are shown (Figure 3). The observed spatial distribution of the water types (Figure 1) showed no discernible pattern from Ca- HCO_3 to Na- HCO_3 . Given the gentle relief in the plain, this suggests a mixed aquifer system as revealed by the mixed Na-Ca- HCO_3 water. Similarly, no clear pattern, in water type, was observed from surface water to groundwater (Figure 3). Nonetheless, there is chemical evolution from Ca+Mg+ SO_4 +Cl (rain), to Ca- HCO_3 (largely groundwater and lakes), and to Na- HCO_3 (basically groundwater, streams, rivers, and dam waters) as indicated by the dotted arrow (Figure 3). It is probable that the dissolution of Na^+ into surface waters from alkali-rich trachytic rocks in the surrounding highlands tends to mask the chemical evolution. The presence of Ca- HCO_3 water in groundwater within the plain, which is sporadic, in surface waters (streams and rivers) discharging from the highlands suggests that the main recharge of groundwater may not necessarily occur at higher altitudes but rather through direct precipitation to the surface and subsequent percolation through the under-saturated zone into the aquifer.

Origin of solutes and hydrochemical controls

The major ion chemistry of groundwater and compositional relations among ionic species can reveal the origin of solutes and processes that generated an observed water composition (Hounslow, 1995; Demlie et al., 2007; Cendon et al., 2011; Tay, 2012). Table 4 shows correlation coefficients between the ionic species in water. The good positive correlation of NO_3^- with Cl^- suggests their anthropogenic origin (Demlie et al., 2007; Fantong et al., 2009). Main potential sources of NO_3^- are numerous shallow pit toilets and oxidation of organic matter given the proximity (>15 m) to shallow groundwater and agricultural dominance, respectively. Fonge et al. (2012) identified relatively high concentrations of NO_3^- and PO_4^{3-} in soil water (<5 cm deep) from rice farms in the study area. The low content of NO_3^- and the absence of PO_4^{3-} in groundwater suggest their sorption on organic colloids (in the under-saturated source of zone) or the location of rice fields rather in low-lying swampy areas. The likely Cl^- is atmospheric inputs given the positive correlation with Na^+ and disinfection of wells through chlorination as noted in the field. Sulfur occurs in a reduced form in igneous rocks and is oxidized to SO_4^{2-} when weathered in contact with aerated water (Hem, 1989). The significant positive correlations of SO_4^{2-} with K^+ , Ca^{2+} and HCO_3^- possibly suggest its igneous origin in

Table 1. Physico-chemical results of groundwater and surface water (n=72) in the Ndop plain (January-February, 2012).

ID	T	pH	EC	TDS	Na ⁺	K ⁺	Ca ²⁺	Mg ²⁺	HCO ₃ ⁻	NO ₃ ⁻	Cl ⁻	SO ₄ ²⁻	F ⁻	SiO ₂	IB
OW06	25.4	5.7	15	9.8	1.0	0.9	0.2	0.4	6.3	0.1	0.1	0	0.03	9.9	2
OW07	24.3	5.9	28	18.2	2.0	1.0	0.6	0.8	10.6	1.4	0.2	0.02	0.04	12.1	1
OW09	24.4	6.2	25	16.3	0.4	0.9	1.7	0.3	7.9	0.2	0.1	0.54	0.02	7.7	2
OW10	24.3	5.5	19	12.4	1.3	0.6	0.4	0.7	8.2	0.5	0.1	0	0.02	10.8	3
OW18	23.8	5.6	9	5.9	0.2	0.5	0.3	0.1	2.5	0.1	0.1	0	0.01	3.8	7
OW19	24.0	5.8	52	33.8	6.1	1.0	0.4	0.6	21.0	0.6	0.1	0.04	0.07	3.7	1
OW20	23.6	5.8	59	38.4	1.4	2.0	5.0	0.8	20.4	0.1	1.1	0.77	0.1	9.8	5
OW21	19.5	5.9	56	36.4	4.0	1.4	2.9	0.7	20.5	0.0	2.1	0.06	0.01	3.1	2
OW22	20.4	5.3	73	47.5	2.8	8.6	2.0	1.1	21.9	7.6	0.9	0.18	0.01	2.7	2
OW28	25.0	6.0	45	29.3	1.1	1.5	2.4	0.6	13.5	0.3	0.2	0.7	0.06	12.1	1
OW32	25.0	5.6	44	28.6	2.9	1.9	0.9	0.9	11.0	5.7	0.4	0.02	0.03	9.8	2
OW37	24.2	5.9	65	42.3	6.1	1.8	0.3	0.7	19.7	3.1	0.1	0.06	0.13	3.6	2
OW39	23.5	5.9	88	57.2	5.1	5.0	0.9	2.1	18.6	0.1	6.2	3.17	0.08	2.7	1
OW49	19.5	6.4	230	149.5	1.8	24.7	9.4	6.7	91.1	0.1	1.2	8.42	0.03	3.2	4
OW50	22.6	5.2	14	9.1	0.9	1.1	0.2	0.1	4.6	0.4	0.2	0.08	0.01	5.9	4
OW56	24.3	6.6	71	46.2	2.7	3.3	4.1	0.3	23.1	0.6	0.2	0.35	0.03	8.1	0
OW59	23.0	6.5	45	29.3	5.4	2.3	0.2	0.2	13.7	1.7	0.2	2.06	0.22	2.3	4
OW62	23.1	5.7	26	16.9	2.5	1.2	0.3	0.4	8.5	0.1	0.5	0.64	0.06	13.4	2
OW64	24.0	5.5	34	22.1	2.5	1.6	0.5	0.6	10.5	1.3	0.6	0.27	0.05	8.0	5
OW66	22.4	5.6	16	10.4	1.7	1.3	0.1	0.2	5.1	0.9	0.2	0.38	0.05	14.9	3
OW67	23.4	6.1	38	24.7	4.7	2.9	0.6	0.7	18.4	1.0	0.5	0.29	0.05	16.4	1
OW72	23.0	6.1	16	10.4	1.1	0.9	0.3	0.3	5.7	0.4	0.2	0.02	0.02	6.5	1
OW74	24.0	6.7	145	94.3	3.3	9.4	12.2	0.9	61.4	0.0	0.2	1.31	0.06	10.2	3
OW82	23.8	5.6	24	15.6	0.7	1.0	0.6	1.1	9.0	0.0	0.4	0.26	0.05	7.3	4
OW85	23.7	5.4	61	39.7	5.3	3.9	1.1	0.9	15.3	0.0	4.7	2.07	0.17	13.7	1
OW86	24.2	5.5	135	87.8	21.5	3.3	1.3	0.4	4.4	15.5	26.9	0.17	0.1	3.1	3
OW88	24.3	5.4	26	16.9	1.4	2.0	0.6	0.3	9.4	0.0	0.3	0.09	0.03	9.5	4
OW90	23.9	6.6	158	102.7	5.8	19.8	3.4	4.7	62.5	0.0	3.1	4.72	0.11	10.5	2
OW125	23.1	6.0	48	31.2	3.1	1.7	1.6	1.3	9.5	7.2	2.6	0.13	0.02	3.1	9
OW126	23.2	5.8	42	27.4	4.4	3.1	0.5	1.0	17.5	0.8	0.3	0.159	0.08	19.0	2
OW127	24.3	5.8	61	39.7	3.0	1.6	2.7	0.9	20.0	1.0	0.3	0.43	0.06	12.1	1
OW129	23.4	5.8	126	81.9	7.5	1.0	3.7	4.7	14.5	27.9	6.6	1.56	0.08	15.3	2
BH02	23.2	5.8	40	26.0	3.0	1.1	1.6	0.5	14.5	0.7	0.1	0.09	0.19	13.1	1
BH11	24.5	5.8	43	28.0	2.7	0.9	1.0	1.0	14.6	1.0	0.2	0.08	0.05	18.8	1
BH29	22.4	6.4	131	85.2	5.6	3.5	3.5	3.1	38.9	3.3	1.0	0.77	0.39	2.2	1
BH41	24.5	6.2	272	176.8	3.8	2.2	1.6	2.3	11.1	12.4	3.0	0.58	0.11	2.2	0
BH52	25.1	6.3	45	29.3	1.4	1.3	2.7	0.2	13.4	0.7	0.2	0.27	0.02	6.6	5
BH53	24.0	5.4	34	22.1	1.5	3.3	1.4	0.3	10.6	1.4	0.7	0.16	0.03	7.2	3
BH55	25.5	5.7	43	28.0	0.9	1.0	3.2	0.3	12.8	0.4	0.4	0.18	0.02	6.5	1
BH60	23.0	6.0	56	36.4	3.3	3.0	2.8	0.2	15.9	0.0	0.1	4.37	0.32	17.5	-16
BH70	25.7	6.1	52	33.8	1.6	1.3	1.3	0.7	9.6	8.6	0.2	0.56	0.07	8.0	5
BH73	24.0	6.7	282	183.3	4.2	24.5	20.3	1.6	83.7	3.8	2.7	12.76	0.09	13.2	0
BH76	25.4	6.3	86	55.9	1.2	2.1	8.0	0.3	30.5	0.0	0.3	0.81	0.04	10.2	1
BH77	23.4	5.7	33	21.5	2.0	2.6	1.1	0.4	11.1	0.0	0.6	1.32	0.13	13.5	1
BH83	24.5	5.7	47	30.6	0.7	1.9	2.4	0.7	14.8	0.0	0.1	0.33	0.08	14.1	1
BH124	22.0	5.9	31	20.2	1.9	1.0	1.2	0.6	12.2	0.2	0.4	0.09	0.02	3.7	1
ST05	22.1	7.5	69	44.9	4.3	2.8	1.4	2.6	31.7	0.4	0.1	0	0.18	19.9	4
ST13	22.9	6.2	12	7.8	1.2	0.7	0.2	0.4	6.2	0.0	0.1	0	0.01	8.7	1
ST15	21.6	6.8	21	13.7	1.3	0.7	0.5	0.6	8.3	0.4	0.0	0	0.04	7.7	0
ST17	18.9	6.7	30	19.5	2.0	1.6	0.6	0.8	12.9	0.0	0.1	0	0.05	10.0	3
ST24	21.6	6.0	21	13.7	0.4	0.7	0.3	0.2	3.8	0.0	0.1	0.04	0	5.1	7

Table 1. Contd.

ST27	20.1	5.8	19	12.4	1.2	0.7	0.3	0.3	5.0	0.0	0.3	0.06	0.07	5.8	1
ST33	21.7	6.5	25	16.3	1.5	0.7	0.3	0.4	6.9	0.1	0.3	0.07	0.04	9.9	1
ST40	20.9	7.2	110	71.5	5.5	2.0	0.8	4.7	41.6	0.1	0.3	0.03	0.18	2.7	1
ST65	19.5	6.9	59	38.4	6.9	2.9	0.4	0.6	23.3	0.1	1.0	0.68	0.13	3.0	0
ST68	19.4	6.9	44	28.6	4.7	2.0	0.3	0.7	19.1	0.1	0.2	0.16	0.08	19.7	1
ST80	19.5	7.7	175	113.8	17.3	2.8	1.2	5.3	78.7	0.0	0.1	0.08	0.3	2.8	1
ST87	21.1	6.4	58	37.7	7.2	3.1	0.2	0.3	24.4	0.0	0.3	0.06	0.06	2.8	2
ST104	18.5	8.2	46	29.9	5.2	2.4	0.2	0.5	18.7	0.1	0.1	0.62	0.08	3.1	0
ST108	19.2	7.9	29	18.9	4.3	2.6	0.1	0.3	14.4	0.2	0.2	0.47	0.1	3.0	3
RW26	21.5	6.7	13	8.5	0.7	1.5	0.3	0.3	6.0	0.2	0.2	0.08	0.02	5.8	1
RW42	20.1	6.7	80	52.0	4.8	2.1	0.8	2.7	29.5	0.6	0.4	0.26	0.09	2.3	1
RW93	19.5	7.4	34	22.1	2.1	1.5	0.5	1.1	12.7	0.4	0.3	0.34	0.04	14.8	2
RW94	21.0	7.1	39	25.4	4.0	1.9	0.2	0.3	14.2	0.1	0.2	0.35	0.08	20.5	1
LK31	26.9	6.3	32	20.8	2.8	0.7	0.1	0.2	7.8	0.0	0.4	0.04	0.06	7.4	6
LK43	21.7	8.4	33	21.5	1.2	1.0	1.8	0.2	8.8	0.0	0.6	0.56	0.03	11.6	-1
LK123	20.2	7.8	44	28.6	2.1	1.4	0.8	1.4	14.8	0.0	1.1	0.096	0.037	9.4	0
DW16	25.3	6.5	47	30.6	3.7	2.6	0.4	0.9	16.5	0.0	0.9	0.01	0.07	15.9	3
DW51	20.2	5.9	46	29.9	3.7	5.2	0.7	0.0	15.7	0.0	1.9	0.02	0.07	13.4	3
DW54	22.7	5.5	24	15.6	2.9	2.0	0.4	0.8	14.4	0.0	0.3	0	0.06	12.2	4
DW75	20.1	6.8	45	29.3	2.9	2.8	0.7	0.9	17.4	0.0	0.5	0	0.11	13.2	1
DW128	27.3	5.8	58	37.7	1.7	0.9	1.0	1.1	12.9	16.1	0.8	0.413	0.03	9.1	-35

OW, Open well; BH, borehole; ST, stream water; RW, river water; LK, lake water; DW, dam water; EC, electrical conductivity ($\mu\text{S}/\text{cm}$); TDS, total dissolved solids (mg/l). All ions (mg/l); Br⁻ was detected in only OW39 (0.02 mg/l); PO₄³⁻, in OW37 (0.43 mg/l), OW86 (0.1 mg/l) and LK43 (0.07 mg/l); NO₂⁻ (>0.3 mg/l) was detected in OW22, OW32, BH29, BH41 and LK16; IB, ionic balance.

Table 2. Statistical summary of physico-chemical data of groundwater and surface water in the study area.

Parameter	Surface and ground water (n=72)				Groundwater (n=46)				Surface water (n=26)			
	Min	Max	Mean	Std	Min	Max	Mean	STD	Min	Max	Mean	Std
Alt. (m)	1135	2272	1235	193	1163	1260	1188	19.24	1135	2272	1317	302
Dtw (m)	-	-	-	-	1.60	27.00	8.81	5.06	-	-	-	-
Dow (m)	-	-	-	-	0.30	8.40	1.57	1.36	-	-	-	-
Tw (°C)	18.5	27.30	22.79	2.04	19.50	25.70	23.65	1.32	18.5	27.3	21.29	2.22
pH	5.20	8.41	6.23	0.71	5.20	6.74	5.90	0.37	5.48	8.41	6.83	0.76
EC ($\mu\text{S}/\text{cm}$)	9.0	282	59.75	54.62	9.00	282	67.16	62.32	12.0	175	46.65	33.47
TDS (mg/l)	5.85	183.30	38.84	35.5	5.85	183.3	43.65	40.51	7.8	113.75	30.33	21.76
Na ⁺ (mg/l)	0.24	21.54	3.37	3.28	0.24	21.54	3.21	3.26	0.41	17.34	3.67	3.29
K ⁺ (mg/l)	0.47	24.69	2.94	4.48	0.47	24.69	3.53	5.45	0.66	5.24	1.89	1.05
Ca ²⁺ (mg/l)	0.11	20.25	1.80	3.02	0.11	20.25	2.50	3.58	0.14	1.77	0.56	0.41
Mg ²⁺ (mg/l)	0.0	6.74	1.04	1.31	0.12	6.74	1.03	1.31	0.0	5.34	1.06	1.31
HCO ₃ ⁻ (mg/l)	2.45	91.12	18.69	17.53	2.45	91.12	19.13	18.80	3.83	78.65	17.92	14.97
NO ₃ ⁻ (mg/l)	0.0	27.92	1.80	4.51	0.00	27.92	2.41	5.05	0.00	16.07	0.73	3.07
Cl ⁻ (mg/l)	0.04	26.87	1.13	3.31	0.05	26.87	1.53	4.07	0.04	1.88	0.42	0.42
SO ₄ ²⁻ (mg/l)	0.0	12.76	0.77	1.91	0.00	12.76	1.12	2.32	0.0	0.68	0.17	0.21
F ⁻ (mg/l)	0.0	0.39	0.08	0.07	0.01	0.39	0.08	0.08	0.0	0.3	0.08	0.06
SiO ₂ (mg/l)	2.18	20.54	9.04	5.10	2.18	18.97	8.93	4.80	2.26	20.54	9.23	5.58

Max, maximum; Min, minimum; STD, standard deviation; Alt, Altitude; Dtw, depth to water (m); Dow, depth of water (m); Tw, water temperature; EC, electrical conductivity; TDS, total dissolved solids.

agreement with the geology. Fluoride showed a distinct positive correlation with Na⁺ relative to Ca²⁺ (Table 4).

The likely source of F⁻ in the granitic basement is fluorite, CaF₂, the most common F⁻-bearing mineral (Edmunds

Table 3. Physico-chemical data of January 2012 sporadic rainfall events in the Ndop Plain and its Environs.

Location	pH	EC	TDS	Na ⁺	K ⁺	Ca ²⁺	Mg ²⁺	HCO ₃ ⁻	NO ₃ ⁻	Cl ⁻	SO ₄ ²⁻	F ⁻	Na/Ca
Bamenda	6.26	36	23.4	0.36	0.90	1.39	0.37	3.5	2.97	2.3	1.33	0.02	0.43
Ndop	6.57	30	19.5	0.26	0.88	1.62	0.43	3.77	2.58	1.56	1.25	0.03	0.27
Ndawara	6.45	28	18.2	0.29	0.87	1.30	0.36	3.97	2.47	1.43	1.12	0.01	0.37
Kumbo	6.53	32	20.8	0.23	1.09	1.37	0.27	4.12	3.73	1.22	2.03	0.03	0.28
Max.	6.57	36	23.4	0.36	1.09	1.62	0.43	4.12	3.73	2.3	2.03	0.03	0.43
Min.	6.26	28	18.2	0.23	0.87	1.3	0.27	3.5	2.47	1.22	1.12	0.01	0.27
Mean	6.45	31.5	20.5	0.29	0.94	1.42	0.36	3.84	2.94	1.63	1.43	0.02	0.34

EC = uS/cm, TDS and all ions = mg/l, Na/Ca

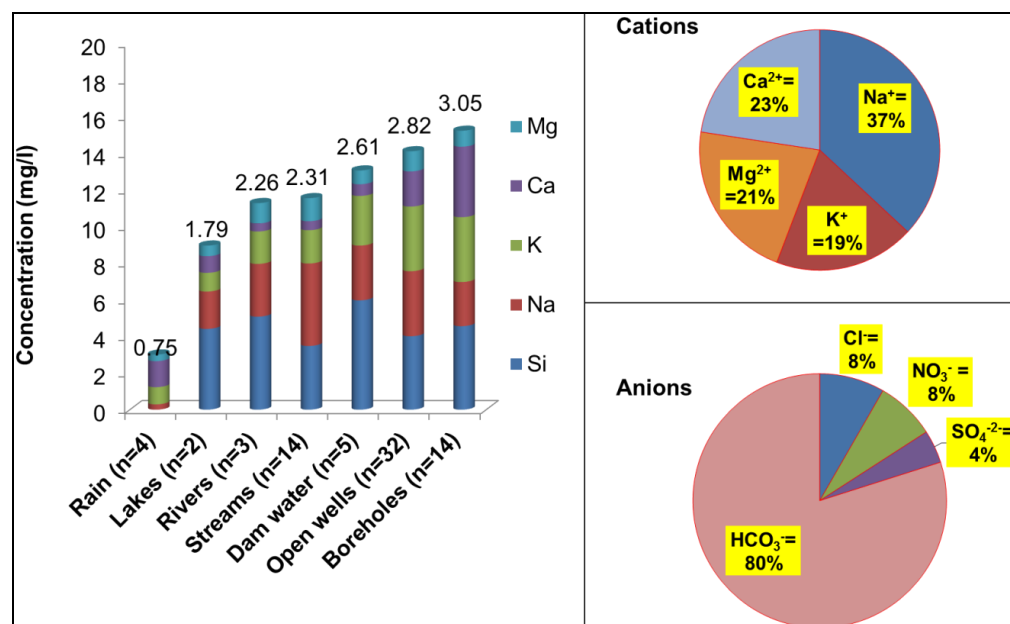


Figure 2. A, Relative mean concentrations of silica and cations (mg/l) in various water sources of the study area including rain. Si was not measured in rain; Si>Na>K>Ca>Mg. B, Pie chart of mean concentrations of ions (meq/l), showing high Na⁺ and dominant HCO₃⁻ in water sources of the study area.

and Smedley, 1996). However, the released Ca²⁺ is possibly exchanged for Na⁺ on clay surfaces, resulting in a relative increase in F⁻ and a decrease in Ca²⁺, hence, the weak correlation between Ca²⁺ and F⁻.

High F⁻ concentrations in groundwater have been identified in North Cameroon, along the CVL, in a granitic-alkaline environment from fluorite, amphiboles and micas (Fantong et al., 2009). The low concentrations of F⁻ in groundwater of the study area may be due to its acidic nature which renders F⁻ immobile (Hem, 1989; Edmunds and Smedley, 1996). For example, the highest value of F⁻ (0.39 mg/l) was identified in BH29 ('borehole') with a pH of 6.4. The strong positive correlations of HCO₃⁻ with Ca²⁺, Mg²⁺, K⁺ and SO₄²⁻ further indicate similar origin of ions. Given the Na-HCO₃ dominance (Figure 3), the weak positive correlation of Na⁺ with HCO₃⁻ suggests that varied processes accounts for its concentration in solution.

Table 5 shows a summary of computed ratios between

some ionic species. The observed Na⁺/Cl⁻ molar ratios were high, relative to that of sea water, 0.86 (Millero et al., 2008). A Na⁺/Cl⁻ molar ratio approximately equal to 1 is usually attributed to halite dissolution, whereas >1 is typically interpreted as reflecting Na⁺ released from silicate weathering reactions (Fisher and Mullican, 1997; Cendon et al., 2010). Therefore, the excess Na⁺ as further shown (Figure 4) is likely from silicate weathering, possibly feldspar mineral dissolution. On a plot of total cations, Na⁺+K⁺+Ca²⁺+Mg²⁺ (TC) versus alkalinity, most of the 72 samples (94 %) plotted on or near the 1:1 line (Figure 5a). The high mean HCO₃⁻/Σanions ratio in the water (Table 5) and the 1:1 relationship (Figure 5a) suggest silicate or carbonate weathering (Hounslow, 1995; Fisher and Mullican, 1997; Kim, 2002), but acid waters (as prevailed in the study area) usually results from dissolution of non-carbonate rocks such as granites (Edmunds and Smedley, 1996), the dominant rock in the

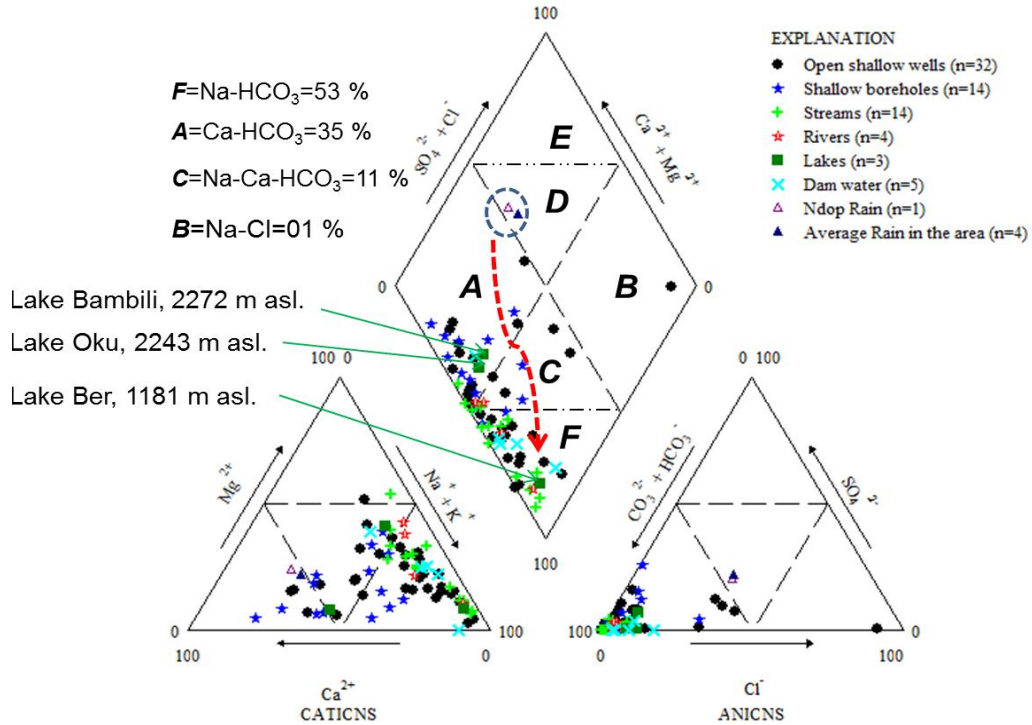


Figure 3. Piper’s diagram showing the water types and proportions in the Ndop Plain. Alkali metals (Na+K) exceed alkali earth metals (Ca+Mg). Weak acids (CO₃+HCO₃) greatly exceed strong acids (SO₄+Cl). The dash line in the diamond section indicates the path of chemical evolution from Ca-Mg-SO₄-Cl (rain), to Ca-HCO₃ (groundwater, lakes and dam water), and to Na-HCO₃ (groundwater, streams and rivers). Ca-Na-HCO₃ represents a transition (mixing zone) from Ca-HCO₃ to Na-HCO₃ water.

Table 4. Pearson correlation coefficients of all analysed water sources (n=72).

Parameter	Na ⁺	K ⁺	Mg ²⁺	Ca ²⁺	HCO ₃ ⁻	Cl ⁻	NO ₃ ⁻	SO ₄ ²⁻	F ⁻	pH
Na ⁺	1.00									
K ⁺	0.12	1.00								
Mg ²⁺	0.35	0.52	1.00							
Ca ²⁺	-0.01	0.73	0.27	1.00						
HCO ₃ ⁻	0.33	0.81	0.72	0.70	1.00					
Cl ⁻	0.69	0.12	0.10	0.06	-0.03	1.00				
NO ₃ ⁻	0.34	-0.01	0.25	0.09	-0.08	0.52	1.00			
SO ₄ ²⁻	0.05	0.87	0.40	0.77	0.68	0.11	0.04	1.00		
F ⁻	0.48	0.07	0.36	0.04	0.35	0.07	0.01	0.17	1.00	
pH	0.17	0.10	0.23	0.08	0.33	-0.16	-0.21	0.08	0.21	1.00

area.

To further determine the likely influence of silicate dissolution, the molar ratio of HCO₃⁻/SiO₂, saturation indices for calcite and aragonite, and Ca²⁺+Mg²⁺ versus SO₄²⁻+HCO₃⁻ relationship were examined. If HCO₃⁻/SiO₂ ratio is greater than 10, (that is, HCO₃⁻>>SiO₂), carbonate weathering predominates. However, if the ratio is low and especially <5, silicate weathering predominates (Hounslow, 1995). The computed HCO₃⁻/SiO₂ ratios (Table 5) were

75% (<5), 19% (5-10) and 6 % (>10). Calculated saturation indices (SI) of the water samples (using AqQA software) showed under-saturation (SI<0) with respect to calcite and aragonite (Table 5) suggesting their absence in the formation and/or not enough time to interact. A charge balance will exist between the Ca²⁺+Mg²⁺ and SO₄²⁻+HCO₃⁻ if they are derived from basic dissolution of calcite, dolomite, and gypsum (Fisher and Mullican, 1997). On the contrary, there was a deficiency in Ca²⁺+Mg²⁺ re-

Table 5. A statistical summary of ratios between some ionic species in the analysed water.

Parameter	Minimum	Maximum	Mean	STD
Na ⁺ /Cl ⁻	1.25	5345	24.42	63.92
Na ⁺ /Ca ²⁺	0.13	27	5.35	6.66
HCO ₃ ⁻ /Σanions	0.06	68.34	9.60	10.93
HCO ₃ ⁻ /SiO ₂	0.34	28.11	3.52	5.31
SI of Calcite	-7.21	-1.41	-4.31	1.28
SI of Aragonite	-7.38	-0.17	-4.39	1.43
R _E Index	1.31	5.84	3.82	1.32
P _{CO2} (atm)	0.0000	0.1082	0.0053	0.01
Chloro-alkali index 1 (CAI 1)	-585	-0.59	-32.59	71
Chloro-alkali index 2 (CAI 2)	-2.37	-0.18	-0.65	0.30
Total Hardness	0.97	57.27	8.77	10.48
SAR	0.08	4.34	0.64	0.65
Kelly's Ratio	0.08	10.03	1.70	2.12
RSC (meq/l)	0.07	2.52	0.48	0.48

STD, Standard deviation; HCO₃⁻/ Σ anions (meq/l); SI, Saturation Index; RE (weathering index) = 2(3K++3Na+2Ca2+-SiO2)/K++Na++Ca2+, RE was calculated using molar concentrations of ions; PCO2 (Partial pressure of CO2) in water; Na+/Ca2+ (meq/l); CAI 1 = Cl - (Na + K)/Cl; CAI 2 = Cl-(Na + K)/(SO4 + HCO3 + CO3 + NO3). Total hardness (as CaCO3 in mg/l) = 2.5(Ca2+)+ 4.1 (Mg2+); SAR (Sodium Adsorption Ratio) = Na+/{Ca2+ + Mg2+}/2)0.5; KR (Kelly's Ratio) = Na+/Ca2+ + Mg2+. RSC (Residual Sodium Carbonate) = (CO32-+HCO3-) + (Ca2++Mg2); CAI, SAR, KR, RSC were calculated from ionic concentrations in meq/l.

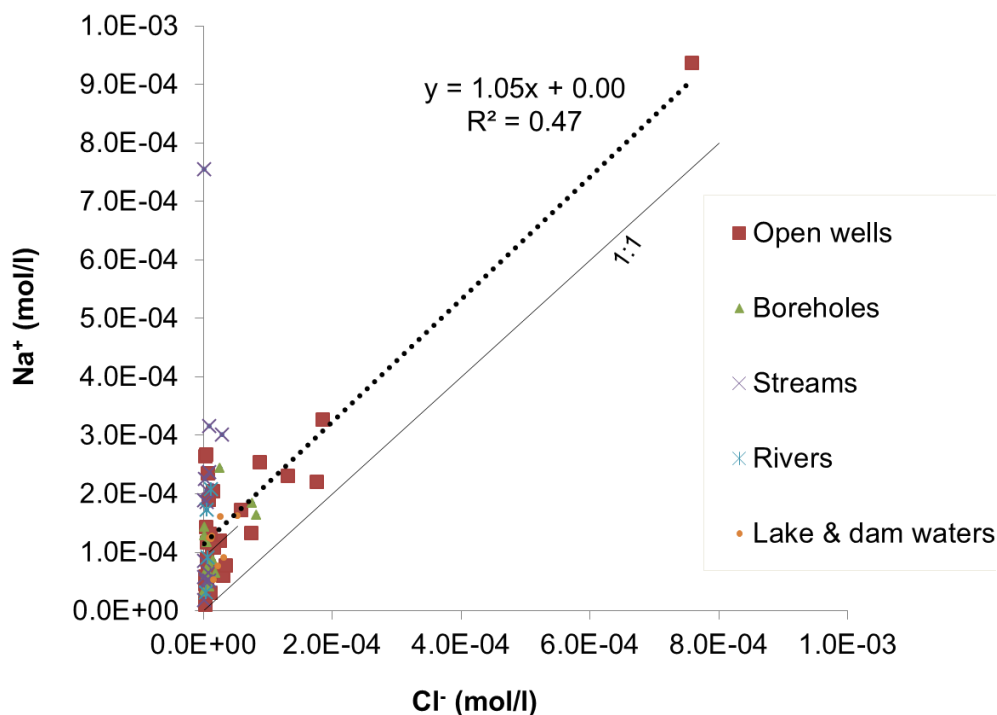


Figure 4. Plot of Na+ as a function of Cl- showing an excess of Na+ over Cl- in water sources.

relative to SO₄²⁻+HCO₃⁻ (Figure 5b). Thus, the 75% dominance of samples with HCO₃⁻/SiO₂ ratios <5, calcite and aragonite under-saturation, and excess of SO₄²⁻+HCO₃⁻ relative Ca²⁺+Mg²⁺ strongly suggest incongruent weathering of silicate minerals (water-rock interaction) as the main control on water chemistry in agreement with the

geology. Similar observations of silicate dissolution in granitic formations (Njitchoua and Ngounou-Ngatcha, 1997; Fantong et al., 2009) and volcanic terrains (Tanyileke et al., 1996; Ako et al., 2012) along the CVL have been reported with the following generalized equation (Tanyileke et al., 1996):

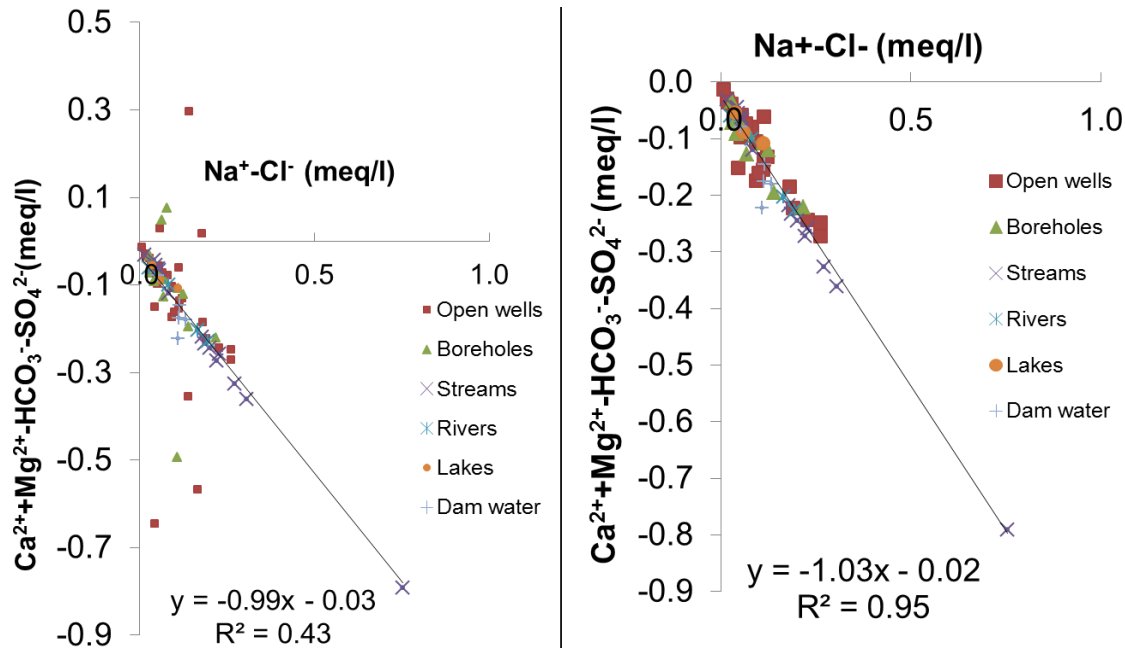


Figure 6. A, Relation of $\text{Ca}^{2+}+\text{Mg}^{2+}-\text{HCO}_3^-+\text{SO}_4^{2-}$ versus Na^+-Cl^- showing an increase in Na^+ relative to a decrease in $\text{Ca}^{2+}+\text{Mg}^{2+}$ or an increase in HCO_3^- and SO_4^{2-} with a slope close to -1.00 and a positive correlation ($n=72$). B, Relation of $\text{Ca}^{2+}+\text{Mg}^{2+}-\text{HCO}_3^-+\text{SO}_4^{2-}$ versus Na^+-Cl^- showing an increase in Na^+ relative to a decrease in $\text{Ca}^{2+}+\text{Mg}^{2+}$ or an increase in HCO_3^- and SO_4^{2-} with an improved linearity after excluding 9 anomalous samples ($n=63$).

and Ca^{2+} in groundwater were being exchanged with Na^+ and K^+ in rocks; hence, favouring cation-anion exchange reactions (chloro-alkaline disequilibrium) (Gupta et al., 2009). The Na^+ enrichment (addition) by ion exchange probably explains its observed weak positive correlation with other cations and SO_4^{2-} . Thus, besides the chemical dissolution of plagioclase feldspar minerals, cation-exchange reactions between water and montmorillonite in the aquifer also play a role in modifying the water composition.

The mean P_{CO_2} in the groundwater (Table 5) was higher than the mean atmospheric value of 0.0003 atm (Appelo and Postma, 2005), suggesting that the major source of CO_2 governing the above reactions was probably from the oxidation of organic matter in the under-saturated zone (Karanth, 1987; Appelo and Postma, 2005). The high P_{CO_2} in groundwater are consistent with findings along the CVL (Njitchoua and Ngounou-Ngatcha, 1997; Fantong et al., 2009; Ako et al., 2012), which has been attributed to the same process. Unlike in these related studies, groundwater in the study is comparatively acidic. The acidic nature probably results from reduction in acid buffering capacity of infiltrating rainwater and leaching of organic constituents from soils into the shallow groundwater.

Suitability for drinking and irrigation

The drinking water guidelines of the WHO (2004) were used to evaluate the quality of water in the study area for

human consumption. Most water sources had a cream colour, likely due to suspended organic colloids. Regardless of the cream colour, the range of all major ions and TDS were below the maximum values of the guidelines for drinking water. However, the F^- content was low (0 to 0.39 mg/l) with a mean of 0.08 mg/l. At low concentrations (<0.2 mg/l) in drinking water, dental caries may result (Edmunds and Smedley, 1996). The water was soft, that is, low total hardness (Table 5) given the low Ca^{2+} and Mg^{2+} . Their concentrations were mostly below the minimum required: 10 mg/l (Mg^{2+}), 20 mg/l (Ca^{2+}) and 60 mg/l total hardness (Kozisek, 2005). Evidence is now available to confirm the existence of health risk from drinking water deficient in Ca^{2+} and Mg^{2+} (Rylander et al., 1991; Dissanayake and Chandrajith, 1999; Kozisek, 2005). Thus, the general water softness could be a health problem since soft water has been linked to cardiovascular ailments (Kozisek, 2005). About 69% of the water sources had pH values below 6.5. For effective disinfection of water with chlorine, the pH should preferably be less than 8, but lower pH water (<6.5) is likely to be corrosive (WHO, 2004). High trace-metal contents, a health problem, are also likely from such low pH waters (Edmunds and Smedley, 1996), hence, a need to assess potentially harmful trace element. The low TDS in groundwater are consistent with the observation that most exploited groundwater resources in the weathered Precambrian basement rocks of Africa area low in dissolved ions and generally suitable for consumption (Adelana et al., 2011). However, the microbial quality of groundwater in the tropi-

cal Africa is a serious health issue (Roche, 1993) as reported in the study area (Wirmvem et al., 2013) and elsewhere (Katte et al., 2003).

Suitability of water for irrigation has been assessed using various properties or ratios. These include EC, Sodium Adsorption Ratio (SAR), Kelley's Ration (KR) and Residual Sodium Carbonate (RSC) (Gupta et al., 2009; Ramesh and Elango, 2012). Electrical conductivity and SAR play a vital role in suitability of water for irrigation. The EC values in 99 % of the analysed samples were <250 $\mu\text{S}/\text{cm}$ and SAR values were <5 (Table 5); thus, classifying the water into the low salinity hazard class (C1) and low sodium hazard class (S1), respectively (USSL, 1954; Gupta et al., 2009). Computed KR (Kelly, 1951) (Table 5) showed that 54% (KR<1), 25 % (KR, 1-2), and 21% (KR>2) were suitable, marginal and unsuitable, respectively, for irrigation. Calculated RSC (Eaton, 1950) classified 93% and 7% of the water as suitable (RSC \leq 1) and marginally suitable (RSC, 1.3-2.5), respectively, for irrigation.

Conclusion

A hydrochemical study, in the Ndop plain, to determine the physico-chemical characteristics, controls on water chemistry and suitability for drinking and irrigation has been carried out by analysing 72 water samples. The first physico-chemical baseline data of groundwater and surface water for water quality assessment, management and monitoring of changes in the hydrochemical system has been made available in the area. About 69% of the water sources had pH values below 6.5, classifying the water as barely acidic. Therefore, careful attention is necessary at all stages of pipe borne water treatment and supply in the area as this could lead to corrosion and scale formation in pipes. The low mean EC (60 $\mu\text{S}/\text{cm}$) and TDS (39 mg/l) classify the water as low-mineralised and freshwater. Major ion concentrations were low, and below maximum values of the WHO standards for drinking water, but the low Ca^{2+} and Mg^{2+} classify the water as soft (<<57 mg/l CaCO_3). This could be a health problem given the relationship between soft water and cardiovascular ailments. The low F^- content in the water sources (<0.39 mg/l) could lead to dental caries. In spite of these, the water sources are considered suitable for drinking as per WHO standards.

The relative abundance of major cations and anions in water (meq/l) is $\text{Na}^+ > \text{Ca}^{2+} > \text{Mg}^{2+} > \text{K}^+$ and $\text{HCO}_3^- > \text{NO}_3^- \geq \text{Cl}^- > \text{SO}_4^{2-}$, respectively. The main water types and proportions are Na- HCO_3 (53%), Ca- HCO_3 (35%) and mixed Na-Ca- HCO_3 (11%). Alkali metals (Na+K) exceed alkali earth metals (Ca+Mg) indicating their dominance in the aquifer system. The major controls on water chemistry are incongruent dissolution of silicate minerals (mainly plagioclase feldspars) and cation-exchange of Na^+ in rocks for Ca^{2+} in solution. The dissolution is governed by biogenic CO_2 and results to montmorillonite clay, which

enhances the ion exchange. The low NO_3^- and general absence PO_4^{3-} in groundwater suggest their sorption by organic matter in the under-saturated zone. The low EC (TDS) and major ions in groundwater depict low solubility of the silicates, short residence time of groundwater, shallow nature of the aquifer and its acidic nature. The water sources are suitable for irrigation. Potentially harmful trace elements should be investigated given the acidic nature of the water. Hydrochemical investigations in the rainy season should also be carried out, to determine the seasonal controls on water chemistry.

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