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**DEPARTMENT OF CIVIL, ENVIRONMENTAL AND ARCHITECTURAL ENGINEERING**

# SUITABILITY OF WATER SOURCES FOR DOMESTIC AND AGRICULTURAL USES IN BIDOU AND DOUKA-LONGO WATERSHEDS: NORTHERN CAMEROON

*A thesis submitted in partial fulfilment of the requirements for the Master of* ***Environmental Engineering*** *in National Advanced School of Public Works, Yaoundé*

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# DEDICATION

*To God Almighty who transformed the little seed I was into a plant,*

*to the whole NSATA family who supervised its growth, particularly*

*to my dear father and name-sake NSATA Simon David who left us during the write-up of this thesis.*

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# LIST OF ACRONYMS

**asl**: Above sea level

**BAC**: Biologically Active Carbon

**BGR**: Federal Institute of Geosciences and Natural Resources

**BIW**: Bidou Igneous Watershed

**BMZ**: Federal Ministry for Economic Cooperation and Development

**BOD**: Biological Oxygen Demand

**CAI**: Chloro-Alkali Index(ces)

**CB** : Projet Centre Bénoué

**CIRAD** : Centre de coopération internationale en recherche agronomique et le développement

**COD**: Chemical Oxygen Demand

**CRDS**: Cavity Ring Down Spectrometer

**DE**: Deuterium Excess

**DEM**: Digital Elevation Model

**DO**: Dissolved Oxygen

**DPPER:** Division du Patrimoine et de l'Environnement Routiers

**DRASTIC**: Depth-Recharge-Aquifer media-Soil-Topography-Impact of vadose zone-Hydraulic conductivity

**DSLW**: Douka Longo Sedimentary Watershed

**EC**: Electrical Conductivity

**FAO**: Food and Agricultural Organization

**GAC**: Granular Activated Carbon

**GIS:** Geographic Information System

**GMWL**: Global Meteoric Water Line

**GPS**: Global Positionning System

**GWP**: Global Water Partnership

**HYSACAM**: Hygiène et Salubrité du Cameroun

**ICP-AES**: Inductively Coupled Plasma Atomic Emission Spectrometry

**IITA** : Institut international d'agriculture tropicale

**IPCS**: International Programme on Chemical Safety

**IRD** : Institut de recherche pour le développement

**IRGM**: Institute of Geological and Mining Research

**IWRM**: Integrated Water Resources Management

**KR**: Kelly Ratio

**MDGs**: Millenium Development Goals

**MED WS&D WG:** Mediterranean Water Scarcity & Drought Working Group

**MH**: Magnesium Hazard

**MINADER**: Ministry of Agriculture and Rural Development

**MINTP**: Ministry of Public Works

**NCRA:** National Cereal Research and Extension

**NEB** : Projet Nord-Est Bénoué

**NGO** : Non-Governmental Organisation

**PAC**: Powdered Activated Carbon

**PCD**: Communal Plan of Development

**PDOB** : Projet de développement de l'Ouest Bénoué

**pH**: Hydrogen ion Potential

**PI**: Permeability Index

**ProFam** : Protection de la Famille

**ProSEP**: Projet Sol-Eau-Plante

**QGIS**: Quantum Geographical Information System

**REEs**: Rare Earth Elements

**RSBC**: Residual Sodium Bi-Carbonate

**RSC**: Residual Sodium Carbonate

**SAR**: Sodium Absorption Ratio

**SDG**: Sustainable Development Goals

**SEB** : Projet Sud-Est Bénoué

**SRTM**: Shuttle Radar Topography Mission

**SSP**: Solute Sodium Percentage

**SWOT**: Strength-Weakness-Opportunities-Threats

**TDS**: Total Dissolved Solids

**TH**: Total Hardness

**THM**: Tri-Halo Methane

**TSS**: Total Soluble Salts

**UN**: United Nations

**UNEP**: United Nations for Environmental Protection

**UNESCO**: United Nations Educational Scientific and Cultural Organization

**UNHCR**: United Nations High Commissioner for Refugees

**UNICEF**: United Nations International Children's Emergency Fund

**USDA**: United States Department of Agriculture

**USEPA**: United States Environmental Protection Agency

**USSL**: United States Salinity Laboratory

**VOCs**: Volatile Organic Compounds

**VSMOW**: Vienna Standard Mean Ocean Water

**WHPA**: Well Head Protection Area

**WHO**: World Health Organization

**WQI**: Water Quality Index

**WRM**: Water Resources Management

**WTF**: Water Table Fluctuation

**WWF**: World Wildlife Fund

**ZIC** : Zone d'Intérêt Cynégétique

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# ABSTRACT

Aridity, climate change, poverty and population growth make the Bidou (BIW) and Douka Longo (DLSW) watersheds more vulnerable to water resource deterioration. In order to determine the quality of this resource for irrigation and domestic use, this study consisted in (1) the evaluation water chemistry to determine its types, anomalies and processes responsible for the observed characteristics; (2) evaluation of water quality for irrigation and domestic consumption and finally (3) the time needed for water resources to be insufficient for domestic use. To do this, 115 water samples (59 in the rainy season of November 2019 and 56 in the dry season of March 2020) were collected for analysis of major ions, $\delta^2H$, $\delta^{18}O$ and trace elements in BIW and DLSW. The results obtained showed that water was predominantly Ca-Mg-$HCO_3$ types BIW and Ca-Mg-$NO_3$ type in DLSW with a reduction of $NO_3^-$ amount during the dry season. Eight heavy metals (As, Ba, Be, Co, Mn, Ni, Pb and U) were found in excess compared to their natural occurrence in raw water. The main process controlling water chemistry was rock-water interactions. Parameters such as EC, SAR, PI, KR and %Na indicated that water was suitable for irrigation with some limitations due to excess $Na^+$ and high PI in BIW. Sampled water was also chemically suitable for consumption as it contained few dissolved solids and generally complied with WHO standards despite the excess of some heavy metals (As, Ni, Pb, U) and excess $NO_3^-$ in DLSW or softness in BIW. The WQIs obtained using the weighted arithmetic method were suitable for 100% and 64% of the samples collected in the rainy season in BIW and DLSW, respectively. Those of the dry season were suitable for 93% and 63% of samples in BIW and DLSW, respectively. The annual recharge obtained using water table fluctuation method was estimated at $2.04\times10^8 m^3$ for BIW and $1.59\times10^9 m^3$ for DLSW, resulting in a probabilistic occurrence of water stress in 2464 and 2210 for domestic consumption only, respectively. In order to improve the living conditions in these catchments, it is compulsory to manage the natural water resources in a sustainable way and to treat them for drinking water supply. This requires the protection of groundwater resources through the sensitization of the population; the restriction of polluting activities near the recharge points and the improvement of the sanitation system. As for drinking water, it should be treated with kaolinite and activated carbon from corn cobs to adsorb $NO_3^-$ and heavy metals in DLSW and enriched in $Ca^{2+}$ in BIW using calcite.

**Keywords**: Water quality, irrigation, domestic use, recharge rate, Northern Cameroon.

# RÉSUMÉ

L'aridité, les changements climatiques, la pauvreté et la croissance de la population rendent les bassins versant de Bidou (BIW) et Douka-Longo (DLSW) plus vulnérables à la détérioration des ressources hydriques. Afin de déterminer la qualité de ces ressources pour l'irrigation et l'usage domestique, cette étude a consisté en (1) l'évaluation de la chimie de l'eau pour en ressortir les types et anomalies et les processus responsables des caractéristiques observées (2) l'évaluation de la qualité de l'eau pour l'irrigation et la consommation et finalement (3) le temps nécessaire pour que les ressources en eau soient insuffisantes pour l'usage domestique. Pour ce faire, 115 échantillons d'eau dont 59 en saison pluvieuse (novembre 2019) et 56 en saison sèche (mars 2020) ont été collectés pour l'analyse des ions majeurs, $\delta^2H$, $\delta^{18}O$ et des éléments trace à BIW et à DLSW. Les résultats obtenus montrent que les eaux étaient majoritairement de types N $Ca\text{-}Mg\text{-}HCO_3$ à BIW et $Ca\text{-}Mg\text{-}NO_3$ à DLSW avec une réduction considérable du $NO_3^-$ en saison sèche. Huit métaux lourds (As, Ba, Be, Co, Mn, Ni, Pb et U) ont été retrouvés en excès par rapport à leurs occurrences naturelles dans les eaux. Le processus majeur contrôlant la chimie de l'eau étaient les interactions eau- roches. Les paramètres tels que EC, SAR, PI, KR et %Na indiquaient que les eaux étaient convenables pour l'irrigation avec quelques limitations dues à un excès de $Na^+$ et des PI très élevés à BIW. Les eaux échantillonnées étaient également chimiquement convenables pour la consommation car elles étaient généralement conformes aux normes de l'OMS malgré l'excès de certains métaux lourds (As, Ni, Pb et U), un excès de $NO_3^-$ à DLSW et la douceur de l'eau à BIW. Les indices de qualité de l'eau obtenus en utilisant la méthode arithmétique étaient convenables pour 100% et 64% des échantillons de BIW et DLSW, respectivement. Ceux de la saison sèche étaient potables à 93% à Bidou et à 63% à DLSW. Les recharges annuelles obtenues par variation du niveau piézométrique étaient de $2.04\times10^8 m^3$ à BIW et $1.59\times10^9 m^3$ à DLSW, résultant en une probable situation de stress hydrique en 2464 à BIW et en 2210 à DLSW. La gestion durable des ressources est impérative pour l'amélioration des conditions de vie dans ces bassins. Ceci passe par la protection des eaux souterraines à travers la sensibilisation de la population, la régulation de l'occupation des sols et l'amélioration du système d'assainissement. Les eaux de consommation doivent être traitées avec le méta-kaolin et le charbon actif d'épis de maïs pour adsorber le $NO_3^-$ et les métaux lourds à DLSW et enrichies en $Ca^{2+}$ à BIW en utilisant le calcaire.

**Mots-clés** : Qualité de l'eau, irrigation, usage domestique, taux de recharge, Nord Cameroun.

# TABLE OF CONTENT

# GENERAL INTRODUCTION

This part of the work presents the context of the study, the problem statement, the research question, the objectives set and the impacts of the research.

## 1. CONTEXT

In volume, 97.5% of Earth water is salty and 70% of the 2.5% of fresh water remaining is frozen (Han et al. 2001). Agriculture is by far the most important consumer of freshwater with about 70% of freshwater withdrawal destined to irrigation (FAO, 2017). In arid and semi-arid zones, physical water scarcity is the main driver for groundwater extraction and wastewater recycling and reuse (Qadir & Sato, 2016). In order to reduce the withdrawal rate of groundwater, countries like India use to recycle wastewater for irrigation (Qadir & Sato, 2016). However, using irrigation water of poor quality is a source of threats for soil, crops, animals and human beings with the reduction of arable lands, productivity and diseases (especially for vegetarians).

The impact of polluted water on life is both social and economic. The higher the pollution, the more expensive its remediation through as common methods like filtration, boiling or chlorination are no more effective. Hence, poor countries facing important problems of water quality are not able to provide good quality water to the population. This results in a high percentage of deaths due to water-borne diseases. Diarrhea is the most known disease linked to unsafe drinking water, responsible for the death of 829,000 people including 297,000 children aged under 5years each year (Prüss-Ustün et al., 2019).

Groundwater is of better quality than surface water and counts for approximately 20% (and 90% to 100% in arid areas) of the water used world-wide (Barry et al, 2005). However, climate change is projected to have significant impact on the water cycle, affecting the availability and quality of surface and groundwater, agricultural production and associated ecosystems (Bates et al., 2008). In african countries, it has immediate and long-term impacts on water resources including flooding, drought, sea-level rise in estuaries, drying up of rivers, poor water quality in surface and groundwater systems, precipitation and water vapour pattern distortions (Urama & Ozor, 2010). This results in the reduction of agricultural yield, the increase of food price, dependance on imported food and health threats (UNESCO, 2009). In semi-arid areas like the Northern Cameroon, which is one the granaries of the continent where people living in rural sites rely on groundwater and practice agriculture to gain their lives, such a problem should be addressed.

## 2. PROBLEM STATEMENT

Being a semi-arid area, Northern Cameroon is more vulnerable to climate change. As a matter of fact, its water resources have continuously been reducing over the past years as a response to the reduction of precipitations (Cheo et al. 2013). From 1950 to 2013, the annual average precipitations decreased at a rate of -0.568mm/year. More so, high temperatures are likely to accelerate the water cycle, altering precipitation, air humidity, evaporation and the intensity of natural disasters like floods and droughts (Frederick, 2002). The most devastating flood event happened in 2012, threatening more than 30 000 people and their socio-economic activities (Bang et al, 2017, Mora-Castro & Saborio-Bejarano, 2012).

Northern Cameroon hosts 37% of the Cameroonian population and more than 56% of all the poor in the country (World Bank, 2019). Population growth rate and flocks of refugees from Central African Republic have contributed to the poverty rates and inability of the State to adequately provide potable water. It has also affected resilience of the populations to natural disasters.

Increase in population due to high birth rate, wars in the Far North and Centre African Republic also contribute to poverty and reduce the ability of the State to provide water to all and the resilience of populations to natural disasters. In 2017, Bang et al., concluded that the main reason for this high poverty is the absence of diversification in livelihood. This keeps the population solely reliant on subsistence rain-fed agriculture that is now threatened by frequent floods.

The sudden alternation between floods and droughts disturbs food production and reduces crop yields. Until the late 80s, Cameroon was considered self-sufficient in agricultural production and played a role of food garret for its neighbouring countries. Since the early 90s, Cameroon began spending billions of francs CFA to import large quantities of food items like rice, maize, onion, tomatoes, milk and poultry produce in Northern Cameroon (Abia et al., 2016).

With the fluctuating climate, farmers have to adapt to their conditions and maintain either their productivity or their gain. They used to work for other farmers, buy more expensive seeds which could adapt to climate or use more fertilizers (chemical or not). Farming is generally a family-run activity with little expertise on agricultural practices which are still rudimentary. The impact of their activities on water is aggravated by the sanitation system applied. For example, traditional pit latrines are built near drinking water wells and are frequently washed-up during floods.

In order to solve the problem raised above, this region is subject to several projects among which: agricultural researches (*IRAD, NCRA, IITA, IRD, CIRAD*), development projects (*NEB, SEB, CB, PDOB),* institutional support (MINADER, NGO), food aid (WFP, French Cooperation) but the results are not satisfactory (Fofiri, 2012). Also, Cameroon is working with international partners to provide drinking water in these areas by sinking building water wells and boreholes.

Presumably Mafany et al. (2006) bring out the importance of knowing the major ion composition of water resources, trace elements and isotopes for adequate use of water. In 2008, Amini et al. showed that Northern Cameroon is among the most vulnerable regions to arsenic contamination. In addition to a complete description of water pollution state in Cameroon, Defo et al. (2016) put an emphasis on water laws and regulations in Cameroon. Recently, Nenkam et al. (2020) found high $NO_3^-$ level in the North region of Cameroon which is 16 times higher than the $NO_3^-$ concentration observed in this region 25 years ago by Njitchoua et al., (1995). In order to assess the suitability of water resources for agriculture and domestic use, the present study seeks to present the hydro-geochemistry of two watersheds in Northern Cameroon namely: Bidou and Douka Longo in Adamaoua and North regions of Cameroon, respectively.

## 3. RESEARCH QUESTION

The problems exposed here lead us to one question:

**Is the water used in Bidou and Douka Longo suitable for irrigation and domestic consumption?**

## 4. OBJECTIVES

- **Main objective**: Evaluate water quality (for agriculture and human consumption) and quantity (for consumption) in Bidou and Douka Longo watersheds.
- **Specific objectives**

  - Determine chemical characteristics of groundwater and surface water in the study area to bring out factors controlling groundwater chemistry
  - Evaluate water suitability for agricultural purposes and consumption
  - Estimate the quantity of groundwater recharge in a hydrological year

## 5. IMPACT OF THE RESEARCH

Promotion of the $6^{th}$ Sustainable Development Goal of Agenda 30 by:

- Improving water quality and reducing water borne diseases by reducing pollution;
- Improving sanitation and hygiene by eliminating open defecation;
- Providing tools like annual rate of recharge, potential water stress periods of Bidou and Douka-Longo watersheds for the implementation of Integrated Water Resources Management;
- Contributing to the improvement of agriculture and the decrease of hunger in Northern Cameroon
- Contributing to the socio-economic well-being and sustainable development of our study area with the enhancement of agricultural productivity;
- Contributing to the protection of water-related ecosystems.

# CHAPTER 1: LITERATURE REVIEW

## Introduction

In this chapter, some concepts needed to better understand why particular attention is paid to water quality and water quantity in a watershed are defined. Also, some methods used in other regions of the world for water quality assessment (for domestic and agricultural purposes), ground-water recharge estimation and projection of population (water demand) are explained. At the end, water treatment techniques for water quality improvement are presented.

## 1.1. WATER SECURTY

Water security can be defined as the availability of, and the access to water sufficient in quantity and quality to meet the production, livelihood and health needs of populations, together with an acceptable level of water-related risks (Calow et al.,2011). Being highly impacted by climate changes trough disturbances in precipitation regimes, the most common areas subject of study for water security are sub-Saharan Africa and South Asia. Here, population growth (hence water demand) is high and water scarcity is foreseeable.

### 1.1.1. Water resources

Known as the "science of water", hydrology broadly refers to the study of water as it occurs above, on or below the Earth's surface as water vapour, precipitation, streamflow, soil moisture and groundwater (Finkl,1984). It includes the study of the occurrence of water, its properties, its distribution and circulation and also its effects on the living beings and their surroundings. Talking about its occurrences, five (05) types of water sources were analysed for this study:

- ***River***: A river is a ribbon-like body of water that flows downhill from the force of gravity. A river can be wide and deep, or shallow enough for a person to wade across. Some rivers flow year-round, while others flow only during certain seasons or when there has been a lot of rain.
- ***Well***: A water well is defined as an excavation or structure created in the ground by digging, driving, boring, or drilling to access groundwater in underground aquifers. The well water is drawn by a pump, or using containers, such as buckets, that are pulled mechanically or by hand. Wells can vary greatly in depth, water volume, and water quality. Well water typically contains more minerals in solution than surface water and may require treatment to soften the water.

- ***Spring****:* A spring is a natural discharge point of subterranean water at the surface of the ground or directly into the bed of a stream, lake, or sea. Water that emerges at the surface without a perceptible current is called a seep. Wells are holes excavated to bring water and other underground fluids to the surface
- ***Borehole****:* A hole drilled in the earth to explore for or release oil, gas, water, etc. or to study the crust of the earth.
- ***Lake****:* A lake really is just another component of Earth's surface water. A lake is where surface-water runoff and groundwater seepage have accumulated in a low spot, relative to the surrounding countryside.
- ***Watershed:*** A catchment is a basin shaped area of land, bounded by natural features such as hills or mountains from which surface and sub-surface water flows into streams, rivers and wetlands. Water flows into, and collects in, the lowest areas in the landscape. The amount of water carried by a stream, the shape of the channel, the chemical composition of its water, and its ability to support life are determined by its catchment. Water quality in many stream catchments and river basins is severely impacted by nutrient enrichment as a result of agriculture. Water-resource managers worldwide are considering the potential role of riparian zones and floodplain wetlands in improving stream-water quality, as there is evidence at the site scale that such wetlands are efficient at removing nutrients from through-flowing water (Verhoeven et al., 2006)[1].

### 1.1.2. Evolution of water demand

Earth’s surface is made of soil (30%) and water (70%) but the largest quantity of this water is not immediately accessible or usable by humans. In fact, only 0.5% of the total water on Earth is readily available for human use (Baker et al., 2016). Moreover, water demand has been increasing worldwide by about 1% per year since the 1980s and is expected to continue increasing at a similar rate until 2050, accounting for an increase of 20 to 30% above the current level of water use (UN Water, 2019). This is a consequence of population growth and industrialization.

According to WHO (2015), people have access to water when they directly have it home or need less than 30 minutes to bring it home. In 2000, approximately 19% of the world population did

[1] Assessment of the impacts of the sugar producing company (SOSUCAM) on the quality of water resources in Mbandjock, Cameroon;2017, TANTAN Bongsiysi

not have access to water. To meet up this water demand, humans are mining water resources. This stress on water resources leads to land subsidence, saline water intrusion in agricultural farm land and water pollution.

The impact of this situation is being felt more and more with climate change and desertification. An area is experiencing water stress, water scarcity and absolute scarcity when annual water supplies drop below 1700m$^3$, 1000m$^3$ and 500m$^3$ per person per year respectively. With its fast-growing population, sub-Saharan Africa has the largest number of waters stressed countries of any region (UN-Water, 2014). In Cameroon for instance, only 1% of the population is subscribed in the cooperation and the aquatic resources estimated at 18500m$^3$ per year are abundant but their exploitation both in urban and rural areas is increasing (Ajeagah & Bissaya, 2017).

### 1.1.3. Estimation of the population

Population projection is a tool for forecasting the population up to a defined horizon. There are 2 main methods of population projection: component methods and ratio methods. Component methods consider 3 components which are fertility, mortality and migration, while ratio methods project population using mathematical functions applied to population size (Pelletier & Spoorenberg, 2016). Component methods are more precise but require many data for each component. So, ratio methods are preferable for extrapolation of population in time. They are generally applied to figure the total population of a locality. Mathematical models of population estimation fit to localities where population growth is fairly regular or only data available is the population size. Among them are:

- <u>Linear growth model</u>

The assumption made here is that the absolute amount of change (Δ) per unit time (year, month, week, day...) is constant but the variation is experienced only at the end of a unit of time. Here, population at the target time ($P_t$) is computed as:

$$P_t = P_0 + \Delta \mathrm{t} \qquad (1)$$

With

$$\Delta = (P_0 - P_b)/y \qquad (2)$$

Where:

$P_0$ = population in the launch year; $P_b$ = initial population (base period); y= number of years in the base period; t= number of years in the projection (between the launch and the target years).

- Geometric growth model

It guesses that population will change by the same percentage rate per unit time as during the base period. This change occurs at discrete intervals and the $P_t$ is equal to:

$$P_t = P_0 * (1 + a)^t \tag{3}$$

With

$$a = (\frac{P_0}{P_b})^{1/y} - 1 \tag{4}$$

Where:

$P_0$= population in the launch year; $P_b$= initial population (base period), y= number of years in the base period, t= number of years in the projection (between the launch and the target years), a= average annual geometric rate of change

- Exponential growth model

This model is similar to the geometric growth but the change occurs continuously. Here, the target population is:

$$P_t = P_0 * e^{a*t} \tag{5}$$

With

$$a = \left[ln\left(\frac{P_0}{P_b}\right)\right]/y \tag{6}$$

Where:

$P_0$= population in the launch year; $P_b$= initial population (base period); y= number of years in the base period e= base of the system of natural logarithms t= number of years in the projection (between the launch and the target years); a= average annual exponential rate of change.

- Logistic growth model

In the logistic growth model, population growth exhibits a "S" shape and presents a behaviour gradually adopted by the population. Population here is computed as:

$$P_t = \frac{a}{[1+b(e^{-c*t})]} \tag{7}$$

Where a, b and c are the parameters determined when population is known at 3 different times. "a" is the upper asymptote b and c define the shape of the logistic curve t is the time.

### 1.1.4. Water scarcity

Water scarcity can refer to scarcity in availability due to physical shortage, or scarcity in access due to the failure of institutions to ensure a regular supply or a lack of adequate infrastructure

(WHO, 2017). It is both a natural (climate change) and man-made (agriculture, population growth, pollution) phenomenon resulting in people lacking water and wetlands disappearing (WWF, 2020).

Two-thirds of the global population are experiencing severe water scarcity at least 1 month of each year (Mekonnen & Hoekstra, 2016), which is expected to be further aggravated by increasing demands and impacts of climate change (Palmer et al.2008; Oki et al. 2014). However, this trend can be reduced with the implementation of integrated water resources management. An example can be taken with the implementation of the MDGs, especially n°7, which consists in reducing by half the number of people lacking access to water and sanitation by 2015.

Despite the progress registered these 15 last years, it seems to be difficult to achieve the SDG n°6 (guarantee access to water and sanitation to all and sustainable management of water resources) for a non negligeable portion of the world population. In 2015, 11% of the world population (844million of people) still don't have access to potable water (WHO/UNICEF, 2017).

## 1.1.5. Vulnerability of water resources

### 1.1.5.1. Water pollution and contamination

Pollution is the degradation of an ecosystem by the introduction, generally human, of substances or radiations altering in a more or less important way the functioning of this ecosystem (OECD, 1974). Water pollution is the result of human activities while contamination may be natural. There are two types of pollution: point source (harmful substances are emitted directly into a water body) and non-point source (pollutant is transported to its last location).

An example of a point source of water pollution is the release of municipal wastewater discharging effluent directly into a river. An example of a nonpoint-source of water pollution is when fertilizer from a farm field is carried into a stream by the rain (run-off). Point sources can be easily monitored compared to non-point sources which appear to be the main contributor to water resources degradation in rural areas of developing countries.

### 1.1.5.2. Vulnerability assessment

Vulnerability is the magnitude of losses resulting from a potentially damaging phenomenon. It comprises exposure (the values and lives present at the respective location) and their lacking capability of resistance or defence to the threat. Vulnerability is an aggregate measure of human welfare that includes environmental, social and economic exposure to a range of harmful perturbations. (MED

WS&D WG, 2007). Vulnerability is a general planning and decision-making tool. It aims at regulating, monitoring, educating and developing policies for areas that need more protection of groundwater quality. Vulnerability of water sources to pollution is higher in recharge areas, permeable land and developing countries where there is neither implementation of a sanitation system nor water treatment facilities. Different methods can be used to assess groundwater vulnerability. Among them, index and overlay methods which generally require limited basic data used in regional studies and which usually cover extensive areas (Abdullahi, 2009; Anim-Gyampo, 2018).

The seemingly uncertainties that accompany intrinsic vulnerability mapping, apart from requiring sensitivity analysis to reduce the degree of subjectivity may further require practical or actual evidence as a support (Barber et al., 1993). Thus, in most cases, vulnerability assessment done by using index-and-overlay methods must be verified, and the most widely used approach is to compare the vulnerability map with the actual occurrences of some common pollutants in groundwater, typically such as nutrient pollution nitrates (Atiqur, 2008; Mamadou et al., 2010; Kumar et al., 2009 and Gad et al., 2015).

## 1.2. WATER QUALITY ASSESSMENT

### 1.2.1. Hydrochemistry

Hydrochemistry is the study of chemical interactions between water body and its surrounding (geosphere, atmosphere and biosphere). Knowledge of hydro-chemical processes in groundwater helps to identify the relationship between geochemical processes and groundwater quality as well as to understand the hydro-chemical evaluation of groundwater (Li et al., 2018). Furthermore, hydrochemistry is an important tool to assess anthropogenic effects on water sources.

It classifies water into different facies according to its physico-chemical characteristics. The parameters studied to assess water quality are turbidity, colour, odour, alkalinity, major ions, electrical conductivity, total dissolved solids etc. Graphical representation of these parameters as function of others provides useful diagrams in water chemistry analysis like those presented below:

- **Stiff diagrams** (Stiff, 1951)

It is a graphical representation of chemical analyses, widely used by hydrogeologists and geochemists to display the major ion composition of a water sample. It can be used to help visualize ionically related waters from which a flow path can be determined, or; if the flow path is known, to show how the ionic composition of a water body changes over space and/or time (Drever, 2002).

- **Piper diagram** (Piper, 1944)

The Piper plot is a specialised plot for water classification. Compositional data (the relative molar amounts) of cations and anions are plotted into the ternary (triangular) coordinate systems, which as a second step are projected onto the central prism. This methodology may be seen as a dimension-reducing technique that reduces the original concentrations of seven major constituents (7 dimensions) into a two-dimensional visualisation (the central prism), where dominating ions may be distinguished (Tröjbom et al., 2008)

- **Bivariate plot**

It is one of the simplest forms of quantitative (statistical) analysis. It involves the analysis of two variables (often denoted as X, Y), for the purpose of determining the empirical relationship between them. Bivariate analysis can be helpful in testing simple hypotheses of association (Earl, 2009).

- **Wilcox diagram**:

Wilcox diagram is a graphical representation of the sodicity hazard (computed as Sodium Absorption Ratio or Sodium percentage) as a function of salinity (Electrical conductivity). It was created in 1955 by the USDA to check the quality of water for irrigation. Nowadays, it is generally associated to USSL classification of water.

- **Gibbs diagram**

Simple plot of the TDS versus the weight ratio (µM/µM) of $Na^+/(Na^++Ca^{2+})$ or $Cl^-/(Cl^-+HCO_3^-)$ and widely used to establish the relationships between the water composition and the lithological characteristics of the aquifer (Gibbs, 1970).

### 1.2.2. Hydrobiology

Hydrobiology studies the living forms in water bodies. Life started in water with the first organic matter and is still naturally present there as phytoplankton and macrophytes. Other forms of aquatic biota are a consequence of an excess of waste released without treatment: algae, viruses and other pathogens. Hence, hydrobiology is a key science for water quality assessment.

Sensitive animals are used to obtain the biological characteristics of water (protozoa, viruses, macrophytes, bacterias) and the conditions of their environment (for example DO, BOD and COD). They are grouped in three (03) categories: pollution sensitive (mayflies, stoneflies, caddisflies), somewhat pollution tolerant (cuds, dragonflies, damselflies) and pollution tolerant (aquatic worms, midge larva). The poor quality of water on that plan is a source of water borne diseases like cholera, schistomiasis and gastrointestinal problems.

Biological monitoring of water can be carried out at two different levels: the response of individual species to changes in their environment and the response of biological communities to changes in their environment.

# 1.3. WATER USES AND STANDARDS

Water is a polar molecule of formula $H_2O$ able to dissolve other polar molecules and ions like sugars and salts. Liquid water naturally occurs as surface (river, lake and stream) and groundwater (confined and unconfined aquifer). Sub-surface water is reached and used through boreholes, wells and springs. Water quality is threatened by natural (incongruent dissolution of rocks minerals for example) and anthropogenic activities releasing waste (solid, liquid or gaseous) into waterbodies, especially surface water. Hence, the number of people relying on groundwater increases every day. In order to assure human health, standards have been established for water quality for each of its purposes. Its use is conditioned by its physico-chemical, biological and radiological characteristics (Diersing & Nancy, 2009). The most common parameters on which water quality is studied are: major cations ($Mg^{2+}$, $Ca^{2+}$, $Na^+$, $K^+$), major anions ($HCO_3^-$, $SO_4^{2-}$, $NO_3^-$, $Cl^-$), pH, dissolved oxygen, salinity, conductivity, total dissolved solids (TDS), colour, turbidity, metals (Pb, Cu, Zn, Co, Cd, Cr just to name a few), temperature and redox potential.

## 1.3.1. Irrigation

Irrigation is the practice of providing a controlled amount of water for agricultural purpose. With the increasing problem of water scarcity, farmers started using wastewater for their crops and the result was quite satisfactory. However, both soil and groundwater quality and crop health problems arose. The quality of irrigation water is related to the yield and quality of crops, maintenance of soils productivity and protection of the environment (Jalal & Kamel, 2012). According to Wilcox (1995), the most important parameters in determining the quality of irrigation water are: concentration of soluble salts, relative proportion of sodium to other principal cations and under some condition, bicarbonate concentration as related to the concentration of calcium and magnesium. Nowadays, several norms and classifications are used for irrigation water classification but they could have different conclusions. This problem may be solved by introducing an additional or corrective procedure for irrigation water assessment (Lijklema, 1995).

#### 1.3.1.1.Salinity hazard

Salinity hazard is the total content of soluble salts. The higher the salinity, the higher the osmotic pressure of the soil solution. Generally, salinity is measured with electrical conductivity in µS/cm or Total Soluble Salts (TSS) in ppm. According to Gebrerufael et al (2019), when electrical conductivity is high, water intake by plant significantly decreases and the productivity is also considerably reduced. The guidelines for these values are presented in Table 1.

**Table 1**:Salinity hazard of irrigation water

| **Hazard** | **Dissolved salt content** | |
|---|---|---|
| | **ppm** | **EC (µS/cm)** |
| **None**–Water for which no detrimental effects will usually be noticed | 500 | 750 |
| **Some**–Water that may have detrimental effects on sensitive crops | 500-1000 | 750-1500 |
| **Moderate**–Water that may have adverse effects on many crops, thus requiring careful management practices | 1000-2000 | 1500-3000 |
| **Severe**–Water that can be used for salt tolerant plants on permeable soils with careful management practices | 2000-5000 | 3000-7500 |

Source: Follett & Soltanpour (2002); Bauder et al. (2011)

#### 1.3.1.2. Sodium hazard

Sodium is a contributor to salinity measured with the Sodium Adsorption Ratio (SAR). It is also a major contributor to soil structure degradation. This breakdown in the soil physical structure, results in the dispersion of soil clay and that causes the soil to become hard and compact when dry, and increasingly impervious to water penetration (due to dispersion and swelling) when wet. Although non-essential for most plants, $Na^+$ can be beneficial to plants in many conditions, particularly when $K^+$ is deficient (Maathuis, 2013). In irrigation water, it can be adsorbed by roots and foliage causing $Ca^{2+}$ and $Mg^{2+}$ deficiency in plants. Hence, the relative concentrations of $Na^+$ to $Ca^{2+}$ and $Mg^{2+}$ are generally used to assess sodicity hazard through the following indices:

***a. Sodium Adsorption Ratio***

Sodium Adsorption Ratio (SAR) is an irrigation water quality parameter used in the management of sodium affected soils. It predicts the potential accumulation of sodium into water. This enables to determine whether the sodium contained in water is not in excess by comparing its concentration to $Ca^{2+}$ and $Mg^{2+}$ using the formula in Equation 8.

$$\text{SAR} = \frac{Na^{+}}{\sqrt{\frac{Ca^{2+}+Mg^{2+}}{2}}} \quad (8)$$

Based on SAR, water is considered excellent, good, fair and unsuitable for agriculture if SAR values are < 10, between 10 and 18, between 18 and 26 and >26, respectively (USSL, 1954). However, its effect on crops is highly dependent on electrical conductivity. This justifies the classification of irrigation water by USSL (1954) and modified by Shahid & Mahmoudi (2014) in 16 categories from C1-S1 to C4-S4 where the indices 1 to 4 represent the hazard level as shown in Table 2.

**Table 2**: USSL irrigation water classification

| Hazard | Classes | Range | Meaning |
|---|---|---|---|
| Salinity expressed as EC (µS.cm$^{-1}$) | C1 | 100-250 | Low |
| | C2 | 250-750 | Medium |
| | C3 | 750-2250 | High |
| | C4 | > 2250 | Very high |
| Sodicity expressed as SAR (mmoles.l$^{-1}$)$^{0.5}$ | S1 | < 10 | Low |
| | S2 | 10-18 | Medium |
| | S3 | 18-26 | High |
| | S4 | > 26 | Very high |

Source: US Salinity Laboratory Staff, (1954)

***b. Permeability Index***

A high permeability index (PI) is associated with subsurface structural features, which facilitate widespread contamination of groundwater (Singh et al., 2020). The concentration of $Ca^{2+}$, $Na^{+}$, $Mg^{2+}$ and $HCO_3^-$ influences permeability of soil profile (Singh et al., 2015). Hence, Doneen (1964) computed the permeability index (PI) as:

$$\text{PI} = \frac{Na^{+}+\sqrt{HCO_3^-}}{Ca^{2+}+Mg^{2+}+Na^{+}} \quad (9)$$

Doneen (1964) identified 3 classes of water based on PI. These are class I (>75% permeability), class II (25-75% permeability) and class III (up to 25% permeability). These classes are presented in the Doneen's chart as a function of the total ion concentration expressed in meq/l. Only water in class I and Class II are recommended for irrigation.

***c. Kelly Ratio***

Kelly's index (KR) is the ratio of $Na^+$ to the bivalent major cations ($Ca^{2+}$, $Mg^{2+}$) which are depleted when $Na^+$ is in excess in water (Kelly, 1963). Its formula is:

$$KR = \frac{Na^+}{Ca^{2+}+Mg^{2+}} \quad (10)$$

Water with KR <1, >1 and >3 indicate suitable water for irrigation, excess level of $Na^+$ in water (some plants can be affected by the sodium content in the soil) and unsuitable water for irrigation, respectively (Ramesh & Elango, 2012; Das & Nag, 2015).

***d. Percentage sodium***

It is the ratio of $Na^+$ concentration to the sum of all the major cations of a water sample. $Na^+$ reacts with $CO_3^{2-}$ and forms alkaline soils, while $Na^+$ reacts with chloride and forms saline soils. Sodium-affected soil (alkaline/saline) retards crop growth (Todd, 1980). If concentration of $Na^+$ in irrigation water is high, then the ions tend toward the clay particles, by removing $Ca^{2+}$ and $Mg^{2+}$ ions through a base-exchange reaction. This exchange process in soil reduces water movement capacity (Rawat et al., 2018). In this condition, air and water cannot move freely or restricted under wet conditions, and such soils have become hard when dry (Collins & Jenkins, 1996; Saleh et al., 1999). The %Na values are calculated as shown in Equation 11.

$$\%Na = \frac{Na^+ + K^+}{Ca^{2+}+Mg^{2+}+Na^+ + K^+} * 100 \quad (11)$$

**1.3.1.3. Carbonate hazard**

Waters high in carbonates ($CO_3^{2-}$) and bicarbonates ($HCO_3^-$) will tend to precipitate calcium carbonate ($CaCO_3$) and magnesium carbonate ($MgCO_3$) when the soil solution becomes concentrated through evapotranspiration. This means that the SAR value will increase, and the relative proportion of sodium ions will become greater. This situation, in turn, will increase the sodium hazard of the soil-water to a level greater than indicated by the SAR value and is used to predict additional sodium hazard (Zaman et al., 2018; Ako et al., 2011). This evaluation is done using the Residual Sodium Carbonate (RSC) (Equation 12) and Residual Sodium Bi-Carbonate (RSBC) (Equation 13) classified as shown in Table 3.

$$RSC = (CO_3^- + HCO_3^-) - (Ca^{2+} + Mg^{2+}) \quad (12)$$

$$RSBC = HCO_3^- - Ca^{2+} \quad (13)$$

**Table 3**:Residual Sodium Carbonates (RSC) and suitability of water for irrigation

| RSC (meq/l) | RSBC (meq/l) | Suitability of water for irrigation |
|---|---|---|
| < 1.25 | <5 | Safe |
| 1.25–2.50 | 5-10 | Marginal |
| > 2.5 | >10 | Unsuitable |

Source: Eaton (1950); Wilcox et al. (1954); Gupta & Gupta (1987)

#### 1.3.1.4. Element toxicity

A part from sodium, two other elements are known to have adverse effects on crop productivity: boron and chloride. Both are essential for plant growth but a small amount is required otherwise, they can be source of plant toxicity or ionic imbalance in plants.

***a. Boron***

Boron toxicity symptoms first appear on older leaves as yellowing, spotting, or drying of leaf tissues at the tips and edges (Zaman et al., 2018). The drying and chlorosis often progresses toward the centre of the leaf, between the veins as boron accumulates over time (Ayers & Westcot, 1985). Wilcox (1960) presented three classes of crops with regard to boron toxicity: sensitive, semi-tolerant and tolerant crops which presents a negative response to chloride concentrations varying from 0.3 mg/l to 1 mg/l; 1 mg/l to 2 mg/l and 2 mg/l to 4 mg/l, respectively.

***b. Magnesium***

Magnesium and calcium are the main contributors to water hardness which is a limiting factor to nutrients intake by plants. Moreover, $Mg^{2+}$, present in water would adversely affect soil quality rendering it unfit for cultivation (Venugopal et al., 2007). If Magnesium Adsorption Ratio (MAR) is < 50, then water is safe and suitable for irrigation (Szabolcs & Darad, 1964).

$$MAR = \frac{Mg^{2+}}{Ca^{2+}+Mg^{2+}} \quad (14)$$

Most of these indices were used in Cameroon to assess the suitability of water used for cropland areas. In 2011, Ako et al. showed that water of the banana plain (Mbanga, Njombe, Penja) of the Cameroon Volcanic Line was excellent for agricultural uses using EC with almost 99% of samples having EC < 250µS/cm, 97% of samples with SAR < 10 and %Na < 20 and finally 95.5% of samples with RSC < 1.25. Recently, Aguiza et al. (2020) assessed water quality for agricultural use in rice farmland of Maga in the Far North region of Cameroon. The results obtained were satisfactory on the basis of PI < 118.67, but magnesium hazard was quite high (MAR > 50).

***b. Chloride***

In high concentrations, chloride inhibits plant growth (salinity). Its effects are similar to those of boron but appear first at the leaf tips (which is a very common symptom for chloride toxicity) and progresses from the leaf tip back along the edges as severity of the toxic effect increases. Table 4 shows the different chloride levels with their corresponding effects.

**Table 4**:Chloride levels of irrigation waters and their effects on crops

| **Effects on crops** | **Chloride concentration** | |
|---|---|---|
| | **meq/l** | **ppm** |
| Generally safe for all plants | < 2 | < 70 |
| Sensitive plants usually show slight to moderate injury | 2-4 | 70–140 |
| Moderately tolerant plants usually show slight to substantial injury | 4-10 | 141–350 |
| Can cause severe problems | > 10 | > 350 |

Source: Ludwick et al., (1990); Bauder et al. (2011)

### 1.3.2. Consumption

According to Mitchell et al. (1945), the brain and heart are composed of 73% water, and the lungs are about 83% water. The skin contains 64% water, muscles and kidneys are 79%, and even the bones are watery: 31% which is totally estimated at 60% of the human body. This water is used for the metabolism; released through urine and transpiration and should constantly be consumed to be replaced.

Water is known as a universal solvent containing different ions necessary for animals (human) and plants' health. Those ions are $Ca^{2+}$, $K^{+}$, $F^{-}$, $H_2PO_4$-, $Na^{+}$, $Mg^{2+}$, $Cl^{-}$, iron (II), chromium (III), copper (II), zinc, iodide, bicarbonate, hydrogen ion, manganese, molybdenum, and selenium. Otherwise, water will be soft and cause weakness of the immune system and body. Nevertheless, high concentration of these electrolytes brings about health problems like skin damages or problems with circulatory systems (for arsenic), kidney damage (for cadmium), bone disease and moulted teeth in children (for fluoride) and hair or fingernail loss, numbness in fingers and toes and circulatory problems (in selenium) (USEPA, 2009). According to World Health Organisation, good quality water should have the characteristics presented in Table 5.

**Table 5**:WHO guidelines for drinking water

| Chemicals | Guidelines (mg/l) | Health significance |
|---|---|---|
| Arsenic (As) | 0.01 | Can cause cancer and skin lesions. It has also been associated with cardiovascular disease and diabetes. In utero and early childhood exposure, it has been linked to negative impacts on cognitive development and increased deaths in young adults |
| Barium (Ba) | 0.7 | Breathing difficulties, increased blood pressures, heart rhythm changes, stomach irritation, muscle weakness, changes in nerve reflexes, swelling of brains and liver, kidney and heart damage |
| Boron (B) | 0.5 | Can infect the stomach, liver, kidneys and brains and can eventually lead to death. When exposure to small amounts of boron takes place, irritation of the nose, throat or eyes may occur |
| Bromate (Br) | 0.01 | Malfunctioning of the nervous system and disturbances in genetic materials. |
| Cadmium (Cd) | 0.003 | Accumulates in kidneys, where it damages filtering mechanisms |
| Chromium (Cr) | 0.05 | May cause heart conditions, disruptions of metabolisms and diabetes |
| Cyanide (C) | 0.07 | |
| Fluoride ($F^-$) | 1.5 | Immediate effects of abdominal pain, excessive saliva, nausea and vomiting. Seizures and muscle spasm may also occur. Dental and bones growth |
| Lead (Pb) | 0.01 | Disruption of the biosynthesis of haemoglobin and anaemia; A rise in blood pressure; Kidney damage; Miscarriages and subtle abortions; Disruption of nervous systems; Brain damage; Declined fertility of men through sperm damage; Diminished learning abilities of children; behavioural disruptions of children, such as aggression, impulsive behavior and hyperactivity |
| Nitrate ($NO_3^-$) | 50 | |
| Uranium (U) | 0.015 | Damage to the central nervous system; Dementia; Loss of memory; Listlessness; Severe trembling |
| Chloride ($Cl^-$) | 250 | Regulate osmotic pressure and the body’s water content, enable the secretion of stomach acid, |

| | | |
|---|---|---|
| Copper ($Cu^{2+}$) | 2 | Irritation of the nose, mouth and eyes and it causes headaches, stomach-aches, dizziness, vomiting and Diarrhoea. Intentionally high uptakes of copper may cause liver and kidney damage and even death |
| Iron (Fe) | 0.3 | Essential part of haemoglobin; the red colouring agent of the blood that transports oxygen through our bodies. May cause conjunctivitis, choroiditis, and retinitis if it contacts and remains in the tissues |
| Manganese (Mn) | 0.1 | |
| Potassium (K+) | | Transmit nerve signals, and contract muscles including the heart, etc. |
| Magnesium (Mg2+) | | Contract muscles, form bones and teeth, activate enzymes, etc. |
| Sodium ($Na^{+}$) | 200 | Regulate osmotic pressure and the body's water content, transmit nerve signals, contract muscles, etc. |
| Calcium ($Ca^{2+}$) | | Transmit nerve signals, contract muscles, form bones and teeth, clot blood |
| Sulphate ($SO_4^{2-}$) | 250 | Heart damage; Effects on eyes and eyesight; Reproductive failure; Damage to immune systems; Stomach and gastrointestinal disorder; Damage to liver and kidney functions; Hearing defect |
| Turbidity | 5NTU | |
| TDS | 1000 | |
| Zinc ($Zn^{2+}$) | 3 | Helps your immune system and metabolism function. Zinc is also important to wound healing and your sense of taste and smell. With a varied diet, your body usually gets enough zinc. |

Source: WHO (2004)

Whatever the use of water, discharges are produced and must be treated: this is sanitation.

## 1.4. SANITATION

Sanitation is a process consisting in making healthy, by eliminating products, substances or waste likely to harm the health of man and his environment. It is therefore maximum reduction of the harmful effects of liquid discharges from human activities on the environment. In the case of liquid sanitation, the objective is to bring waste water into compliance before it is reintroduced into the water cycle (in watercourses).

Wastewater is of different types and contains different pollutants depending on its origin. Wastewater from domestic use contains nutrients and heavy metals that contribute to the increase in the conductivity of raw water. This situation is more alarming in developing countries where only 71% of urban areas versus 39% of rural areas are treated.

# 1.5. GROUNDWATER RECHARGE AND EXPLOITATION

## 1.5.1. Recharge estimation

### 1.5.1.1. Darcy's method

According to Darcy's law, the flux of a fluid is proportional to its gradient head and the hydraulic conductivity of the porous media it is passing through (Equation 15).

$$Q = -k * A * \frac{dh}{dl} \tag{15}$$

Where Q is the rate of water flow; K is the hydraulic conductivity; A is the column cross-section area and dh/dl indicate a hydraulic gradient.

Similarly, the recharge which is also a flux can be computed as:

$$R = \frac{[-k(h).dH]}{[dz]} = -k(h) * (d/dz)(h+z) = -k(h) * [(dh/dz)+1] \tag{16}$$

Where k(h) is the hydraulic conductivity (unsaturated conditions); H is the total head; h is the metric potential head; z is the distance between the two points where hydraulic head is measured.

### 1.5.1.2. Numerical model

This model uses software like HYDRUS 1D to obtain a relation among aquifers characteristics (precipitation, surface estimation, runoff, percolation, land use, topography...) and the recharge. Hence, on the basis of water balance equation, numerical models can be used to assess groundwater recharge. Errors may arise from the approximation made to obtain the aquifer characteristics from previous works.

### 1.5.1.3. Tracer techniques

There are different types of tracers that can be used to compute recharge: heat tracer, applied tracers ($Br^-$, $I^-$,$^3H$), historical tracers ($^3H$,$^{36}Cl$), environmental tracers ($Cl^-$, $NO_3^-$,$^3H$,$^{18}O$) and fluorescent tracers (rhodamine WT, fluorescent) (Vries et al., 2002; Scalon et al., 2002; Cervi et al., 2014). Natural tracers commonly used in recharge studies are $^3H$, $^{14}C$, $^{15}N$, $^{18}O$, $^2H$, $^{13}C$, $^{36}Cl$. $^3H$, $^{14}C$ and $^{36}Cl$ are radioactive with half-lives 12.3, 5730 and $3 \times 10^5$ years respectively (Elliot, 2014). Chlorine

36 has the highest half-life and is good for the analysis of areas with low recharge rates. $^{3}H$, $^{2}H$, $^{18}O$ used for water motion analysis and groundwater origin. According to (Qinghua et al., 2016), the methods of tracing and modelling were considered as the most valuable methods in the world over the past 20 years, especially chlorine mass balance (CMB).

According to Lihe et al., (2011), CMB is the most reliable method in arid and semi-arid regions, especially where $Cl^-$ originates from precipitation. It assumes that chloride at the surface equals the flux of chloride carried beneath the root zone by infiltrating water. Then, it can be applied to areas where agriculture is practiced. The process is the following:

$$Peff \times (Clp + Cls) = R \times Clsw \tag{17}$$

Where:

$P_{eff}$ is effective precipitation (L/T) is the total precipitation deducted of the amount of runoff and evaporation; $Cl_p$, $Cl_s$ are the chloride concentrations of wet (precipitation) and dry deposition, respectively ($M/L^3/T$); $Cl_{sw}$ is the chloride concentration of soil water below the root zone ($M/L^3$).

The mean resident time of soil water can also be calculated according to the profile of chloride concentration. The time represented by chloride concentration at depth z is evaluated by dividing the total mass of soil water chloride from the surface to the certain depth d by the annual chloride flux at the soil surface.

### 1.5.1.4. Water Table fluctuation

In this method, the assumption is that the rise in the groundwater level in unconfined aquifer is only due to recharge water arriving at the water table. It is calculated as:

$$R = Sy * (\Delta h/\Delta t) \tag{18}$$

Where: R is the Recharge rate; Sy the Specific yield; Δh the Water table rise; Δt the Time within which rise dh take place.

The specific yield (Sy) is defined as the ratio of the volume of water that a saturated rock or soil will yield by gravity to the total volume of the rock or soil. This method is applicable for unconfined aquifers and the recharge rate must not be steady (only if the water table varies). According to Healy & Cook (2002), water table fluctuation method might be the most widely used method for recharge estimation.

### 1.5.2. Groundwater withdrawal

Groundwater is the world's most extracted raw material, with withdrawal rates currently in the estimated range of 982km$^3$/year (Margat & Van der Gun, 2013). In arid and semi-arid areas where surface water is scarce and inaccessible, it contributes to cover almost all the human needs for drinking water and domestic uses. Moreover, its good quality results in the enlargement of its application domains. In developing countries for instance, in addition to domestic well-being improvement, it has brought important benefits to the rural community including agricultural productivity (Foster, 2000).

However, groundwater exploitation results in the depletion of the aquifer reserves, the ingress of water of poor quality, significantly increased pumping costs, land subsidence, or depletion of river flows below acceptable rates (Khan & Mawdsley, 2009). In order to prevent these negative consequences, Lee (1915) recommends to withdraw groundwater at a "safe yield". This last corresponds to the limit to the quantity of water which can be withdrawn regularly and permanently without dangerous depletion of the storage reserve. In the late 1980s; this concept changed to that of "sustainable yield" of withdrawal with the aim of meeting the needs of present generations without compromising the ability of future generations to meet their own needs (UN-water, 1987). Hence, this includes the renewability of groundwater. For Alley et al. (1999), groundwater sustainability is the development and use of groundwater in such a way that it can be maintained for an indefinite time without undesired environmental, economic or social effects. This stage cannot be reached without the implementation of an adequate water resources management.

## 1.6. INTEGRATED WATER RESOURCES MANAGEMENT

Water Resources Management (WRM) is the process which includes all activities of planning, design, construction and operation of water resources systems. When it takes into consideration both natural aspect of water (physio-chemistry); spatial variation of water demand and availability; interaction between water basin and the interests of each of the stakeholder, it is called Integrated Water Resources Management (IWRM).

IWRM is a process which promotes the coordinated development and management of water, land and related resources in order to maximize the resultant economic and social welfare, paving the way towards sustainable development, in an equitable manner without compromising the sustainability of vital ecosystems (GWP, 2000). It is a promising approach in ensuring sustainable use of water resources and aims at focusing on proper usage and development of water resources, through efficient and environmentally sound manner which not only satisfy demands for water but also safeguard freshwater 9. This means the protection of raw water quality and avoidance of water mining compared to recharge for groundwater.

According to GWP (2008), IWRM has 9 main goals: secure water for people; secure water for food production; develop other job creating activities; protect vital ecosystems; deal with variability of water in time and space; manage water risks; create popular awareness and understanding; forge the political will to act and ensure collaboration across sectors and boundaries. Its implementation depends on national objectives and can be summarised as presented by Figure 1. To master these challenges, several tools such as vulnerability assessment are used by water managers.

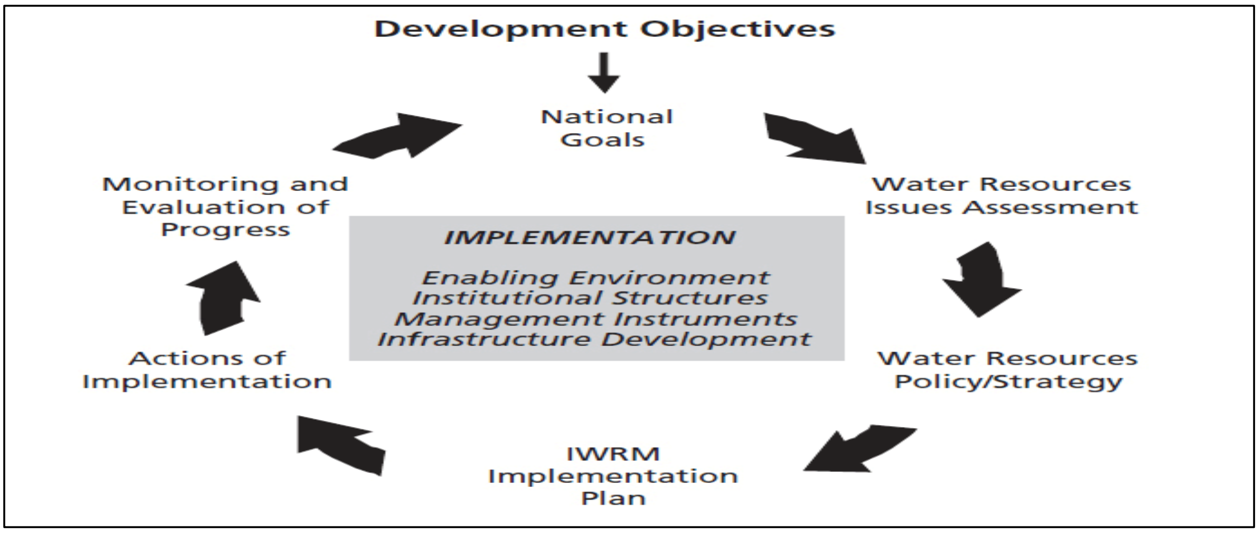


**Figure 1**:Stages in IWRM planning and implementation

The strength of integrated water resources management lies in its 04 principles, also known as the Dublin principles:

- **Principle N° 1:** Freshwater - a fragile and non-renewable resource - is essential for life, development and the environment and should therefore be managed in a way that brings together all stakeholders;
- **Principle N° 2**: Water resources management and development must involve users, planners and decision-makers at all levels;

- **Principle N° 3**: Women play a key role in the provision, management and preservation of water. This principle requires that special attention be given to women as they are more in contact with water resources than men;
- **Principle N° 4**: Water, used for multiple purposes, has an economic value and should therefore be recognised as an economic good. This principle is both a deterrent and a remedy as it limits anthropogenic contamination while providing the necessary compensation for damage to water resources.

# 1.7. WATER QUALITY IMPROVEMENT

## 1.7.1. Treatment techniques

The need of science-based solutions for uncontaminated water provisioning results in several water treatment methods to address the problem. Of course, the suitable technology is based on raw water characteristics (nature, extent of contamination...); infrastructure (power, manpower, availability of chemicals), affordability/ cost as well as acceptability (Sharma & Bhattacharya, 2016). This study concerns two (02) water uses which are irrigation and drinking. The pollutants released by these activities and the natural environment are: nutrients ($NO_3^-$, $NO_2^-$, $PO_4^-$), pesticides, salts ($SO_4^{2-}$ , $Cl^-$, $K^+$, $Na^+$, $Ca^{2+}$, $HCO_3^-$), sediments, organic matter, pathogens, metals (Se, Pb, Cu, Hg, As, Mn...) and emerging pollutants. These pollutants can be removed using the following methods:

### 1.7.1.1. Precipitation and coagulation

It consists of the addition of a chemical substance capable of reacting with the contaminant to remove it by forming a solid compound called precipitate. It is applied to reduce heavy metals (Cr, Cu, As, Al), hardness, phosphorous, fluorine and dye levels in water (Sharma & Bhattacharya, 2017). This technique has the advantage that the treatment is done on-site, it is efficient on heavy metals, calcium, magnesium and natural organic pollutants. However, due to the constant need of chemicals (cost), management of by-products and sludge, this method is not recommended for developing countries (Sharma & Bhattacharya, 2017).

### 1.7.1.2. Distillation

Distillation is a separation technique based on the differences in boiling point. The boiling point depends on the concentration of the components present. The energy added to the system raises vapour until it reaches its surrounding pressure and differences of volatility in the mixture causes distillation to occur. It is effective on inorganic substances (lead, cadmium, magnesium), bacteria and organic substances with boiling points higher than 100°C. Hence, additional treatments are needed after distillation. Even if this method removes several contaminants, it is expensive and treats water mainly for industrial purpose.

#### 1.7.1.3. Adsorption

It is the physical process of separation in which dissolved contaminants adhere to the porous surface of solid particles (Jiuhui, 2008). Following this process, the contaminant (adsorbate) is trapped onto surface of the adsorbent material. The adsorbent material should be as porous as possible (in the range of nanometre). Adsorption can originate from Vander Waals forces or covalent forces. One of the most common isotherms used to evaluation water contaminants adsorption is Freundlich (1909) expressed as:

$$\frac{x}{m} = k * Ce^{1/n} \qquad (19)$$

Where: x is the mass of solute adsorbed; m is the mass of the adsorbent; Ce is the equilibrium concentration of solute and k, n are the experimental constants.

The following materials are used as adsorbent:

***a. Activated carbon***

It is common coal treated at high temperature (1300°C) without (or with a reduce amount of) oxygen (physical method) or chemical activating agents (phosphoric acids, zinc chloride so that part of it are oxidized in $CO_2$ and steam. There are two (02) forms of activated carbon commonly used: granular activated carbon (GAC) and powdered activated carbon (PAC). Only GAC can be reused (reactivated). GAC and PAC are cost effective, trap VOCs, chlorine, THMs and improve organoleptic characteristics of water (colour, odour). The limitation of activated carbon comes from the fact that frequent filters change is required as impurities clog on the GAC and fine particles can remain in water.

***b. Activated alumina***

Also known as calcined alumina or alumina oxide ($Al_2O_3$), it is prepared at low temperature (300-600°C) with aluminium hydroxide ($Al(OH)_3$). It is non soluble in water and exists as activated alumina sorbent, activated alumina desiccant and activated alumina catalyst carrier. Activated alumina adsorbs $As^{5+}$, $PO_4^{3-}$, $Cl^-$, $F^-$, Se, Sb, Pb and Br from water but is useless to treat raw water for consumption.

#### *c. Zeolite*

Zeolite are aluminosilicates with tetrahedral network of silicon combined with oxygen atoms and some of the silicate atoms are replaced by aluminium. They are good both for adsorption and ion exchange. Adsorption with zeolite is fit for the treatment of water polluted by inorganic anions, radionuclides, humic substances and microorganisms. In addition to its cost, its accumulation in water causes a problem of sludge management.

#### *d. Silicate gel*

Silica gel is an amorphous hard glass-like granules or beaded material made of silicon dioxide ($SiO_2$). It is a naturally occurring mineral which is purified and processed. According to Heckel & Seebach (2000), silica gel is a high-capacity adsorbent with fine pores on the surface and can be used especially as desiccant, moisture-proof, rust inhibitor as well as catalysis.

Various silica gels exist and their uses depend on their characteristics: surface area, pore volume, strength, silica concentration, temperature, pH, activation temperature (Iler, 1979). Using silica gel as adsorbent has the advantages that the process is well performed because of the high surface area and porosity; it is neither toxic nor corrosive. However, the preparation of the process needs precise control and maintenance.

### 1.7.1.4. Bioremediation

#### *a. Phytotreatment*

Phytoextraction involves metal accumulation into the harvestable parts of the roots and the above ground shoot. Rhizo-filtration indicates the absorption, precipitation and concentration of toxic metals from polluted effluents. Phyto-stabilization is a process in which mobility of heavy metals is reduced through the use of tolerant plants, whereas phyto-transformation/phytodegradation is the process in which contaminants can be eliminated via phytodegradation or phyto-transformation by plant enzymes or enzyme co-factors (Sharma & Bhattacharya, 2016).

#### *b. Vegetated filter strips*

They are vegetated surfaces designed to treat sheet flow from adjacent surfaces (Dillaha et al.1989; Delgado et al.1995). It works on plant nutrients and pesticides, through plant uptake (adsorption) and can remove pathogens. The critical steps of this method are the selection of the crop and the design.

#### c. *Biologically active carbon (BAC) filtration*

BAC is another form of activated carbon consisting of microbial cells, either immobilized on the surface of the GAC (substratum) or embedded in an extracellular microbial organic polymer matrix (Ghosh et al., 1999; Lawrence & Tong, 2005). This process is quite similar to adsorption in GAC media even if bio-degradation can also operate. Biomass control is imperative.

### 1.7.2. Adsorption onto clay

Adsorption is considered the most simple and efficient method to remove pollutants from water sources (Srinivasan, 2011; Bhatnagar et al., 2008). It has numerous economic advantages and can be applied with cheap and affordable materials. This method can either be natural or man-made. Among the natural and most effective adsorbent are zeolite and clay which have high degree of open pores and surface area. Zeolites consist of interconnected aluminosilicate building blocks of $AlO_4$ and $SiO_4$ tetrahedral units, which form three-dimensional framework with linked channel systems and well defined micropores (Guerra-Nunez et al., 2017). As for clays, these are hydrated aluminosilicate whose chemical formula is $Al_2O_3 \cdot 2SiO_2 \cdot 2H_2O$ with properties such as the exchange capacity, good catalytic support, large surface area, mechanical and chemical stability and low price, make them suitable as heterogeneous adsorbent (Guerra-Nunez et al., 2017). Among the main types of clay used for sorption are montmorillonites, iron-enriched zeolites, kaolinite, allophanes, goethite, magnetite and wustite (Garrido-Ramírez et al., 2013).

To increase the efficiency of adsorption of clay, they can be enriched or modified through pillaring or delamination (Pérez et al., 2014). The Pillared Inter Layered Clays (PILCs) synthesis procedure can be divided into 03 main steps (Ramirez et al.,2007): preparation of polyoxocations by hydrolysis of certain multivalent cations, which under appropriate conditions give rise to cationic polymeric species; the ionic exchange of the original charge-compensating cations of swellable smectite clays by the polyoxocations before synthesized, this exchange giving rise to the so called “intercalated clays” and finally the stabilisation of the intercalated clays by calcination at relatively high temperatures, which transforms the metastable polyoxocations into “pillars”, stable metallic clusters, close to oxi-hydroxidic phases. The most widely used pillaring agent is aluminium, however, there are different poly-oxohydroxymetal cations can be used as pillaring agents like chromium, titanium and iron (Park, Jung, Seo, & Kwon, 2009).

# CHAPTER 2: METHODOLOGY

## Introduction

In this chapter, the study area will be described, as well as the steps taken in order to achieve the objectives set in the introduction of this research. These steps include general characterization of the study area; desk studies; samples collection and analysis and finally methods and tools used for analysis and interpretation of the results obtained from the laboratory.

## 2.1. PRESENTATION OF THE STUDY AREA

The studied watersheds were situated in Adamaoua and North regions of Cameroon: the Bidou (Figure 2c) and Douka Longo watersheds (Figure 2b), respectively.

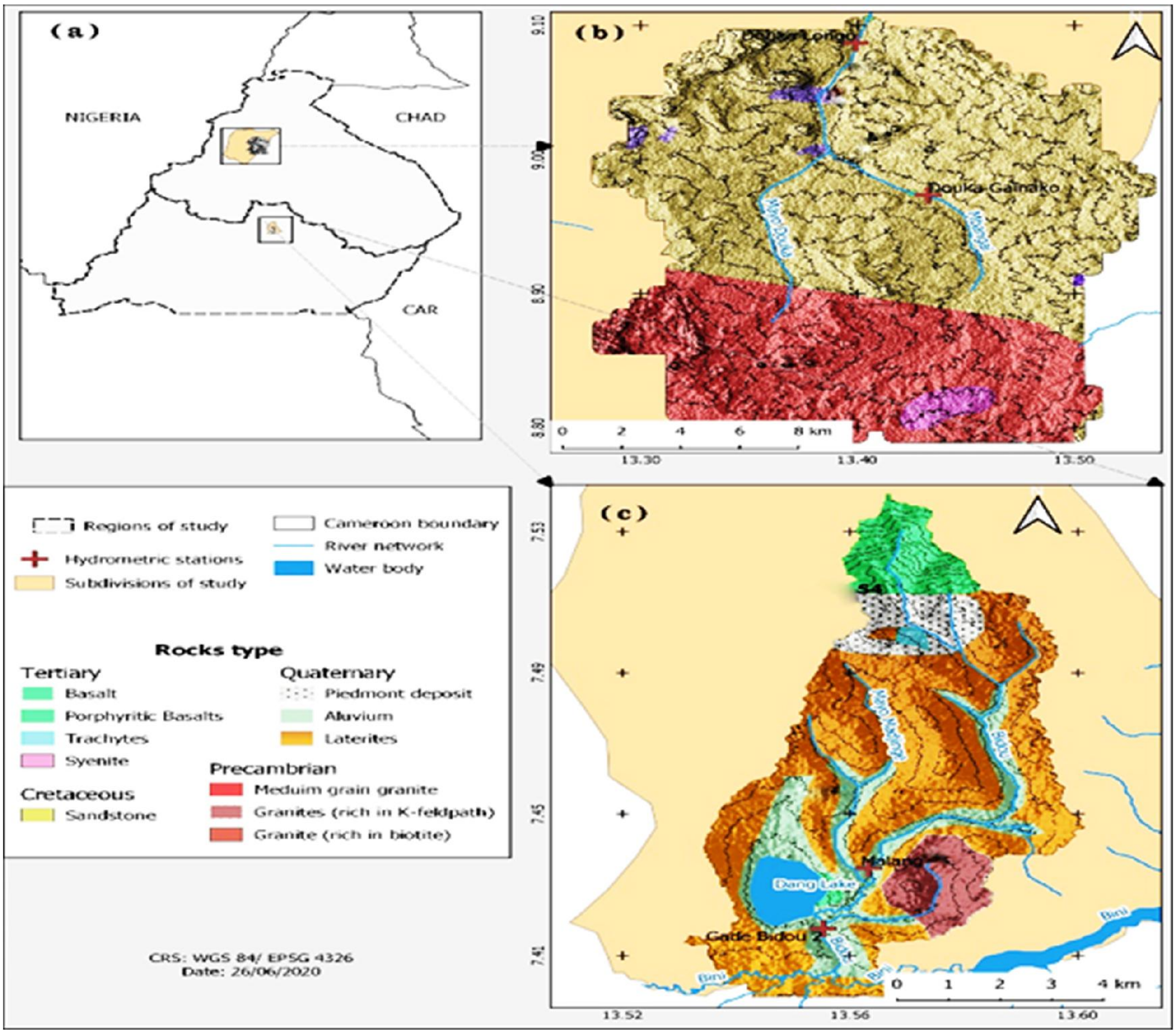


**Figure 2**:Locations of Bidou (c) and Douka Longo (b) watersheds are on Northern Cameroon (a) map

### 2.1.1. Bidou watershed

The Bidou watershed is located in Ngaoundéré III, Adamaoua Cameroon. It is geographically situated between latitudes 7.40 and 7.53 N and longitudes 13.52 and 13.58 E (Figure 2c). It covers a surface area of 61 km². It is referred to in this work as Bidou Igneous Watershed (BIW).

#### 2.1.1.1. Physical environment

***a. Climate***

The climate is tropical with two distinct seasons: a dry season from November to February and a wet season from March to October (Olivry, 1986), with an annual rainfall of ca. 2000 mm. Mean annual temperature is 23°C and mean relative annual humidity is 65% (Etame et al., 2000).

***b. Vegetation***

Its dominant vegetation is savannah type and it is drained dendritically by the Dang, Madjinge, Maso and Bidou streams. It consists of shruby and woody savannahs. These savannahs originally populated with *Danielliaoliveri and Lophira lanceolata* (Fantong et al., 2015).

***c. Hydrology***

The main water courses are the Dang, Madjinge, Maso and Bidou streams. The Dang stream and discharged groundwater accumulate to form the Dang Lake whose outlet meets with the confluence of Madjinge, Maso and Bidou tributaries downstream to form the Bidou river that empties into the Bini River (PCD, 2013).

***d. Relief***

The topography drops drastically with valleys dividing gentle slopes of Tertiary basaltic domes from 1377 m.asl in the northern upstream. Southwardly, the altitude drops considerably and varies from 1149 m.asl to 1070 m.asl (PCD, 2013).

***e. Geology***

The Bidou is an igneous watershed covered by granite and trachyte both altered and fresh. While Ferralitic soils are the dominant types, with rich clay (40 à 60%), low organic matter (less than3%), low soil exchange capacity from 15 to 20 meq/100g and the pH 4.7 to 5.6 (Edet,2004; Edmunds et al., 2002). Even if Humbel (1966) distinguishes some outcrops of ferruginous soils trapped between the chaos of balls that cover steep slopes, they are essentially training courses ferrallitics from various ancient rocks that dominate the region (PCD, 2013). This is a consequence of the presence of laterite which increases the runoff, hence the chemical and physical erosion.

#### *f. Fauna*

In this vegetation is a natural fauna that includes, rabbits, antelopes, monkeys, warthogs and other guinea fowl and francolins. In addition to these animals, there are reptiles such as snakes.

### 2.1.1.2. Human environment

#### *a. Water supply and sanitation*

Access to drinking water and basic sanitation infrastructure is limited. The Commune therefore intends to improve this situation by increasing the rate of access to drinking water to 75%. To do so, municipality will have to: conduct studies for rehabilitation of existing water points, carry out extensions to the existing water supply network ranging from Malang in Yala-Yarna by a feasibility study, building capacity and improvement of the sanitation system (PCD, 2013). The sanitation system reflects the poverty of the community. Toilets are traditionally pit latrines and waste water are neither collected nor treated. This means that they are released around water sources used in homes.

#### *b. Health*

The expanded vaccination programme is applied there and great attention is attached to children as they are generally affected by illnesses related to poor nutrition (kwashiorkor, slump), waterborne diseases (gastroenteritis, cholera).

#### *c. Economy*

Agriculture is still rudimentary and exploited area are small (as 0.5 to 1ha). Livestock remains the main economic activity practiced by more than 20% of the rural population. Other activities like hunting, fishing and crafts are practiced at an artisanal scale in the region. (Jacob et al., 2019)

- **Subsistence agriculture and farming**

This sector is also strongly marked by the breeding of cattle which is practiced in rural areas such as Tchabal Baouro, Tchabal Moungel. Generally speaking, the productive sectors are characterized by the following characteristics low production capacity (lack of mastery of production techniques), rudimentary means of production and a limited access to capital (loans). The foodstuffs produced are potatoes, cassava, cocoyam, beans, corn, mangoes, avocados, guava, papaya, carrot, artemesia...

- **Farming**

Agropastoral conflicts are significant in the municipality and farmers have to raise fences to avoid the destruction of their crops by animals. Beekeeping, a secondary activity, nevertheless constitutes an important source of income. Traditional hives are made during the dry season and honey produced is sold. Bushfires are limiting factors of production. By burning down the flowers, it affects harvest and consequently reduces honey production crop production.

## 2.1.2. Douka Longo watershed

Douka Longo catchment is located in the North Region of Cameroon, in the municipality of Ngong. It has a surface area of 678 km². It is situated between latitudes 8.80 and 9.10 N and longitudes 13.30 and 13.50 E (Figure 2b).

### 2.1.2.1. Physical environment

***a. Climate***

The climate is Sudano-Sahelian semi-arid with a mean annual temperature of 28 $^{o}$C, maximum atmospheric temperature of 45 $^{o}$C that drops to 19 $^{o}$C in December (Molua, 2006; Fantong et al., 2020). Two seasons can be distinguished: a rainy season that last for 5 months (May to September) and a 7 months (October to April) dry season. Situated under the Sahara Desert, it is highly affected by dry and violent wind called Harmattan.

***b. Hydrology***

This watershed is divided in two regions: The Mayo Douka and Mayo Mbangai, which are tributaries that dendritically drain the watershed to form the Douka Longo river. In the dry season, these water courses reduce considerably and might even run dry.

***c. Relief***

Douka Longo presents some massive mountains in the localities of Baroumé, OuroSouka, Kéïni, Hossérékilbou, and Laïndé Massa. Some of these massive are picturesque and used as touristic site (PCD, 2013). It is the case of mount Fandou in Baroumé. Here, the altitudes range from 285 to 197 m.asl.

#### *d. Geology*

Geologically, 80 % of the watershed drains Cretaceous siliceous, ferruginous and arkosic sandstones, and poorly sorted immature polymict basal conglomerates, that megascopically consist of the minerals quartz and feldspars.

#### *e. Flora*

The vegetation found in the municipality is a shrubby Sudanese savannah with the aspect of clear and degraded savannah around the villages and more marked density in the hunting zone (ZIC 14). The following wood species have been recorded: *Isoberliniadoka*, *Eucalyptus Camadulensis*, *Borassus aethiopium*, *Isoberlinatomatosa Anogeissusleiocarpus*, *Khaya senegalensis*, *Afzeliaafricana*, *Daniela oliveri*, *Terminalia marcroptera*, *Terminalia laxiflora*, *Acacia* (PCD Ngong, 2013).

#### *f. Fauna*

The fauna is very diverse and can be classified into four major groups: large mammals (buffalo, hippopotamus), small mammals (rabbits, rats, goats), reptiles (crocodiles, vipers) and prey birds (guinea fowl, partridges, pigeons). The fishing resources are made up of: captains, catfish, tilapias and some sardines (PCD Ngong, 2013).

### 2.1.2.2. Human environment

#### *a. Water supply and sanitation*

There is no functional water supply system and the rate of access to water is 23%. With regard to the sectoral policy which recommends a 1/ 300 inhabitants, the scale of the needs imposes specific actions: Rehabilitation or construction of new water points (PCD Ngong, 2013). The water used in households is from unprotected wells and streams.

#### *b. Health*

People do not easily have access to health centre. They use to go in the seven undistributed services of the municipality. Here, water-borne diseases (gastroenteritis, cholera, typhoid, etc...), malaria and sexually transmitted infections are treated but the equipment available in hospitals is insufficient (PCD Ngong, 2013).

***c. Economy***

- **Agriculture and farming**

Agriculture is the main activity of the municipality. There are about 106,000 active farmers representing 72% of the active population. The common products are corn, maize, paddy rice, niébé, cocoyam, penicillaire, potatoes, sesame, cassava, onion, groundnuts, sugarcane, cotton.... Like Nga-oundéré III, this municipality is also a large producer of cattle and poultry, sold at affordable prices.

- **Fishing**

The Benue River, the Mayos and the lakes are privileged areas for fishing. The average number of fishermen is 50 per lake. Several fishermen carry out this activity along the permanent Mayos, and many of them use phytosanitary products to dispose of the fish. The species caught are: tilapias, carp, catfish, sardines and captains. Fishing techniques are still traditional, with the use of: lines, nets, traps and canoes. In order to derive added value from this activity, the sector has dryers or dry fishermen. This activity is carried out in an artisanal way and the actors are not structured so they cannot benefit from institutional support. They sell their products to local traders. However, they point out that those from neighbouring countries are willing to offer them the better prices.

## 2.2. DESK STUDY

This involved the scooping of relevant documents and knowledge to:

- Ensure the significance of this study both at local and international scales;
- Better understand the problems posed above and how to handle them;
- Organise both the field work and the writing of this study;
- Manage the data collected on the field for reliable analysis with the adequate software: Diagrammes 6.51 for hydrochemical analysis (Piper and Stiff diagrams); QGIS 3.14.16 to produce maps; Excel 2019 for bivariate plots and statistical analysis, Paint and Paint 3D for Stiff maps.

## 2.3. FIELD WORK

### 2.3.1. Water sampling

To assess the hydrochemistry of water used by the population, surface and groundwater samples were randomly collected during the rainy and dry seasons in the two study areas, near houses and in cultivated areas. As much as possible, the collected samples are uniformly distributed throughout the study areas to ensure representativity. Fifty-nine samples were collected during the rainy season (November 2019) from 18 wells, 2 springs, 12 rivers, 1 lake, 1 borehole in Bidou and 14 wells, 3 springs, 7 rivers and 1 borehole in Douka Longo with the material presented in Figure 3. During the dry season (March 2020), 56 samples were collected from 16 wells, 2 lakes, 10 rivers and 1 spring in Bidou and from 17 wells, 8 rivers and 2 boreholes in Douka Longo. The procedure (Figure 4) can be described as follows:

- Geographic localisation (latitude, longitude, altitude) of water source with Garmin 64s Global Positioning Systems (Figure 3a);
- Calibration of the electrodes used for in-situ parameters measurements with the solution provided by the manufacturer for this purpose;
- Rinsing of the sampling material that will be in contact with water to sample three times with this water, except for the buckets used by the population to pull water from wells;
- Measurement of in-situ parameters (electrical conductivity (EC), pH and water temperature (T)) using a WTW 3320 make pH meter model HI 991,001, pH/EC waterproof meter, and a custom CT-450WR thermometer, respectively (Figure 3e).
- Filling of the three sampling bottles for:
  - Anions and alkalinity analysis: water was collected in a 100 ml polyethylene bottle (Figure 3b) and preserved unacidified to determine the dissolved anions ($SO_4^{2-}$, $Cl^-$, $F^-$, $Br^-$, $NO_3^-$, and $PO_4^{3-}$);
  - Cations and trace elements analysis: water was filtered in a 250 ml polyethylene bottle (Figure 3b) through a 0.45 µm cellulose filters (Figure 3c) and acidified with pure nitric acid for the determination of cations ($Ca^{2+}$, $Mg^{2+}$, $Na^+$, $K^+$, $NH_4^+$, and $H_4SiO_4$) and trace elements ($Fe^{2+}$, $Mn^{2+}$, $Al^{3+}$, Pb, Cd, Ni, Zn, Cu, Ti, Sn, Mo, As, Co, Sb, Ba, U, Sr, La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu, and Y). Acidification was done to pH ca. 2 with supra-pure $HNO_3$;
  - Isotopes ($^{18}O$ and $^2H$): water was collected without filtration and acidification in a 50 ml glass bottle filled to the rim (Figure 3b) and sealed at the end of the sampling to prevent evaporation.

- The samples were labelled with permanent ink marker and conserved in a cooler (Figure 3d) at 4°C. They were later sent to the laboratory of the BGR (Hannover, Germany) for analysis.

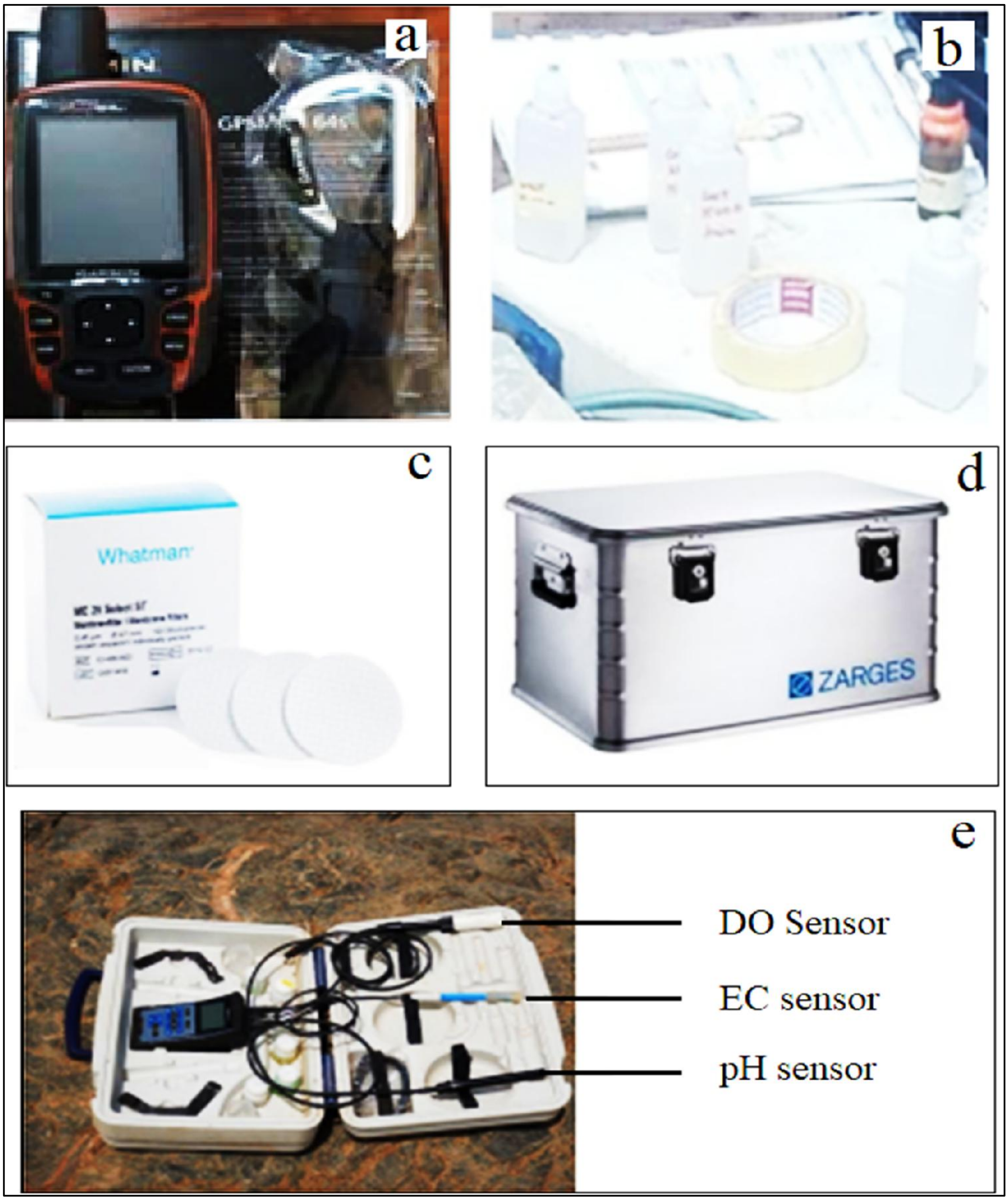


**Figure 3**: Sampling materials


**Figure 4**: Important steps of water sampling: calibration (a), geo-localisation (b), rinsing of the electrodes with water sample (c), measurement of in-situ parameters (d), filtration (e), acidification (f)

## 2.3.2. Piezometric measurements

In order to compute the groundwater recharge using the Water Table Fluctuation (WTF) method, three parameters were measured during wells sampling: length of the coping, top to water, depth to water table and total depth of the well. Figure 5 is a schematic representation of these parameters.

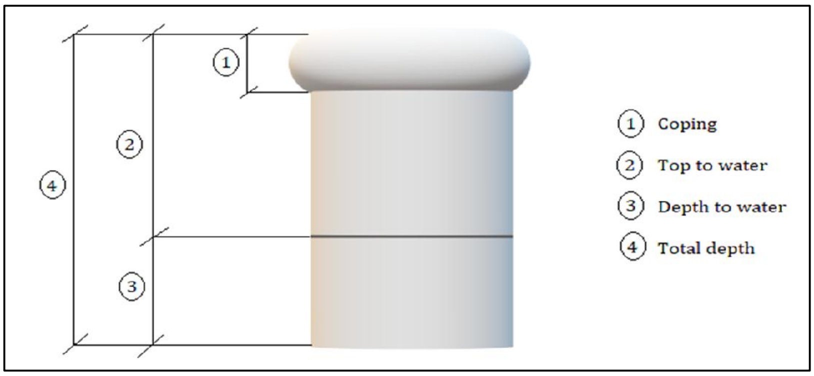


**Figure 5**: Schematic representation of piezometric measurements

Piezometric data enable to know the difference in water depth in wells during the rainy and dry seasons. They were measured with a multipoint borehole extensometer (Figure 6). It has two heavy heads able to sink into water to measure the depth of the well and a light head able to float and measure depth to water. The length of the coping was measured using a decametre.

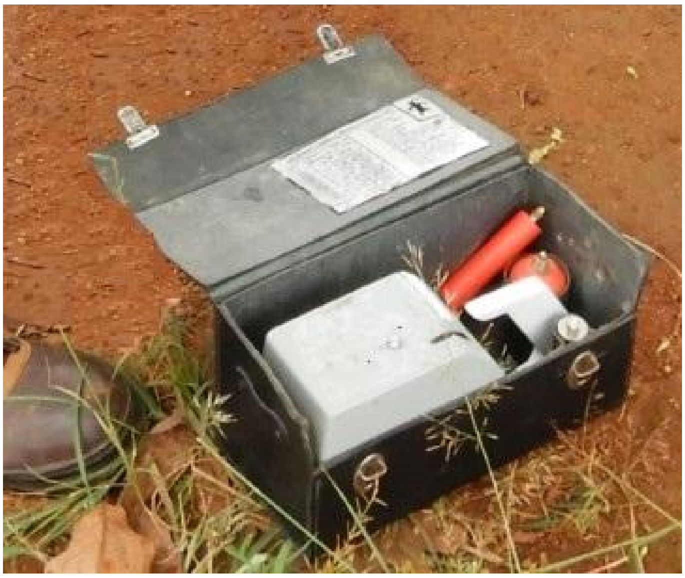

**Figure 6**: Piezometric measurement with floating (orange) and sinking (grey) heads

All the material used during the field work and its utility is summarised in Table 6

**Table 6**:Sampling material with the corresponding uses

| MATERIAL | USE |
|---|---|
| Garmin 64s GPS | Geographic coordinates (latitude, longitude, altitude) |
| 250 ml PE, 100 ml PE and 50 ml glass bottles | Sampling water for cations with metals, alkalinity and anions; and finally stable environmental isotopes, respectively |
| 1:1 $HNO_3^-$ acid | Fix the concentration of anions |
| Multimeter 3320 | Measurement of the in-situ parameters (pH, electrical conductivity and temperature, respectively) |

| | |
|---|---|
| Cellulose filter | Removed suspended particles from samples collected for cations and trace elements |
| Icebox | Maintain temperature of samples at 4°C until the transfer to the laboratory |
| Borehole extensometer | Piezometric measurements (total depth, static level) |

# 2.4. ANALYSES

## 2.4.1. Laboratory analysis

Major ions were quantified using a Spectro Ciros Inductively Coupled Plasma Atomic Emission Spectrometry (ICP-AES) and a DIONEX ICS 3000 ion chromatography. Stable environmental isotopes ratios were determined on a PICARRO cavity ring down spectrometer (CRDS model L2120-i) at the BGR laboratories (Hannover, Germany). The obtained stable isotope ratios were given in the conventional delta (d) expression in parts per mil (%) relative to Vienna Standard Mean Ocean Water (VSMOW) with analytical precisions of ±1‰ for δD and ±1.5‰ for $\delta^{18}O$. Finally, trace elements were measured on an Agilent 7500ce ICPMS also at the BGR laboratory. It is an inductively coupled plasma-mass spectrometry with a low detection limit (µg/L). Hence, it can determine metals at very low concentrations.

## 2.4.2. Data analysis

### 2.4.2.1. Water chemistry

The reliability of the chemical measurements was verified by using the charge balance equation (Appelo and Postma, 1993) for major elements. If all ions are correctly determined by the laboratory, the sum of cations should equal sum of anions (all in meq/l) hence converting the values of the major ions from mg/l to meq/l was through the Equation 19:

$$Equivalent Concentration\left(\frac{meq}{l}\right) = Concentration(mg/l) \times Charge/Formula Weight \tag{20}$$

With the values for the major ions converted to meq/L, the ion balance was gotten through the aid of the following formula:

$$E = \left|\frac{\sum Cations - Anions}{\sum Cations + \sum Anions} * 100\right| \tag{21}$$

The analytical results were analysed by comparing and contrasting them with the WHO guidelines. The concentrations of the major ions (cations and anions) in the various water samples were gotten form the laboratory, expressed in mg/l. The results were presented in tables, then the different ratios used for the interpretation of these results were calculated with concentrations in meq/l for each water sample. The values of electrical conductivity were obtained in µS/cm and those of isotopes in (‰).

The values for the major ions were analysed using the software Diagrammes in order to obtain Piper and Stiff for chemical characterization of water resources. The Piper diagrams were used to show the concentrations of the various water samples for easy comparison and classification of water types. Stiff diagrams were plotted with the software Diagrammes and inserted on maps with Photoshop to show the evolution of mineralisation in the watersheds with space and depth

To determine the potential sources of ions in the watershed and the mechanisms controlling their presence in the water sources, their molar ratio was used to plot on the Gibbs diagram. The conversion of the concentrations from mg/l to µM was done using Equation 21:

$$EquivalentConcentration(\mu M) = Concentration(mg/l) \times Charge/Molecular\ Weight \quad (22)$$

Also, knowing that ions with significant positive correlation may have common origin, Pearson correlation matrix and bivariate plots were used to assess the impact of lithogenic processes and man-made activities. These analysis tools were done with Microsoft Excel.

The plot of Cl against Na (Meybeck, 1987) produced the model required to identify the process(s) likely to control groundwater chemistry as it proceeds from recharge zones towards discharge area. The estimation of the molar ratio Na/Cl provides the basis to confirm or otherwise whether cationic exchange reaction play any role in the alteration of groundwater chemistry. The determination of the type of ion exchange reaction likely to occur in groundwater in this study was achieved by using the model developed by Schoeller (1965). This approach analyses the estimated CAI-1 and CAI-2 of each sample using Equation 23 and Equation 24:

$$CAI_1 = \frac{Cl-(Na+K)}{Cl} \quad (23)$$

$$CAI_2 = \frac{Cl-(Na+K)}{SO4+HCO3+NO3} \quad (24)$$

QGIS 3.14.16 and ArcGis software were used to display the GPS points on a map with SRTM files downloaded from openDEM site which was extracted from OpenStreetMap. The results in this were represented in the form of maps for each water sample that was collected.

#### 2.4.2.2. Water quality assessment

Weighted Arithmetic Water Quality Index was used to sort out the overall quality of water samples based on several parameters that may impose health implications on human health. According to Sahu & Sikdar (2008), WQI reflects the composite influence of different water quality parameters on the quality of groundwater mostly for domestic use. The selected parameters used to estimate the WQI in this study were pH, EC, K, Mg, Na, Ca, $NO_3$, F, Cl, SO4, Zn, Pb, $HCO_3$, TDS, TH, As, Ba, Be, Mn, Ni, B, Cu, U. Each of these parameters has a weight (wn) which is a function of its guideline value (Si) (Table 7).

**Table 7**:Assigned and relative weight with respective WHO (2017) guideline

| ID | EC | pH | K | Na | Cl | Mg | Ca | SO4 | $HCO_3^-$ | Fe(II) |
|---|---|---|---|---|---|---|---|---|---|---|
| Si | 750 | 6.5 | 100 | 200 | 250 | 30 | 75 | 250 | 250 | 3 |
| Vi | 0 | 7 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| wn | 1.36E-05 | 0.0005 | 0.0003 | 0.0005 | 0.0003 | 0.0006 | 0.0002 | 0.0177 | 0.0003 | 0.754 |
| ID | $NO_3^-$ | $F^-$ | TDS | TH | As | Ba | Be | Mn | Ni | Pb |
| Si | 10 | 1.5 | 500 | 100 | 10 | 2400 | 12 | 50 | 70 | 10 |
| Vi | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| wn | 3.691E-05 | 0.0615 | 1.685E-05 | 4.840E-05 | 0.0685 | 4.043E-06 | 0.0267 | 0.0003 | 0.001 | 0.067 |

Applying this method, WQI were computed in four steps:

- Computation of the proportionality constant k using Equation 25

$$k = \frac{1}{\frac{1}{\sum_{i=1}^{n} Si}} \tag{25}$$

- Computation of the quality rating ($q_i$) of each parameter knowing the estimated value of the i[th] parameter in the water sample ($V_i$), its ideal value in pure water ($V_0$) and its permissible value in drinking water ($S_i$)

$$q_i = \frac{V_i - V_0}{S_i - V_0} \tag{26}$$

- Computation of the weight ($w_i$) of the parameters used

$$w_i = \frac{k}{S_i} \tag{27}$$

- Computation of the WQI

$$WQI = \frac{\sum W_n * q_n}{\sum W_n} \tag{28}$$

Knowing the WQI, water is classified as excellent, good, poor and very poor for drinking if it ranges from 0 to 25; 25 to 50; 50 to 75 and from 76 to 100 (Chatterji & Raziuddin, 2002). When WQI>100, it is unsuitable for drinking.

# 2.5. GROUNDWATER RECHARGE AND UTILISATION

## 2.5.1. Groundwater recharge

Piezometric measurements were done during the two sampling campaigns. They allow to obtain the static levels in wells and the mean variation of the water table in BIW and DLSW. Knowing their surface area and the value of the specific yield (here it is equal to 1 as water wells dry up in the dry season), the recharge of the aquifer was computed using Water Table Fluctuation (WTF) method (Equation 23). The 3D-representations of the recharge were done with Qgis, Arcgis and Paint 3D.

$$R = A * h * t \tag{29}$$

Where A is the surface area of the watershed, h is the mean variation of water level from the rainy to the dry season and t is the time over which recharge is evaluated (1 hydrologic year).

## 2.5.2. Groundwater exploitation

Groundwater consumption was computed on the basis of population growth. According to Malthus (1978), population with unlimited resources growths very rapidly, exhibiting exponential growth. However, it must be noted that population growth considerably reduces the available resources. Thus, the population cannot grow exponentially because resources diminish over time and their accessibility is competitive. Assuming that the chances of access to resources are the same for everyone, the logistic growth model has been developed and population is modelled as shown in Equation 24

$$P(t) = P_0 * (1 + a)^t \tag{30}$$

Where t is the time spe, P(t) the population at time t, $P_0$ the population at time t=0 and “a” the growth rate

Knowing, the population in the watershed at two different years, the growth rate can be deduced using Equation 5

$$a = \sqrt[t]{P/P0} - 1 \tag{31}$$

Considering that the population is equitably distributed in these regions, the adjustment factor used for population is the ratio of surface areas of the watershed and the municipality (Equation 31).

$$\mathrm{Pw(t)} = \mathrm{P(t)} * \frac{\mathrm{Sw}}{\mathrm{Sm}} \tag{32}$$

Annual water demand for consumption is computed as:

$$\mathrm{D(t)} = \mathrm{c} * \mathrm{Pw(t)} * 365 \tag{33}$$

In this equation, D is the water demand during a year, c is the daily consumption per person, t is the time and P is the population.

## 2.6. DIFFICULTIES

- With the corona virus pandemic, human resources and time allowed for field work were reduced;
- The study area was in the rural parts of Ngaoundéré III and Ngong municipalities. Hence, the quality of the road was very bad, especially in the rainy season where sampling sites were only accessible by foot;
- In the rainy season, water depth was very high in DLSW and access to rivers was very tricky. This situation was felt more when a flood event occurred during sampling (more than 2m of water covered the basin in 1 hour);
- Proximity of populations and pasture to roads lead to accident in the traffic.

## Conclusion

Materials and methods employed for the preparation of the field work and the analysis of the data collected in BIW and DLSW were presented in this chapter. These are documentary research, observations, discussion with inhabitants on the field and laboratory analysis used to reaffirm the hypothesis after interpretation of the results. At the end, difficulties encountered for the acquisition of the data obtained were presented.

# CHAPTER 3: RESULTS- INTERPRETATION- DISCUSSION

## Introduction

This chapter represents the results of the tests and analysis carried out to assess water quality. They seek to meet up the set objectives and affirm the hypothesis stated at the beginning of this work. They are presented in tables, diagrams and plots and interpreted accordingly in the form of maps, piper's and stiff diagrams, bivariate plots and Wilcox diagram with respect to the set objectives of this study.

## 3.1. RESULTS PRESENTATION AND RELIABILITY

### 3.1.1. Descriptive results of the rainy and dry seasons

Samples collected for chemical analysis are distributed in both watersheds depending on the accessibility of water sources and the presence of users (Figure 7). A statistical summary of the results obtained from the laboratory for the rainy and dry seasons are presented in Table 8 for BIW and Table 9 for DLSW. The complete tables of the results are in appendix 1, 2, 3 and 4 for major ions and trace elements in the rainy and dry season, respectively.

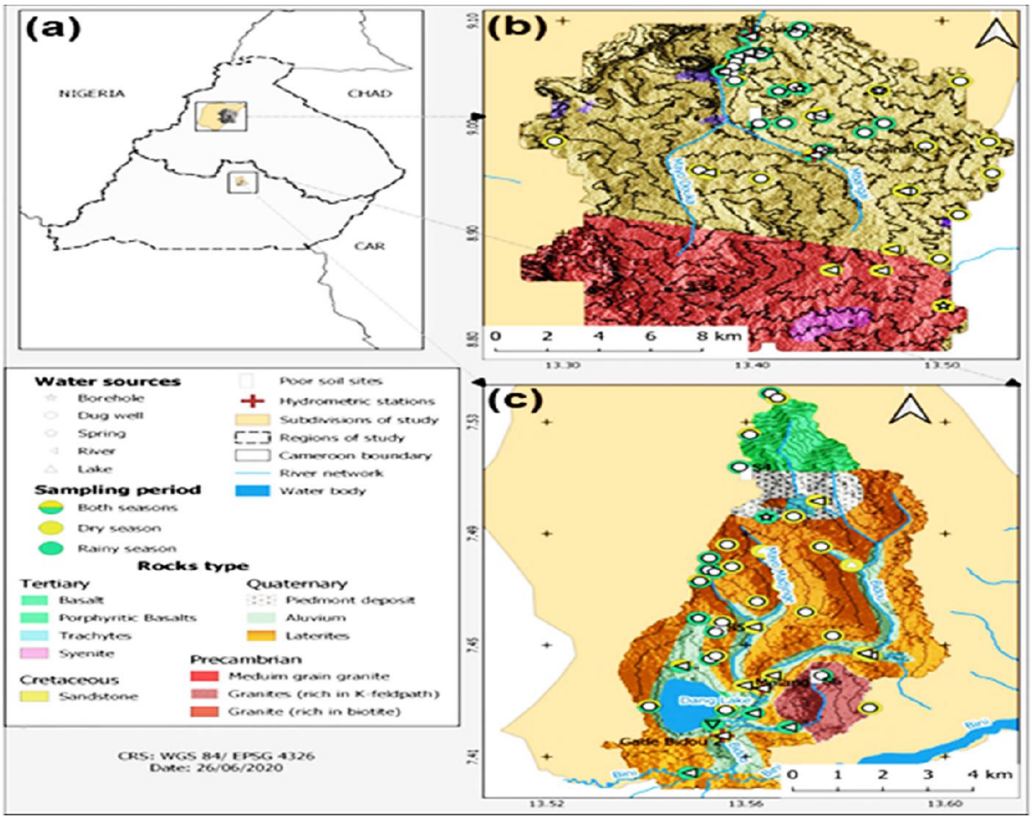


**Figure 7**: Spatial distribution of sampling sites selected for hydro-chemical analysis in DLSW (a) and BIW (b) during the rainy and dry seasons

**Table 8**:Statistical summary of the results obtained from the laboratory and in-situ parameters in BIW

| | | RAINY SEASON | | | | DRY SEASON | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Min | Mean | Max | SD | Min | Mean | Max | SD |
| EC | µS/cm | 9.00 | 34.03 | 160.00 | 37.45 | 11.00 | 34.10 | 168.00 | 39.27 |
| pH | - | 5.60 | 6.45 | 7.70 | 0.53 | 5.20 | 6.02 | 7.60 | 0.74 |
| K | mg/l | 0.00 | 0.51 | 1.50 | 0.39 | 0.10 | 0.56 | 1.80 | 0.48 |
| Na | mg/l | 0.40 | 2.47 | 25.00 | 5.09 | 0.30 | 1.49 | 17.00 | 3.09 |
| Cl | mg/l | 0.01 | 1.14 | 16.90 | 3.93 | 0.01 | 0.68 | 16.40 | 3.03 |
| Mg | mg/l | 0.08 | 1.02 | 5.05 | 1.26 | 0.10 | 0.89 | 5.51 | 1.33 |
| Ca | mg/l | 0.40 | 2.57 | 10.80 | 2.50 | 0.53 | 2.87 | 15.70 | 3.78 |
| SO4 | mg/l | 0.00 | 0.59 | 18.70 | 3.20 | 0.00 | 0.04 | 0.38 | 0.08 |
| HCO3 | mg/l | 3.30 | 15.40 | 66.40 | 15.40 | 1.90 | 14.94 | 80.70 | 18.94 |
| NO3 | mg/l | 0.00 | 2.24 | 37.90 | 6.68 | 0.00 | 2.02 | 44.40 | 8.24 |
| F | mg/l | 0.01 | 0.04 | 0.15 | 0.04 | 0.00 | 0.03 | 0.14 | 0.03 |
| TDS | mg/l | 5.55 | 25.37 | 95.91 | 24.12 | 10.00 | 31.79 | 143.00 | 33.62 |
| TH | mg/l | 1.31 | 10.60 | 47.71 | 11.34 | 1.74 | 10.84 | 61.10 | 14.32 |
| As | µg/l | 0.01 | 0.04 | 0.11 | 0.02 | 0.01 | 0.04 | 0.10 | 0.02 |
| B | µg/l | 2.38 | 11.34 | 20.00 | 4.66 | 3.77 | 12.87 | 43.60 | 7.86 |
| Ba | µg/l | 18.90 | 56.83 | 141.00 | 24.82 | 27.90 | 84.15 | 339.00 | 64.03 |
| Be | µg/l | 0.01 | 0.07 | 0.30 | 0.07 | 0.01 | 0.06 | 0.24 | 0.06 |
| Cd | µg/l | 0.00 | 0.01 | 0.03 | 0.01 | 0.00 | 0.01 | 0.04 | 0.01 |
| Co | µg/l | 0.06 | 1.06 | 6.22 | 1.19 | 0.14 | 3.20 | 50.70 | 9.33 |
| Cr | µg/l | 0.03 | 0.27 | 2.00 | 0.42 | 0.14 | 0.48 | 4.84 | 0.90 |
| Cu | µg/l | 0.07 | 0.38 | 1.01 | 0.18 | 0.10 | 0.35 | 0.70 | 0.15 |
| Mn | µg/l | 2.03 | 45.50 | 407.00 | 73.21 | 5.99 | 215.63 | 3574.00 | 659.22 |
| Ni | µg/l | 0.20 | 1.00 | 5.89 | 1.16 | 0.24 | 2.13 | 19.70 | 4.02 |
| Pb | µg/l | 0.02 | 0.06 | 0.26 | 0.04 | 0.02 | 0.06 | 0.16 | 0.04 |
| U | µg/l | 0.00 | 0.01 | 0.02 | 0.00 | 0.00 | 0.01 | 0.05 | 0.01 |
| Zn | µg/l | 2.48 | 30.79 | 70.50 | 13.91 | 31.80 | 307.36 | 540.00 | 147.93 |
| $\delta^{18}O$ | (‰) | -4.51 | -3.36 | -0.86 | 0.54 | -3.81 | -3.02 | -2.14 | 0.37 |
| $\delta^{2}H$ | (‰) | -24.47 | -15.91 | -11.54 | 2.14 | -17.40 | -13.18 | -9.20 | 1.84 |
| DE | (‰) | -4.69 | 11.00 | 13.06 | 2.93 | 7.00 | 10.93 | 13.00 | 1.41 |
| Dy | µg/l | 0.002 | 0.012 | 0.038 | 0.010 | 0.001 | 0.014 | 0.036 | 0.010 |
| Er | µg/l | 0.001 | 0.008 | 0.026 | 0.007 | 0.002 | 0.007 | 0.026 | 0.010 |
| Eu | µg/l | 0.008 | 0.022 | 0.055 | 0.010 | 0.012 | 0.026 | 0.101 | 0.020 |
| Ga | µg/l | 0.003 | 0.017 | 0.044 | 0.011 | 0.003 | 0.019 | 0.069 | 0.020 |
| Gd | µg/l | 0.0 | 0.0 | 0.0 | 0.0 | 0.003 | 0.018 | 0.043 | 0.010 |
| La | µg/l | 0.009 | 0.054 | 0.206 | 0.043 | 0.01 | 0.072 | 0.188 | 0.050 |
| Nd | µg/l | 0.01 | 0.07 | 0.23 | 0.05 | 0.013 | 0.078 | 0.174 | 0.050 |
| Pr | µg/l | 0.002 | 0.016 | 0.053 | 0.012 | 0.003 | 0.019 | 0.052 | 0.010 |
| Rb | µg/l | 0.112 | 1.682 | 4.080 | 1.222 | 0.12 | 1.237 | 4.96 | 1.250 |
| Sm | µg/l | 0.00 | 0.02 | 0.05 | 0.01 | 0.002 | 0.018 | 0.041 | 0.010 |
| Sr | µg/l | 4.680 | 30.362 | 115.000 | 28.987 | 10.3 | 34.966 | 154 | 38.530 |
| Tb | µg/l | 0.001 | 0.003 | 0.007 | 0.002 | 0.001 | 0.003 | 0.006 | 0.000 |
| Y | µg/l | 0.014 | 0.087 | 0.302 | 0.077 | 0.013 | 0.078 | 0.329 | 0.060 |
| Yb | µg/l | 0.00 | 0.01 | 0.03 | 0.01 | 0.001 | 0.006 | 0.016 | 0.000 |

**Table 9**: Statistical summary of the results obtained from the laboratory and in-situ parameters in DLSW

| | | RAINY SEASON | | | | DRY SEASON | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Min | Mean | Max | SD | Min | Mean | Max | SD |
| EC | µS/cm | 58.00 | 179.76 | 698.00 | 161.57 | 36.00 | 241.07 | 893.00 | 202.62 |
| pH | - | 4.20 | 6.42 | 7.40 | 0.88 | 4.60 | 6.32 | 8.10 | 0.88 |
| K | mg/l | 2.90 | 13.18 | 75.30 | 15.02 | 2.00 | 9.51 | 25.60 | 5.99 |
| Na | mg/l | 1.40 | 6.64 | 27.00 | 5.52 | 0.80 | 11.17 | 72.20 | 14.14 |
| Cl | mg/l | 0.80 | 8.37 | 43.20 | 10.17 | 0.07 | 7.69 | 36.70 | 8.59 |
| Mg | mg/l | 0.40 | 3.50 | 11.60 | 2.68 | 0.33 | 5.56 | 22.60 | 6.57 |
| Ca | mg/l | 1.34 | 10.24 | 24.60 | 6.32 | 1.20 | 20.13 | 87.90 | 21.30 |
| SO4 | mg/l | 0.01 | 0.81 | 7.01 | 1.44 | 0.00 | 1.28 | 7.27 | 1.89 |
| HCO3 | mg/l | 1.70 | 25.14 | 55.50 | 18.30 | 1.90 | 82.96 | 497.00 | 125.87 |
| NO3 | mg/l | 0.51 | 51.55 | 266.00 | 69.92 | 0.19 | 37.29 | 182.00 | 47.59 |
| F | mg/l | 0.02 | 0.13 | 0.94 | 0.23 | 0.02 | 0.14 | 0.99 | 0.20 |
| TDS | mg/l | 48.95 | 121.30 | 451.59 | 99.64 | 57.00 | 207.11 | 746.00 | 170.51 |
| TH | mg/l | 4.99 | 39.95 | 109.06 | 26.09 | 4.37 | 73.13 | 312.41 | 78.75 |
| As | µg/l | 0.02 | 1.45 | 17.70 | 4.59 | 0.02 | 0.24 | 1.43 | 0.30 |
| B | µg/l | 6.33 | 19.70 | 64.40 | 14.08 | 6.84 | 15.18 | 48.90 | 8.79 |
| Ba | µg/l | 165.00 | 783.84 | 3922.00 | 946.57 | 28.10 | 707.52 | 2864.00 | 699.21 |
| Be | µg/l | 0.03 | 1.92 | 22.90 | 5.30 | 0.01 | 0.51 | 5.11 | 1.10 |
| Cd | µg/l | 0.00 | 0.02 | 0.21 | 0.05 | 0.00 | 0.07 | 0.78 | 0.17 |
| Co | µg/l | 0.12 | 10.16 | 108.00 | 24.85 | 0.04 | 5.12 | 61.30 | 12.34 |
| Cr | µg/l | 0.06 | 0.40 | 1.65 | 0.41 | 0.09 | 0.62 | 2.45 | 0.59 |
| Cu | µg/l | 0.28 | 4.48 | 54.50 | 11.86 | 0.10 | 1.44 | 9.85 | 2.03 |
| Mn | µg/l | 6.63 | 158.04 | 1755.00 | 360.49 | 0.14 | 194.82 | 1016.00 | 325.09 |
| Ni | µg/l | 0.65 | 7.66 | 72.70 | 16.04 | 0.35 | 4.12 | 31.00 | 6.30 |
| Pb | µg/l | 0.07 | 4.08 | 56.30 | 12.36 | 0.04 | 0.86 | 10.70 | 2.18 |
| U | µg/l | 0.01 | 4.06 | 66.70 | 14.44 | 0.01 | 0.82 | 9.69 | 2.05 |
| Zn | µg/l | 8.44 | 50.43 | 139.00 | 34.67 | 20.40 | 111.50 | 569.00 | 168.19 |
| $\delta^{18}O$ | (‰) | -5.31 | -4.50 | -2.79 | 0.51 | -5.03 | -4.04 | 1.86 | 1.25 |
| $\delta^{2}H$ | (‰) | -30.73 | -26.25 | -21.30 | 2.35 | -32.70 | -23.55 | -1.70 | 5.03 |
| DE | (‰) | 1.01 | 9.79 | 12.08 | 2.50 | -17.00 | 8.74 | 12.00 | 5.52 |
| Dy | µg/l | 0.024 | 7.296 | 95.400 | 24.674 | 0.002 | 0.405 | 7.28 | 1.415 |
| Er | µg/l | 0.010 | 3.195 | 43.300 | 10.834 | 0.001 | 0.17 | 2.82 | 0.548 |
| Eu | µg/l | 0.062 | 3.404 | 41.600 | 10.981 | 0.009 | 0.405 | 4.74 | 0.886 |
| Ga | µg/l | 0.028 | 3.102 | 40.300 | 10.101 | 0.005 | 0.304 | 2.88 | 0.622 |
| Gd | µg/l | 0.0 | 9.7 | 121.0 | 32.6 | 0.005 | 0.581 | 10.5 | 2.042 |
| La | µg/l | 0.185 | 14.918 | 193.000 | 47.560 | 0.012 | 1.124 | 7.91 | 1.910 |
| Nd | µg/l | 0.18 | 49.73 | 658.00 | 167.83 | 0.01 | 2.581 | 44.2 | 8.603 |
| Pr | µg/l | 0.042 | 8.974 | 119.000 | 29.988 | 0.002 | 0.472 | 6.62 | 1.304 |
| Rb | µg/l | 7.200 | 27.924 | 83.500 | 20.052 | 1.76 | 23.223 | 60.3 | 17.923 |
| Sm | µg/l | 0.04 | 11.23 | 139.00 | 37.86 | 0.007 | 0.679 | 13 | 2.530 |
| Sr | µg/l | 36.500 | 184.988 | 611.000 | 135.805 | 25.1 | 406.659 | 2163 | 463.223 |
| Tb | µg/l | 0.004 | 1.391 | 17.900 | 4.705 | 0.001 | 0.093 | 1.47 | 0.310 |
| Y | µg/l | 0.115 | 35.547 | 485.000 | 120.693 | 0.014 | 1.811 | 29.9 | 5.707 |
| Yb | µg/l | 0.01 | 2.40 | 32.30 | 8.12 | 0.002 | 0.142 | 2.14 | 0.433 |

### 3.1.2. Ion balance

As mentioned in the previous chapter, the ion balance was calculated to check the accuracy of the results obtained from the laboratory. The plots in Figure 8 shows that the ionic balances computed using Equation 21 for each sample in the rainy (Figure 8a) and dry (Figure 8b) seasons are generally between ±5%. They confirm that the results obtained from the laboratory are satisfactory and can be used for water quality assessment.

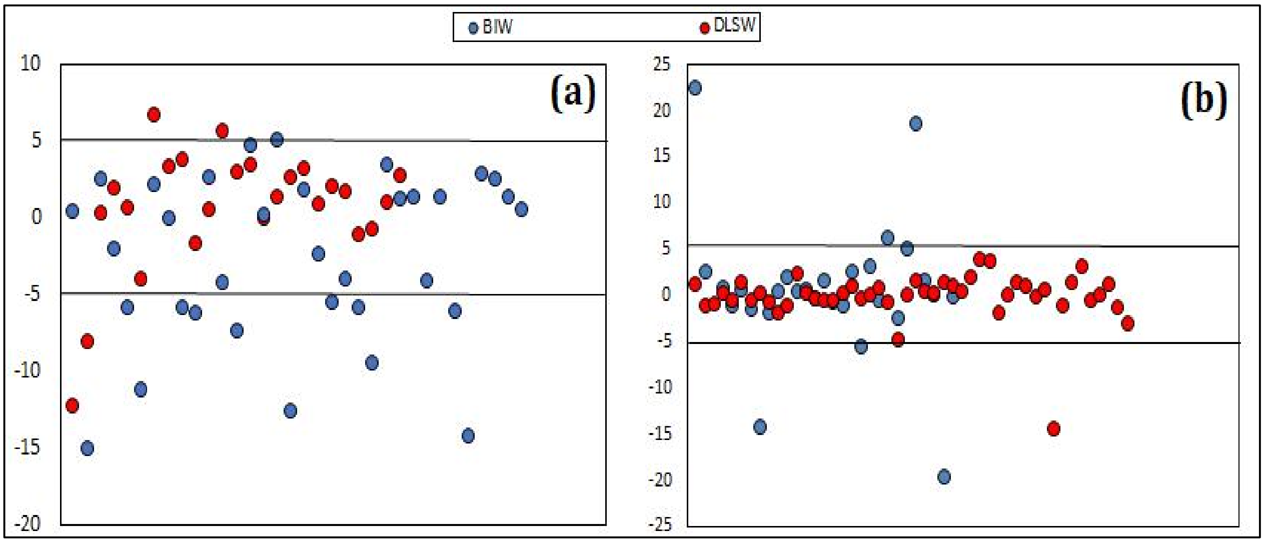


**Figure 8**:Ion balance of the water samples collected in the rainy (a) and the dry season (b)

## 3.2. HYDROCHEMISTRY OF THE WATERSHEDS

### 3.2.1. Major ions chemistry

#### 3.2.1.1. Water facies

During the rainy season, average values of major ions in water samples (in mg/l) are decreasing in this order: $HCO_3^-$> $Ca^{2+}$> $Na^+$> $Mg^{2+}$> $K^+$> $Cl^-$; $HCO_3^-$> $Ca^{2+}$> $Na^+$> $K^+$> $Cl^-$>$Mg^{2+}$> $NO_3^-$> $SO_4^{2-}$; $HCO_3^-$> $Ca^{2+}$> $Na^+$> $K^+$>$NO_3^-$> $Mg^{2+}$>$Cl^-$ > $SO_4^{2-}$ and $NO_3^-$> $K^+$> $Cl^-$> $Ca^{2+}$> $Na^+$> $Mg^{2+}$ > $SO_4^{2-}$ for surface water in BIW and DLSW and groundwater in BIW and DLSW, respectively. In the dry season, the same trend can be observed with a reduction of nitrate in the catchments (Figure 9). $HCO_3^-$ and $NO_3^-$ appear to be the most dominant anions in BIW and DLSW, respectively.

The values of major anions and cations show that their concentrations are higher in water samples from DLSW than in BIW. This observation depicts that DLSW is more sensitive to anthropogenic inputs than BIW. In the rainy season, Piper's diagram (Piper, 1944) plots (Figure 10a) suggest that the hydro-chemical facies are predominantly Ca- Mg-$NO_3$ type in DLSW, whereas in BIW the groundwaters show Ca-Mg- $HCO_3$ facies, while springs and rivers vary between facies of Ca-Mg-$HCO_3$ and Na-K-$HCO_3$. Consistently with the results of Meybeck et al. (1987), this is a proof that there is ion exchange and recharge in BIW and DLSW with the replacement of calcium by sodium and the Ca-$HCO_3$ predominant type.

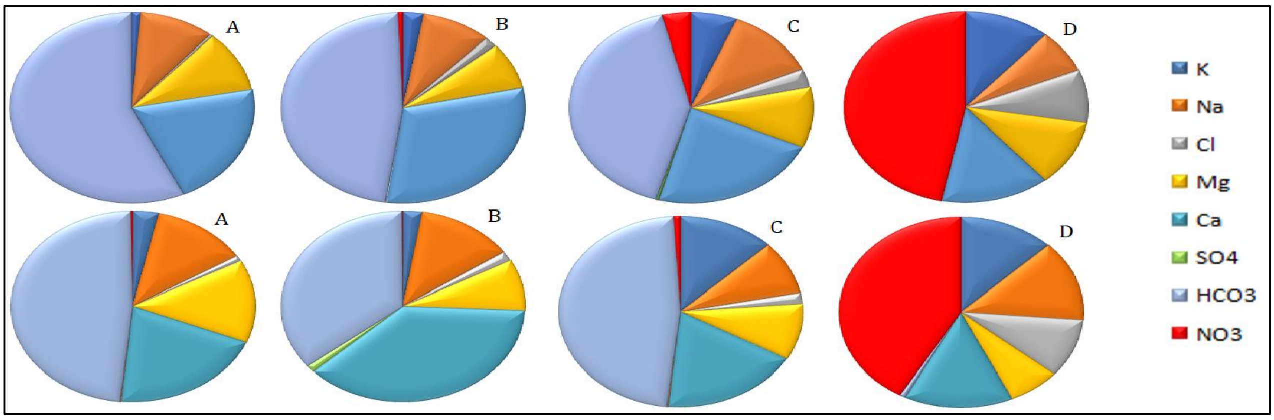


**Figure 9**:Pie charts of surface (A and C) and groundwater samples (B and D) collected in BIW and DLSW, respectively, and during the rainy (First row) and dry (second row) seasons with concentrations in mg/l

In the dry season, BIW presents the same mixing types as those observed in the rainy season. As for DLSW, it has approximately the same water facies than BIW. They mostly belong to the Ca-$HCO_3$ group with 03 samples (11%) belonging to the Na-Cl group. This can be the result of a negligible amount of nitrate input in the watersheds during the dry season. However, some shallow groundwater remains in the Na-K-Cl-$NO_3$ groups as nitrate is accumulated here. This evolution shows the effects of the geology and land-use in DLSW and BIW where nitrate is introduced through surface water and accumulated in groundwater.

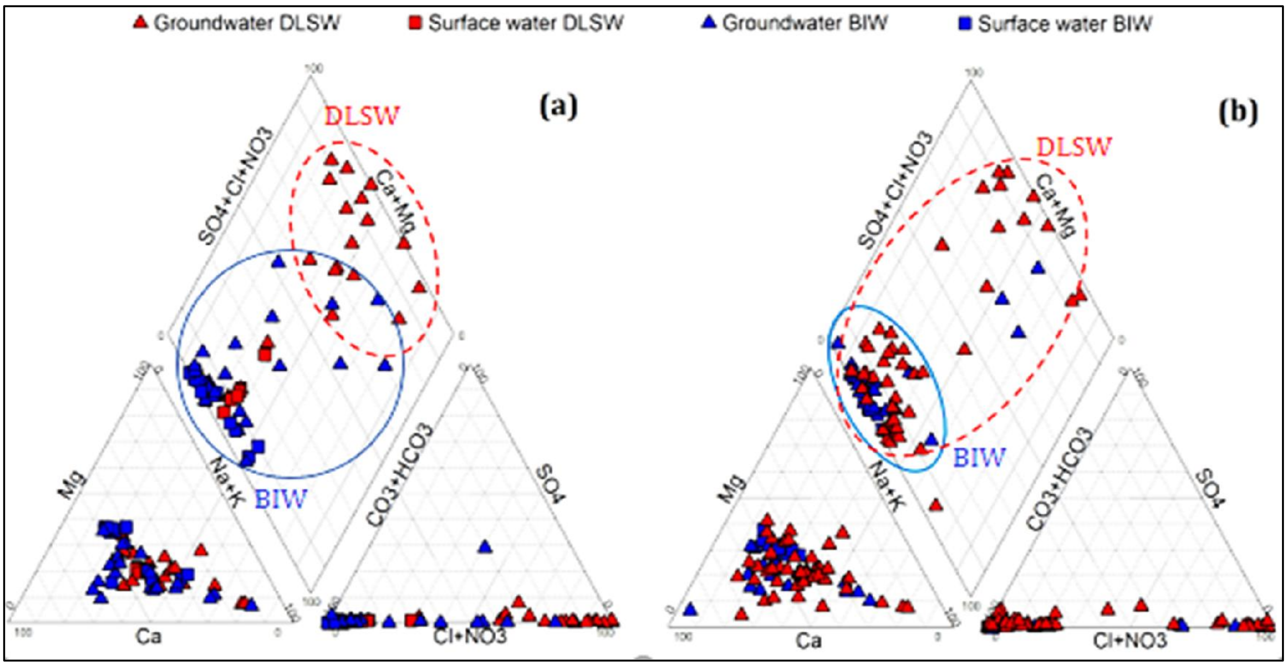


**Figure 10**:Piper diagram of the water sampled in the rainy (a) and the dry (b) seasons

### 3.2.1.2. Mineralisation

The generally low TDS values are possible indications of the occurrence of young or re-charging groundwaters since high values of TDS are mostly associated with old or discharging groundwaters (Freeze & Cherry, 1979). Together with the EC, they represent the mineralisation degree of water. In the rainy season, EC values range from 9 µS/cm to 160 µS/cm with a mean of 34.24 µS/cm in BIW and from 58 µS/cm to 698 µS/cm with a mean of 156 µS/cm in DLSW. In the dry season, it remains the most varying parameter in both watersheds and mineralisation is generally less advanced in surface water than groundwater. In the rainy season, except for $Mg^{2+}$ and $HCO_3^-$ in BIW and $HCO_3^-$ , $Na^+$, $Ca^{2+}$ and $SO_4^{2-}$ in DLSW, concentrations of major ions are higher in ground-water than surface water. In the dry season, TDS is higher in groundwater than surface water for every watershed but $K^+$, $Mg^{2+}$ and $SO_4^{2-}$ in BIW and $Mg^{2+}$, $Ca^{2+}$ and $HCO_3^-$ are more present in surface than groundwater. In agreement with the results of Fantong et al. (2020), such observation depicts that the observed groundwater has a longer residence time in the aquifer than surface water, and that the hydrological regime is dominantly a stream losing system in DLSW. Contrary to DLSW, BIW is a stream gaining system as surface water is less mineralized than groundwater. The evolution of the mineralisation in the two watersheds is presented in Figure 11. In both watersheds, water flows eastward.

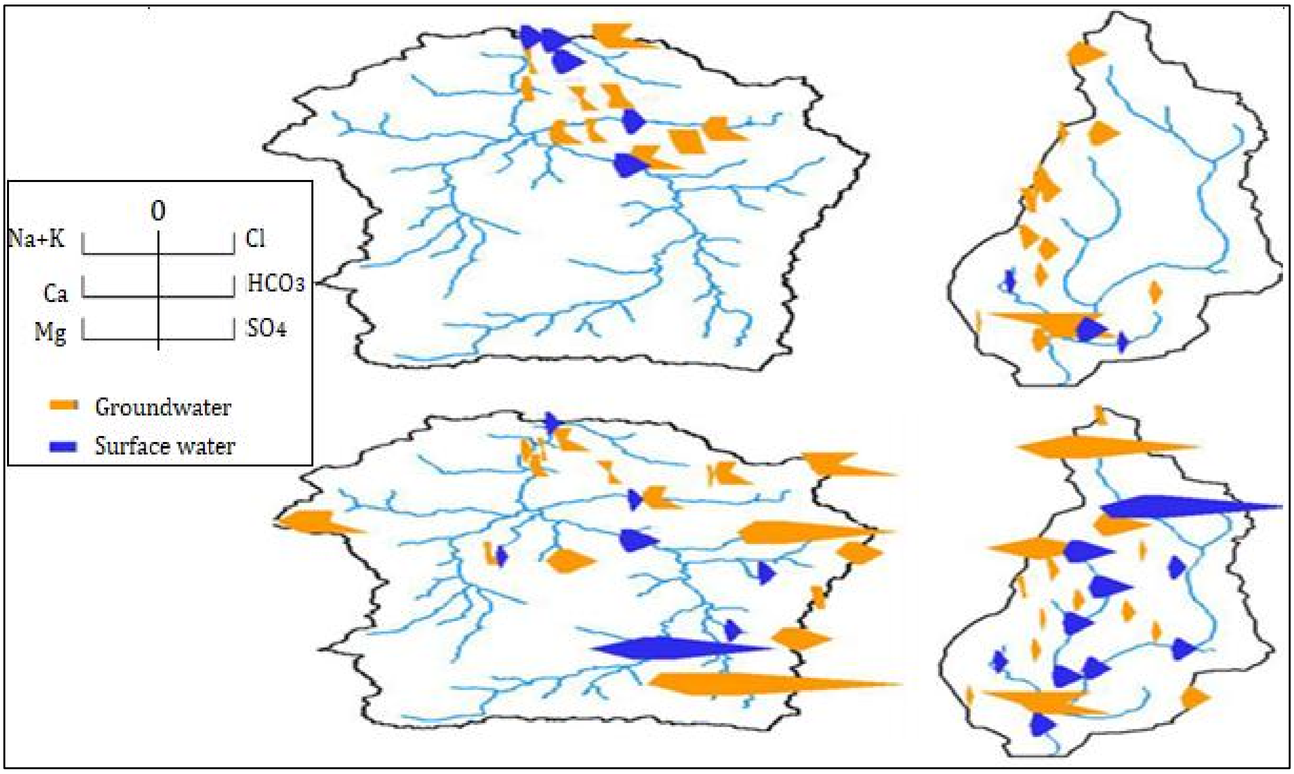


**Figure 11**: Stiff maps of BIW and DLSW during the rainy (First row) and dry (Second row) sea-sons presenting variation of water chemistry with space and depth

Electrical conductivity is a function of the lithology and structure of the soil. These results are in accordance with this assertion. As observed by Brickl & Melissa (2012) in the south fork of the flathead river in Montana, conductivity is higher in sedimentary watershed than in igneous watershed. Moreover, wells are generally dug close to residences to ease access to water for inhabitant. Yet, this means that they are also close to unprotected traditional toilets and waste water from household activities. For rivers, the excessive mineralisation is caused by sustenance agriculture with the fertilizers used, clothes and dishes washed in the river or wastes dumped near water courses. Population use to produce goods directly in contact with water sources to ease their work for the transportation of irrigation water and to minimise the effects of drought on their productivity.

## 3.2.2. Trace elements

"Metals" is the term used to mean an element that displays cationic behaviour in aqueous solution or has an oxide that is soluble in acids (Parish, 1977). They can be classified as heavy metals (most known) and rare earth elements (REEs). The following heavy metals were found to be in abnormal concentrations compared to others in the same sample:

### 3.2.2.1. Heavy metals

***a. Arsenic***

Concentration of arsenic in water is usually less than 10 µg/l although higher levels may occur near natural mineral deposits or anthropogenic sources (ATSDR, 2007). It has almost the same concentration in BIW during the rainy and dry seasons. It ranged from 0.01 µg/l to 0.11 µg/l with a mean pH value of 6.45 in the rainy season and 6.02 in the dry season. In DLSW, the maximum values of arsenic are observed in the rainy season (17.7 µg/l) and its concentration is very small in the dry season (maximum concentration is 1.43 µg/l). In agreement with the findings of Savarimuthu et al. (2006) in India and Smedley et al. (2002) in Argentina, such a behaviour is attributed to the local dissolution of iron oxyhydroxides with an environment becoming more reducing.

***b. Barium***

Barium generally occurs in water at concentrations less than 100ug/l and originates primarily from natural sources (WHO, 2017). It varied from 18.9 µg/l to 141ug/l in the rainy season and from 27.9 µg/l to 339 µg/l in the dry season BIW. For DLSW, barium concentrations varied from 165 µg/l to 3922 µg/l in the rainy season and from 28.1 to 2864 µg/l in the dry season. Contrarily to BIW, barium concentration is higher in the rainy season due to erosion of natural deposits and runoff in cropland areas. Moreover, the dissolution of limestones and sandstones increases the concentration of barium in raw water. As observed by Moore & Staubitz (1984), these rocks contain barite which is one of the most common sources of barium in raw water.

***c. Beryllium***

Beryllium is not likely to be found in natural water above trace levels as a result of the insolubility of its oxides and hydroxides at the normal pH range (WHO,2017). In the rainy season, 8% of the water sampled in DLSW shows very high concentrations of beryllium as compared to the concentration observed in all the samples collected. Very closed to these wells are anthropogenic activities leading to the reduction of pH values. This causes increase in the mobility of heavy metals. Consistently with the results of IPCS (2001) beryllium in the watershed originate from coal burning and rock weathering.

***d. Cobalt***

Cobalt is a naturally occurring element found in small amounts in most rocks, soil, water, plants and animals (Obasi & Akudinobi, 2020). In the study area, its concentration varied from 0.06µg/l to 6.22µg/l in BIW and from 0.12µg/l to 108µg/l in DLSW during the wet season. Smaller values are observed during the dry season in DLSW with cobalt levels ranging from 0.04µg/l to 61.3µg/l while it is the opposite in BIW (0.14µg/l to 50.7µg/l). In addition to rock-water interaction are sewage effluents and agricultural run-off that are the main contributors to cobalt input in water. Cobalt is more concentrated in DLSW compared to BIW due to the high turbidity of water in this watershed. In agreement with the results of Nagpal (2004) studying water guidelines for cobalt, it binds to suspended solids and becomes parts of bed sediments.

***e. Lead***

Unlike many other drinking water contaminants, lead is not present at source but rather results from the distribution system. It is a cumulative poison with important impacts on health. In BIW, it ranges from 0.02µg/l to 0.26µg/l in the rainy season and from 0.02µg/l to 0.16µg/l in the dry season. In DLSW, its level is higher, varying from 0.07µg/l to 56.3µg/l in the rainy season and from 0.04µg/l to 10.7µg/l in the dry season. In the study area, high concentrations of lead are observed only in 8% of the samples collected in DLSW. This suggests the impact of anthropogenic activities on this watershed. Among them are combustion of coal, waste incineration and use of pesticides in agriculture that are common sources of lead. In 2007, Abadin et al. reported similar sources of lead establishing its toxicological profile.

***f. Manganese***

Manganese is one of the most abundant metallic elements in natural water, present in igneous and metamorphic rocks (Reyes-Tascano et al., 2020). In the rainy season, it varied from 2.03µg/l to 407µg/l in BIW and from 6.63 to 1755µg/l in DLSW. In the dry season, manganese concentrations ranged from 5.99 to 3574µg/l in BIW and from 0.14µg/l to 1016µg/l in DLSW. The highest concentrations of manganese are observed in shallow groundwater and during the rainy season for BIW and the dry season for DLSW. Similar results to those obtained in BIW were observed by Nienie et al. (2017) in the sub-urban area of Kikwit in Democratic Republic of Congo which has a similar geology. This suggests natural weathering of rocks as the main reason for the high levels of manganese in water.

***g. Nickel***

Nickel is the 24$^{th}$ most abundant element in the Earth's crust, comprising about 3% of the composition of the earth. It is the 5th most abundant element by weight after iron, oxygen, magnesium and silicon (Cempel & Nikel,2005). Its normal concentration in surface water is lower than 5 µg/l (McIlveen & Negusanti, 1994). In the rainy season, it varies from 0.202 µg/l to 5.89 µg/l in BIW and from 0.652 µg/l to 72.7 µg/l in DLSW. During the dry season, it ranges from 0.242 µg/l to 19.7 µg/l in BIW and from 0.345 µg/l to 31 µg/l in DLSW. Its presence in water may be a consequence of the dissolution of ore-bearing rocks or anthropogenic sources. Consistently with the land use around the wells, Ni originates from waste deposits, fertilizers from agriculture, organic manure and fuel combustion.

***h. Uranium***

Uranium is found ubiquitously in nature at low concentrations in soil, rock and water (Melo & Burkart, 2011). High values of uranium are observed only in GW001 (66.695 µg/l) and GW002 (31.074 µg/l). In the remaining part of the samples, it exists as traces (less than 0.1 µg/l). High levels of As, Co, Cu and Ni are observed only in these wells. This is consistent with the findings of Rose & Wright (1980) which show that these metals are pathfinders of uranium.

#### *3.2.2.2. Rare Earth Elements*

Rare Earth Elements (REEs) or Rare Earth Metals are technically defined as the 15 elements in the lanthanide (La) series, yttrium (Y) and scandium (Sc) (Koltun & Tharumarah, 2014). During the rainy and dry seasons, their concentrations are found to be very small in both watersheds except in GW001 and GW002. Here, the REEs presenting positive anomalies compared to other samples in the watersheds are: Dy, Er, Eu, Ga, Gd, Hf, Ho, La, Li, Lu, Nd, Pr, Rb, Sb, Sm, Tb and Ti (GS002, GW003, GS003). Contrarily to the findings of Rose & Wright (1980), molybdenum which is also a pathfinder of uranium is not in excess where its maximum concentrations are observed in the rainy season.

### 3.2.3. Stable environmental isotopes

Stable isotopes are widely used in arid and semi-arid environments to determine the evaporation extent of recharge sources, recharge conditions, and mixing proportions of water (Brunel et al., 1995; Pasvanoglu & Celik, 2018). Apart from NR74 in the dry season, values of deuterium and oxygen-18 are negative in both seasons. This means that water samples are depleted in these isotopes. Moreover, the standard deviation of these stable environmental isotopes is small in both watersheds (with smallest values in the rainy season) and plotted along the Global Meteoric Water Line (GMWL) of Craig (1961) in Figure 12. Hence, they can be regarded as conservative during water-rock interactions (Gat, 2010; Taylor & Howard, 1996). Factors that can affect the recharging rainfall are mostly mixing with paleo-waters and to a limited extent, evaporation (for 03 samples in BIW and 01 sample in DLSW during the rainy season). Similar results were obtained by Fantong et al. (2009) in the Mayo Tsanaga River Basin with a greater influence of evaporation.

A secondary stable environmental isotope which is deuterium excess (d-excess) was also investigated (Table 8 and Table 9). It ranged from -4.16 to 12.08 in the rainy season with 80% and 100% of water samples in DLSW and BIW, respectively having values above 10‰ (Figure 13a). Similar results are obtained in the dry season (Figure 13b). These high values of d-excess show that the recharge of the aquifers takes place under low relative humidity conditions. Sixty-six years ago, Njitchoua et al. obtained the same results in upper Cretaceous aquifer of the Garoua basin. The implication of the δ-space diagram and d-excess indicate hydraulic connectivity within shallow aquifer that does not only favour mixing between surface and shallow groundwater as observed in the Piper diagram (Figure 10), but also the vulnerability of the watershed to contamination and pollution.

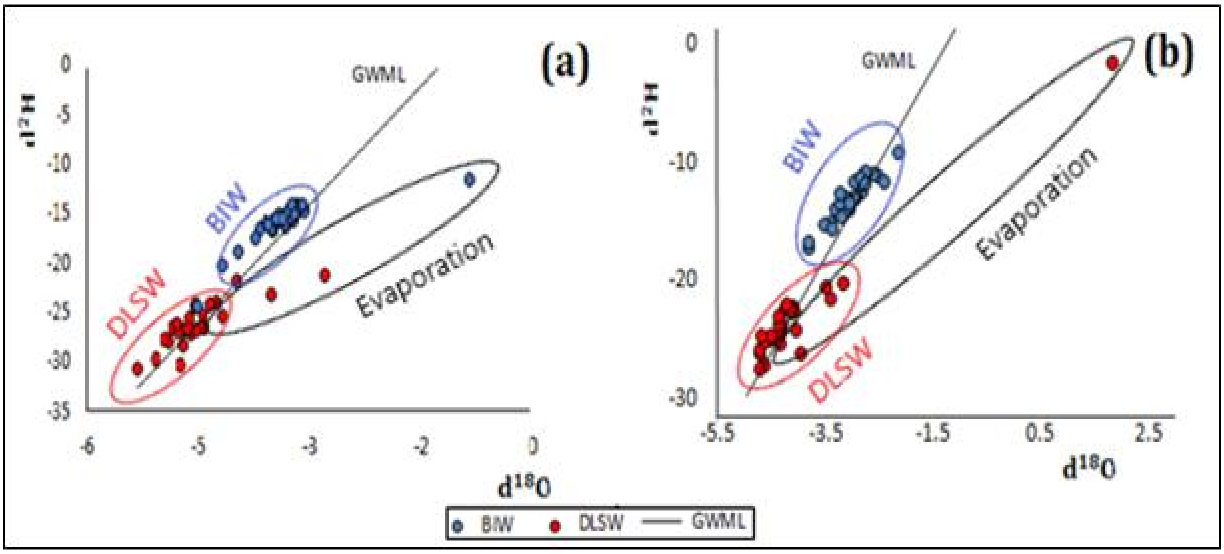


**Figure 12**: Correlation between $\delta^{18}O$ and $\delta^{2}H$ in BIW and DLSW during the rainy (a) and dry (b) seasons with the GMWL showing mixing water and limited evaporation in both seasons

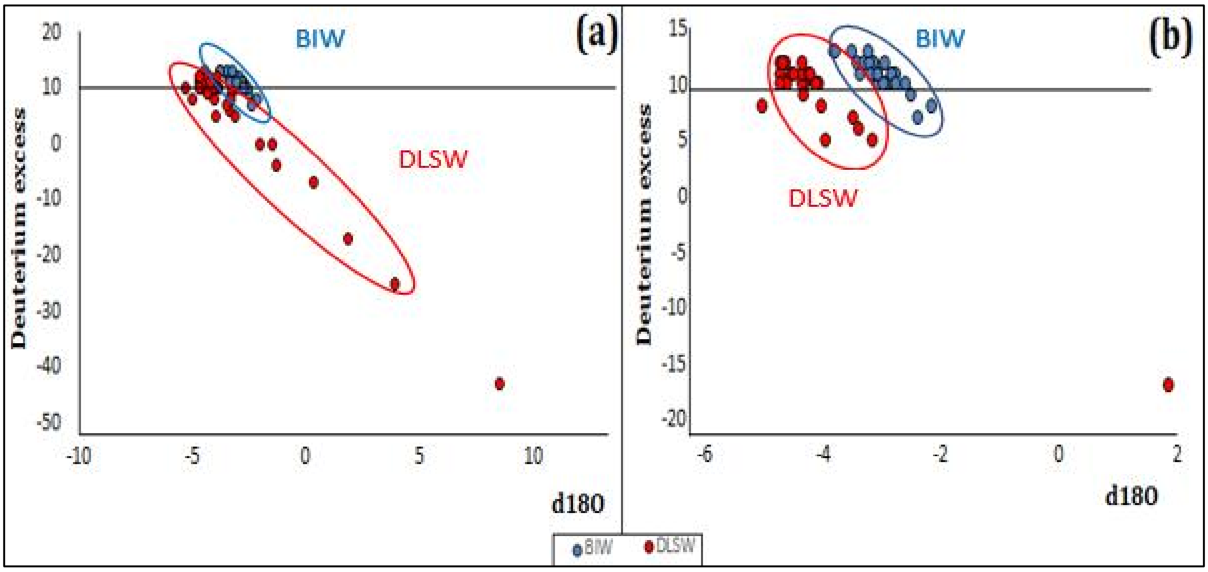


**Figure 13**: Correlation between d-excess and $\delta^{18}O$ in BIW and DLSW during the rainy (a) and dry (b) seasons presenting

## 3.3. FACTORS CONTROLLING WATER CHEMISTRY

Several factors are responsible for the modification of water chemistry. They can be classified as natural or anthropogenic and assessed through major ion chemistry and compositional relations among ionic species.

### 3.3.1. Natural factors

The sources of ions in groundwater can either be lithogenic or anthropogenic. Since the studied regions experience dry and semi-arid climatic conditions, evaporation may also contribute to their water chemistry. Hence, Gibbs plots (Figure 14) is employed to understand and differentiate the influences of rock-water interactions, evaporation and rainfall on water chemistry in the study area (Gibbs, 1970).

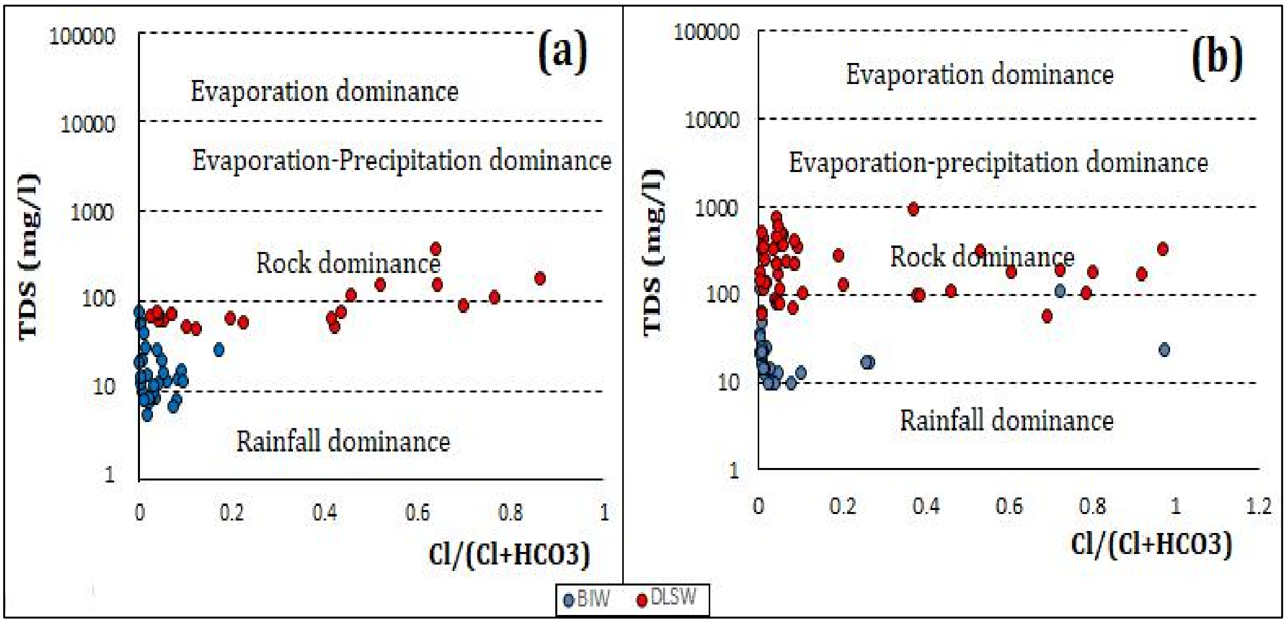


**Figure 14**: Gibbs diagram of the study area during the rainy (a) and dry (b) seasons showing the contribution of rock weathering, rainfall and evaporation to water chemistry with ratios in µM/µM

### 3.3.1.1. Rock-water interactions and rainfall

In the rainy and dry seasons, Gibbs diagrams show data points for the sampled water in BIW and DLSW distributed in water-rock dominant domain. This means that incongruent dissolution of silicate minerals is a dominating source of inorganic ions into water as a result of root respiration. The same factors were observed in the Mayo Tsanaga River Basin (Far North Region of Cameroon) by Fantong et al. (2009). Only 3% (in the rainy season) and 5% (in the dry season) of samples fall in the rainfall dominant domain, suggesting evolution from the rainwater chemical signature. These samples belong to BIW. As a matter of fact, igneous rocks are solid and weather less easily than sedimentary rocks. This result is consistent with the one obtained by Fernades et al. (2020) in the Sorocaba River basin in Sao Paulo State of Brazil.

### 3.3.1.2. Saline water intrusion

The computation of the Na/Cl ratio is a well-known method used to determine the origin of salinity in groundwater systems. It can be termed as natural (from seawater, if less than 0.86) or man-made (if greater than 1) (Sudaryanto & Naily, 2017). In the present cases, it varied from 1.81 to 180 in BIW and from 0.62 to 9.23 in DLSW during the rainy season. In the dry season, this ratio ranged from 0.68 to 176.4 in BIW and from 0.48 to 229.58 in DLSW. Only 10.3% and 12.5% of samples in the rainy and dry season, respectively have Na/Cl molar ratio less than 0.86, coming from lithogenic sources. Despite the great importance of anthropogenic activities, this implies that $Na^+$ in groundwater originates from the weathering of silicate minerals (Meybeck, 1987) like albite as illustrated by the equation below:

$$\underset{\text{(Albite)}}{2NaAlSi_3O_8} + 2CO_2 + 11H_2O \rightarrow \underset{\text{(Kaolinite)}}{Al_2Si_2O_5(OH)_4} + 2Na^+ + 2HCO_3^- + 4H_4SiO_4$$

### 3.3.1.3. Ion exchange

In the study area, CAIs are negative during the wet and dry seasons except for NW40 in the dry season. These negative values indicate that $Mg^{2+}$ and $Ca^{2+}$ from water are exchanged with $Na^+$ and $K^+$ in rocks, favouring cation-anion exchange reactions (chloro-alkaline disequilibrium) (Gupta et al, 2009). The CAIs are negative when $Na^+$ and $K^+$ content is high. This situation occurs when groundwater has been strongly in contact with minerals able to yield these interchangeable cations easily. This exchange is common with aluminosilicate clays formed by layers whose cohesion is ensured by the existence of interlayer cations and water. Consistently with the results of Wotany et al. (2013) in the Rio del Rey Basin (South-West Region of Cameroon), the surface of the layers is negatively charged, thus promoting the possibility of cation exchange with groundwater.

## 3.3.2. Anthropogenic activities

Adding to the natural processes identified, anthropogenic activities are generally great contributors to water chemistry alteration.

### 3.3.2.1. Nitrate and chloride in the watersheds

In DLSW, many samples have excess $NO_3^-$ in the wet and dry seasons while the concentrations are generally low in BIW. Concentrations of $NO_3^-$ are a result of different pollution sources such as municipal wastewater, fertilizers and pesticides application in agriculture. Delmie et al. (2007) illustrates that a positive correlation of $NO_3^-$ and $Cl^-$ should be a diagnostic indicator of anthropogenic activity. The correlation coefficients obtained between $NO_3^-$ and $Cl^-$ are shown in the bivariate plot of $NO_3^-$ with $Cl^-$ (Figure 15).

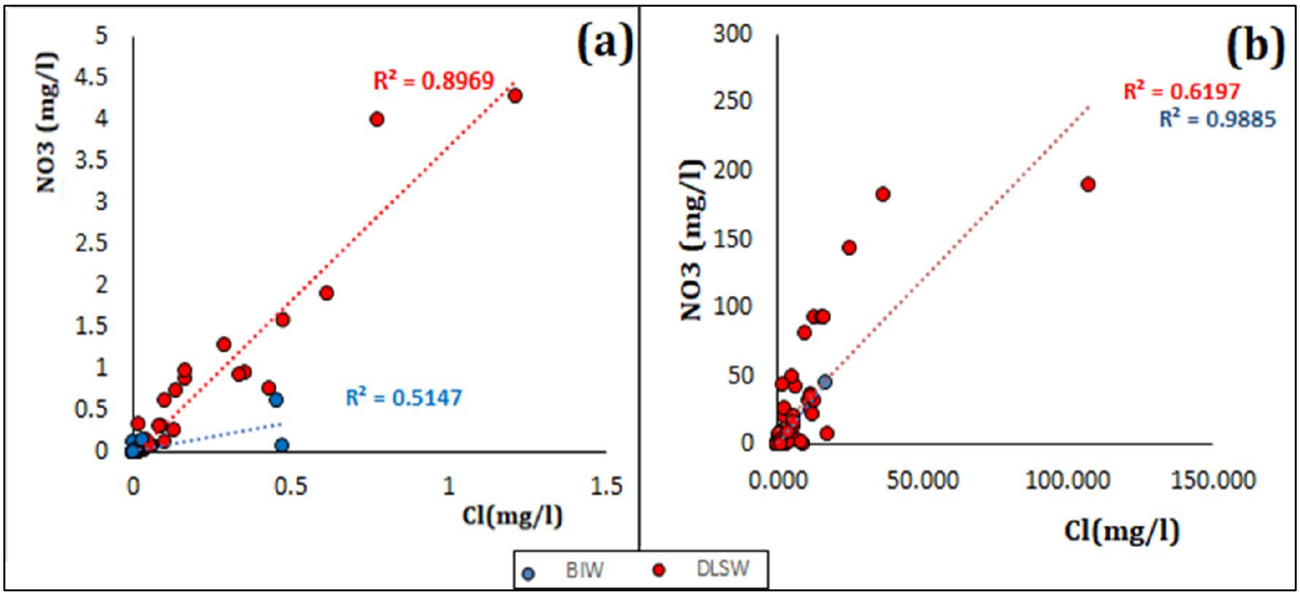


**Figure 15**: Bivariate plot of $NO_3^-$ and $Cl^-$ presenting the correlation between these major ions as an indicator of the impact of anthropogenic activities on water sources in the rainy (a) and dry (b) seasons

In both catchments, $NO_3^-$ has a strong positive correlation with $Cl^-$, indicating the impact of anthropogenic activities around water sources. From the observation on the field, these man-made sources of pollution are leachates from solid waste, wastewater disposal and agricultural activities (application of fertilizers, weedicides, pesticides, manure).

### 3.3.2.2. Heavy metals in the watersheds

The main components of chemical fertilizers are N, P and K assimilated as $NO_3^-$, $NH_4^+$, $PO_4^{2-}$ and $K^+$ by plants. During the rainy and dry seasons, these ions show high correlation with some of the heavy metals observed in excess (Table 10).

Ammonium ($NH_4^+$) is the second main form of nitrogen intake by plants. In DLSW, it is found in excess quantity as $NO_3^-$ due to agricultural activities on-site. During the rainy season, arsenic has a strong positive correlation with $NH_4^+$ ($r^2$=0.46) and $NO_3^-$ ($r^2$=0.881). Scheiber et al. (2016) observed similar results in the confined deep portion of the Niebla-Posadas aquifer where groundwater is mostly used for irrigation. At the same period, this metal is also correlated to $K^+$ in DLSW ($r^2$=0.889). In 2018, Murphy et al. found that arsenic is generally accumulated in rice and maize farmland due to the use of K-As fertilizers. These nutrients show a high correlation with Ba and Mn in BIW during the rainy season and Co ($r^2$ =0.981 with $NO_3^-$) during the dry season. The strongest relations are observed in DLSW during the rainy season with As, Ba, Be, Co, Ni, Pb and U. As concluded by Wyszkowski & Brodowska (2020), increasing nitrate fertilization increase the content of water in Mn and Co while increased potassium fertilization leads to Mn excess.

**Table 10**: Pearson correlation between heavy metals and nutrients from agricultural activities

| RAINY SEASON | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| BIW | | **As** | **Ba** | **Be** | **Co** | **Mn** | **Ni** | **Pb** | **U** |
| | $NH_4^+$ | -0.160 | **0.627** | -0.025 | 0.181 | **0.857** | -0.093 | -0.060 | -0.127 |
| | $NO_3^-$ | -0.229 | **0.712** | 0.122 | 0.330 | **0.856** | -0.084 | -0.080 | -0.210 |
| | $K^+$ | 0.045 | 0.020 | -0.355 | -0.180 | 0.370 | -0.343 | -0.100 | **0.484** |
| DLSW | | As | Ba | Be | Co | Mn | Ni | Pb | U |
| | $NH_4^+$ | **0.463** | **0.507** | **0.615** | **0.622** | 0.100 | **0.660** | **0.678** | **0.664** |
| | $NO_3^-$ | **0.881** | **0.950** | **0.875** | **0.885** | 0.157 | **0.893** | **0.827** | **0.815** |
| | $K^+$ | **0.889** | **0.828** | **0.790** | **0.786** | 0.164 | **0.772** | **0.713** | **0.687** |
| DRY SEASON | | | | | | | | | |
| BIW | | **As** | **Ba** | **Be** | **Co** | **Mn** | **Ni** | **Pb** | **U** |
| | $NH_4^+$ | 0.337 | 0.343 | -0.186 | 0.320 | 0.381 | 0.026 | 0.204 | 0.368 |
| | $NO_3^-$ | 0.391 | **0.785** | -0.214 | **0.981** | 0.002 | 0.252 | -0.105 | |
| | $K^+$ | -0.016 | 0.381 | 0.071 | 0.025 | 0.113 | -0.124 | -0.011 | -0.090 |
| DLSW | | As | Ba | Be | Co | Mn | Ni | Pb | U |
| | $NH_4^+$ | 0.208 | **0.686** | 0.393 | **0.422** | 0.092 | **0.548** | 0.333 | 0.240 |
| | $NO_3^-$ | 0.089 | 0.255 | 0.032 | 0.213 | **0.506** | 0.281 | 0.016 | -0.088 |
| | $K^+$ | 0.070 | **0.684** | 0.316 | 0.379 | 0.093 | **0.568** | 0.233 | 0.189 |

## 3.4. SUITABILITY FOR IRRIGATION

Four basic criteria are used to evaluate water quality for irrigation purpose: salinity, sodicity, carbonate content and excess of ions causing plants toxicity. The molar ratio and indices computed to assess these parameters during the rainy and dry seasons are presented in Appendix 4 and Appendix 5 for the rainy and dry seasons, respectively. These are Sodium Adsorption Ratio (SAR), Permeability Index (PI), Solute Sodium Percentage (SSP), Kelly Ratio (KR), Residual Sodium Bi-Carbonate (RSBC), Magnesium Adsorption Ratio (MAR), boron (B), chloride ($Cl^-$).

### 3.4.1. Salinity

Westcott & Ayers (1984) indicated that if EC is greater than 3000 µS/cm, crop productivity is highly affected, and it is good if EC is less than 250 µS/cm. During the rainy season, none of the samples collected in BIW exceed this guideline. The highest values of EC is observed in DLSW with 4 samples (namely, GW001, GW002, GW007 and GW009) for which EC is greater than 250 µS/cm. In the dry season, 100% of water sampled in BIW show excellent quality for electrical conductivity. In DLSW, these values range from 36 to 893 µS/cm. Almost 19% and 11% of samples have EC values greater than 250 µS/cm and 500 µS/cm, respectively. Independently of the season, EC values are less than 3000 µS/cm and can be used for agricultural purposes as confirmed by the Wilcox diagrams in Figure 16.

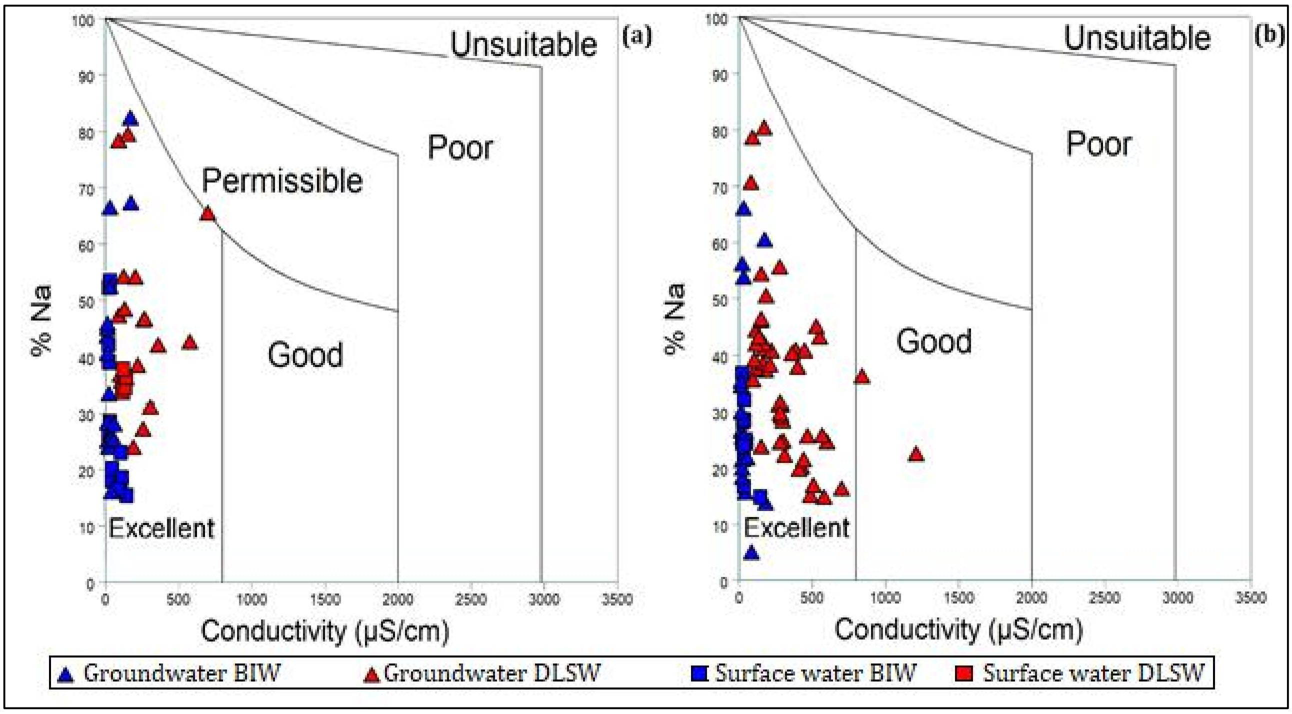


**Figure 16**:Wilcox diagrams of the samples collected during the rainy (a) and dry (b) seasons showing salinity hazard combined to sodicity hazard.

## 3.4.2. Sodicity

### 3.4.2.1. Percentage sodium

The percentage sodium (%Na) or solute sodium percentage (SSP) in the study area ranges between 15.38 and 82.07 in BIW and 23.5 and 79.15 in DLSW during the rainy season. During the dry season, it varied from 4.76 to 92.76 in BIW and 16.05 to 80.04 in DLSW. According to Todd (1980), water is excellent, good, permissible, doubtful and unsuitable if SSP (%) is < 20, between 20 and 40, between 40 and 60, between 60 and 80 and >80, respectively. This is 97.1% and 100% of water sampled in BIW and DLSW during the rainy season, suitable for irrigation. In the dry season, 96.5% and 96.3% of water samples are suitable for irrigation in BIW and DLSW, respectively. These values were combined to the EC values to plot the Wilcox diagram presented in Figure 16 which shows reduced water quality due to sodicity hazards only (high %Na).

### 3.4.2.2. Sodium Adsorption Ratio

During the rainy season, the SAR values ranges from 0.07 to 3.11 in BIW and from 0.15 to 1.29 in DLSW. Based on USSL (1954), water is considered excellent, good, fair and unsuitable for agriculture if SAR values are < 10, between 10 and 18, between 18 and 26 and >26, respectively. Hence, water quality in this period is excellent to good for irrigation (Figure 17). The results obtained in the dry season provide different ranges of SAR. In BIW, it varies from 0.04 to 1.45 and from 0.16 to 1.86 in DLSW. This is 100% of samples classified as excellent in BIW and DLSW. All samples have good SAR values. In each catchment, SAR is higher in the rainy season. As observed by Suarez et al. (2008), the interaction of irrigation water with rainfall is expected to result in sodicity hazard because of the low EC of rain.

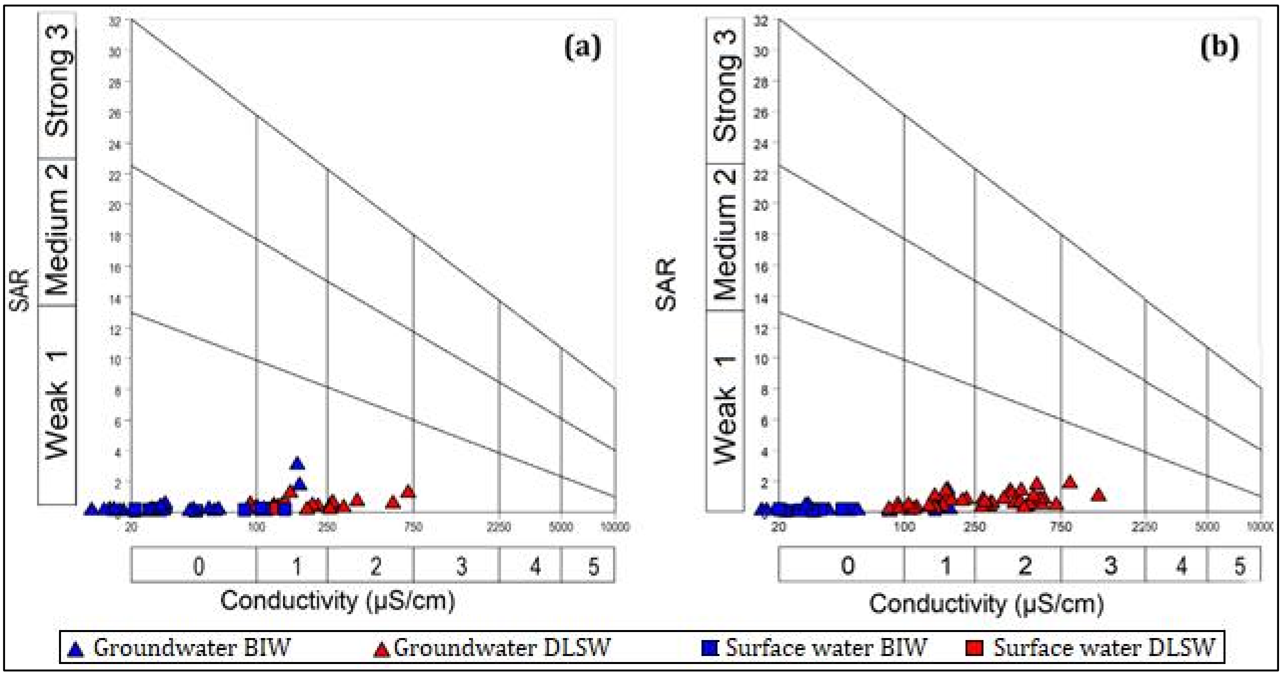


**Figure 17**: USSL classification of water sampled in the study area during the rainy (a) and dry seasons (b) showing these samples are not exposed to sodicity hazard but to salinity hazard due to high values of EC in some water points.

As might be expected, SAR values are higher in BIW than in DLSW. Indeed, the high clay content of DLSW considerably reduces the sodium content by adsorbing it onto its surface as it forms direct bond with its surface (an example is taken with montmorillonite by Zengqiang et al. (2016)).

### 3.4.2.3. Permeability index

In the rainy season, PI ranges from 107.3 to 572.4 in BIW with a standard deviation of 124.2 and from 22.2 to 181 in DLSW. In the dry season, it ranges from 92 to 519.3 in BIW and from 34.8 to 452.1 in DLSW. Based on PI, water can be class I (>75% permeability), class II (25-75% permeability) and class III (up to 25% permeability). Only few samples can be represented in the Doneen's chart (Figure 18) due to the high PI values in BIW. This diagram shows that 100% samples collected in BIW are in class III while in DLSW, water is clustered in Class I (16%), Class II (12%) and Class III (72%) during the rainy season and Class I (59%) and Class II (41%) during the dry season.

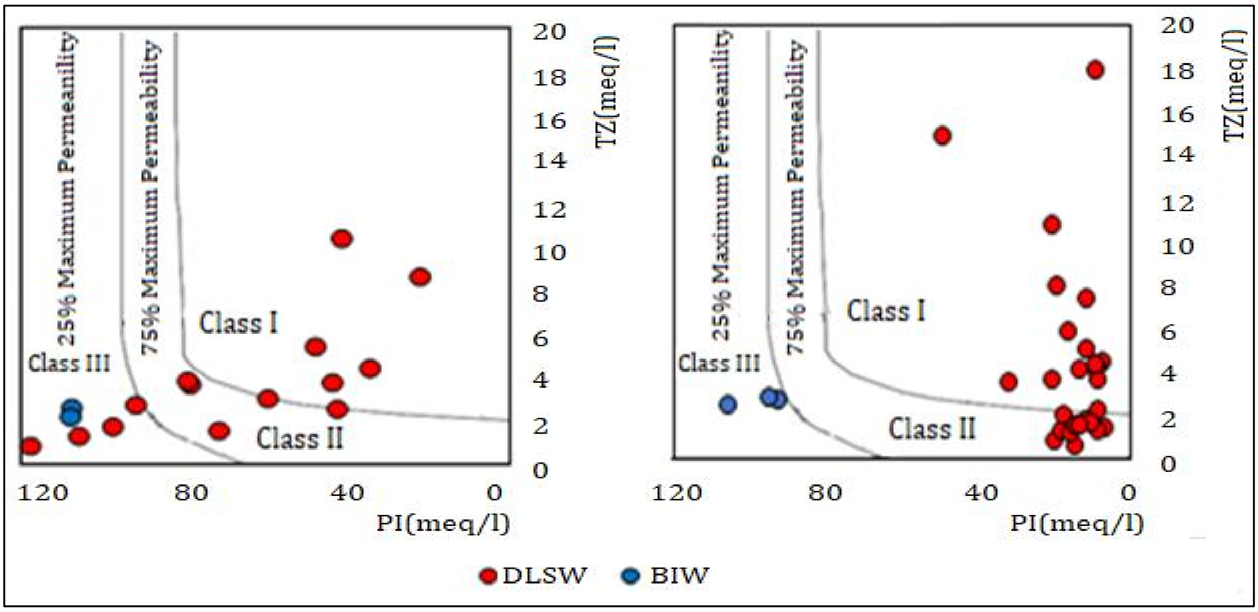


**Figure 18**: Doneen's chart of samples collected in BIW and DLSW during the rainy (left) and the dry (right) seasons showing high PI values in BIW compared to those obtained in DLSW

### 3.4.2.4. Kelly ratio

In the rainy season, KR varies from 0.14 to 4.46 in BIW and from 0.14 to 79.08 in DLSW. Smaller values are observed in the dry season: they range from 0.03 to 1.43 in BIW and from 0.12 to 2.21 in DLSW. Kelly's ratio with values <1, >1 and >3 indicate suitable water for irrigation, excess level of $Na^+$ in water (some plants can be affected by the sodium content in the soil) and unsuitable water for irrigation, respectively (Ramesh &Elango, 2012; Das & Nag, 2015**)**. Hence, during the rainy season, water is suitable for irrigation in BIW (91.2%) and in DLSW (98%). In the dry season, 89.7% and 88.9% of water sampled in BIW and DLSW respectively, are suitable for irrigation.

## 3.4.3. Acidity and alkalinity

Hydrogen potential (pH) defines the acidity of a solution. Hounslow (1995), characterized water according to pH as moderately acidic when pH values range is 4-6.5; neutral when the range is 6.5-7.8; moderately alkaline is 7.8-9 while water with pH greater than 9 is alkaline. In the rainy season, it ranges from 6.3 to 7.7 in BIW and 4.2 to 7.4 in DLSW with the smallest values in the groundwater. In the dry season, it ranges from 5.2 to 7.6 in BIW and from 4.6 to 8.1 in DLSW. This means that water is classified as acidic for groundwater samples and moderately alkaline for surface water samples. Only 3.4% of the samples have pH<5.5.

Bicarbonates occur in low salinity waters and their concentration usually decreases with an increase in EC. The proportion of $HCO_3^-$ is higher than that of $Ca^{2+}$ and has been considered to be undesirable because bicarbonate ions tend to precipitate calcium ions after evaporation of irrigation water. The classification of irrigation waters with respect to bicarbonate or carbonate alkalinity hazard is done on the basis of Residual Sodium Carbonate (RSC)and Residual Sodium Bi-Carbonate (RSBC). Residual Sodium Bi-Carbonate varied from -1.23 to 0.55 in the rainy season with the highest values in DLSW and from -1.28 to 4.35 in the dry season with extreme values in BIW. According to Gupta & Gupta (1987), water with RSBC<5.5; between 5.5 and 10 and >10 should be considered as safe; marginal and unsatisfactory for irrigation, respectively. Hence, both in the rainy and dry seasons, water quality is excellent for irrigation based on RSBC for 100% samples.

## 3.4.4. Specific ion toxicity

### 3.4.4.1. Magnesium Adsorption Ratio

In the wet season, MAR ranged from 13 to 48.4 in BIW and from 21.7 to 60.5 in DLSW. Smaller values are observed during the dry season: from 6.6 to 44.7 in BIW and from 14.22 to 45.4 in DLSW. Marginal water quality is observed only in DLSW (GB001) during the wet season. Consistent with the analysis of Haritast et al. (2008), highest MAR values are observed in the sedimentary watershed due to the presence of dolomite (good correlation between $Ca^{2+}$ and $HCO_3^-$, r=0.96 in BIW in the rainy season, r=0.93 in BIW in the dry season and r=0.89 in DLSW during the dry season).

### 3.4.4.2. Boron

Boron is not easily adsorbed by soils. Even essential for plant growth, it causes leaf-burning when accumulated in water. The most sensible plants present adverse effects of the presence of boron when it reaches 0.5 mg/l (Ludwick et al. 1990; Ayers &Westcott, 1985). In the rainy season, it varies from 6.35 µg/l to 64.4 µg/l in BIW and from 2.39µg/l to 20.01µg/l in DLSW. During the dry season, it varies from 3.77 µg/l to 43.6 µg/l BIW to 6.84 µg/l to 48.9 µg/l. Following this classification, the main crops cultivated in BIW and DLSW (garlic, potato, cotton, corn, onion...) fall in the group of boron sensitive crops for which the hazard is effective at 0.5mg/l. This means that there is no threat to crops in the study area.

#### 3.4.4.3. Chloride

Ayers and Westcott (1985) reported that $Cl^-$ toxicity on plants appears first at the leaf tips (which is a very common symptom for chloride toxicity) and progresses from the leaf tip back along the edges as severity of the toxic effect increases. Available classification shows that concentrations of chloride under 70mg/l are safe for all plants. In the rainy season, it varied from 0.006mg/l to 43.2mg/l with the highest values in DLSW. In the dry season, chloride concentration in the study area is between 0.01mg/l and 36.7mg/l. This low content in chloride is suitable for agricultural uses.

## 3.5. SUITABILITY FOR CONSUMPTION

Major ions concentrations and important physico-chemical parameters such as total hardness (TH), pH, electrical conductivity (EC), total dissolved solids (TDS) and trace elements were compared to WHO (2017) guidelines to assess suitability of drinking water. A summary of these results is provided in Table 11.

**Table 11**: Groundwater quality and compliance with WHO (2017) drinking water standards

| | BIW | | DLSW | | |
|---|---|---|---|---|---|
| | **Rainy season** | **Dry season** | **Rainy season** | **Dry season** | **WHO (2017)** |
| **pH** | 5.6-7.7 | 5.2-7.6 | 4.2-7.4 | 4.6-8.1 | **6.5-8.5** |
| **Ec** | 9-160 | 11-168 | 58-698 | 36-893 | **750** |
| **$Ca^{2+}$** | 0.4-10.8 | 0.53-15.7 | 1.34-24.6 | 1.2-87.9 | **75** |
| **$Mg^{2+}$** | 0.08-5.05 | 0.1-5.51 | 0.4-11.6 | 0.33-22.6 | **30** |
| **$Na^+$** | 0.4-25 | 0.3-17 | 1.4-27 | 0.8-72.2 | **200** |
| **$K^+$** | 0-1.5 | 0.1-1.8 | 2.9-75.3 | 2-25.6 | **100** |
| **$Cl^-$** | 0.01-16.9 | 0.01-16.40 | 0.8-43.2 | 0.07-36.7 | **250** |
| **$NO_3^-$** | 0-37.9 | 0-44.4 | 0.51-266 | 0.19-182 | **10** |
| **$SO_4^{2-}$** | 0-18.7 | 0-0.38 | 0.01-7.01 | 0-7.27 | **250** |
| **$HCO_3^-$** | 3.3-66.4 | 1.9-80.7 | 1.7-55.5 | 1.9-497 | **200** |
| **$F^-$** | 0.01-0.15 | 0-0.14 | 0.02-0.94 | 0.02-0.99 | **1.5** |
| **TDS** | 5.55-95.91 | 10-143 | 48.95-451.59 | 57-746 | **500** |
| **TH** | 1.31-47.71 | 1.74-61.1 | 4.99-109.06 | 4.37-312.41 | **100** |

### 3.5.1. Total Dissolved Solids

According to WHO (2017) maximum permissible limit of TDS in drinking water is 500 mg/l. The maximum value of TDS in the study area is 442.08mg/l during the rainy season so water is fresh and suitable for consumption. In the dry season, 100% of samples collected in BIW are suitable for consumption with TDS varying from 10mg/l to 143mg/l while 88.9% of samples collected in DLSW is suitable for consumption. In agreement with DLSW lithology, more TDS were expected to be higher in DLSW compared to BIW. They ranged from 57 to 746mg/l in DLSW. Water with TDS < 50mg/l is similar to distilled and low mineralized water having negative taste characteristics to which consumer may adapt with time (WHO, 2017). Such a water remains highly aggressive to human body.

### 3.5.2. Total Hardness

Total hardness (TH) varies from 3.31 mg/l to 113.7 mg/l in the wet season and from 2.38 to 312.41 in the dry season, with the highest and most varying values in Douka Longo catchment. None of the samples exceed the acceptable limits of hardness. According to Saravanakumar & Ranjith (2011) water may be classified as soft when TH values are less than 75 mg/l, moderately soft when TH values are between 76-150 mg/l, hard when values are between 150 - 300 mg/l and very hard when TH exceeds 300 mg/l. This means that almost 93% of the water sampled is soft and need to be enriched in calcium or magnesium for consumption during the rainy season.

### 3.5.3. Nitrate

According to WHO (2004), the maximum permissible limit of nitrate is 50 mg/l in drinking water. Except for 9 samples (36%) in DLSW (Figure 19), water in the study area is generally consistent with WHO guideline in the rainy season. Nitrate contamination of water generally originates from the use of chemical fertilizers that are less used in the dry season due to the scarcity of water resources during this period, disabling agricultural practices in non-irrigated lands. Hence, during the dry season the Piper diagrams (Figure 10) presents very low input of nitrate in the watersheds. It ranges from 0.19 to 182mg/l with 22.2% out of the WHO guidelines in DLSW and but does not exceed this guideline in BIW where the maximum concentration of nitrate is 0.14mg/l. High concentrations of nitrate were observed in this part of Northern Cameroon since 1995 by Njitchoua et al. It is associated to increased heart rate, nausea, headaches and abdominal cramps in adults while it is responsible for diarrhoea and vomiting in infants.

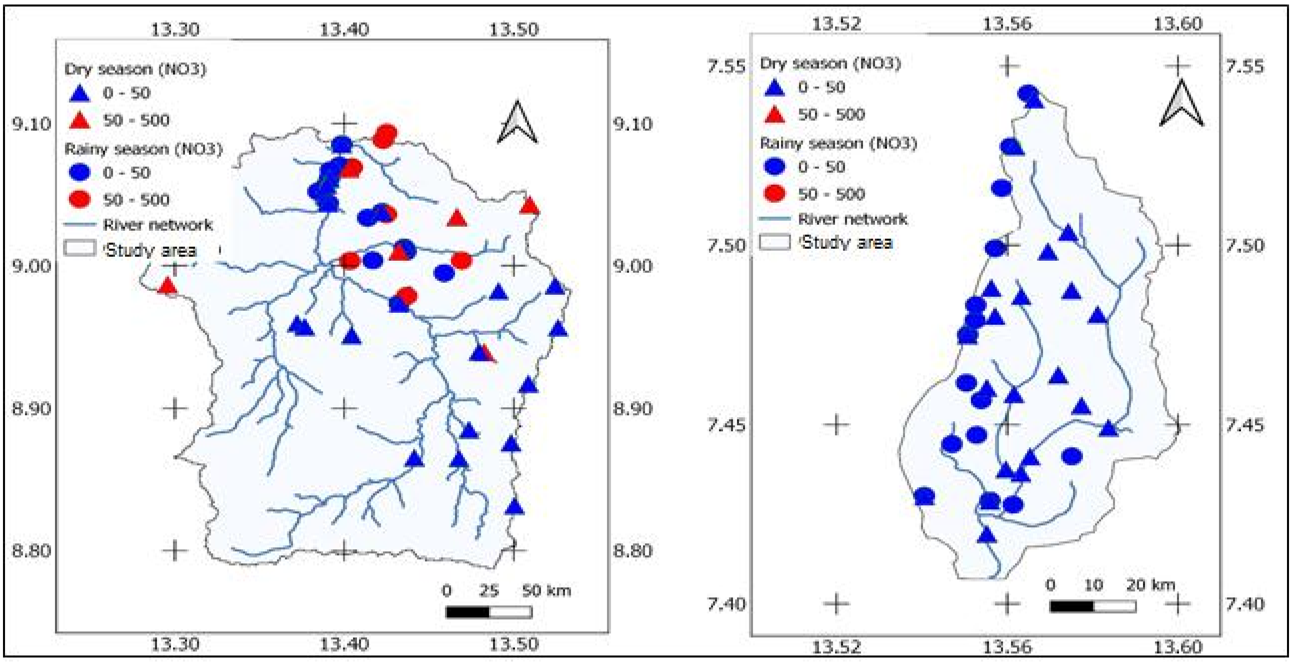


**Figure 19**: Nitrate maps in BIW and DLSW during the rainy and dry seasons

### 3.5.4. Chloride

Chloride has a key importance in the metabolism of the human body. According to WHO (2017), concentration of chloride should not exceed 250 mg/l. In the study areas, the chloride values are less than 250mg/l both in the rainy and dry seasons. Hence, water is safe for consumption based on this parameter.

### 3.5.5. Calcium

Calcium accounts for 1 to 2% of adult human body weight. Over 99 percent of total body calcium is found in bones. The high deficiency of calcium in humans may cause rickets, poor blood clotting and bones fracture while excess of calcium produces cardiovascular diseases (Meride & Ayenew, 2016). Its maximum permissible value in drinking water is 75 mg/l. In the study areas, the maximum concentration of calcium is 10.8mg/l in the rainy season and 87.9 in the dry season. The maximum concentrations are observed in DLSW, varying from 1.2mg/l to 87.9mg/l. Anomalous concentrations of calcium are observed in NR74 and NR73.

### 3.5.6. Trace elements

In the wet season, samples exceed WHO guidelines for arsenic (8%), barium (36%), beryllium (8%), uranium (8%), manganese (40%), cobalt (44%), nickel (4%) and lead (8%) in DLSW while in BIW, there is excess of manganese (20.59%) and cobalt (14.7%) (Figure 12). Here, the 8%

of contamination are those of wells GW001 and GW002 where the pH conditions are moderately acidic (4.2 and 4.3, respectively. In such conditions, trace elements are likely to be highly mobile (Edmunds & Smedley, 1996). In the dry season, DLSW is contaminated by barium (16.67%), manganese (31.25%), lead (2.1%) and cobalt (20.7%). The reduction in water volume leads to the increase in concentrations of barium (3.4%), manganese (48.3%) and cobalt (20.7%) (Figure 20). In both seasons, water quality is highly altered by heavy metals and needs to be treated before consumption.

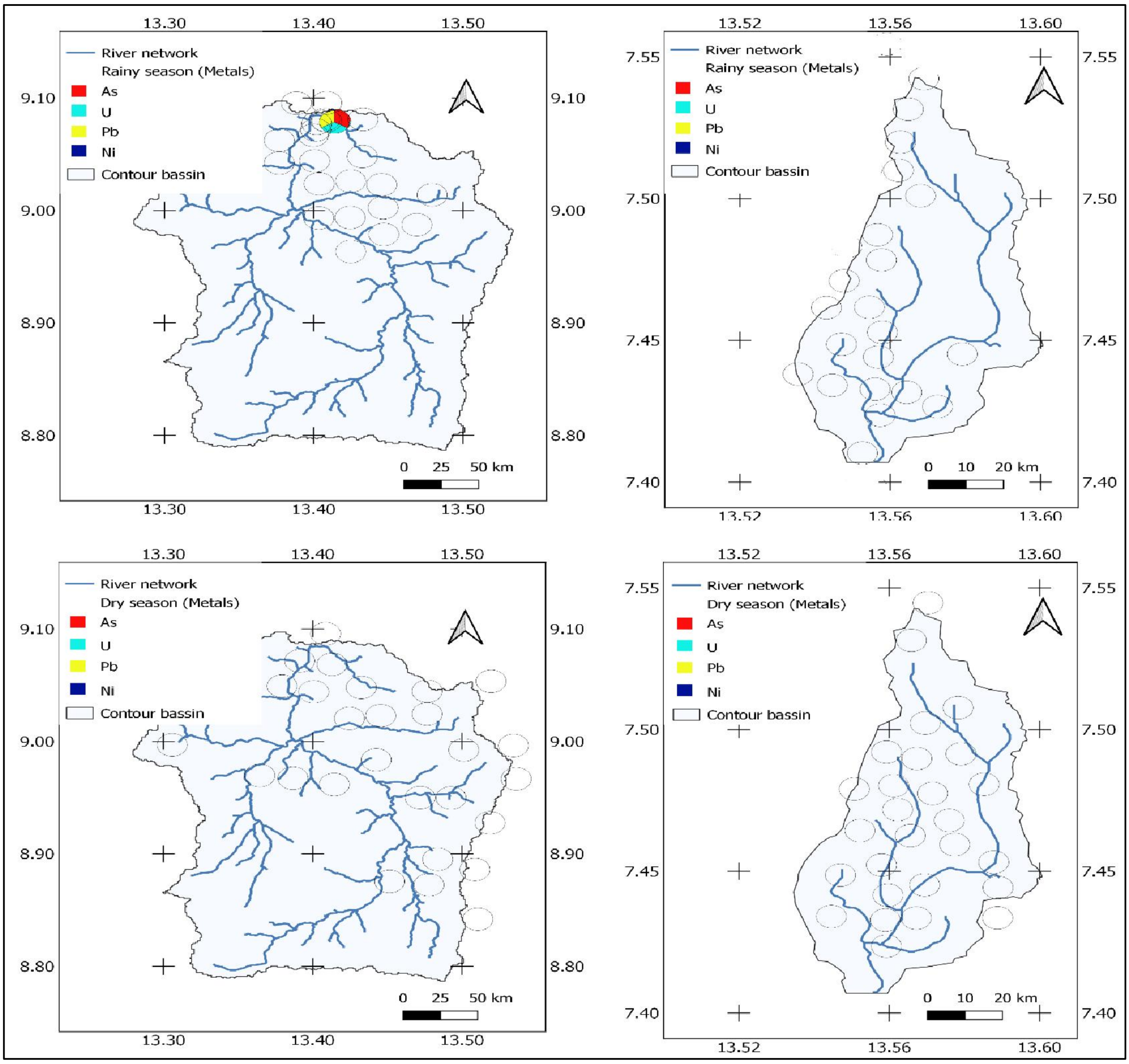


**Figure 20**:Distribution of heavy metals of health concern in the watersheds during the rainy (first row) and dry season (second row)

### 3.5.7. Water Quality Indices

The WQIs obtained are shown in Appendix 4 and Appendix 5 for the rainy and dry season samples, respectively. They vary from 4 - 97 and from 15 – 203 in the dry season for BIW and DLSW, respectively (Figure 21). The worst and best results are observed during the rainy season with WQIs varying from 0.6 to 37.9 in BIW and from 8.65 to 847.2 in DLSW (Figure 21). This is 100% and 64% of samples suitable for consumption in BIW and DLSW during the rainy season, respectively. In the dry season, 93.1% and 63% of samples are suitable for consumption in BIW and DLSW, respectively.

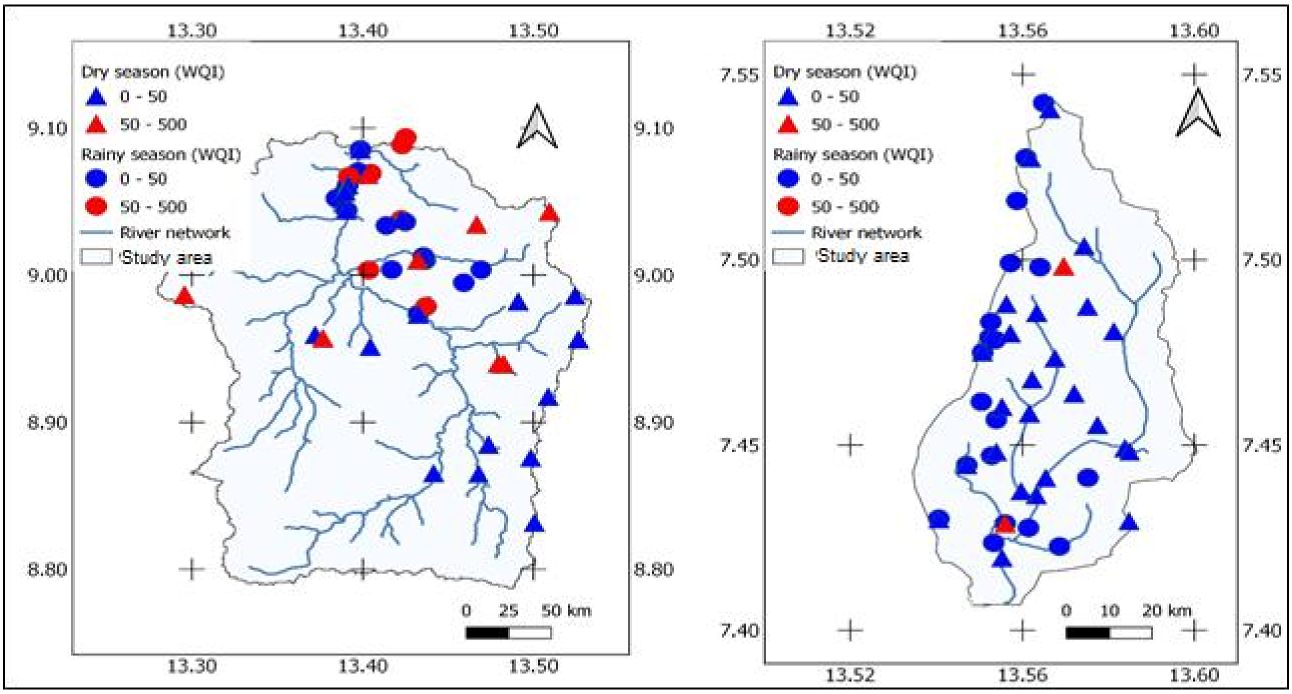


**Figure 21**:Water Quality Indices for consumption in BIW and DLSW during the rainy and the dry seasons

# 3.6. GROUNDWATER RECHARGE

## 3.6.1. Quantification of the recharge

The results of the piezometric measurements used to compute groundwater fluctuations are reported in Appendix 5 and Appendix 6 for BIW and DLSW during the rainy and dry seasons, respectively. The surface area for each watershed obtained from the watershed delineation maps are 61km² and 678km² for BIW and DLSW, respectively. The variation of the static levels measured between the rainy and dry seasons allows to obtain Figure 23 for BIW and Figure 24 for DLSW and consequently the recharge of each catchment.

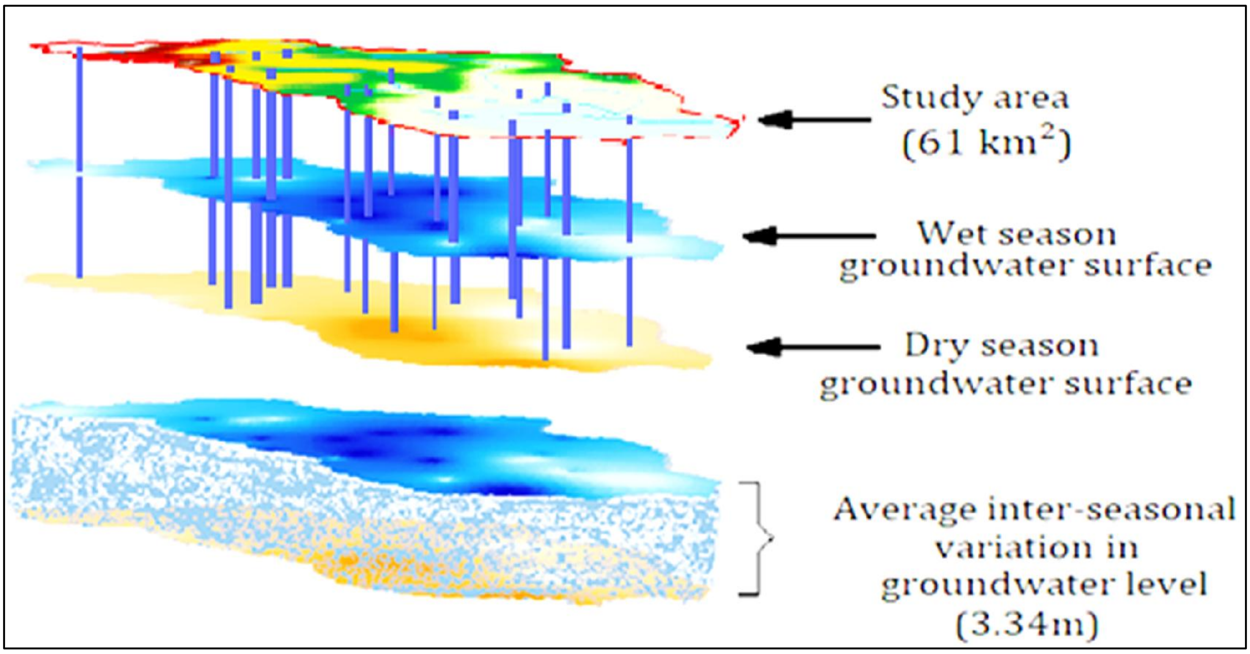


**Figure 22**:Representation of the variation in water level in BIW from the wet season to the dry season

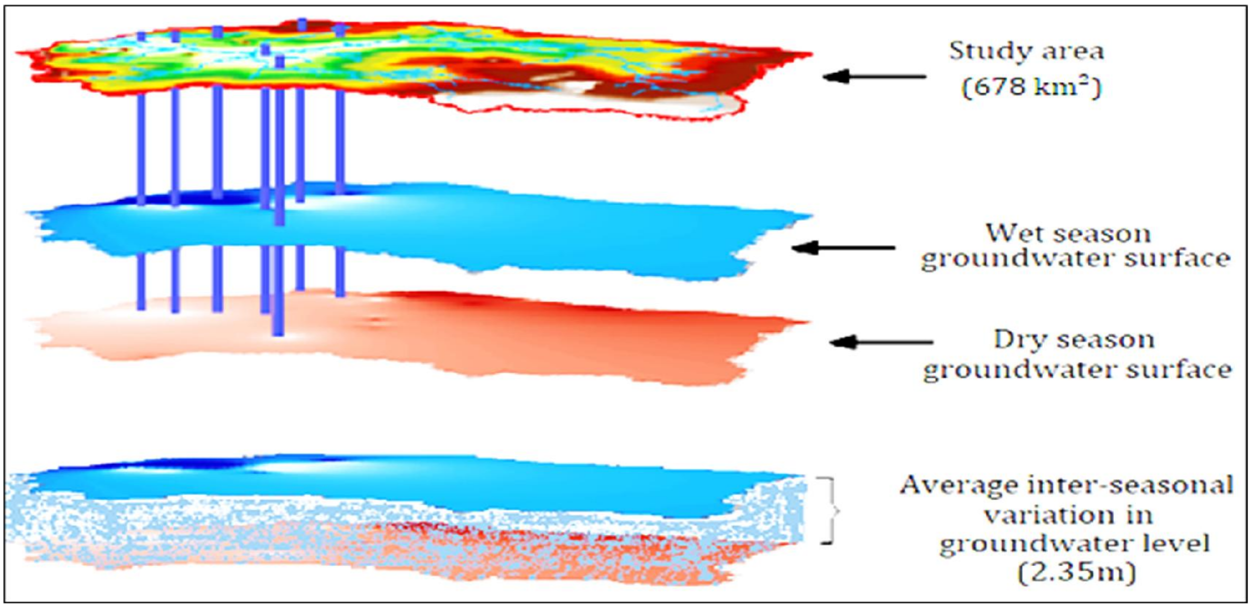


**Figure 23**: Representation of the variation in water level in DLSW from the wet season to the dry season

Population relying on groundwater for consumption, the maximum volume of water than can be used to satisfy this need is the amount recharged in the aquifers. This is $2.04\times10^{8}m^{3}$ and $1.59\times10^{9}m^{3}$ in BIW and DLSW, respectively). As expected, water fluctuation is higher in BIW (3.34m) than DLSW (2.35m). This reflects the important rainfall amount in the city of Ngaoundéré which is about 1500mm compared to precipitation in the city of Garoua that could be less than 1000mm. Moreover, topography observed is a contributing factor to the recharge. Altitude is higher in Ngaoundéré III than in Ngong so as the recharge. Similar conclusion was obtained by Brown (2002) in the Rocky Mountain Cordillera of North America.

With the constant increase in population, one issue should draw the attention of water managers: Is the recharge in each watershed sufficient to cover the needs of the population? If sufficient, how long will it take for this populations to exceed the available water resources?

## 3.6.2. Projection of water availability

### 3.6.2.1. Water availability for current populations

In 2005, the resident population of Ngaoundéré III and Ngong was respectively, 17,527 and 92,658 inhabitants (3rd GDPH, 2005). From its communal development plan, Ngong had a population estimated at 147,385 inhabitants in 2011 with a corresponding surface area of 2788km². This means that the density was about 53 inhabitants/km² in Ngong. From this density, it can be assumed that the population of DLSW was about 35,934 inhabitants. Similarly, population density in Ngaoundéré III was 45 inhabitants/km² and the population was 2,745 inhabitants. As it can be observed in Figure 25, these population increased from 2005 to 2011, especially in Ngong.

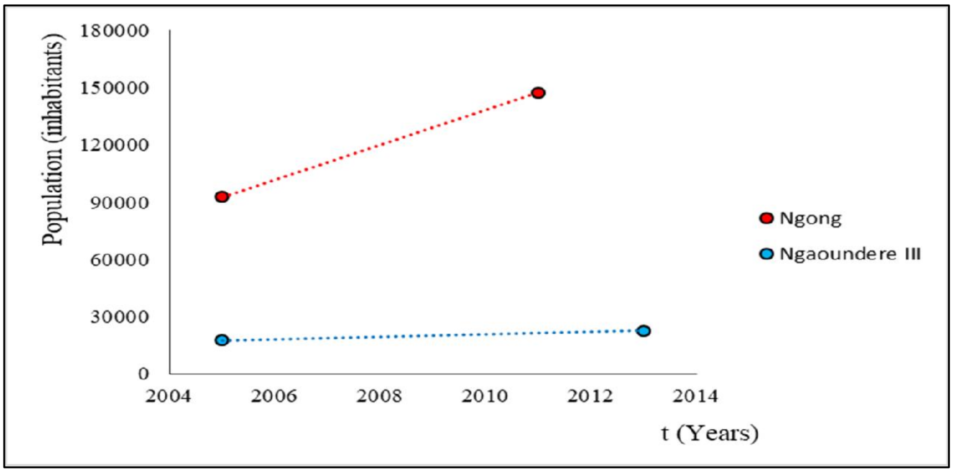


**Figure 24**:Population increase in BIW from 2005 to 2013 and in DLSW from 2005 to 2011

Using the geometric approach (Equations (3) and (4)), the values obtained for the growth rate in Ngaoundéré III and Ngong are 0.032 and 0.33, respectively. Hence, the populations in 2021 for BIW and DLSW are 34 342 and 54 662 inhabitants, respectively. With the actual recharge in the watersheds, water available per inhabitant daily (d) is:

- In BIW:

$$d = \frac{Recharge}{Population * 365} = \frac{2.04 * 10^{11} l/year}{34342 inh * 365} = \mathbf{16,\frac{275l}{day}/inh}$$

- In DLSW:

$$d = \frac{Recharge}{Population * 365} = \frac{1.59 * 10^{12} l/year}{54662 inh * 365} = \mathbf{79,\frac{693l}{day}/inh}$$

At the present time, water potential in each watershed is 16,275l/day/inh in BIW and 79,963l/day/inh in DLSW. According to WHO, domestic water consumption (drinking, cooking, personal washing and washing clothes) is at least 40l/day which is very small compared to the quantity of water that each inhabitant can have in these watersheds.

#### 3.6.2.2. Projected population and water demand

From the previous computations, it comes out that, water in the watershed is greater than the need of the inhabitants for domestic use. However, the constant increase in population may result in water stress with time. Assuming that groundwater recharge is constant, the years at which it will no more be sufficient for human consumption can be computed as follow:

Recharge (R) =Domestic water consumption (C)

$$\Rightarrow \Delta h * A * \Delta t = Population\ (P)(t) * consumption\ (c)$$

$$\Rightarrow P_0 * \frac{S_B}{S_M} * (1+a)^t = \frac{\Delta h * A * \Delta t}{c}$$

$$\Rightarrow (1+a)^t = \frac{R * P_0 * S_M}{c * S_B}$$

$$\Rightarrow t = ln\left(\frac{R * S_M}{c * S_B * P_0}\right) * \frac{1}{\ln(1+a)} \quad (33)$$

**In BIW**:

For domestic use:

$$t = ln\left(\frac{2.04 * 10^8 * 10^3 l * 393 km^2}{40 l/inh * 61 km^2 * 17527 inh}\right) * \frac{1}{\ln(1+0.032)} \simeq \mathbf{4\ 59 years}$$

For drinking:

$$t = ln\left(\frac{2.04 * 10^8 * 10^3 l * 393 km^2}{10 l/inh * 61 km^2 * 17527 inh}\right) * \frac{1}{\ln(1+0.032)} \simeq \mathbf{50\ 3 years}$$

**In DLSW**:

For domestic use:

$$t = ln\left(\frac{1.59 * 10^{9} * 10^{3} l * 2788 km^{2}}{40 l/inh * 678 km^{2} * 92658 inh}\right) * \frac{1}{ln(1 + 0.08)} \simeq \mathbf{18\ 7 years}$$

For drinking:

$$t = ln\left(\frac{1.59 * 10^{9} * 10^{3} l * 2788 km^{2}}{10 l/inh * 678 km^{2} * 92658 inh}\right) * \frac{1}{ln(1 + 0.08)} \simeq \mathbf{20\ 5 years}$$

From these calculations, groundwater recharge will be equal to domestic water consumption (40l/inh) in 2464 in BIW and in 2192 in DLSW. As for drinking water consumption, water in the watersheds will be exhausted in 2508 in BIW and in 2210 in DLSW. These results are summarised in Figure 25.

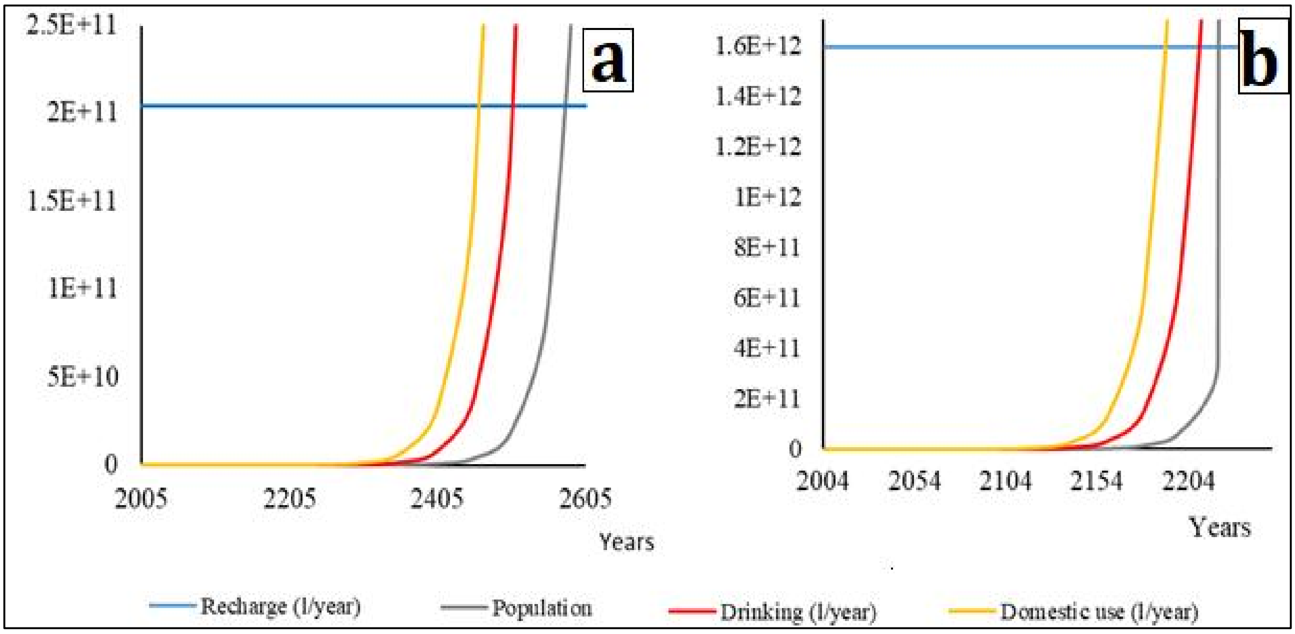


**Figure 25**: Groundwater recharge in BIW (a) and DLSW (b)

With the assumption made in Figure 25 (constant annual recharge in time), water situation in terms of quantity is better in BIW. In fact, even if the recharge is higher in DLSW, population growth is too high in this watershed. In 2021, demand is about 343m$^3$ in BIW and 564m$^3$ in DLSW. Nowadays, neither BIW nor DLSW show signs of water scarcity. However, in these conditions, water resources will be exhausted in 2192 in DLSW and in 2464 in BIW. Hence, groundwater resources can be exploited for drinking water adduction in both watersheds.

# CHAPTER 4: RECOMMENDATIONS

## Introduction

The results obtained show that presently, water quantity is not an issue in BIW and DLSW. However, its quality is highly affected by natural (geology, climate) and anthropogenic (soap, fertilizers, pesticides) factors. The worst quality was observed in DLSW with the presence of heavy metals and excess nitrate. In order to make water clean and safe for consumption, those pollutants should be removed. Efficient methods enabling to reach this objective considering poverty in these regions are adsorption onto clay (kaolinite) and activated carbon. However, a prerequisite for treating water is to stop, otherwise limit, the pollution of water sources. Thus, several steps contributing to the preservation of the quality of natural water resources must first be implemented. The SWOT matrix presented in Table 12 allows to analyse the problems that need to be solved in order to improve water quality in these watersheds.

**Table 12**:SWOT matrix of the water situation in the study area

| STRENGTHS | WEAKNESSES |
|---|---|
| - Absence of industries<br>- Mentality of inhabitants<br>- Limited use of man-made products<br>- Abundance of water resources<br>- Will of the municipality to manage its water resources | - Increasing water demand (population)<br>- Unplanned management of water resources<br>- Sanitation system (use of traditional pit toilets, no waste management)<br>- Education level and poverty<br>- Accessibility (DLSW)<br>- Agricultural practices |
| **OPPORTUNITIES** | **THREATS** |
| - Implication of international partners like GWP and proFAM to build water points<br>- Dependency of many countries on exported agricultural goods (cotton and peanut for example) | - Climate change<br>- Floods<br>- Harmattan wind |

In the context of poverty and dependency on groundwater observed in Northern Cameroon, this matrix allows to conclude that water quality and the living conditions of populations will be better if groundwater is protected and drinking water is treated. This means: create awareness, plan the land-use in the watersheds, improve sanitation system and treat water for drinking.

## 4.1. CREATING AWARENESS

The basis of awareness here is established by Cameroonian laws on the protection of the environment. The decree n° 2001 / 165 / PM of 08 may 2001 prohibits the discharge of liquid (wastewater) and solid substances (solid waste) into the water that are likely to alter its quality. In 2004, the law n° 2004/019 of 22 July 2004 organising decentralisation, recognises the capacity of municipalities to ensure compliance with these ordinances in their area of competence. However, such tasks cannot be efficiently implemented without the participation of the inhabitants of the municipality.

Public involvement is essential for every development project. Stakeholders must understand that their activities contribute to the deterioration of their water resources, favour the appearance of water-related diseases that frequently threat them and lead to the reduction of the agricultural yield in their farms. Administrators are responsible for the population and should themselves understand the situation they face. Hence, the role of the scientific community is to emphasize the necessity to take care of water quality.

After that, sensitisation of population could effectively start. It means, to explain the importance of water quality in such a way that they can get the concern for their health (diseases) and economy (diseases of the animals they sold, poor agricultural yield). Hence, they will adapt their habits to their water resources. It will consist in direct meetings between population and authorities to understand their needs and decide together what must be done.

Farmers play an important role in the economy of the regions but also in the degradation of water resources. In fact, they use to enrich the soil (hence water) with excess fertilizers that may already be contained in the soil or are not necessary for plants (in this amount) and uncontrolled quantity of pesticides. This results in excess nutrients in water bodies for the particular case of Douka Longo. In Bidou, the opposite situation is observed as water is too soft and need to be enriched in nutrients (N, K, P, Ca and Mg just to name a few).

Knowing that agriculture is the main activity in Ngong (Douka Longo) and Ngaoundéré III (Bidou), these municipalities should organize training sessions for farmers in cooperation with

MINADER considering the common practices that are already in use. The intended results are the ability of farmers to master:

- The soil they are working on, the nutrients naturally available, those missing and agricultural technics adapted to their context;
- The needs of their crops in terms of nutrients and conditions (weather, water, temperature, period favourable for their growth) but also how they can be combined for multiple production.

In order to ensure that the decisions taken by mutual agreement with the population are implemented, agents of the municipality must carry out field visits and report to the municipality.

## 4.2. RESTRICTIONS OF THE LAND-USE

Water resources can be protected using three methods: protection of the estuarine areas, protection of each water source and well head protection area delineation. For municipalities facing financial limitations in their budget, the Well Head Protection Area (WHPA) or Source Water Protection Area delineation is preferable as the contaminant is stopped at source. The tools needed to implement WHPA include land use restriction and legal regulations.

The most cost-effective method to ensure good water quality is to avoid its contamination. Such a task should be planned by municipalities considering hydro-geochemistry, land-use, politics, economy and Geographical Information System (GIS) tools. As a matter of fact, the pollutants contained in water sources strongly depend on the land use. Hence, in sensitive areas where raw water is used for drinking without treatment, land use should be subject to regulatory controls and zoning. For groundwater protection, it consists in the mapping of the vulnerability of watersheds. One of the easiest and most common models employed for vulnerability mapping is the DRASTIC model. This acronym stands for:

- **Depth to water**: It allows to know the length of geologic material through which anthropogenic inputs travel before it reaches groundwater. It is the value obtained when measuring the depth to water in wells. The higher the depth to water, the lower the amount of contaminant reaching groundwater.
- **Recharge**: The main components of the hydrologic cycle are the precipitation, run-off and infiltration. A negligible fraction of infiltrated water is trapped by the plants and the remaining fraction recharges the aquifer. Depending on the land-use of the considered area, it loads contaminants into groundwater. In BIW and DLSW, nutrients such as nitrate were accumulated in the aquifer at

different rates. In areas where the net recharge is higher (DLSW), the contamination rate is higher too.

- **Aquifer media**: An aquifer is a permeable, porous layer or mass with a saturated zone, sufficiently conductive of groundwater to allow significant groundwater flow and capture of appreciable quantities of water. This layer can be consolidated or not. In confined aquifers, the water bearing material is found between 2 aquitards. Generally, water quality is better in these types of aquifers, the aquitard layer offering some protection against contamination from the surface.
- **Soil media**: This parameter of the DRASTIC model refers to the grain size and porosity of the soil. Porosity of the aquifer media affects the effective surface area of materials hence the time needed to degrade water sources. As observed in BIW, sediments with large grain size (high porosity) are more favourable to infiltration than small grain size rocks.
- **Topography**: The relief highly influences the pollutant load in groundwater. It allows to determine the likelihood of a pollutant to remain on a flat surface or to displace downslope. Hence, topography is inversely proportional to the vulnerability of groundwater to contamination.
- **Impact of vadose zone**: The vadose zone is the zone above the water table which is unsaturated or discontinuously saturated. Depending on the soil type, several processes can take place in the vadose and reduce contaminant load: Biodegradation, neutralization, mechanical filtration, chemical reaction, volatilization and dispersion.
- **Hydraulic Conductivity of the Aquifer**: Hydraulic conductivity or transmissivity is the ability of the aquifer material to transmit water. It depends on the connection of voids inside the aquifer. Vulnerability increases with hydraulic conductivity.

The overlapping of the vulnerability maps obtained enables to to assess the vulnerability of the aquifer to contamination. Knowing these points, three levels of protection (zones) can be determined depending on the flow direction, flow velocity and land-use history (contaminants that could be accumulated in the watershed from past and current activities):

- **Zone 1**: It corresponds to the area where contaminants need less than 2 years travel time. This zone is used to protect against microbial (bacteria and viruses for example) and chemical contaminants;
- **Zone 2**: it corresponds to the area where the travel time of the contaminant is between 2 and 5 years. This zone is used to protect against pollutants that are more persistent and mobile than those concerned in zone 1. Among them are petroleum contaminants which contain aromatic compounds needing advanced treatment processes for removal;

- **Zone 3**: it is used for contaminants having a travelling time between 5 and 25 years. These contaminants can be chlorinated solvents like pesticides and nitrate for example. This area is the one needed in agricultural lands like DLSW where nitrate is accumulated in the watershed.

These 03 zones must be materialized and monitored by communal agents and experts. It will therefore be a matter of:

- Drafting and publishing the legal and technical documents that will regulate the implementation of the groundwater protection measures described above
- Install plates and fences indicating where are the different zones and the proscribed activities
- Analyse at least twice every year (during the rainy and dry seasons) to check if there is any contamination of water resources. The results obtained should be published and accessible to scientific community for further investigations

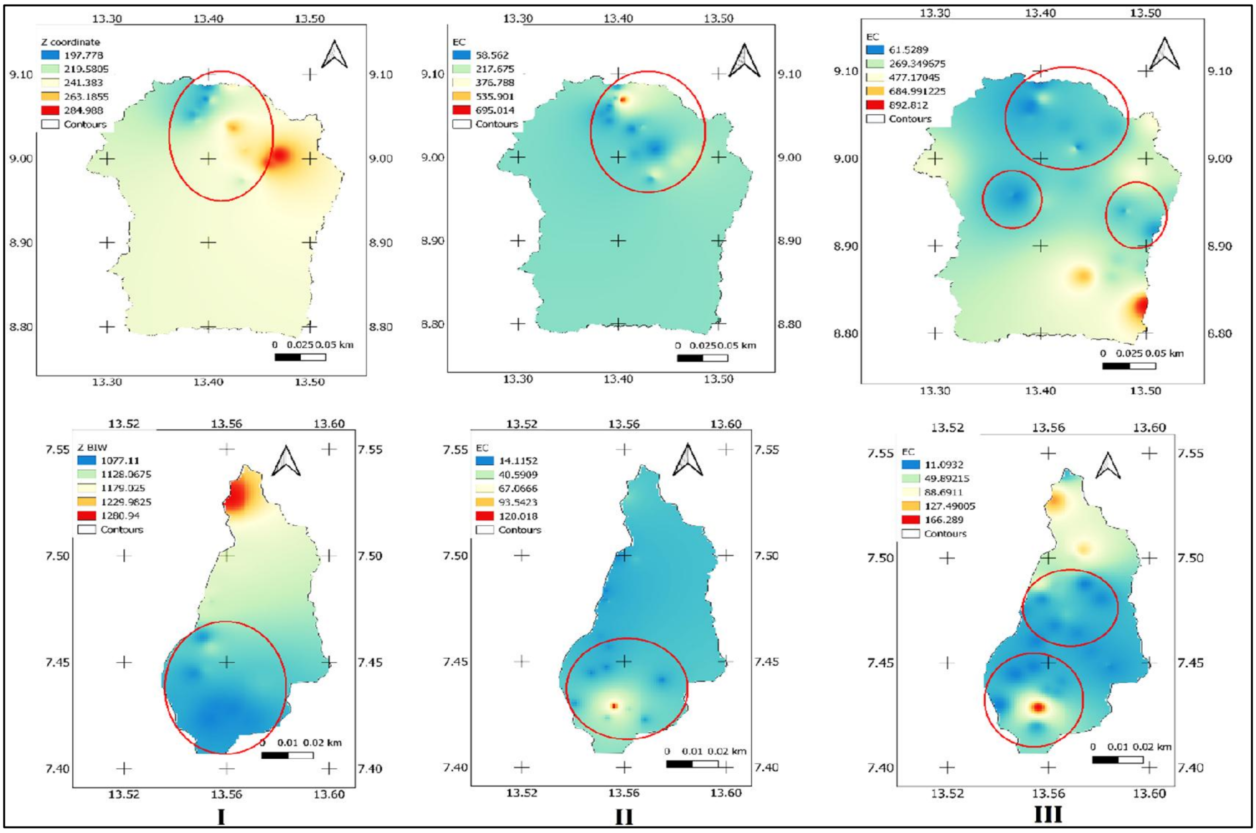


**Figure 26**:Identification of the recharge areas based on altitude (I) and electrical conductivity during the rainy (II) and dry (III) seasons

From the chemical point of view, water should be less mineralised in a recharge area. This means that electrical conductivity (EC) and TDS are lower here than elsewhere in the watershed. Figure 26 shows the most vulnerable areas circled in red and representing the places where land use should be restricted to less polluting activities like recreation.

## 4.3. IMPROVEMENT OF THE SANITATION SYSTEM

### 4.3.1. Solid waste management

Solid wastes are dumped behind houses or very close to rivers even where HYSACAM is in charge of their collection. In places where collection is impossible, they are burned. This inappropriate management of waste leads to increase in $NO_3^-$ and metals into water. In order to solve this problem, the solution proposed is curb-side collection of wastes as access to houses is sometime difficult in these watersheds.

### 4.3.2. Wastewater management

The organization of the society is such that, water points are meeting areas during domestic tasks and the consumption of the traditional red millet-bear (for the particular case of DLSW). Hence, wastewaters are produced directly in rivers or near water wells (<25m). In order to limit the impact of these wastewaters on water sources, they must be collected and treated. The proposed system combines the use of double pit urine-diverting dry toilets and infiltration well for grey water collection. Urine-diverting dry toilet has many advantages in the present case. It doesn't need permanent water supply and above all, suit to areas vulnerable to floods. The choice of infiltration well is justified by the will to maintain the habits of inhabitants. It enables women to continue working together (laundry, vessel) and can be used as manhole for wastewater sampling during further investigations.

The principle of double pit urine-diverting dry toilet is similar to the one of traditional pit latrines with the particularity that they are impermeable and are used for 1year before they are sealed. After 1year, sludge contained in the sealed tank is removed and the compost produced can be used as fertilizer. Tilley et al. (2008) present the functioning of these toilets as shown in Figure 27.

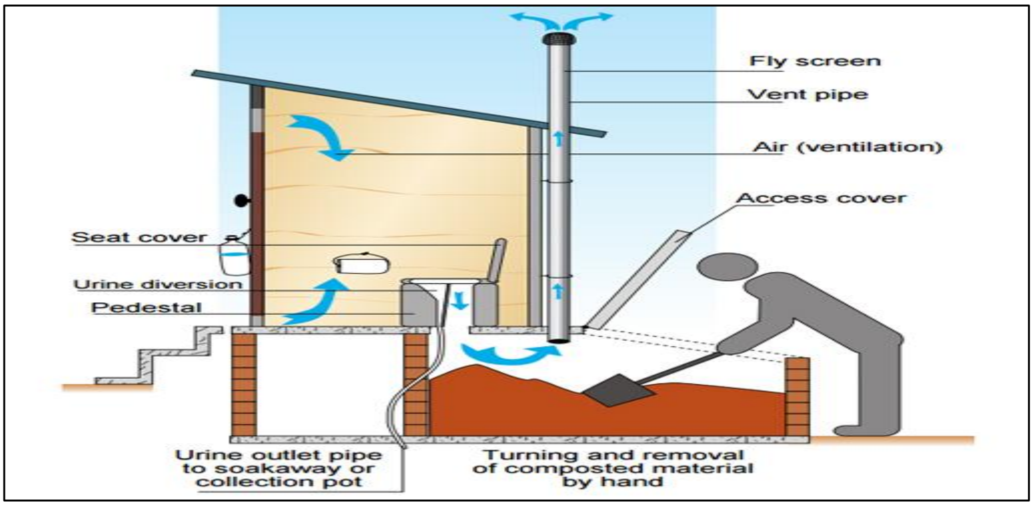


**Figure 27**: Principle of a Double pit Urine Diverting Dry toilets

Urines contain urea ($CH_4N_2O$) rejected by the organism after metabolism. They can be used in agriculture to provide nitrogen necessary for plant growth. However, urine should be conserved at least for a period of 1 month in order to be hygienicses and usable for irrigation. Urines should not be poured directly on plants or too near their roots but on soil. Moreover, their high nitrate content unables their direct use. They must be diluted to the third (1:3) or the tenth (1:10) with irrigation water before amendment. Generally, it is considered that it is better to harvest urine through plastic pipes since it corrodes metal due to its high pH. This pipe will be connected to infiltration well for urine collection.

As for grey water, it comes from kitchen, crockery, laundering and shower. Being separated from black water, it represents a reduced danger but non-negligible threat to water sources. As the study area is vulnerable to floods, grey water cannot be easily treated on-site. However, such waters are commonly reused for irrigation but a reduction of the pollutant load should be done. This task can be done through the installation of an irrigation system in which grey water will be filtered by gravel and sand layers. Then, the filtered water will be collected in a wetland and directed in pipes to irrigate crops. This method uses the natural process of adsorption of pollutants by the soil with an increase of the reaction time between soil particles and wastewater.

## 4.3.3. Design and cost estimate of urine-diverting dry toilets

In 2005, the average size of households in Cameroon was 5.1 with 4.8 in urban areas and 5.5 in rural areas (BUCREP, 2005). However, as the population is generally organised in concessions of 04 families (family of each co-wife) generally, they can be divided into groups of 24 people. In 1 year, a person produces 50l of sludge (Tilley et al. 2008). In order to reduce the material and space needed for construction, a rectangular shape is preferred. The pit can then be designed as follows:

V=Accumulation*Users*Time

= 50l/person/year*24persons*1year

= $1.2m^3$

To be sure that earth material can be added before the pit is sealed, a higher volume is used for the design of the pit. The chosen height is the one corresponding to the number of stairs needed to reach the toilets. A few details about the assumptions made for the calculation are given below and the cost estimate is provided in Table 13.

- The dimensions of the pit for this typical latrine are:

2.5 m (length) *x* 1.30 m (width) *x* 1.2 m (depth)

- A 60 cm high foundation around the perimeter of the pit is made to support the slabs and the superstructure;
- To each designation is associated the parts of the latrine for which these materials were intended;
- The superstructure is presented as a small house of 2.20 m high;
- For the number of breeze blocks, a ratio of 12.5 blocks/m² is considered
- For the unit price in concrete and mortar, the calculation made from the unit prices of sand, cement and gravel taking the following quantities:
    - 1 $m^3$ of concrete requires 800 l of gravel, 400 l of sand, 350 kg of cement, water
    - 1 $m^3$ of mortar requires 1 $m^3$ of sand, 350 kg of cement, water.

# 4.4. WATER TREATMENT FOR DRINKING

Depending on the catchment, different problems are observed. In DLSW, there is an excess of nutrients (nitrate and potassium) and presence of heavy metals while in BIW, there is no threshold exceedance of heavy metals but water is generally soft. Metals cannot be easily degraded. Thus, until they are removed from drinking water, they will accumulate in human organisms and affect their health. The method proposed for the removal of these pollutants is their adsorption with clay, especially kaolinite which is already present in DLSW combined to activated carbon.

## 4.4.1. Nitrate and heavy metals removal

Among the most effective methods to remove nitrate from contaminated water sources are ion exchange and adsorption on zeolite. In the Douka Longo watershed, clay minerals can be used as sorbent material. From the results, it stands out that kaolinite is present in this watershed (strong positive correlation between $HCO_3^-$ and $Ca^{2+}$). This clay mineral has the natural capacity to attenuate pollution in aqueous phase. The main concerns are the conditions needed for effective nitrate adsorption. This is the retention time required for the removal of this nutrient, pH and temperature. To improve its efficiency, kaolin is pyrolyzed to produce kaolinite which has a higher surface area.

Agriculture is the principal activity in Ngong where heavy metals are detected in anomalous concentrations. Hence, agricultural wastes constitute a non-negligible fraction of the total wastes and can be found everywhere. One of the most cultivated crops is corn and its cob is not used. Corn cobs released after corn cleansing is a lignocellulosic material that can be used to produce AC. Activated carbon from corn cob can be produced using the following process:

- Washing and drying of the collected corn cobs
- Pyrolysis of the corn cobs at 900°C in a stainless-steel chamber for 60 min to ensure pyrolysis is carried to completion as much as possible
- Cooling of the char obtained
- Physical activation of the char samples at 900°C using steam as activation agent

Adsorption generally lowers heavy metal level considerably. However, for some metals, ion exchange or reverse osmosis process need to be added to reduce the treatment time. Here, it is the case for barium and beryllium in DLSW. A natural and cheap way to exchange ions is the use of zeolite. For houses these two methods can be combined through the use of a ceramic filter.

### 4.4.2. Water softness management

Soft water generally has high concentration of sodium. It increases blood pressure and cardiovascular ailments. Accordingly, water sampled in BIW have this ion as major cation in surface water samples. In order to increase hardness of soft water especially in BIW, ions should be added to their natural composition. Knowing that there are two types of hardness (temporary and permanent) and that the last one is more difficult to manage if water becomes too hard, the goal here will be to increase temporary hardness. This is done by adding calcium hydrogencarbonate ($Ca(HCO_3)_2$) to water.

A particular feature of $Ca(HCO_3)_2$ is that it only exists in the dissolved form and precipitate as $CaCO_3$ in water following this reaction:

$$Ca(HCO\,3)_{2(aq)} \leftrightarrow CaCO_{3(s)} + CO_{2(g)} + H_2O$$

The smallest hardness computed in $CaCO_3$ is 1.3116mg/l, to reach an acceptable hardness of 20mg/l, 18.7mg of $CaCO_3$ should be added into water. This means that the mass of $Ca(HCO_3)_2$ needed for 1l can be computed as follows:

$$n\,[Ca(HCO_3)_2] = n[CaCO_3] \tag{34}$$

$$\Rightarrow \frac{m\,[Ca(HCO3)2]}{MW\,[Ca(HCO3)2]} = \frac{m[CaCO3]}{MW[CaCO3]}$$

$$\Rightarrow m\,[Ca(HCO\,3)2] = \frac{\mathrm{m[CaCO3]*MW\,[Ca(HCO3)2]}}{\mathrm{MW[CaCO3]}}\frac{18.7*16\;\;2}{100} = \mathbf{30.3}\boldsymbol{mg}$$

For all the watershed and during 1 year, 3,798t of calcium carbonate need to be added

## Further Works:

- Extent this study and include biological parameters of the watersheds for complete handling of the sanitation and the design of drinking water treatment plant for distribution in the municipilaties
- Mapping of the minerals of these regions that can be used for water treatment (zeolites)

Cross-link of the seasonal variation of water quality to human health and fate of contamination.

**Table 13**:Cost estimate of the solutions proposed per habitat in each watershed

| LOT | DESIGNATION | QUANTITY | UNITS | UNIT COST | TOTAL |
|---|---|---|---|---|---|
| **1000** | **SANITATION** | | | | |
| **1100** | **FOUNDATION-ELEVATION-STRUCTURAL ELEMENTS** | | | | |
| 1101 | 15 Cinder blocks | 167 | U | 250 | 41,750 |
| 1102 | 10 Cinder blocks | 245 | U | 200 | 49,000 |
| 1103 | Concrete | 1,2022 | $m^3$ | 175,000 | 210,385 |
| 1104 | Bliding concrete | 0,41 | $m^3$ | 65,000 | 26,650 |
| 1105 | Steal bars (Ø8) | 08 | U | 2,900 | 23,200 |
| 1106 | Steal bars (Ø10) | 03 | U | 4,700 | 14,100 |
| 1107 | Steal bars (Ø6) | 06 | U | 1,500 | 9,000 |
| 1108 | Mortar for joints | 0,65 | $m^3$ | 65,000 | 42,250 |
| 1109 | Morter for plastering | 39,9 | $m^2$ | 1,000 | 39,900 |
| 1110 | Rafter | 03 | U | 2,500 | 7,500 |
| 1112 | Laths | 03 | U | 1,500 | 4,500 |
| 1113 | Corrugated sheet | 03 | U | 6,000 | 18,000 |
| 1114 | Planks | 08 | U | 3,000 | 24,000 |
| | SUB-TOTAL LOT 1100 | | | | 510,235 |
| **1200** | **PLUMBING** | | | | |
| 1201 | Glue for pipe | 01 | U | 2,000 | 2,000 |
| 1202 | Seat | 01 | U | 15,000 | 15,000 |
| 1203 | PVC pipe (Ø63) | 02 | U | 4,000 | 8,000 |
| 1204 | Drainage elbow | 03 | U | 1,500 | 4,500 |
| 1205 | Ciphon | 02 | U | 1,500 | 3,000 |
| 1206 | Drainage T | 01 | U | 1,500 | 1,500 |
| 1207 | PVC pipe (Ø100) | 02 | U | 7,000 | 14,000 |
| | SUB-TOTAL LOT 1200 | | | | 48,000 |
| **1300** | **OPENINGS** | | | | |
| 1301 | Door (Toilets) | 01 | U | 2,500 | 2,500 |
| 1302 | Door (Metallic) | 02 | U | 20,000 | 40,000 |
| | SUB-TOTAL LOT 1300 | | | | 42,500 |
| | TOTAL COST (SANITATION) | | | | 600,735FCFA |
| | LABOUR (30% OF TOTAL) | | | | 180,220.5FCFA |
| | **SANITATION** | | | | **737,780.5FCFA** |
| **2000** | **KAOLINITE-ACTIVATED CARBON FILTER** | | | | |
| 2001 | Ceramic filter | 01 | U | 10,000 | 10,000 |

| | | | | | |
|---|---|---|---|---|---|
| 2002 | Activated carbon | 01 | U | 5,000 | 5,000 |
| 2003 | Kaolinite | 01 | U | 5,000 | 5,000 |
| 2004 | Adaptation | 01 | ff | 2,000 | 2,000 |
| | **SUB-TOTAL LOT 2000** | | | | **22,000** |
| 3000 | **WATER SOFTNESS MANAGEMENT** | | | | |
| 3001 | Ceramic filter | 01 | U | 10,000 | 10,000 |
| 3002 | Calcite | 01 | U | 7,500 | 7,500 |
| 3003 | Adaptation | 01 | ff | 2,000 | 2,000 |
| | **SUB-TOTAL LOT 3000** | | | | **19,500** |
| | **TOTAL COST FOR DOUKA-LONGO** | | | | **759,780.5FCFA** |
| | **TOTAL COST FOR BIDOU** | | | | **757,280.5FCFA** |

# GENERAL CONCLUSION

This research consisted in the use of hydrochemistry and piezometric measurements to investigate the impact of natural phenomena and human activities on the waters of the Bidou (BIW) and Douka Longo (DLSW) catchments in order to determine their suitability for irrigation and domestic use. To this effect, the work was organized in 3 main parts: the identification of the types and anomalies of water in each basin, their mineralisation and the origin of the detected contaminants; the processes responsible for the observed water chemistry and finally the suitability of the water in Bidou and Douka Longo for irrigation (quality) and domestic use (quality and quantity).

The methodology employed to reach these objectives consisted in documentary research, chemical analysis of shallow groundwater and surface water samples, interviews and field observations. This methodology permitted the identification and collection of 115 water samples (59 and 56 samples in the rainy and the dry season, respectively) from various water resources in BIW and DLSW ranging from surface (rivers and lake) to groundwater (springs, wells and boreholes) samples. Also, piezometric measurements were done during groundwater sampling to obtain the variation of the piezometric level betweens the rainy to the dry seasons. It resulted that:

- During the rainy season, the water types are predominantly Ca-Mg-$HCO_3$ in BIW and Ca-Mg-$NO_3$ in DLSW. In the dry season, these results remain the same with low $NO_3^-$ input. Water type evolves from Ca-Mg-$HCO_3$ to Na-K-$SO_4$-Cl in BIW and DLSW during the rainy season. In the dry season, water type evolves from Ca-Mg-$HCO_3$ to Na-K-$SO_4$-Cl-$NO_3$ and Na-K -Cl-$NO_3$ in DLSW;
- Water flows Eastward and the BIW is less mineralised than DLSW. The recharge areas (low mineralisation) are highly vulnerable to contamination as they are very close to highly mineralised areas;
- Anomalous concentrations of heavy metals compared to their natural occurrence in raw or their concentrations in other samples of the same watershed. These are: As, Ba, Be, Co, Pb, Mn, Ni and U in DLSW and Ba, Mn and Ni in BIW. As for REEs, they are in excess in DLSW where the smallest values of pH are observed with high values of Dy, Er, Eu, Ga, Gd, Hf, Ho, La, Li, Lu, Nd, Pr, Rb, Sb, Sm, Tb and Ti;
- The variation of stable environmental isotopes of $\delta^2H$ et $\delta^{18}O$ is generally negative and the samples are almost all plotted along the GMWL, showing that water recharged in the aquifer mainly originates from rainfall;

- The processes responsible of the alteration for water quality are incongruent dissolution of siliceous rocks; intrusion of salty waters; cation exchange; enrichment in nutrients ($NO_3^-$, $NH_4^+$, $PO_4^-$, $K^+$) and heavy metals of anthropogenic (Be, Co, Pb, Ni) and natural origin (As, Ba, Be, Co, Pb, Mn, Ni, U, REEs) as well as evaporation;
- Groundwater is acidic and the surface water moderately alkaline. Water in BIW and DLSW is suitable for irrigation with:
  - Low salinity hazard in 100% of the Bidou basin samples in the dry season and in the rainy season, 100% of the Douka Longo samples in the rainy season and 81% of those of the dry season samples
  - Low sodicity hazard in 98.25% and 96.7%, 100% and 100%, 0% and 64% (preferable in the dry season) and 90.45% and 93.45% of water sampled in BIW and DLSW, respectively and on the basis of SSP, SAR, PI and KR, respectively;
  - Low alkalinity hazard in 100% of samples collected with RSBC<10. However, very small values of pH and high values of EC in GW001 and GW002 reduce water quality in DLSW;
  - No elemental toxicity with small values of MAR, B and $Cl^-$;
- Water is suitable for consumption with:
  - Low mineralisation in BIW (TDS<500mg/l) for every samples except for 11.1% of the samples located in BIW during the rainy season. However, very small values of TH makes water unsuitable for drinking for almost 93% of sampled water;
  - Every sample collected in BIW having $NO_3^-$ concentration less than 50mg/l. In DLSW, 36% and 22.2% of sampled water are out of the WHO guidelines for $NO_3^-$ in drinking water during the rainy and dry seasons, respectively;
  - Absence of heavy metals of health concern in the watersheds during the dry season. The worst water quality is observed in the rainy season with excess As (8%), Ni(4%), Pb (8%) and U(8%) in DLSW and no heavy metals of health concern in BIW;
  - Good WQIs in the dry season compared to those of the rainy season. This is 100% and 64% of the rainy season samples suitable for consumption in BIW and DLSW, respectively. In the dry season, 93.1% and 63% of samples suitable for BIW and DLSW;
- The annual recharge of groundwater in the watershed is $2.04\times10^8 m^3$ in BIW and $1.59\times10^9 m^3$ in DLSW. This corresponds to a potential for daily intake of $16m^3$/inhabitant

in BIW and 79m$^3$/inhabitant in DLSW which is greater than the 40L required daily consumption of water for 1 person. With the current rate of population growth, these watersheds are susceptible to experience water stress in 2464 for BIW and 2192 for DLSW.

- Water resources in the watersheds are present in sufficient quantity but need to be protected and treated before use. The steps needed to reach these objectives are sensitisation of inhabitants, regulation of the land-use in the watersheds (especially in the recharge areas), improvement of the sanitation system (curbside collection of solid waste, collection of wastewater in wetland for reuse in agriculture and installation of double pit urine-diverting dry toilets);
- The main problems identified in drinking water were excess $NO_3^-$ and heavy metals in DLSW and softness of drinking water in BIW. Water treatment by adsorption of $NO_3^-$ onto kaolinite and heavy metals onto activated carbon from corn cobs in DLSW is recommended. In BIW, water can be enriched in calcium by addition of calcite before consumption.

# CONCLUSION GENERALE

Ce travail de recherche a consisté en l'utilisation de l'hydrochimie et des mesures piézométriques pour vérifier l'impact des phénomènes naturels et humains sur les eaux de Bidou (BIW) et de Douka Longo (DLSW) afin d'en déterminer la convenance pour l'irrigation et l'usage domestique. Pour ce faire, il a été organisé en 3 principales parties : la détermination des types et anomalies des eaux de chaque bassin, leur minéralisation et l'origine des contaminants détectés, les processus responsables de l'hydrochimie observée et finalement leur convenance pour l'irrigation (qualité) et l'usage domestique (qualité et quantité).

La méthodologie de travail employée pour atteindre ces objectifs a consisté en des recherches documentaires, des analyses chimiques des eaux superficielles et souterraines, des interviews et observations de terrain. Celle-ci a permis de collecter 115 échantillons d'eau (59 en saison sèche et 56 en saison pluvieuse) de différentes sources d'eau à BIW et à DLSW de natures souterraine (source, puits, forages) et superficielle (rivières, lacs). Aussi, les mesures piézométriques ont été effectuées lors des échantillonnages d'eau souterraines à fin d'obtenir la variation du niveau piézométrique entre la saison pluvieuse et la saison sèche. Il en résulte que :

- Pendant la saison pluvieuse, les eaux sont majoritairement un mélange des types Na-K-Cl et Ca-Mg-$HCO_3$ à BIW et de type Ca-Mg-$NO_3$-$SO_4$ à DLSW. Pendant la saison sèche, ces résultats restent les même avec une réduction considérable de la quantité de $NO_3^-$. Le type d'eau évolue de Ca-Mg-$HCO_3$ à Na-K-$SO_4$-Cl à BIW et à DLSW pendant la saison pluvieuse. En saison sèche, les types d'eau évoluent de Ca-Mg-$HCO_3$ à Na-K-$SO_4$-Cl-$NO_3$ et reste de type Na-K-$SO_4$-Cl-$NO_3$ à DLSW ;
- Les eaux circulent vers l'Est dans les deux bassins et celles de BIW sont moins minéralisées que celles de DLSW. Les zones de recharge (faiblement minéralisées) sont très vulnérables à la contamination car elles sont très proches des zones fortement minéralisées ;
- Des concentrations anormales de métaux lourds comparées à leur occurrence naturelle dans les eaux et à leurs concentrations dans les autres échantillons du bassin. Il s'agit de : As, Ba, Be, Co, Pb, Mn, Ni et U à DLSW et Ba, Mn et Ni à BIW. En ce qui concerne les elements traces rares (REEs), ils sont en excès à DLSW dans les échantillons ayant les plus pH les plus bas. Il s'agit de : Dy, Er, Eu, Ga, Gd, Hf, Ho, La, Li, Lu, Nd, Pr, Rb, Sb, Sm, Tb et Ti ;

- La variation des isotopes environnementaux stables ($\delta^2H$ et $\delta^{18}O$) est généralement négative et les échantillons sont généralements regroupées autour de la ligne globale des eaux atmosphériques, montrant que les eaux rechargées dans les aquifèrent proviennent des précipitations ;
- Les processus responsables de l'altération de la qualité de l'eau sont les dissolutions incongruentes de roches silicieuses, les intrusions d'eaux salines, les échanges cationiques ; l'enrichissement en nutriments ($NO_3^-$, $NH_4^+$, $PO_4^-$, $K^+$) et en métaux lourds d'origines anthropogène (Be, Co, Pb, Ni) et naturelle (As, Ba, Be, Co, Pb, Mn, Ni, U, REEs) ainsi que l'évaporation ;
- Les eaux souterraines sont acides et les eaux de surface sont modéremment alcalines. Les eaux de BIW et DLSW sont convenables pourl'irrigation avec :
  - Un faible risque lié à la salinité dans : 100% des échantillons de Bidou pendant les saisons sèches et pluvieuses, 100% et 81% des échantillons de Douka Longo en saisons sèche et pluvieuse, respectivement ;
  - Un faible risque lié à la sodicité dans : 98,25% et 96,7%, 100ù et 100%, 0% et 64% (préférable en saison sèche) et 90,45% des échantillons de BIW et DLSW, pendant la saison pluvieuse et la saison sèche sur la base du pourcentage de sodium (SSP), du ratio d'adsorption de sodium (SAR), de l'indice de perméabilité (PI) et du ratio de Kelly (KR), respectivement ;
  - Un faible risque lié à l'alcalinité dans 100% des échantillons collectés qui ont des quantités de résiduelle de bicarbonate (RSBC) RSBC<10. Cependant, de très faibles valeurs du pH et des conductivités électriques (EC) très élevées à GW001 et GW002 réduisent la qualité de l'eau à DLSW ;
  - Pas de risque lié à des éléments toxiques pour les plantes avec de faibles valeurs de ratio d'adsorption de magnésium (MAR), de bore (B) et de $Cl^-$ ;
- Les eaux sont convenables pour la consommation avec :
  - Une faible minéralisation à BIW (TDS<500mg/l) pour tous les échantillons sauf dans 11.1% des échantillons de BIW pendant la saison pluvieuse. Néanmoins, de très faibles valeurs de la dureté de l'eau rendent les eaux non potables pour près de 93% des eaux échantillonées ;
  - Tous les échantillons collectés à BIW ayant des concentrations en $NO_3^-$ <50mg/l. À DLSW, 36% et 22.2% des eaux échantillonnées ne sont pas conformes aux

normes de l'OMS pour le $NO_3^-$ dans l'eau de boisson pendant les saisons sèches et pluvieuses, respectivement;

- Une absence de métaux lourds affectant la santé humaine pendant la saison sèche. La pire qualité de l'eau est observée en saison pluvieuse avec un excès de As (8%), Ni(4%), Pb (8%) and U(8%) à DLSW et pas de métaux reconnus comme dangereux pour la santé par l'OMS ;
- De bons indices de la qualité de l'eau pendant la saison sèche comparés à ceux de la saison pluvieuse. En saison pluvieuse, 100% et 64% des échantillons sont convenables pour la consommation à BIW et à DLSW, respectivement. En saison sèche, 93,1% et 63% des échantillons sont convenables pour la consommation à BIW et à DLSW, respectivement ;

- La recharge annuelle des eaux souterraines est de $2.04\times10^8 m^3$ à BIW et $1.59\times10^9 m^3$ à DLSW. Ceci correspond à un potentiel de consommation journalière de $16m^3$/habitant à BIW et $79m^3$/habitant à DLSW qui sont largement supérieurs aux 40L de consommation journalière recommandés par l'OMS pour une personne. Au rythme actuel de croissance de la population, ces bassins sont susceptibles d'être en situation de stress hydrique en 2464 pour BIW et en 2192 pour DLSW.
- Les ressources en eau sont présentes en quantité suffisantes dans les bassins mais doivent être protégées et traitées avant usage. Les étapes nécessaires pour atteindre cet objectif sont la sensibilisation des populations, la planification de l'occupation des espaces (spécialement dans les zones de recharge), amélioration du système d'assainissement (collecte des déchets solides par apport volontaire, collecte des eaux usées dans un lac pour être réutilisées en agriculture et l'installation de toilettes sèches à double fosses et à séparation d'urines) ;
- Les problèmes majeurs de l'eau de consommation identifiés sont un excès de $NO_3^-$ et de métaux lourds à DLSW et la douceur de l'eau à BIW. Le traitement de l'eau par adsorption du $NO_3^-$ sur le méta kaolin et des métaux lourds sur le charbon actif fait à base d'épis de maïs est recommandé. À BIW, les eaux peuvent être enrichies en calcium par ajout de calcaire avant consommation.

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https://www.lenntech.com/periodic/elements/ho.htm#Health%20effects%20of%20holmium (26/02/2021)

# APPENDIX

**Appendix 1:** Results of major ions, $SiO_2$ and stable environmental isotopes of groundwater (n=36) and surface water (n=16), sampled during the rainy season in the Bidou and Douka Longo watersheds

| Sample ID | Long (dd.dd) | Lat (dd.dd) | Temp (°C) | PH | EC (µS/cm) | HCO3 (mg/l) | K (mg/l) | Na (mg/l) | Cl (mg/l) | Mg (mg/l) | Ca (mg/l) | Fe (mg/l) | Mn mg/l) | $SO_4^{2+}$ (mg/l) | $NO_3^-$ (mg/l) | Br (mg/l) | $NH_4^+$ (mg/l) | F (mg/l) | $SiO_2$ (mg/l) | $\delta^{18}O$ (‰) | $\delta^2H$ (‰) | DE (‰) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| GW001 | 13.404659 | 9.069337 | 30.4 | 4.2 | 623 | - | 38.0 | 14.4 | 27.50 | 11.6 | 24.6 | 0.04 | 0.64 | 0.347 | 249 | - | 0.34 | 0.941 | 10.2 | -4.43 | -25.4 | 10 |
| GW002 | 13.403722 | 9.068414 | 30.4 | 4.3 | 698 | - | 75.3 | 27.0 | 43.20 | 8.29 | 19.6 | 0.05 | 0.4 | 2.69 | 266 | - | 0.04 | 0.809 | 8.7 | -3.98 | -21.9 | 10 |
| GS001 | 13.398551 | 9.069614 | 32.3 | 6.9 | 189 | 12.4 | 12.0 | 6.4 | 12.60 | 4.23 | 12.0 | 0.05 | 0.05 | 0.011 | 59.7 | 0.023 | 0.05 | 0.031 | 12.8 | -4.60 | -27.3 | 10 |
| GR001 | 13.397299 | 9.070506 | 28.9 | 7.3 | 100 | 48.7 | 4.6 | 5.4 | 2.11 | 2.40 | 8.62 | 0.59 | 0.07 | 0.396 | 4.52 | 0.010 | 0.01 | 0.094 | 14.1 | -4.26 | -24.1 | 10 |
| GW003 | 13.389630 | 9.056756 | 29.9 | 6.7 | 80 | 40.5 | 6.8 | 1.7 | 1.42 | 1.29 | 7.78 | 0.04 | 0.01 | 0.444 | 1.02 | 0.010 | 0.03 | 0.085 | 15.8 | -4.90 | -28.0 | 11 |
| GW004 | 13.391245 | 9.061435 | 29.4 | 5.6 | 65 | 4.9 | 8.9 | 2.9 | 3.17 | 0.400 | 1.34 | 0.02 | 0.04 | 0.083 | 19.8 | 0.009 | 0.17 | 0.024 | 11.6 | -4.61 | -25.7 | 11 |
| GS002 | 13.384551 | 9.052257 | 33.9 | 6.9 | 82 | 15.7 | 8.2 | 4.6 | 4.70 | 1.37 | 4.78 | 0.44 | 0.04 | 0.314 | 16.4 | 0.016 | 0.05 | 0.089 | 16.2 | -3.51 | -23.3 | 5 |
| GR002 | 13.384553 | 9.052258 | 28.9 | 7.4 | 106 | 50.3 | 4.6 | 5.9 | 2.22 | 2.56 | 9.12 | 0.48 | 0.04 | 0.405 | 4.53 | 0.010 | 0.02 | 0.100 | 14.1 | -4.42 | -26.6 | 9 |
| GW005 | 13.390569 | 9.044049 | 30.4 | 6.4 | 80 | 14.1 | 5.4 | 2.5 | 2.91 | 1.37 | 6.74 | 0.13 | 0.01 | 1.02 | 19.2 | 0.012 | 0.04 | 0.042 | 11.7 | -5.31 | -30.7 | 12 |
| GW006 | 13.422484 | 9.037825 | 31.1 | 5.2 | 122 | 1.7 | 11.8 | 9.0 | 4.85 | 0.788 | 2.36 | 0.02 | 0.07 | 0.033 | 45.8 | 0.012 | 0.05 | 0.036 | 14.7 | -4.54 | -24.4 | 12 |
| GB001 | 13.424827 | 9.036211 | 34.0 | 6.7 | 170 | 19.9 | 19.2 | 5.9 | 5.98 | 4.70 | 5.13 | 0.06 | 0.05 | 0.203 | 54.3 | 0.010 | bdl | 0.075 | 12.3 | -4.71 | -28.4 | 9 |
| GS003 | 13.413819 | 9.033756 | 34.0 | 6.8 | 68 | 24.5 | 2.9 | 4.0 | 1.57 | 1.70 | 5.81 | 0.14 | 0.02 | 0.635 | 8.83 | bdl | 0.11 | 0.085 | 12.0 | -4.73 | -30.4 | 7 |
| GR004 | 13.398575 | 9.085263 | 27.2 | 7.3 | 82 | 41.1 | 5.8 | 2.9 | 1.10 | 2.06 | 7.00 | 0.65 | 0.27 | 0.299 | 2.04 | 0.008 | 0.01 | 0.088 | 13.9 | -4.18 | -25.5 | 8 |
| GR005 | 13.398614 | 9.085513 | 27.3 | 7.3 | 99 | 48.1 | 4.9 | 5.4 | 2.03 | 2.41 | 8.67 | 0.53 | 0.08 | 0.382 | 4.12 | 0.009 | 0.01 | 0.093 | 14.0 | -4.47 | -26.7 | 9 |
| GW007 | 13.422984 | 9.088572 | 29.8 | 6.1 | 332 | 10.0 | 18.1 | 15.3 | 22.00 | 5.72 | 22.1 | 0.02 | 0.15 | 0.755 | 118 | 0.040 | 0.06 | 0.032 | 11.5 | -4.34 | -24.2 | 11 |
| GW008 | 13.425094 | 9.093570 | 30.2 | 6.5 | 221 | 31.0 | 19.7 | 8.2 | 12.10 | 3.20 | 14.9 | 0.01 | 0.06 | 2.20 | 57.0 | 0.029 | 0.02 | 0.112 | 15.4 | -5.07 | -29.8 | 11 |
| GR006 | 13.391867 | 9.067199 | 26.5 | 6.9 | 132 | 55.5 | 5.5 | 4.8 | 0.80 | 2.55 | 9.03 | 1.94 | 1.66 | 0.511 | 0.506 | 0.004 | 0.01 | 0.136 | 12.6 | -2.79 | -21.3 | 1 |
| GR007 | 13.432431 | 8.973531 | 28.6 | 7.4 | 110 | 55.1 | 4.5 | 6.6 | 1.92 | 2.60 | 9.80 | 0.43 | 0.07 | 0.356 | 4.15 | 0.011 | 0.02 | 0.100 | 12.8 | -4.53 | -26.9 | 9 |
| GW009 | 13.436909 | 8.978741 | 31.0 | 6.3 | 273 | 7.1 | 15.3 | 6.8 | 16.90 | 7.21 | 19.1 | 0.01 | 0.04 | 0.648 | 98.4 | 0.026 | 0.05 | 0.019 | 14.1 | -4.84 | -26.7 | 12 |
| GW010 | 13.459058 | 8.994897 | 29.8 | 6.7 | 227 | 33.5 | 17.3 | 10.8 | 15.50 | 4.21 | 14.3 | 0.02 | 0.02 | 7.01 | 46.8 | 0.033 | 0.03 | 0.118 | 14.8 | -4.71 | -26.9 | 11 |
| GW011 | 13.469292 | 9.003684 | 30.2 | 6.6 | 228 | 15.5 | 12.5 | 4.5 | 10.40 | 6.38 | 17.6 | 0.01 | 0.02 | 0.730 | 80.0 | 0.019 | 0.05 | 0.037 | 10.9 | -4.55 | -24.3 | 12 |
| GW012 | 13.436425 | 9.009940 | 29.7 | 5.9 | 58 | 5.0 | 5.7 | 1.4 | 0.80 | 1.08 | 2.91 | 0.01 | 0.03 | 0.036 | 21.4 | 0.008 | 0.01 | 0.018 | 12.6 | -4.77 | -27.0 | 11 |
| GW013 | 13.416880 | 9.003815 | 29.1 | 5.7 | 106 | 4.0 | 9.7 | 3.0 | 3.63 | 2.01 | 4.90 | 0.01 | 0.05 | 0.251 | 38.9 | 0.020 | 0.23 | 0.019 | 10.9 | -4.95 | -27.8 | 12 |
| GW014 | 13.403423 | 9.003431 | 30.6 | 6.2 | 158 | 7.2 | 6.5 | 3.2 | 6.02 | 5.29 | 11.2 | 0.01 | 0.02 | 0.103 | 61.1 | 0.025 | 0.01 | 0.025 | 13.6 | -4.79 | -26.2 | 12 |
| GR008 | 13.435463 | 9.012744 | 28.1 | 7.2 | 85 | 32.4 | 6.3 | 3.3 | 3.71 | 2.00 | 6.70 | 0.65 | 0.04 | 0.334 | 7.13 | 0.010 | 0.02 | 0.066 | 14.2 | -4.62 | -26.8 | 10 |
| NW001 | 13.575147 | 7.441163 | 23.4 | 6.5 | 12 | 5.4 | 0.2 | 0.4 | 0.12 | 0.180 | 1.15 | 0 | 0.01 | 0.012 | 0.071 | bdl | bdl | 0.015 | 3.0 | -3.65 | -16.5 | 13 |
| NR001 | 13.568552 | 7.422618 | 19.5 | 6.3 | 15 | 7.6 | 0.1 | 0.5 | 0.03 | 0.277 | 0.92 | 0.77 | 0.03 | bdl | bdl | bdl | 0.01 | 0.016 | 3.3 | -3.42 | -15.7 | 12 |
| NR002 | 13.561354 | 7.427649 | 21.0 | 6.9 | 31 | 18.1 | 0.4 | 1.1 | 0.06 | 1.37 | 3.02 | 0.21 | 0.03 | 0.024 | 0.246 | bdl | bdl | 0.060 | 5.3 | -3.52 | -16.4 | 12 |

| Sample ID | Long (dd.dd) | Lat (dd.dd) | Temp (°C) | PH | EC (µS/cm) | HCO3 (mg/l) | K (mg/l) | Na (mg/l) | Cl (mg/l) | Mg (mg/l) | Ca (mg/l) | Fe (mg/l) | Mn mg/l) | $SO_4^{2+}$ (mg/l) | $NO_3^-$ (mg/l) | Br (mg/l) | $NH_4^+$ (mg/l) | F (mg/l) | $SiO_2$ (mg/l) | $\delta^{18}O$ (‰) | $\delta^{2}H$ (‰) | DE (‰) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| NW002 | 13.555943 | 7.428783 | 24.2 | 6.3 | 160 | 16.4 | 1.2 | 19.1 | 16.30 | 1.66 | 5.79 | 0.07 | 0.42 | 0.097 | 37.9 | 0.012 | 0.88 | 0.019 | 4.0 | -3.60 | -15.9 | 13 |
| NL001 | 13.553277 | 7.423592 | 22.2 | 6.3 | 23 | 10.8 | 0.0 | 1.1 | 0.38 | 0.318 | 1.88 | 1.58 | 0.04 | 0.003 | bdl | bdl | 0.01 | 0.021 | 2.5 | -0.86 | -11.5 | -5 |
| NW003 | 13.540553 | 7.430123 | 25.0 | 5.6 | 14 | 3.3 | 0.1 | 0.4 | 0.04 | 0.076 | 0.40 | 0.01 | 0.01 | 0.019 | 0.131 | bdl | 0.01 | 0.006 | 2.4 | - | - | - |
| NR004 | 13.547029 | 7.444575 | 23.0 | 6.5 | 12 | 6.4 | 0.3 | 0.9 | 0.12 | 0.225 | 0.92 | 0.26 | 0.03 | 0.029 | 0.095 | bdl | 0.03 | 0.021 | 3.5 | -3.42 | -15.1 | 12 |
| NW004 | 13.552817 | 7.447113 | 24.5 | 6.0 | 12 | 5.4 | 0.3 | 0.4 | 0.27 | 0.101 | 1.13 | 0.03 | 0.01 | 0.051 | 0.222 | bdl | 0.03 | 0.006 | 2.3 | -3.26 | -15.2 | 11 |
| NW005 | 13.553888 | 7.456847 | 24.2 | 6.2 | 16 | 9.9 | 0.7 | 0.4 | 0.24 | 0.231 | 1.92 | 0.15 | 0.04 | 0.012 | 0.012 | bdl | 0.10 | 0.012 | 3.0 | -3.23 | -15.7 | 10 |
| NR005 | 13.548583 | 7.406232 | 21.5 | 6.9 | 32 | 17.5 | 0.4 | 1.2 | 0.06 | 1.33 | 2.77 | 0.53 | 0.06 | 0.017 | 0.207 | bdl | bdl | 0.044 | 5.6 | -3.50 | -16.7 | 11 |
| NW006 | 13.547873 | 7.394513 | 23.7 | 5.8 | 19 | 5.1 | 0.2 | 0.4 | 0.08 | 0.186 | 0.85 | 0.01 | 0.03 | 0.012 | 0.045 | bdl | bdl | 0.009 | 3.1 | -3.33 | -16.4 | 10 |
| NR006 | 13.551145 | 7.394119 | 20.3 | 6.6 | 14 | 8.0 | 0.3 | 0.9 | 0.15 | 0.292 | 0.98 | 0.71 | 0.04 | 0.081 | 0.021 | bdl | bdl | 0.029 | 4.0 | -3.72 | -17.5 | 12 |
| NR007 | 13.555889 | 7.386998 | 21.8 | 6.7 | 17 | 7.0 | 0.7 | 1.2 | 0.10 | 0.275 | 0.83 | 0.34 | 0.04 | 0.031 | 0.147 | bdl | 0.03 | 0.034 | 5.0 | -3.43 | -15.8 | 12 |
| NW007 | 13.556961 | 7.380283 | 23.6 | 6.6 | 156 | 24.9 | 0.9 | 25.0 | 16.90 | 1.05 | 3.13 | 0.04 | 0.03 | 18.7 | 4.47 | 0.067 | 0.15 | 0.039 | 4.4 | -3.35 | -15.3 | 11 |
| NR008 | 13.557086 | 7.379384 | 20.6 | 6.8 | 19 | 7.8 | 1.1 | 1.3 | 0.39 | 0.358 | 0.89 | 0.53 | 0.01 | 0.021 | 0.163 | bdl | 0.04 | 0.025 | 4.8 | -3.96 | -18.9 | 13 |
| NS001 | 13.550409 | 7.461674 | 23.1 | 6.1 | 18 | 11.0 | 0.9 | 1.2 | 0.11 | 0.232 | 1.00 | 0.83 | 0.03 | 0.015 | 0.089 | bdl | 0.04 | 0.014 | 4.8 | -3.25 | -15.4 | 11 |
| NW009 | 13.550726 | 7.475015 | 24.6 | 6.0 | 21 | 4.8 | 0.7 | 2.1 | 0.26 | 0.190 | 0.81 | 0.02 | 0.01 | 0.015 | 5.38 | bdl | bdl | 0.012 | 4.4 | -3.08 | -14.7 | 10 |
| NW010 | 13.552442 | 7.479017 | 24.4 | 5.9 | 12 | 5.0 | 0.1 | 0.7 | 0.07 | 0.190 | 0.67 | 0.02 | 0.02 | 0.005 | 0.456 | bdl | 0.01 | 0.008 | 2.4 | -3.16 | -14.8 | 11 |
| NS002 | 13.553641 | 7.478358 | 25.5 | 6.2 | 27 | 10.1 | 0.2 | 0.8 | 0.01 | 0.476 | 1.51 | 0.08 | 0 | 0.003 | | bdl | bdl | 0.026 | 5.3 | -3.51 | -16.2 | 12 |
| NW011 | 13.552615 | 7.483249 | 25.0 | 6.0 | 13 | 6.0 | 0.2 | 0.4 | 0.07 | 0.245 | 0.97 | 0.01 | 0.02 | 0.021 | 0.099 | bdl | bdl | 0.006 | 2.6 | -3.39 | -15.8 | 11 |
| NW012 | 13.557178 | 7.499107 | 24.9 | 5.9 | 12 | 4.6 | 0.2 | 0.6 | 0.03 | 0.106 | 0.60 | 0.01 | 0.03 | 0.003 | 0.484 | bdl | bdl | 0.007 | 3.0 | -4.18 | -20.4 | 13 |
| NW014 | 13.558682 | 7.515927 | 26.1 | 6.0 | 18 | 5.0 | 0.1 | 0.9 | 0.32 | 0.407 | 1.01 | 0.02 | 0.01 | bdl | 2.78 | bdl | bdl | 0.015 | 4.3 | -3.29 | -14.8 | 12 |
| NW015 | 13.560761 | 7.527547 | 23.3 | 7.1 | 33 | 17.6 | 0.5 | 0.9 | 0.41 | 1.43 | 3.20 | 0.04 | 0 | 0.129 | 0.820 | bdl | 0.08 | 0.091 | 10.1 | -3.24 | -14.3 | 12 |
| NW016 | 13.564896 | 7.542343 | 25.5 | 6.0 | 25 | 4.2 | 0.3 | 1.8 | 0.14 | 0.300 | 1.10 | 0.01 | 0.17 | 0.016 | 7.04 | bdl | 0.06 | 0.012 | 2.8 | -4.51 | -24.5 | 12 |
| NW017 | 13.568838 | 7.546501 | 24.6 | 5.9 | 9 | 3.3 | 0.4 | 0.4 | 0.22 | 0.099 | 0.50 | 0.01 | 0.05 | 0.025 | 1.24 | bdl | 0.05 | 0.005 | 2.0 | -3.09 | -14.2 | 11 |
| NR012 | 13.512759 | 7.426373 | 22.5 | 7.2 | 61 | 36.8 | 0.7 | 2.0 | 0.24 | 2.85 | 6.03 | 0.55 | 0.09 | 0.032 | 0.536 | bdl | bdl | 0.075 | 9.0 | -3.35 | -15.5 | 11 |
| NB001 | 13.564022 | 7.498004 | 25.8 | 6.3 | 27 | 15.0 | 0.4 | 0.7 | 0.01 | 1.11 | 2.53 | 0.01 | 0 | 0.369 | bdl | bdl | bdl | 0.035 | 6.3 | -3.20 | -15.2 | 10 |

**Appendix 2:** Results of major ions, $SiO_2$ and stable environmental isotopes of groundwater (n=36) and surface water (n=16), sampled during the dry season in the Bidou and Douka Longo watersheds

| ID | Long | Lat | T | PH | HCO3 | K | Na | Cl | Mg | Ca | Fe(II) | Mn | $SO_4^{2-}$ | $NO_3^-$ | B | $NH_4^+$ | F | $SiO_2$ | $\delta^{18}O$ | $\delta^{2}H$ | DE |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | dd | dd | °C | | mg/l | mg/l | mg/l | mg/l | mg/l | mg/l | mg/l | µg/L | mg/l | mg/l | µg/L | mg/l | mg/l | mg/l | (‰) | (‰) | (‰) |
| AW01 | 13.581741 | 7.323184 | 22.8 | 5.7 | 4.4 | 0.2 | 0.6 | 0.120 | 0.212 | 1.51 | 0.265 | 19.9 | 0.120 | 0.013 | 8.01 | 0.02 | 0.009 | 3.2 | -3.4 | -15.3 | 12 |
| AW02 | 13.58478 | 7.429559 | 24 | 5.8 | 13.7 | 0.4 | 0.6 | 0.065 | 0.881 | 2.60 | 0.015 | 242 | bdl | bdl | 6.47 | bdl | 0.021 | 5.8 | -3.1 | -13.4 | 11 |
| AR03 | 13.563165 | 7.436497 | 20.7 | 7 | 12.0 | 0.4 | 0.9 | 0.086 | 0.766 | 1.87 | 0.199 | 32.8 | 0.046 | 0.088 | 3.77 | 0.01 | 0.035 | 4.4 | -3.05 | -14.1 | 10 |
| AR04 | 13.559645 | 7.437568 | 21.3 | 6.9 | 13.0 | 0.6 | 1.3 | 0.148 | 0.755 | 1.80 | 0.238 | 50.2 | 0.048 | 0.063 | 9.40 | bdl | 0.035 | 4.3 | -2.79 | -12.5 | 10 |
| AR05 | 13.565345 | 7.44117 | 20.4 | 6.4 | 11.4 | 0.2 | 0.6 | 0.017 | 0.752 | 1.87 | 0.317 | 32.6 | 0.004 | 0.108 | 16.4 | bdl | 0.035 | 4.2 | -3.1 | -14 | 11 |
| AW06 | 13.577387 | 7.455417 | 25.5 | 5.2 | 5.1 | 0.1 | 0.3 | 0.045 | 0.211 | 1.07 | 0.013 | 64.0 | bdl | 0.046 | 8.75 | bdl | | 3.2 | -3.5 | -15.4 | 13 |
| AR07 | 13.583748 | 7.449215 | 22.4 | 6.7 | 10.7 | 0.3 | 0.7 | 0.065 | 0.659 | 1.64 | 0.425 | 62.0 | 0.007 | 0.068 | 7.68 | 0.01 | 0.032 | 4.6 | -3.05 | -13.3 | 11 |
| AR08 | 13.584893 | 7.448289 | 19.5 | 5.4 | 7.0 | 0.1 | 0.5 | 0.019 | 0.296 | 0.76 | 1.036 | 27.0 | 0.007 | bdl | 15.1 | bdl | 0.009 | 4.9 | -2.92 | -13 | 10 |
| AW09 | 13.571954 | 7.463948 | 24.7 | 5.3 | 6.6 | 0.4 | 0.3 | 0.105 | 0.205 | 1.40 | 0.135 | 41.7 | 0.044 | 0.146 | 13.8 | 0.03 | 0.005 | 2.9 | -3.81 | -17.4 | 13 |
| AD10 | 13.58119 | 7.480702 | 24.1 | 6.2 | 7.1 | 0.3 | 0.5 | 0.022 | 0.381 | 1.20 | 0.093 | 36.2 | bdl | 0.106 | 11.2 | bdl | 0.022 | 3.7 | -2.51 | -11.2 | 9 |
| AW11 | 13.575059 | 7.487408 | 24.7 | 5.2 | 3.8 | 0.2 | 0.3 | 0.070 | 0.165 | 0.75 | 0.012 | 20.4 | 0.005 | 0.118 | 22.1 | bdl | 0.005 | 2.6 | -3.79 | -16.9 | 13 |
| AD12 | 13.563283 | 7.485742 | 23.4 | 6.7 | 20.7 | 0.6 | 1.6 | 0.047 | 1.33 | 3.07 | 0.094 | 43.6 | 0.005 | 0.076 | 8.88 | bdl | 0.061 | 5.9 | -2.14 | -9.2 | 8 |
| AW13 | 13.556229 | 7.488081 | 24.7 | 6.5 | 39.6 | 0.4 | 0.5 | 0.124 | 0.508 | 12.0 | 0.029 | 23.8 | 0.383 | 0.229 | 43.6 | 0.01 | 0.031 | 6.6 | -2.96 | -13.3 | 10 |
| AS14 | 13.574768 | 7.319549 | 24.1 | 5.5 | 9.6 | 0.2 | 0.8 | 0.007 | 0.468 | 1.58 | 0.150 | 5.99 | 0.005 | bdl | 14.8 | bdl | 0.02 | 5.4 | -3.29 | -14 | 12 |
| AW15 | 13.557141 | 7.480202 | 24.5 | 5.6 | 5.6 | 1.8 | 0.4 | 0.368 | 0.184 | 0.70 | 0.050 | 98.4 | bdl | 0.486 | 13.8 | bdl | 0.005 | 2.3 | -3.06 | -13.2 | 11 |
| AR16 | 13.567513 | 7.473446 | 21 | 6.2 | 18.3 | 0.7 | 1.3 | 0.028 | 1.17 | 2.56 | 0.301 | 202 | bdl | bdl | 20.6 | bdl | 0.05 | 5.3 | -2.6 | -11.1 | 10 |
| AW17 | 13.562201 | 7.467736 | 26.2 | 5.2 | 5.7 | 0.2 | 0.3 | 0.046 | 0.351 | 0.92 | 0.014 | 73.3 | bdl | bdl | 18.4 | 0.01 | 0.008 | 3.8 | -2.82 | -11.5 | 11 |
| AR18 | 13.561569 | 7.458552 | 22.8 | 6.7 | 12.6 | 0.6 | 1.1 | 0.041 | 0.799 | 1.85 | 0.158 | 93.2 | 0.015 | 0.024 | 4.96 | bdl | 0.04 | 4.6 | -2.81 | -11.9 | 11 |
| AW19 | 13.540574 | 7.430037 | 24.7 | 5.2 | 3.4 | 0.2 | 0.3 | 0.077 | 0.102 | 0.53 | 0.149 | 12.0 | 0.035 | 0.043 | 18.7 | 0.01 | bdl | 2.9 | -3.13 | -13.1 | 12 |
| AR20 | 13.547007 | 7.444647 | 20.7 | 6.4 | 5.8 | 0.3 | 0.7 | 0.035 | 0.235 | 0.92 | 0.249 | 14.2 | 0.017 | bdl | 5.29 | bdl | 0.018 | 3.6 | -2.94 | -11.8 | 12 |
| AW21 | 13.553925 | 7.448196 | 25.1 | 5.3 | 4.6 | 0.2 | 0.4 | 0.059 | 0.161 | 0.81 | 0.037 | 19.9 | 0.011 | bdl | 17.0 | bdl | bdl | 2.6 | -3.2 | -13.6 | 12 |
| AW22 | 13.555204 | 7.460343 | 25.3 | 5.2 | 3.1 | 0.5 | 0.3 | 0.149 | 0.190 | 0.64 | 0.030 | 152 | 0.006 | 0.608 | 13.3 | 0.01 | bdl | 2.6 | -2.75 | -11 | 11 |
| AW23 | 13.555945 | 7.428766 | 25 | 5.8 | 10.8 | 1.4 | 17.0 | 16.4 | 2.10 | 6.86 | 0.216 | 667 | 0.150 | 44.4 | 9.50 | 0.01 | 0.013 | 4.3 | -3.22 | -12.7 | 13 |
| AR24 | 13.555208 | 7.419585 | 22 | 6.8 | 10.6 | 0.3 | 0.9 | 0.049 | 0.722 | 1.81 | 0.327 | 39.9 | 0.022 | 0.044 | 5.57 | bdl | 0.036 | 4.3 | -2.82 | -11.5 | 11 |
| AW25 | 13.550687 | 7.475027 | 24.2 | 5.5 | 1.9 | 0.9 | 1.6 | 0.400 | 0.169 | 0.69 | 0.016 | 27.3 | 0.018 | 3.31 | 8.01 | bdl | 0.015 | 5.2 | -3.17 | -14.8 | 11 |
| AW26 | 13.561859 | 7.527467 | 20.4 | 7.6 | 80.7 | 1.5 | 3.5 | 0.404 | 5.33 | 15.7 | 0.110 | 111 | 0.230 | 1.71 | 8.24 | bdl | 0.121 | 21.2 | -2.75 | -12 | 10 |
| AW27 | 13.566295 | 7.540712 | 23.3 | 5.2 | 3.1 | 0.3 | 1.8 | 0.625 | 0.332 | 0.95 | 0.023 | 296 | 0.017 | 5.70 | 16.3 | 0.04 | 0.007 | 2.5 | -3.36 | -15.8 | 11 |
| AW28 | 13.569537 | 7.498268 | 26.5 | 5.8 | 30.5 | 1.3 | 0.9 | 0.111 | 0.970 | 3.73 | 2.379 | 3574 | 0.008 | 0.007 | 17.7 | 0.48 | 0.026 | 2.7 | -3.05 | -13.5 | 11 |
| AR29 | 13.574295 | 7.503703 | 22.8 | 7.5 | 71.8 | 1.5 | 3.2 | 0.096 | 5.51 | 11.4 | 0.665 | 171 | bdl | 1.19 | 5.87 | bdl | 0.141 | 12.6 | -2.39 | -11.8 | 7 |
| NR51 | 13.39854 | 9.08554 | 25.2 | 6.8 | 39.7 | 6.8 | 2.9 | 0.918 | 1.59 | 5.03 | 1.41 | 431 | 0.135 | 0.724 | 6.84 | 0.01 | 0.036 | 18.2 | -3.39 | -21.6 | 6 |
| NW52 | 13.402835 | 9.068427 | 30.9 | 4.6 | 1.9 | 17.8 | 11.4 | 12.7 | 3.03 | 10.4 | 0.031 | 343 | 0.002 | 93.3 | 20.5 | 0.01 | 0.33 | 12.4 | -4.11 | -22.8 | 10 |
| NW53 | 13.391291 | 9.06141 | 28.2 | 5 | 1.9 | 8.8 | 2.5 | 2.46 | 0.396 | 1.20 | 0.082 | 46.8 | 0.037 | 20.1 | 20.2 | 0.01 | 0.37 | 12.4 | -4.3 | -24.4 | 10 |
| NW54 | 13.389619 | 9.056755 | 29.5 | 5.9 | 29.1 | 7.0 | 1.4 | 0.770 | 1.24 | 6.06 | 0.120 | 18.8 | 0.354 | 7.22 | 18.5 | bdl | 0.163 | 16.0 | -4.35 | -24.7 | 10 |
| NW55 | 13.390558 | 9.044059 | 29.5 | 6 | 12.5 | 7.1 | 5.4 | 6.21 | 2.44 | 9.43 | 0.007 | 11.3 | 0.587 | 42.7 | 8.46 | bdl | 0.233 | 12.9 | -4.29 | -23.8 | 11 |

## **Appendix 2** (Continued)

| | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| NW56 | 13.42246 | 9.037811 | 30.1 | 4.7 | 2.2 | 13.5 | 9.9 | 4.72 | 0.872 | 2.44 | 0.014 | 74.8 | 0.011 | 49.4 | 17.7 | bdl | 0.05 | 14.3 | -4.35 | -23.9 | 11 |
| NB57 | 13.466635 | 9.034482 | 32 | 5.8 | 16.4 | 6.7 | 0.8 | 0.068 | 0.327 | 1.21 | -0.003 | 2.62 | 0.351 | 0.376 | 14.5 | 0.01 | 0.768 | 21.2 | -4.72 | -26.3 | 11 |
| NW58 | 13.466634 | 9.03448 | 29.6 | 5.7 | 6.5 | 14.6 | 6.1 | 15.2 | 6.76 | 17.5 | 0.012 | 38.0 | 0.432 | 92.0 | 9.30 | 0.11 | 0.105 | 16.3 | -4.54 | -25.1 | 11 |
| NR59 | 13.432507 | 8.973478 | 23.6 | 7.4 | 102 | 5.7 | 12.3 | 2.96 | 4.49 | 14.8 | 0.526 | 983 | 0.478 | 0.189 | 32.1 | | 0.488 | 15.6 | -3.15 | -20.4 | 5 |
| NW60 | 13.404356 | 8.951507 | 28.9 | 6.7 | 108 | 4.1 | 10.2 | 5.90 | 5.90 | 24.8 | 0.016 | 24.9 | 0.718 | 13.4 | 7.59 | 0.52 | 0.123 | 29 | -4.23 | -22.5 | 11 |
| NW61 | 13.372166 | 8.959557 | 30.1 | 5.7 | 4.3 | 10.9 | 3.0 | 1.52 | 2.01 | 6.43 | 0.023 | 62.9 | 0.352 | 43.9 | 11.9 | 0.01 | 0.2 | 17.3 | -4.08 | -22.3 | 10 |
| NR62 | 13.376677 | 8.957149 | 27.4 | 5.8 | 29.3 | 3.9 | 2.5 | 1.50 | 1.47 | 5.23 | 0.125 | 632 | 0.629 | 0.664 | 16.1 | 0.01 | 0.237 | 14.6 | -4.03 | -24.4 | 8 |
| NR63 | 13.435493 | 9.012744 | 25 | 6.7 | 38.4 | 7.5 | 1.8 | 1.05 | 1.50 | 5.15 | 1.19 | 237 | 0.020 | 0.942 | 8.62 | bdl | 0.475 | 17.6 | -3.47 | -20.7 | 7 |
| NW64 | 13.432195 | 9.010297 | 29.5 | 5.7 | 10.5 | 12.0 | 6.6 | 15.8 | 5.92 | 20.9 | 0.010 | 14.0 | 0.167 | 93.2 | 8.86 | bdl | 0.617 | 16 | -4.71 | -26 | 12 |
| NW65 | 13.524463 | 8.986212 | 27.6 | 7.3 | 128 | 13.3 | 19.2 | 17.4 | 4.07 | 28.6 | 0.170 | 2.32 | 7.27 | 7.13 | 16.7 | bdl | 0.557 | 30.7 | -4.61 | -27.3 | 10 |
| NW66 | 13.526302 | 8.956553 | 25 | 7.5 | 94.6 | 9.5 | 8.3 | 2.40 | 2.55 | 25.7 | 0.017 | 18.3 | 0.733 | 25.8 | 13.5 | 0.01 | 0.303 | 33.8 | -4.62 | -25.3 | 12 |
| NW67 | 13.508729 | 8.917554 | 29.4 | 6 | 16.2 | 8.6 | 3.1 | 5.96 | 1.72 | 5.53 | 0.022 | 12.2 | 0.333 | 20.5 | 14.4 | 0.01 | 0.568 | 24.9 | -4.49 | -24.9 | 11 |
| NW68 | 13.482643 | 8.939645 | 29.9 | 6.1 | 11.1 | 11.9 | 5.8 | 9.82 | 4.83 | 17.0 | 0.004 | 10.9 | 0.170 | 81.7 | 8.96 | bdl | 0.253 | 23.2 | -4.35 | -23.2 | 12 |
| NR69 | 13.479565 | 8.939943 | 25 | 6.9 | 50.8 | 5.5 | 3.9 | 3.50 | 1.77 | 5.37 | 7.52 | 1016 | 0.306 | 1.86 | 10.5 | 0.44 | 0.362 | 13.8 | -3.96 | -26.3 | 5 |
| NW70 | 13.491145 | 8.98224 | 26.8 | 8.1 | 324 | 4.3 | 28.6 | 1.09 | 21.7 | 43.6 | 0.086 | 46.9 | 1.04 | 2.64 | 20.8 | 0.01 | 1.15 | 47.4 | -4.72 | -27.6 | 10 |
| NW71 | 13.498559 | 8.875992 | 29.7 | 6.7 | 103 | 4.9 | 13.0 | 5.60 | 3.03 | 25.4 | 0.009 | 2.63 | 1.18 | 16.5 | 9.14 | 0.01 | 0.173 | 30.3 | -4.06 | -22.6 | 10 |
| NR72 | 13.47364 | 8.885043 | 28 | 6.6 | 40.0 | 2.5 | 5.3 | 1.24 | 1.58 | 6.67 | 0.140 | 95.9 | 0.639 | 0.214 | 13.5 | bdl | 0.056 | 13 | -5.03 | -32.7 | 8 |
| NB73 | 13.50061 | 8.831842 | 32 | 7.3 | 497 | 2.0 | 72.2 | 12.3 | 22.6 | 76.1 | 0.003 | 0.137 | 5.50 | 22.3 | 9.48 | 0.01 | 0.087 | 23.1 | -4.12 | -22.7 | 10 |
| NR74 | 13.441413 | 8.865442 | 26 | 7.3 | 398 | 16.4 | 17.8 | 11.2 | 22.6 | 87.9 | -0.003 | 4.46 | 1.66 | 34.7 | 48.9 | 0.01 | 0.019 | 12.3 | 1.86 | -1.7 | -17 |
| NR75 | 13.467784 | 8.864926 | 31.5 | 6.8 | 134 | 3.4 | 15.4 | 3.51 | 5.46 | 27.4 | 0.009 | 126 | 2.98 | 9.33 | 11.8 | 0.02 | 0.061 | 15.1 | -4.32 | -25.5 | 9 |
| NW76 | 13.295712 | 8.986812 | 29.9 | 6.1 | 38.4 | 22.6 | 7.8 | 25.2 | 9.89 | 38.2 | 0.004 | 18.2 | 4.12 | 144 | 11.5 | 0.01 | 0.023 | 13.3 | -4.21 | -22.2 | 11 |
| NW77 | 13.509494 | 9.043289 | 29.3 | 5.4 | 2.1 | 25.6 | 24.5 | 36.7 | 10.5 | 25.4 | 0.007 | 986 | 4.46 | 182 | 19.4 | 0.02 | 0.03 | 14.8 | -4.67 | -24.9 | 12 |

**Appendix 3:** Trace element data of groundwater and surface water sampled during the rainy season in the Bidou and Douka Longo watersheds

| ID | Sc | Y | Ag | As | B | Ba | Be | Bi | Cd | Ce | Co | Cr | Cs | Cu |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Douka Longo watershed** | | | | | | | | | | | | | | |
| GW001 | 0,265 | 484,898 | 0,017 | 15,581 | 16,421 | 3921,168 | 22,885 | <0.002 | 0,214 | 168,041 | 107,929 | 0,389 | 2,413 | 54,535 |
| GW002 | 0,165 | 382,287 | 0,018 | 17,744 | 21,944 | 3037,584 | 15,166 | <0.002 | 0,152 | 272,674 | 70,717 | 0,102 | 2,262 | 29,213 |
| GS001 | 0,174 | 0,206 | <0.003 | 0,104 | 10,900 | 834,656 | 0,141 | <0.002 | 0,019 | 0,424 | 1,557 | 0,180 | 0,315 | 0,548 |
| GR001 | 0,496 | 1,174 | <0.003 | 0,187 | 15,251 | 197,546 | 0,102 | <0.002 | 0,005 | 2,623 | 0,664 | 0,443 | 0,028 | 1,055 |
| GW003 | 0,337 | 0,799 | 0,024 | 0,110 | 15,734 | 246,050 | 0,105 | <0.002 | 0,012 | 0,979 | 0,123 | 0,666 | 0,151 | 0,748 |
| GW004 | 0,198 | 0,366 | <0.003 | 0,032 | 6,596 | 282,772 | 0,512 | <0.002 | 0,012 | 1,174 | 4,413 | 0,232 | 0,168 | 1,381 |
| GS002 | 0,609 | 3,227 | 0,033 | 0,231 | 24,438 | 255,421 | 0,609 | <0.002 | 0,012 | 8,607 | 1,182 | 1,263 | 0,060 | 3,884 |
| GR002 | 0,317 | 0,483 | <0.003 | 0,185 | 11,654 | 184,633 | 0,077 | <0.002 | 0,005 | 1,616 | 0,305 | 0,535 | 0,031 | 1,129 |
| GW005 | 0,499 | 3,949 | <0.003 | 0,200 | 21,479 | 191,690 | 0,210 | 0,003 | 0,005 | 1,832 | 0,236 | 1,238 | 0,135 | 1,689 |
| GW006 | 0,138 | 0,557 | <0.003 | 0,038 | 6,785 | 1246,914 | 2,361 | <0.002 | 0,013 | 1,435 | 16,310 | 0,065 | 0,436 | 3,754 |
| GB001 | 0,272 | 0,115 | 0,004 | 0,023 | 20,127 | 1434,251 | 0,893 | <0.002 | 0,014 | 0,224 | 3,564 | 0,216 | 0,310 | 0,711 |
| GS003 | 0,484 | 2,950 | 0,003 | 0,251 | 64,427 | 292,043 | 0,343 | 0,002 | 0,008 | 3,064 | 0,482 | 1,654 | 0,060 | 2,034 |
| GR004 | 0,271 | 0,226 | <0.003 | 0,160 | 8,796 | 181,023 | 0,035 | <0.002 | <0.002 | 0,603 | 0,932 | 0,157 | 0,023 | 0,394 |
| GR005 | 0,266 | 0,407 | <0.003 | 0,184 | 19,441 | 169,399 | 0,062 | <0.002 | 0,004 | 1,562 | 0,463 | 0,415 | 0,025 | 1,248 |
| GW007 | 0,192 | 2,443 | <0.003 | 0,075 | 8,933 | 2069,113 | 1,229 | <0.002 | 0,041 | 0,686 | 17,236 | 0,218 | 0,634 | 1,489 |
| GW008 | 0,271 | 0,659 | <0.003 | 0,117 | 19,368 | 726,985 | 1,084 | <0.002 | 0,008 | 0,998 | 5,715 | 0,210 | 0,167 | 1,346 |
| GR006 | 0,295 | 0,628 | <0.003 | 0,524 | 48,597 | 289,733 | 0,079 | <0.002 | 0,008 | 2,718 | 7,503 | 0,475 | 0,034 | 1,731 |
| GR007 | 0,212 | 0,189 | <0.003 | 0,129 | 8,776 | 164,795 | 0,031 | <0.002 | 0,005 | 0,575 | 0,304 | 0,214 | 0,013 | 0,566 |
| GW009 | 0,221 | 0,348 | <0.003 | 0,037 | 18,617 | 957,330 | 0,504 | <0.002 | 0,009 | 0,229 | 3,548 | 0,256 | 0,129 | 0,390 |
| GW010 | 0,246 | 0,530 | <0.003 | 0,080 | 17,814 | 468,542 | 0,301 | <0.002 | 0,014 | 0,763 | 0,213 | 0,237 | 0,068 | 0,853 |
| GW011 | 0,142 | 0,412 | <0.003 | 0,043 | 6,351 | 876,008 | 0,075 | <0.002 | 0,009 | 0,338 | 0,942 | 0,058 | 0,201 | 0,276 |
| GW012 | 0,162 | 0,143 | <0.003 | 0,022 | 11,889 | 315,003 | 0,288 | <0.002 | 0,004 | 0,217 | 2,640 | 0,092 | 0,136 | 0,338 |
| GW013 | 0,152 | 0,794 | <0.003 | 0,084 | 47,300 | 469,292 | 0,537 | <0.002 | 0,009 | 0,968 | 5,122 | 0,184 | 0,104 | 0,732 |
| GW014 | 0,216 | 0,473 | <0.003 | 0,035 | 19,412 | 518,896 | 0,232 | <0.002 | 0,008 | 0,110 | 1,423 | 0,151 | 0,100 | 0,968 |
| GR008 | 0,368 | 0,608 | <0.003 | 0,174 | 21,864 | 263,113 | 0,074 | <0.002 | 0,003 | 1,560 | 0,453 | 0,291 | 0,032 | 1,044 |
| **Bidou watershed** | | | | | | | | | | | | | | |
| NW001 | 0,025 | 0,042 | <0.003 | <0.01 | 8,017 | 23,696 | 0,056 | <0.002 | 0,005 | 0,076 | 0,472 | 0,033 | 0,006 | 0,263 |
| NR001 | 0,073 | 0,019 | <0.003 | 0,080 | 15,935 | 54,018 | <0.007 | <0.002 | 0,003 | 0,076 | 0,581 | 0,104 | 0,004 | 0,224 |
| NR002 | 0,069 | 0,032 | <0.003 | 0,042 | 13,416 | 64,441 | <0.007 | <0.002 | 0,002 | 0,145 | 0,245 | 0,108 | <0.003 | 0,462 |
| NW002 | 0,098 | 0,302 | <0.003 | 0,020 | 9,506 | 141,486 | 0,071 | <0.002 | 0,018 | 0,202 | 2,285 | 0,031 | 0,129 | 0,251 |
| NL001 | 0,098 | 0,041 | <0.003 | 0,045 | 12,947 | 45,726 | <0.007 | <0.002 | 0,003 | 0,116 | 0,137 | 0,105 | 0,005 | 0,452 |
| NW003 | 0,034 | 0,150 | <0.003 | 0,018 | 20,014 | 55,940 | 0,060 | <0.002 | 0,007 | 0,050 | 0,894 | 0,252 | 0,007 | 0,665 |
| NR003 | 0,151 | 0,085 | <0.003 | 0,027 | 8,011 | 36,934 | <0.007 | <0.002 | <0.002 | 0,236 | 0,884 | 0,134 | 0,007 | 0,280 |
| NR004 | 0,073 | 0,014 | <0.003 | 0,053 | 2,393 | 21,754 | <0.007 | <0.002 | <0.002 | 0,085 | 0,344 | 0,027 | 0,005 | 0,071 |

| | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| NW004 | 0,034 | 0,038 | <0.003 | 0,019 | 15,399 | 52,298 | 0,036 | <0.002 | 0,006 | 0,048 | 0,468 | 0,074 | 0,006 | 0,408 |
| NW005 | 0,049 | 0,052 | <0.003 | 0,041 | 16,609 | 61,349 | 0,049 | <0.002 | 0,006 | 0,113 | 0,700 | 0,077 | 0,011 | 0,281 |
| NR005 | 0,132 | 0,059 | <0.003 | 0,056 | 15,537 | 57,262 | <0.007 | <0.002 | 0,003 | 0,181 | 0,601 | 0,120 | 0,007 | 0,350 |
| NW006 | 0,054 | 0,032 | <0.003 | 0,018 | 19,869 | 65,425 | 0,077 | <0.002 | 0,005 | 0,025 | 0,441 | 0,113 | 0,005 | 0,343 |
| NR006 | 0,068 | 0,015 | <0.003 | 0,108 | 4,918 | 18,929 | <0.007 | <0.002 | 0,006 | 0,083 | 0,420 | 0,035 | 0,015 | 0,160 |
| NR007 | 0,098 | 0,034 | <0.003 | 0,075 | 17,487 | 54,460 | <0.007 | <0.002 | 0,002 | 0,171 | 0,249 | 0,099 | 0,025 | 0,474 |
| NW007 | 0,073 | 0,243 | <0.003 | 0,030 | 10,240 | 84,575 | 0,007 | <0.002 | 0,005 | 0,150 | 0,992 | 0,041 | 0,038 | 0,453 |
| NR008 | 0,088 | 0,047 | <0.003 | 0,085 | 8,787 | 44,184 | <0.007 | <0.002 | <0.002 | 0,299 | 0,062 | 0,102 | 0,014 | 0,399 |
| NS001 | 0,122 | 0,148 | <0.003 | 0,030 | 12,604 | 74,534 | 0,096 | <0.002 | 0,005 | 0,366 | 0,946 | 0,070 | 0,011 | 0,406 |
| NR009 | 0,156 | 0,081 | <0.003 | 0,056 | 3,643 | 35,114 | 0,010 | <0.002 | 0,002 | 0,234 | 1,122 | 0,180 | 0,010 | 0,296 |
| NW009 | 0,049 | 0,051 | <0.003 | 0,010 | 14,173 | 71,537 | 0,173 | <0.002 | 0,006 | 0,076 | 0,316 | 0,178 | 0,043 | 0,337 |
| NW010 | 0,000 | 0,078 | <0.003 | <0.01 | 17,885 | 75,397 | 0,134 | <0.002 | 0,006 | 0,107 | 1,947 | 0,136 | 0,005 | 0,289 |
| NS002 | 0,103 | 0,035 | <0.003 | 0,016 | 11,027 | 62,068 | 0,040 | <0.002 | 0,004 | 0,128 | 0,482 | 0,205 | 0,006 | 0,258 |
| NW011 | 0,069 | 0,046 | <0.003 | <0.01 | 13,794 | 84,811 | 0,113 | <0.002 | 0,004 | 0,034 | 3,016 | 0,209 | 0,007 | 0,399 |
| NW012 | 0,113 | 0,063 | <0.003 | 0,018 | 11,849 | 55,680 | 0,094 | <0.002 | 0,008 | 0,066 | 2,627 | 0,165 | 0,007 | 0,485 |
| NW013 | 0,132 | 0,098 | <0.003 | 0,011 | 10,747 | 60,333 | 0,053 | <0.002 | 0,003 | 0,036 | 1,604 | 1,332 | 0,014 | 0,220 |
| NR010 | 0,206 | 0,059 | <0.003 | 0,044 | 7,898 | 43,281 | 0,007 | <0.002 | <0.002 | 0,173 | 0,802 | 0,236 | 0,016 | 0,245 |
| NR011 | 0,191 | 0,050 | <0.003 | 0,055 | <2 | 26,858 | 0,009 | <0.002 | <0.002 | 0,090 | 0,330 | 0,172 | 0,009 | 0,381 |
| NW014 | 0,098 | 0,018 | <0.003 | <0.01 | 10,330 | 47,699 | 0,110 | <0.002 | 0,003 | 0,036 | 2,512 | 0,550 | 0,004 | 0,406 |
| NW015 | 0,108 | 0,248 | <0.003 | 0,026 | 10,746 | 44,535 | 0,014 | <0.002 | 0,002 | 0,323 | 0,133 | 2,001 | 0,008 | 0,716 |
| NW016 | 0,029 | 0,122 | <0.003 | 0,023 | 8,055 | 113,250 | 0,298 | <0.002 | 0,032 | 0,042 | 6,219 | 0,125 | 0,020 | 0,206 |
| NW017 | 0,059 | 0,031 | <0.003 | 0,011 | 12,528 | 42,741 | 0,036 | <0.002 | 0,005 | 0,043 | 0,318 | 0,055 | 0,005 | 1,005 |
| NW018 | 0,133 | 0,217 | <0.003 | <0.01 | 13,875 | 74,824 | 0,038 | <0.002 | 0,014 | 2,049 | 1,509 | 0,530 | 0,011 | 0,457 |
| NW019 | 0,177 | 0,175 | <0.003 | 0,022 | 6,005 | 31,308 | 0,022 | <0.002 | 0,010 | 0,260 | 0,477 | 0,300 | 0,023 | 0,544 |
| NR012 | 0,172 | 0,207 | <0.003 | 0,033 | 7,414 | 52,965 | 0,017 | <0.002 | 0,006 | 0,617 | 0,938 | 0,229 | 0,010 | 0,570 |
| NB001 | 0,084 | 0,033 | <0.003 | <0.01 | 2,998 | 53,800 | 0,146 | <0.002 | 0,006 | 0,046 | 0,822 | 1,172 | 0,014 | 0,242 |

# Appendix 3 (Continued)

| Ref. code | Ga | Hf | In | Li | Mn | Mo | Nb | Nd | Ni | Pb | Pr | Rb | Sb | Sn |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Douka Longo watershed** | | | | | | | | | | | | | | |
| GW001 | 32,563 | 0,159 | 0,026 | 22,166 | 626,811 | <0.02 | <0.004 | 552,413 | 72,682 | 56,304 | 97,117 | 83,497 | 0,066 | 0,025 |
| GW002 | 40,329 | 0,159 | 0,026 | 21,004 | 378,308 | 0,048 | <0.004 | 658,209 | 44,519 | 29,730 | 119,478 | 64,946 | 0,029 | 0,117 |
| GS001 | 0,050 | <0.002 | 0,026 | 4,170 | 43,657 | 0,022 | <0.004 | 0,275 | 4,345 | 0,129 | 0,067 | 40,170 | 0,010 | <0.02 |
| GR001 | 0,232 | 0,003 | 0,027 | 0,812 | 62,654 | 0,040 | 0,038 | 1,846 | 1,039 | 0,530 | 0,418 | 8,339 | 0,013 | <0.02 |
| GW003 | 0,358 | 0,020 | 0,028 | 1,011 | 9,112 | <0.02 | 0,140 | 1,346 | 1,111 | 0,369 | 0,346 | 18,086 | 0,016 | 0,022 |
| GW004 | 0,125 | 0,020 | 0,026 | 3,487 | 42,242 | <0.02 | 0,032 | 0,666 | 3,311 | 0,540 | 0,171 | 26,085 | 0,007 | 0,025 |
| GS002 | 0,830 | 0,034 | 0,026 | 3,518 | 46,777 | <0.02 | 0,216 | 4,543 | 2,948 | 1,761 | 1,174 | 21,497 | 0,006 | 0,222 |
| GR002 | 0,236 | 0,022 | 0,027 | 0,751 | 41,019 | 0,044 | 0,113 | 0,778 | 0,963 | 0,447 | 0,207 | 8,466 | 0,011 | <0.02 |
| GW005 | 0,747 | 0,036 | 0,026 | 1,050 | 6,626 | <0.02 | 0,187 | 6,820 | 1,553 | 0,568 | 1,660 | 13,118 | 0,008 | 0,049 |
| GW006 | 0,081 | <0.002 | 0,026 | 8,068 | 62,206 | <0.02 | <0.004 | 0,711 | 6,958 | 2,485 | 0,203 | 41,578 | 0,018 | <0.02 |
| GB001 | 0,029 | <0.002 | 0,027 | 4,148 | 46,119 | <0.02 | <0.004 | 0,180 | 1,280 | 0,554 | 0,045 | 60,916 | <0.005 | <0.02 |
| GS003 | 0,796 | 0,026 | 0,027 | 0,921 | 22,015 | <0.02 | 0,160 | 5,924 | 2,045 | 0,946 | 1,541 | 7,781 | 0,005 | 0,039 |
| GR004 | 0,047 | <0.002 | 0,026 | 0,970 | 261,951 | 0,048 | <0.004 | 0,408 | 0,652 | 0,138 | 0,096 | 13,026 | 0,007 | <0.02 |
| GR005 | 0,154 | 0,006 | 0,027 | 0,744 | 77,845 | 0,045 | 0,041 | 0,769 | 1,186 | 0,457 | 0,190 | 8,790 | 0,014 | <0.02 |
| GW007 | 0,146 | 0,007 | 0,026 | 3,867 | 141,811 | <0.02 | <0.004 | 1,659 | 9,087 | 0,310 | 0,368 | 44,441 | 0,018 | <0.02 |
| GW008 | 0,121 | <0.002 | 0,026 | 4,515 | 55,083 | 0,035 | 0,012 | 1,142 | 6,184 | 0,256 | 0,279 | 32,174 | 0,015 | <0.02 |
| GR006 | 0,206 | 0,007 | 0,026 | 0,452 | 1755,128 | 0,260 | 0,079 | 1,102 | 3,078 | 0,758 | 0,282 | 8,108 | 0,038 | <0.02 |
| GR007 | 0,075 | 0,005 | 0,027 | 0,513 | 66,100 | 0,048 | 0,014 | 0,304 | 0,933 | 0,176 | 0,079 | 7,196 | 0,014 | <0.02 |
| GW009 | 0,034 | <0.002 | 0,026 | 3,277 | 37,084 | <0.02 | <0.004 | 0,332 | 7,805 | 0,073 | 0,069 | 43,221 | <0.005 | <0.02 |
| GW010 | 0,062 | 0,005 | 0,026 | 0,838 | 16,731 | <0.02 | 0,020 | 0,807 | 2,318 | 0,215 | 0,189 | 26,162 | 0,011 | <0.02 |
| GW011 | 0,039 | <0.002 | 0,027 | 0,922 | 21,154 | <0.02 | <0.004 | 0,515 | 3,265 | 0,135 | 0,130 | 33,239 | 0,011 | <0.02 |
| GW012 | 0,028 | <0.002 | 0,026 | 2,441 | 30,579 | <0.02 | <0.004 | 0,214 | 1,764 | 0,101 | 0,042 | 19,272 | <0.005 | <0.02 |
| GW013 | 0,121 | 0,004 | 0,026 | 3,730 | 49,575 | <0.02 | 0,013 | 1,300 | 6,859 | 4,080 | 0,330 | 30,265 | 0,158 | <0.02 |
| GW014 | 0,039 | <0.002 | 0,027 | 1,902 | 14,887 | <0.02 | <0.004 | 0,539 | 4,478 | 0,354 | 0,138 | 22,055 | 0,012 | <0.02 |
| GR008 | 0,094 | 0,005 | 0,026 | 1,204 | 35,459 | <0.02 | <0.004 | 0,949 | 1,178 | 0,536 | 0,242 | 15,467 | 0,006 | <0.02 |
| **Bidou watershed** | | | | | | | | | | | | | | |
| NW001 | 0,008 | <0.002 | 0,026 | 0,308 | 5,098 | <0.02 | <0.004 | 0,050 | 0,315 | 0,028 | 0,018 | 0,572 | 0,007 | <0.02 |
| NR001 | 0,006 | <0.002 | 0,026 | 0,149 | 24,392 | <0.02 | <0.004 | 0,025 | 0,291 | <0.02 | 0,005 | 0,205 | <0.005 | <0.02 |
| NR002 | 0,019 | <0.002 | 0,027 | 0,125 | 28,649 | <0.02 | <0.004 | 0,037 | 2,048 | 0,030 | 0,009 | 1,138 | <0.005 | <0.02 |
| NW002 | 0,023 | <0.002 | 0,027 | 0,325 | 406,570 | <0.02 | <0.004 | 0,092 | 0,582 | 0,043 | 0,024 | 4,083 | 0,014 | <0.02 |
| NL001 | 0,019 | <0.002 | 0,026 | 0,213 | 40,280 | <0.02 | <0.004 | 0,045 | 0,552 | 0,146 | 0,009 | 0,112 | 0,011 | <0.02 |
| NW003 | 0,003 | <0.002 | 0,026 | 0,460 | 4,939 | <0.02 | <0.004 | 0,051 | 5,891 | 0,057 | 0,013 | 0,379 | <0.005 | <0.02 |
| NR003 | 0,020 | <0.002 | 0,026 | <0.1 | 94,113 | <0.02 | <0.004 | 0,086 | 0,505 | 0,082 | 0,020 | 3,449 | 0,008 | <0.02 |
| NR004 | 0,013 | <0.002 | 0,026 | 0,168 | 29,997 | <0.02 | <0.004 | 0,030 | <0.2 | <0.02 | 0,004 | 1,522 | <0.005 | <0.02 |
| NW004 | <0.002 | <0.002 | 0,026 | 0,292 | 13,461 | <0.02 | <0.004 | 0,056 | 3,361 | 0,049 | 0,011 | 0,749 | 0,009 | <0.02 |
| NW005 | 0,010 | 0,003 | 0,027 | 0,302 | 35,512 | <0.02 | <0.004 | 0,091 | 0,850 | 0,054 | 0,018 | 1,988 | 0,009 | <0.02 |
| NR005 | 0,032 | <0.002 | 0,027 | 0,210 | 55,900 | <0.02 | <0.004 | 0,068 | 0,423 | 0,040 | 0,019 | 1,399 | <0.005 | <0.02 |
| NW006 | <0.002 | <0.002 | 0,027 | 0,602 | 25,795 | <0.02 | <0.004 | 0,005 | 0,302 | 0,035 | 0,002 | 0,505 | 0,017 | <0.02 |
| NR006 | 0,010 | <0.002 | 0,026 | 0,184 | 41,178 | <0.02 | <0.004 | 0,020 | 0,202 | <0.02 | 0,006 | 1,816 | <0.005 | <0.02 |
| NR007 | 0,024 | <0.002 | 0,026 | 0,299 | 33,660 | <0.02 | <0.004 | 0,049 | 1,168 | 0,066 | 0,010 | 3,128 | 0,010 | <0.02 |
| NW007 | 0,015 | <0.002 | 0,026 | 0,253 | 28,660 | 0,056 | <0.004 | 0,229 | 0,335 | 0,036 | 0,053 | 2,264 | 0,005 | <0.02 |
| NR008 | 0,024 | <0.002 | 0,026 | 0,154 | 12,926 | <0.02 | <0.004 | 0,074 | 0,899 | 0,074 | 0,018 | 4,012 | <0.005 | <0.02 |
| NS001 | 0,025 | <0.002 | 0,026 | 0,386 | 33,032 | <0.02 | <0.004 | 0,205 | 0,310 | 0,048 | 0,041 | 2,499 | 0,008 | <0.02 |
| NR009 | 0,027 | <0.002 | 0,026 | 0,150 | 119,877 | <0.02 | <0.004 | 0,101 | 0,393 | 0,028 | 0,022 | 3,616 | 0,006 | <0.02 |
| NW009 | 0,016 | <0.002 | 0,026 | 1,116 | 14,387 | <0.02 | <0.004 | 0,044 | 0,385 | 0,026 | 0,011 | 1,540 | <0.005 | <0.02 |
| NW010 | 0,009 | <0.002 | 0,026 | 0,531 | 17,555 | <0.02 | <0.004 | 0,093 | 0,936 | 0,047 | 0,018 | 0,428 | <0.005 | <0.02 |
| NS002 | 0,014 | <0.002 | 0,026 | 0,342 | 4,714 | <0.02 | <0.004 | 0,030 | 0,231 | 0,037 | 0,009 | 0,680 | <0.005 | <0.02 |
| NW011 | 0,009 | <0.002 | 0,027 | 0,568 | 17,948 | <0.02 | <0.004 | 0,023 | 2,175 | 0,040 | 0,009 | 0,680 | <0.005 | <0.02 |
| NW012 | 0,016 | 0,004 | 0,026 | 0,537 | 26,138 | <0.02 | <0.004 | 0,056 | 0,867 | 0,037 | 0,012 | 0,644 | 0,018 | <0.02 |
| NW013 | 0,009 | <0.002 | 0,026 | 0,271 | 2,114 | <0.02 | <0.004 | 0,040 | 1,800 | 0,020 | 0,009 | 1,381 | <0.005 | <0.02 |
| NR010 | 0,020 | <0.002 | 0,026 | 0,165 | 42,747 | <0.02 | <0.004 | 0,054 | 0,529 | 0,031 | 0,016 | 2,581 | 0,008 | <0.02 |
| NR011 | 0,018 | <0.002 | 0,026 | 0,223 | 24,671 | 0,068 | <0.004 | 0,046 | 0,361 | 0,051 | 0,009 | 3,649 | 0,009 | <0.02 |
| NW014 | 0,005 | <0.002 | 0,026 | 1,031 | 7,340 | <0.02 | <0.004 | 0,026 | 2,517 | 0,021 | 0,006 | 0,396 | 0,005 | <0.02 |
| NW015 | 0,039 | <0.002 | 0,026 | 0,241 | 2,032 | <0.02 | <0.004 | 0,161 | 0,847 | 0,053 | 0,030 | 0,897 | 0,005 | <0.02 |
| NW016 | 0,003 | <0.002 | 0,026 | 0,894 | 172,368 | <0.02 | <0.004 | 0,026 | 0,228 | 0,069 | 0,005 | 0,787 | <0.005 | <0.02 |
| NW017 | 0,004 | <0.002 | 0,027 | 0,372 | 52,870 | <0.02 | <0.004 | 0,018 | 0,322 | 0,047 | 0,003 | 0,712 | 0,007 | <0.02 |
| NW018 | 0,024 | <0.002 | 0,027 | 0,639 | 19,159 | <0.02 | <0.004 | 0,079 | 1,112 | 0,067 | 0,026 | 1,648 | <0.005 | <0.02 |
| NW019 | 0,037 | <0.002 | 0,026 | 0,396 | 22,795 | <0.02 | <0.004 | 0,092 | 0,257 | 0,046 | 0,019 | 3,669 | <0.005 | <0.02 |
| NR012 | 0,044 | <0.002 | 0,026 | 0,108 | 83,183 | <0.02 | <0.004 | 0,180 | 0,653 | 0,049 | 0,048 | 2,242 | <0.005 | <0.02 |
| NB001 | 0,010 | <0.002 | 0,026 | 0,699 | 2,683 | <0.02 | <0.004 | 0,019 | 1,391 | 0,260 | 0,006 | 1,810 | <0.005 | <0.02 |

**Appendix 4**: Trace element data of groundwater and surface water sampled during the dry season in the Bidou and Douka Longo watersheds

| ID | Sc | Y | Ag | Ag | B | Ba | Be | Bi | Cd | Ce | Co | Cr | Cs | Cu |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Bidou watershed** | | | | | | | | | | | | | | |
| AW01 | 0.100 | 0.036 | <0.003 | <0.003 | 8.01 | 38.7 | 0.052 | <0.002 | 0.005 | 0.097 | 0.715 | 0.148 | <0.003 | 0.338 |
| AW02 | 0.105 | 0.035 | <0.003 | <0.003 | 6.47 | 49.3 | 0.012 | <0.002 | 0.016 | 0.030 | 4.58 | 0.518 | 0.039 | 0.282 |
| AR03 | 0.075 | 0.099 | <0.003 | <0.003 | 3.77 | 27.9 | <0.007 | <0.002 | 0.010 | 0.284 | 0.233 | 0.171 | 0.011 | 0.259 |
| AR04 | 0.105 | 0.107 | <0.003 | <0.003 | 9.40 | 83.3 | <0.007 | <0.002 | 0.008 | 0.504 | 0.242 | 0.326 | 0.011 | 0.503 |
| AR05 | 0.105 | 0.071 | <0.003 | <0.003 | 16.4 | 76.1 | <0.007 | <0.002 | 0.006 | 0.252 | 0.295 | 0.270 | <0.003 | 0.282 |
| AW06 | 0.050 | 0.055 | <0.003 | <0.003 | 8.75 | 50.0 | 0.050 | 0.005 | 0.014 | 0.056 | 1.39 | 0.517 | 0.015 | 0.698 |
| AR07 | 0.050 | 0.044 | <0.003 | <0.003 | 7.68 | 36.7 | <0.007 | <0.002 | 0.004 | 0.139 | 0.615 | 0.154 | 0.009 | 0.326 |
| AR08 | 0.171 | 0.037 | <0.003 | <0.003 | 15.1 | 75.1 | <0.007 | 0.002 | 0.007 | 0.096 | 0.546 | 0.208 | 0.005 | 0.273 |
| AW09 | 0.105 | 0.148 | <0.003 | <0.003 | 13.8 | 69.5 | 0.039 | 0.006 | 0.015 | 0.292 | 1.83 | 0.925 | 0.009 | 0.478 |
| AD10 | 0.050 | 0.017 | <0.003 | <0.003 | 11.2 | 57.1 | <0.007 | <0.002 | 0.005 | 0.053 | 0.487 | 0.139 | <0.003 | 0.213 |
| AW11 | 0.045 | 0.056 | <0.003 | <0.003 | 22.1 | 67.5 | 0.122 | 0.002 | 0.007 | 0.072 | 1.11 | 0.192 | <0.003 | 0.347 |
| AD12 | 0.101 | 0.028 | <0.003 | <0.003 | 8.88 | 59.6 | <0.007 | <0.002 | <0.002 | 0.058 | 0.795 | 0.150 | 0.004 | 0.163 |
| AW13 | 0.151 | 0.050 | <0.003 | <0.003 | 43.6 | 78.1 | 0.015 | 0.002 | 0.006 | 0.118 | 0.366 | 0.675 | 0.012 | 0.566 |
| AS14 | 0.116 | 0.036 | <0.003 | <0.003 | 14.8 | 68.3 | 0.029 | 0.003 | 0.007 | 0.077 | 0.419 | 0.279 | <0.003 | 0.302 |
| AW15 | 0.055 | 0.030 | <0.003 | <0.003 | 13.8 | 72.2 | 0.034 | 0.002 | 0.009 | 0.048 | 1.97 | 0.317 | 0.025 | 0.238 |
| AR16 | 0.080 | 0.013 | <0.003 | <0.003 | 20.6 | 99.9 | <0.007 | <0.002 | 0.003 | 0.031 | 2.07 | 0.187 | 0.008 | 0.096 |
| AW17 | <0.02 | 0.026 | <0.003 | <0.003 | 18.4 | 98.8 | 0.043 | 0.002 | 0.019 | 0.043 | 2.17 | 4.84 | 0.007 | 0.557 |
| AR18 | 0.131 | 0.043 | <0.003 | <0.003 | 4.96 | 51.7 | <0.007 | 0.002 | 0.004 | 0.125 | 0.449 | 0.148 | 0.014 | 0.136 |
| AW19 | 0.091 | 0.069 | <0.003 | <0.003 | 18.7 | 94.8 | 0.062 | 0.002 | 0.010 | 0.131 | 1.25 | 0.352 | <0.003 | 0.493 |
| AR20 | 0.080 | 0.075 | <0.003 | <0.003 | 5.29 | 47.5 | <0.007 | 0.005 | 0.009 | 0.249 | 0.137 | 0.151 | 0.011 | 0.187 |
| AW21 | 0.060 | 0.096 | <0.003 | <0.003 | 17.0 | 70.3 | 0.052 | 0.004 | 0.013 | 0.208 | 0.552 | 0.152 | 0.010 | 0.260 |
| AW22 | 0.040 | 0.076 | <0.003 | <0.003 | 13.3 | 73.2 | 0.038 | 0.004 | 0.016 | 0.099 | 2.61 | 0.364 | 0.014 | 0.302 |
| AW23 | 0.131 | 0.329 | <0.003 | <0.003 | 9.50 | 199 | 0.059 | 0.004 | 0.015 | 0.385 | 4.75 | 0.169 | 0.121 | 0.377 |
| AR24 | 0.106 | 0.098 | <0.003 | <0.003 | 5.57 | 46.4 | <0.007 | <0.002 | 0.006 | 0.359 | 0.315 | 0.181 | 0.007 | 0.261 |
| AW25 | 0.106 | 0.121 | <0.003 | <0.003 | 8.01 | 62.2 | 0.088 | 0.007 | 0.015 | 0.145 | 0.264 | 0.171 | 0.012 | 0.364 |
| AW26 | 0.342 | 0.131 | <0.003 | <0.003 | 8.24 | 48.6 | <0.007 | 0.003 | 0.011 | 0.312 | 0.865 | 1.65 | 0.015 | 0.505 |
| AW27 | 0.054 | 0.100 | <0.003 | <0.003 | 16.3 | 218 | 0.244 | 0.005 | 0.036 | 0.110 | 9.10 | 0.161 | 0.031 | 0.539 |
| AW28 | 0.099 | 0.118 | 0.007 | 0.007 | 17.7 | 339 | 0.013 | <0.002 | 0.012 | 0.185 | 50.7 | 0.158 | 0.040 | 0.290 |
| AR29 | 0.306 | 0.118 | <0.003 | <0.003 | 5.87 | 81.5 | <0.007 | <0.002 | 0.006 | 0.249 | 1.95 | 0.199 | 0.022 | 0.626 |
| **Douka Longo watershed** | | | | | | | | | | | | | | |
| NR51 | 0.512 | 0.308 | <0.003 | <0.003 | 6.84 | 156 | 0.050 | 0.005 | 0.005 | 1.14 | 1.33 | 0.856 | 0.031 | 0.588 |
| NW52 | 0.172 | 29.9 | <0.003 | <0.003 | 20.5 | 2864 | 5.11 | 0.005 | 0.784 | 12.6 | 61.3 | 0.287 | 0.745 | 9.85 |
| NW53 | 0.425 | 0.537 | <0.003 | <0.003 | 20.2 | 356 | 0.533 | 0.007 | 0.026 | 1.70 | 4.57 | 0.860 | 0.223 | 0.714 |
| NW54 | 0.967 | 1.82 | <0.003 | <0.003 | 18.5 | 311 | 0.203 | 0.012 | 0.016 | 2.78 | 0.435 | 2.45 | 0.295 | 1.19 |
| NW55 | 0.209 | 0.292 | <0.003 | <0.003 | 8.46 | 501 | 0.288 | <0.002 | 0.030 | 0.096 | 0.882 | 0.176 | 0.066 | 0.411 |
| NW56 | 0.280 | 0.775 | <0.003 | <0.003 | 17.7 | 1654 | 2.51 | <0.002 | 0.009 | 1.76 | 18.3 | 0.152 | 0.400 | 4.56 |
| NB57 | 0.332 | 0.014 | 0.013 | 0.013 | 14.5 | 226 | 0.113 | <0.002 | 0.005 | 0.011 | 0.535 | 0.197 | 0.190 | 4.67 |
| NW58 | 0.303 | 0.375 | <0.003 | <0.003 | 9.30 | 958 | 0.468 | <0.002 | 0.008 | 0.328 | 3.12 | 0.524 | 0.098 | 0.515 |
| NR59 | 0.346 | 0.075 | <0.003 | <0.003 | 32.1 | 329 | <0.007 | <0.002 | 0.002 | 0.269 | 1.72 | 0.210 | 0.003 | 0.270 |
| NW60 | 0.616 | 0.075 | <0.003 | <0.003 | 7.59 | 406 | 0.029 | <0.002 | 0.005 | 0.093 | 0.335 | 0.309 | 0.020 | 0.339 |
| NW61 | 0.261 | 0.327 | <0.003 | <0.003 | 11.9 | 457 | 0.170 | <0.002 | 0.058 | 0.283 | 1.18 | 0.247 | 0.149 | 0.467 |
| NR62 | 0.588 | 3.41 | 0.009 | 0.009 | 16.1 | 329 | 0.420 | <0.002 | 0.009 | 10.0 | 6.72 | 1.06 | 0.084 | 2.21 |
| NR63 | 0.359 | 0.425 | <0.003 | <0.003 | 8.62 | 239 | 0.046 | <0.002 | 0.006 | 1.30 | 1.54 | 0.268 | 0.044 | 0.532 |
| NW64 | 0.373 | 0.539 | <0.003 | <0.003 | 8.86 | 1050 | 0.447 | <0.002 | 0.062 | 0.101 | 0.682 | 0.342 | 0.154 | 0.716 |
| NW65 | 0.796 | 0.028 | <0.003 | <0.003 | 16.7 | 467 | 0.009 | <0.002 | 0.004 | 0.014 | 0.088 | 0.122 | 0.015 | 1.50 |
| NW66 | 0.744 | 0.084 | <0.003 | <0.003 | 13.5 | 559 | 0.040 | <0.002 | 0.004 | 0.160 | 0.306 | 0.779 | 0.044 | 0.614 |
| NW67 | 0.428 | 0.213 | <0.003 | <0.003 | 14.4 | 520 | 0.141 | <0.002 | 0.331 | 0.356 | 0.475 | 1.80 | 0.091 | 0.397 |
| NW68 | 0.409 | 0.048 | <0.003 | <0.003 | 8.96 | 746 | 0.113 | <0.002 | 0.407 | 0.029 | 0.280 | 0.465 | 0.166 | 1.22 |
| NR69 | 1.12 | 3.28 | <0.003 | <0.003 | 10.5 | 379 | 0.388 | <0.002 | 0.011 | 13.4 | 11.6 | 1.74 | 0.093 | 1.50 |
| NW70 | 1.26 | 0.566 | <0.003 | <0.003 | 20.8 | 1712 | 0.088 | <0.002 | 0.016 | 1.29 | 0.394 | 1.03 | 0.056 | 1.15 |
| NW71 | 0.603 | 0.049 | <0.003 | <0.003 | 9.14 | 251 | 0.075 | <0.002 | 0.007 | 0.029 | 0.041 | 0.427 | 0.009 | 0.288 |
| NR72 | 0.380 | 0.629 | <0.003 | <0.003 | 13.5 | 160 | 0.116 | <0.002 | 0.011 | 1.33 | 0.985 | 0.888 | 0.027 | 0.901 |
| NB73 | 0.343 | 0.017 | <0.003 | <0.003 | 9.48 | 28.1 | <0.007 | <0.002 | 0.002 | <0.002 | 0.046 | 0.093 | 0.140 | 0.101 |
| NR74 | 0.292 | 0.032 | <0.003 | <0.003 | 48.9 | 481 | <0.007 | <0.002 | <0.002 | 0.008 | 0.399 | 0.336 | <0.003 | 1.29 |
| NR75 | 0.351 | 0.070 | <0.003 | <0.003 | 11.8 | 229 | 0.008 | <0.002 | 0.004 | 0.244 | 0.239 | 0.157 | 0.004 | 0.348 |
| NW76 | 0.273 | 1.95 | <0.003 | <0.003 | 11.5 | 2249 | 0.075 | <0.002 | 0.041 | 0.073 | 1.94 | 0.738 | 0.324 | 0.479 |
| NW77 | 0.346 | 3.07 | <0.003 | <0.003 | 19.4 | 1486 | 0.761 | <0.002 | 0.037 | 1.85 | 18.7 | 0.180 | 0.701 | 1.97 |

# **Appendix 4** (Continued)

| ID | Dy | Ga | Hf | In | Li | Mn | Mo | Nb | Nd | Ni | Pb | Pr | Rb |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Bidou watershed** | | | | | | | | | | | | | |
| AW01 | 0.006 | 0.003 | <0.002 | 0.000 | 0.382 | 19.9 | 0.030 | <0.004 | 0.085 | 0.983 | 0.056 | 0.019 | 0.266 |
| AW02 | 0.001 | 0.005 | <0.002 | 0.000 | 0.826 | 242 | <0.02 | <0.004 | 0.017 | 1.64 | 0.030 | 0.003 | 1.99 |
| AR03 | 0.023 | 0.021 | <0.002 | 0.001 | 0.171 | 32.8 | <0.02 | <0.004 | 0.100 | 0.242 | 0.061 | 0.029 | 1.26 |
| AR04 | 0.019 | 0.069 | 0.007 | 0.000 | 0.139 | 50.2 | 0.023 | 0.024 | 0.170 | 0.367 | 0.155 | 0.052 | 1.04 |
| AR05 | 0.013 | 0.029 | <0.002 | 0.000 | 0.202 | 32.6 | <0.02 | <0.004 | 0.108 | 0.354 | 0.055 | 0.026 | 0.308 |
| AW06 | 0.009 | 0.005 | <0.002 | 0.000 | 0.410 | 64.0 | <0.02 | <0.004 | 0.053 | 2.35 | 0.059 | 0.011 | 0.474 |
| AR07 | 0.012 | 0.024 | <0.002 | 0.001 | 0.209 | 62.0 | <0.02 | <0.004 | 0.055 | 0.447 | 0.064 | 0.012 | 0.783 |
| AR08 | 0.006 | 0.017 | <0.002 | 0.000 | 0.222 | 27.0 | <0.02 | <0.004 | 0.049 | 0.397 | 0.044 | 0.010 | 0.120 |
| AW09 | 0.036 | 0.036 | 0.020 | 0.002 | 0.510 | 41.7 | <0.02 | 0.005 | 0.174 | 3.74 | 0.145 | 0.038 | 1.18 |
| AD10 | 0.003 | 0.015 | <0.002 | 0.000 | 0.186 | 36.2 | <0.02 | <0.004 | 0.017 | 0.433 | 0.088 | 0.006 | 0.251 |
| AW11 | 0.020 | 0.009 | <0.002 | 0.000 | 0.429 | 20.4 | <0.02 | <0.004 | 0.060 | 0.374 | 0.032 | 0.020 | 0.260 |
| AD12 | 0.006 | 0.007 | <0.002 | 0.001 | 0.140 | 43.6 | <0.02 | <0.004 | 0.030 | 0.293 | 0.020 | 0.007 | 1.25 |
| AW13 | 0.008 | 0.009 | <0.002 | 0.000 | 0.677 | 23.8 | 0.027 | <0.004 | 0.049 | 1.13 | 0.050 | 0.013 | 0.862 |
| AS14 | 0.006 | 0.008 | <0.002 | 0.000 | 0.375 | 5.99 | <0.02 | <0.004 | 0.032 | <0.2 | <0.02 | 0.010 | 0.280 |
| AW15 | 0.004 | 0.005 | <0.002 | 0.000 | 0.501 | 98.4 | <0.02 | <0.004 | 0.032 | 4.99 | <0.02 | 0.010 | 1.77 |
| AR16 | <0.001 | 0.005 | <0.002 | 0.000 | <0.1 | 202 | <0.02 | <0.004 | 0.013 | 0.743 | <0.02 | 0.003 | 1.70 |
| AW17 | 0.007 | 0.012 | <0.002 | 0.000 | 1.33 | 73.3 | <0.02 | <0.004 | 0.035 | 19.7 | 0.024 | 0.007 | 0.480 |
| AR18 | 0.007 | 0.015 | <0.002 | 0.000 | 0.159 | 93.2 | <0.02 | <0.004 | 0.059 | 0.432 | 0.024 | 0.011 | 1.03 |
| AW19 | 0.015 | 0.026 | <0.002 | 0.000 | 0.547 | 12.0 | <0.02 | 0.004 | 0.091 | 1.27 | 0.050 | 0.019 | 0.338 |
| AR20 | 0.016 | 0.022 | <0.002 | 0.000 | 0.134 | 14.2 | <0.02 | <0.004 | 0.102 | <0.2 | 0.028 | 0.024 | 0.275 |
| AW21 | 0.014 | 0.017 | 0.002 | 0.000 | 0.467 | 19.9 | <0.02 | 0.006 | 0.080 | 0.938 | 0.156 | 0.023 | 0.424 |
| AW22 | 0.019 | 0.017 | <0.002 | 0.000 | 0.461 | 152 | <0.02 | <0.004 | 0.068 | 3.11 | 0.032 | 0.018 | 1.29 |
| AW23 | 0.028 | 0.030 | <0.002 | 0.001 | 0.341 | 667 | <0.02 | <0.004 | 0.160 | 0.619 | 0.064 | 0.031 | 4.88 |
| AR24 | 0.018 | 0.032 | 0.005 | 0.000 | 0.168 | 39.9 | <0.02 | <0.004 | 0.120 | <0.2 | 0.041 | 0.033 | 0.526 |
| AW25 | 0.025 | 0.013 | 0.005 | 0.000 | 1.02 | 27.3 | <0.02 | 0.005 | 0.097 | 0.328 | 0.054 | 0.027 | 1.60 |
| AW26 | 0.018 | 0.039 | 0.003 | 0.001 | 0.144 | 111 | 0.079 | 0.009 | 0.135 | 0.581 | 0.138 | 0.034 | 3.11 |
| AW27 | 0.007 | 0.011 | 0.002 | 0.000 | 0.949 | 296 | <0.02 | <0.004 | 0.060 | 0.802 | 0.038 | 0.013 | 0.756 |
| AW28 | 0.016 | 0.044 | <0.002 | 0.000 | 0.507 | 3574 | <0.02 | <0.004 | 0.099 | 8.26 | 0.056 | 0.022 | 2.42 |
| AR29 | 0.017 | 0.018 | <0.002 | 0.000 | <0.1 | 171 | 0.049 | 0.008 | 0.103 | 0.747 | 0.067 | 0.020 | 4.96 |
| **Douka Longo watershed** | | | | | | | | | | | | | |
| NW52 | 7.28 | 2.88 | 0.015 | 0.000 | 9.42 | 343 | 0.029 | <0.004 | 44.2 | 31.0 | 10.7 | 6.62 | 53.1 |
| NW53 | 0.111 | 0.351 | 0.032 | 0.004 | 3.91 | 46.8 | 0.036 | 0.205 | 0.917 | 2.96 | 0.464 | 0.225 | 28.3 |
| NW54 | 0.360 | 1.34 | 0.099 | 0.004 | 1.89 | 18.8 | 0.131 | 0.597 | 3.01 | 2.13 | 0.862 | 0.716 | 21.9 |
| NW55 | 0.042 | 0.032 | <0.002 | 0.000 | 2.19 | 11.3 | 0.026 | <0.004 | 0.311 | 2.43 | 0.053 | 0.062 | 22.4 |
| NW56 | 0.148 | 0.135 | <0.002 | 0.001 | 8.69 | 74.8 | <0.02 | <0.004 | 1.13 | 7.92 | 2.46 | 0.273 | 45.6 |
| NB57 | 0.002 | 0.005 | <0.002 | 0.000 | 1.98 | 2.62 | <0.02 | <0.004 | 0.010 | 1.17 | 0.049 | 0.003 | 20.9 |
| NW58 | 0.058 | 0.042 | <0.002 | 0.000 | 3.53 | 38.0 | <0.02 | <0.004 | 0.413 | 8.04 | 0.110 | 0.101 | 46.0 |
| NR59 | 0.018 | 0.021 | <0.002 | 0.000 | 0.369 | 983 | 0.195 | <0.004 | 0.138 | 2.22 | 0.081 | 0.023 | 6.71 |
| NW60 | 0.012 | 0.009 | <0.002 | 0.000 | 3.21 | 24.9 | 0.094 | <0.004 | 0.073 | 0.817 | 0.052 | 0.022 | 5.93 |
| NW61 | 0.071 | 0.041 | <0.002 | 0.002 | 2.54 | 62.9 | <0.02 | <0.004 | 0.455 | 5.55 | 0.134 | 0.110 | 32.9 |
| NR62 | 0.681 | 0.900 | 0.019 | 0.004 | 1.19 | 632 | 0.025 | 0.163 | 5.12 | 4.06 | 1.02 | 1.32 | 11.0 |
| NR63 | 0.091 | 0.080 | <0.002 | 0.000 | 1.37 | 237 | 0.039 | <0.004 | 0.785 | 1.53 | 0.357 | 0.203 | 20.5 |

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| NW64 | 0.073 | 0.036 | <0.002 | 0.001 | 3.69 | 14.0 | <0.02 | <0.004 | 0.415 | 8.12 | 0.077 | 0.111 | 42.9 |
| NW65 | 0.002 | 0.008 | <0.002 | 0.000 | 5.60 | 2.32 | 0.150 | <0.004 | 0.025 | 1.26 | <0.02 | 0.005 | 13.0 |
| NW66 | 0.015 | 0.012 | <0.002 | 0.000 | 5.16 | 18.3 | 0.056 | <0.004 | 0.088 | 0.452 | 0.100 | 0.019 | 25.2 |
| NW67 | 0.039 | 0.035 | <0.002 | 0.000 | 1.31 | 12.2 | <0.02 | <0.004 | 0.241 | 1.40 | 0.134 | 0.066 | 22.7 |
| NW68 | 0.006 | <0.002 | <0.002 | 0.000 | 3.14 | 10.9 | 0.038 | <0.004 | 0.030 | 2.11 | 0.045 | 0.006 | 32.3 |
| NR69 | 0.683 | 0.832 | 0.017 | 0.002 | 0.769 | 1016 | 0.058 | 0.089 | 4.89 | 2.74 | 1.45 | 1.26 | 13.4 |
| NW70 | 0.095 | 0.373 | 0.023 | 0.002 | 4.12 | 46.9 | 0.068 | 0.120 | 0.622 | 1.06 | 0.594 | 0.136 | 8.64 |
| NW71 | 0.007 | 0.007 | <0.002 | 0.000 | 5.93 | 2.63 | 0.080 | <0.004 | 0.027 | 0.345 | 0.039 | 0.008 | 5.92 |
| NR72 | 0.113 | 0.224 | 0.012 | 0.000 | 0.670 | 95.9 | <0.02 | 0.063 | 0.737 | 1.12 | 0.330 | 0.178 | 3.06 |
| NB73 | <0.001 | 0.007 | <0.002 | 0.001 | 12.8 | 0.137 | 18.5 | <0.004 | <0.002 | <0.2 | <0.02 | <0.001 | 2.75 |
| NR74 | 0.002 | 0.012 | <0.002 | 0.000 | 0.337 | 4.46 | 0.812 | 0.005 | 0.017 | 0.471 | <0.02 | 0.002 | 3.24 |
| NR75 | 0.009 | 0.020 | <0.002 | -0.001 | 0.352 | 126 | 0.138 | <0.004 | 0.071 | 0.433 | 0.048 | 0.018 | 1.76 |
| NW76 | 0.141 | 0.027 | <0.002 | 0.002 | 1.29 | 18.2 | 0.020 | <0.004 | 0.512 | 3.70 | 0.055 | 0.087 | 59.3 |
| NW77 | 0.412 | 0.174 | <0.002 | 0.000 | 6.40 | 986 | 0.054 | <0.004 | 2.39 | 13.1 | 1.16 | 0.563 | 60.3 |

## **Appendix 4** (Continued)

| ID | Sr | Ta | Tb | Te | Th | Ti | Tl | Tm | U | V | W | Zn | Zr |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| AW01 | 11.0 | <0.001 | 0.001 | 0.023 | <0.004 | <0.04 | 0.007 | <0.001 | 0.011 | 0.032 | <0.05 | 39.3 | <0.005 |
| AW02 | 28.3 | <0.001 | <0.001 | 0.034 | <0.004 | 0.151 | 0.009 | <0.001 | 0.003 | 0.043 | <0.05 | 31.8 | 0.011 |
| AR03 | 31.9 | <0.001 | 0.002 | 0.011 | 0.009 | 0.241 | 0.011 | <0.001 | 0.012 | 0.097 | <0.05 | 533 | 0.033 |
| AR04 | 26.9 | 0.002 | 0.004 | <0.01 | 0.023 | 4.07 | 0.008 | 0.001 | 0.018 | 0.248 | <0.05 | 222 | 0.253 |
| AR05 | 26.9 | <0.001 | 0.003 | <0.01 | 0.007 | 0.196 | 0.006 | 0.001 | 0.008 | 0.120 | <0.05 | 276 | 0.055 |
| AW06 | 18.3 | <0.001 | 0.001 | 0.011 | <0.004 | 0.121 | 0.010 | <0.001 | 0.009 | 0.032 | <0.05 | 358 | 0.014 |
| AR07 | 24.1 | <0.001 | 0.001 | 0.022 | 0.006 | 0.151 | 0.006 | <0.001 | 0.006 | 0.057 | <0.05 | 274 | 0.026 |
| AR08 | 13.0 | <0.001 | 0.001 | 0.011 | 0.009 | 0.316 | 0.007 | <0.001 | 0.004 | 0.031 | <0.05 | 322 | 0.021 |
| AW09 | 20.7 | <0.001 | 0.006 | 0.022 | 0.011 | 0.376 | 0.011 | 0.002 | 0.038 | 0.192 | <0.05 | 536 | 0.094 |
| AD10 | 16.0 | <0.001 | <0.001 | 0.011 | <0.004 | 0.105 | 0.006 | <0.001 | 0.005 | 0.010 | <0.05 | 145 | 0.016 |
| AW11 | 12.8 | <0.001 | 0.002 | 0.022 | <0.004 | 0.045 | 0.006 | <0.001 | 0.011 | 0.033 | <0.05 | 237 | 0.028 |
| AD12 | 40.7 | <0.001 | <0.001 | 0.033 | <0.004 | 0.150 | 0.005 | <0.001 | 0.004 | 0.044 | <0.05 | 154 | 0.017 |
| AW13 | 22.4 | <0.001 | 0.002 | 0.044 | <0.004 | 0.286 | 0.008 | <0.001 | 0.006 | 0.573 | <0.05 | 195 | 0.043 |
| AS14 | 23.1 | <0.001 | 0.002 | 0.011 | 0.006 | 0.150 | 0.009 | <0.001 | 0.007 | 0.176 | <0.05 | 230 | 0.022 |
| AW15 | 11.0 | <0.001 | 0.001 | <0.01 | <0.004 | 0.165 | 0.015 | <0.001 | 0.013 | 0.038 | <0.05 | 209 | 0.013 |
| AR16 | 34.3 | <0.001 | <0.001 | 0.022 | <0.004 | 0.120 | 0.007 | <0.001 | 0.002 | <0.007 | <0.05 | 51.3 | <0.005 |
| AW17 | 15.1 | <0.001 | <0.001 | 0.011 | <0.004 | 0.195 | 0.005 | <0.001 | 0.005 | 0.041 | <0.05 | 261 | 0.036 |
| AR18 | 28.4 | <0.001 | 0.001 | <0.01 | 0.007 | 0.180 | 0.005 | <0.001 | 0.005 | 0.067 | <0.05 | 235 | 0.024 |
| AW19 | 10.3 | <0.001 | 0.003 | <0.01 | 0.008 | 0.690 | 0.007 | 0.001 | 0.011 | 0.074 | <0.05 | 326 | 0.063 |
| AR20 | 19.7 | <0.001 | 0.004 | <0.01 | 0.015 | 0.120 | 0.006 | 0.001 | 0.009 | 0.074 | <0.05 | 448 | 0.028 |
| AW21 | 13.2 | <0.001 | 0.002 | 0.022 | 0.006 | 0.285 | 0.007 | 0.002 | 0.012 | 0.088 | <0.05 | 440 | 0.049 |
| AW22 | 12.2 | <0.001 | 0.002 | 0.032 | <0.004 | 0.105 | 0.010 | <0.001 | 0.017 | 0.057 | <0.05 | 282 | 0.035 |
| AW23 | 154 | <0.001 | 0.006 | 0.022 | 0.007 | 0.135 | 0.046 | 0.004 | 0.008 | 0.150 | <0.05 | 367 | 0.016 |
| AR24 | 29.3 | <0.001 | 0.004 | <0.01 | 0.015 | 0.165 | 0.007 | 0.001 | 0.010 | 0.211 | <0.05 | 365 | 0.078 |
| AW25 | 18.5 | <0.001 | 0.004 | 0.021 | 0.005 | 0.165 | 0.008 | 0.001 | 0.013 | 0.173 | <0.05 | 540 | 0.075 |
| AW26 | 124 | <0.001 | 0.003 | 0.031 | 0.007 | 1.61 | 0.008 | <0.001 | 0.048 | 4.86 | <0.05 | 463 | 0.087 |
| AW27 | 24.6 | <0.001 | 0.002 | <0.01 | <0.004 | 0.178 | 0.010 | 0.002 | 0.007 | 0.060 | <0.05 | 450 | 0.033 |
| AW28 | 55.3 | <0.001 | 0.004 | <0.01 | 0.021 | 0.444 | 0.089 | 0.001 | 0.008 | 0.055 | <0.05 | 494 | 0.053 |

**Appendix 4** (Continued)

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| AR29 | 148 | <0.001 | 0.004 | <0.01 | 0.019 | 0.251 | 0.013 | <0.001 | 0.018 | 0.216 | <0.05 | 429 | 0.068 |
| NR51 | 89.2 | 0.011 | 0.012 | 0.029 | 0.142 | 32.6 | 0.029 | 0.003 | 0.049 | 1.61 | <0.05 | 183 | 0.930 |
| NW52 | 385 | 0.004 | 1.47 | <0.01 | 0.005 | 0.144 | 0.428 | 0.384 | 9.69 | 0.133 | <0.05 | 533 | 0.017 |
| NW53 | 47.8 | 0.013 | 0.018 | 0.019 | 0.131 | 39.0 | 0.165 | 0.009 | 0.118 | 1.29 | 0.051 | 569 | 1.10 |
| NW54 | 88.5 | 0.042 | 0.061 | 0.029 | 0.483 | 133 | 0.121 | 0.023 | 0.224 | 3.53 | 0.070 | 549 | 3.84 |
| NW55 | 175 | <0.001 | 0.005 | 0.029 | <0.004 | 0.244 | 0.108 | 0.002 | 0.025 | 0.257 | <0.05 | 46.7 | <0.005 |
| NW56 | 205 | <0.001 | 0.026 | 0.039 | <0.004 | 0.387 | 0.361 | 0.007 | 1.32 | 0.110 | <0.05 | 63.5 | <0.005 |
| NB57 | 25.1 | <0.001 | <0.001 | 0.019 | <0.004 | 0.215 | 0.091 | <0.001 | 0.058 | 0.107 | <0.05 | 62.1 | <0.005 |
| NW58 | 339 | <0.001 | 0.010 | 0.019 | <0.004 | 0.401 | 0.177 | 0.004 | 0.031 | 0.251 | <0.05 | 49.7 | 0.005 |
| NR59 | 302 | <0.001 | 0.004 | <0.01 | 0.011 | 0.342 | 0.015 | <0.001 | 0.093 | 0.091 | <0.05 | 76.8 | 0.032 |
| NW60 | 299 | 0.002 | 0.001 | <0.01 | 0.004 | 0.500 | 0.018 | <0.001 | 0.024 | 2.02 | <0.05 | 31.4 | 0.010 |
| NW61 | 110 | <0.001 | 0.011 | 0.028 | 0.005 | 0.800 | 0.172 | 0.004 | 0.033 | 0.243 | <0.05 | 52.5 | 0.020 |
| NR62 | 75.7 | 0.011 | 0.128 | 0.028 | 0.130 | 31.9 | 0.069 | 0.038 | 0.367 | 0.814 | <0.05 | 52.4 | 0.939 |
| NR63 | 76.5 | <0.001 | 0.016 | <0.01 | 0.045 | 0.329 | 0.070 | 0.005 | 0.063 | 0.441 | <0.05 | 36.5 | 0.037 |
| NW64 | 305 | <0.001 | 0.012 | 0.018 | <0.004 | 0.258 | 0.160 | 0.004 | 0.024 | 0.183 | <0.05 | 42.3 | <0.005 |
| NW65 | 465 | <0.001 | <0.001 | <0.01 | <0.004 | 0.531 | 0.031 | <0.001 | 0.068 | 3.55 | <0.05 | 20.4 | 0.010 |
| NW66 | 391 | <0.001 | 0.002 | <0.01 | <0.004 | 0.531 | 0.057 | <0.001 | 0.104 | 3.66 | <0.05 | 33.2 | 0.008 |
| NW67 | 145 | <0.001 | 0.008 | <0.01 | <0.004 | 1.22 | 0.104 | 0.002 | 0.061 | 0.558 | <0.05 | 46.0 | 0.017 |
| NW68 | 553 | <0.001 | <0.001 | 0.018 | <0.004 | 0.187 | 0.176 | <0.001 | 0.018 | 0.890 | <0.05 | 44.2 | <0.005 |
| NR69 | 173 | 0.007 | 0.119 | 0.037 | 0.253 | 20.5 | 0.054 | 0.045 | 0.481 | 4.55 | <0.05 | 33.4 | 0.648 |
| NW70 | 2163 | 0.009 | 0.017 | 0.027 | 0.127 | 31.0 | 0.019 | 0.006 | 0.677 | 3.35 | 0.079 | 31.9 | 0.853 |
| NW71 | 501 | <0.001 | 0.002 | <0.01 | <0.004 | 0.332 | 0.021 | <0.001 | 0.008 | 4.93 | <0.05 | 30.2 | 0.011 |
| NR72 | 117 | 0.004 | 0.020 | 0.018 | 0.039 | 12.4 | 0.013 | 0.008 | 0.072 | 1.63 | <0.05 | 43.0 | 0.360 |
| NB73 | 1207 | 0.003 | <0.001 | 0.018 | <0.004 | 0.376 | 0.004 | <0.001 | 4.28 | 5.04 | 0.097 | <0.7 | 0.009 |
| NR74 | 1173 | 0.003 | <0.001 | 0.036 | <0.004 | 0.290 | 0.011 | <0.001 | 3.56 | 1.43 | <0.05 | <0.7 | 0.013 |
| NR75 | 365 | <0.001 | 0.002 | <0.01 | <0.004 | 0.188 | 0.016 | <0.001 | 0.157 | 1.86 | <0.05 | 40.4 | 0.011 |
| NW76 | 729 | 0.002 | 0.025 | 0.027 | <0.004 | 0.261 | 0.186 | 0.010 | 0.596 | 0.277 | <0.05 | 55.3 | 0.009 |
| NW77 | 475 | <0.001 | 0.069 | 0.027 | <0.004 | 0.334 | 0.579 | 0.028 | 0.072 | 0.639 | <0.05 | 61.6 | 0.005 |

**Appendix 5:** TDS, molar ratio computed to assess ion origin (Na/Cl, Cl/(Cl+$HCO_3$), CAI-1, CAI-2), suitability of water for irrigation (SAR, KR, %Na, PI, RSBC) and consumption (WQI) for the rainy season samples

| ID | TDS | Na/Cl | Cl/ (Cl+HCO3) | CAI1 | CAI2 | WQI | SAR | RSBC | PI | %Na | KR | MAR |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| GW001 | 376,573 | 0,80822134 | 1 | -1,0660302 | -110,2153 | 847.24 | 0,59903268 | -1,23 | 22,2741789 | 42,281915 | 0,28657374 | 43,70020155 |
| GW002 | 451,589 | 0,96467391 | 1 | -1,5513014 | -29,394987 | 541.66 | 1,28764348 | -0,98 | 41,3900914 | 65,1288204 | 0,70619614 | 41,04569986 |
| GS001 | 127,212 | 0,78398896 | 0,63583719 | -0,6508998 | -1006,9368 | 36.84 | 0,40413739 | -0,3967213 | 59,4520456 | 38,195207 | 0,29347826 | 36,71875 |
| GR001 | 71,460 | 3,95013394 | 0,06928982 | -4,9345792 | -34,67961 | 16.55 | 0,41881055 | 0,36736066 | 130,693305 | 35,946695 | 0,37354189 | 31,4273929 |
| GW003 | 60,604 | 1,84782609 | 0,05682347 | -5,2068004 | -21,835508 | 15.67 | 0,14854488 | 0,27493443 | 156,168829 | 33,3948127 | 0,14926716 | 21,44157172 |
| GW004 | 51,127 | 1,41201481 | 0,52643472 | -2,9676243 | -152,8512 | 45.6030949 | 0,56409859 | 0,01332787 | 181,191499 | 78,001155 | 1,2618562 | 32,94757218 |
| GS002 | 66,073 | 1,5106383 | 0,33967182 | -2,0987452 | -41,953833 | 58.5848947 | 0,4768958 | 0,01837705 | 128,194687 | 53,8384622 | 0,568574 | 32,05540672 |
| GR002 | 73,715 | 4,10203682 | 0,07049197 | -4,9881537 | -36,072449 | 15.0934443 | 0,44429772 | 0,36859016 | 126,144314 | 35,966311 | 0,38476361 | 31,60337761 |
| GW005 | 59,342 | 1,32601225 | 0,26179099 | -2,0151479 | -7,2326037 | 38.2221335 | 0,2292124 | -0,1058525 | 105,554785 | 35,464498 | 0,24167629 | 25,07068286 |
| GW006 | 90,387 | 2,86418646 | 0,83057271 | -4,0788309 | -809,77703 | 91.6949731 | 1,29412165 | -0,0901311 | 97,2278997 | 79,1432788 | 2,13995941 | 35,46833506 |
| GB001 | 119,763 | 1,52282972 | 0,34052444 | -3,4453921 | -136,03037 | 40.2980632 | 0,45229506 | 0,06972951 | 91,9802201 | 53,7890078 | 0,39873973 | 60,12940616 |
| GS003 | 52,230 | 3,93242869 | 0,09919007 | -4,613794 | -14,879941 | 33.3294049 | 0,37488848 | 0,11113934 | 133,645902 | 36,5810787 | 0,40405644 | 32,50742173 |
| GR004 | 59,847 | 4,06916996 | 0,04396684 | -7,8687038 | -38,434836 | 11.421146 | 0,24738457 | 0,32377049 | 146,665415 | 34,5948428 | 0,24268618 | 32,63366337 |
| GR005 | 70,865 | 4,10580424 | 0,06761568 | -5,3029749 | -37,248547 | 18.4057401 | 0,4177078 | 0,35502459 | 129,555085 | 36,3228652 | 0,37157736 | 31,39236879 |
| GW007 | 219,507 | 1,07341897 | 0,79080731 | -0,8223117 | -30,331355 | 87.076347 | 0,74942908 | -0,9410656 | 47,7512672 | 41,7477795 | 0,42215068 | 29,87608216 |
| GW008 | 151,412 | 1,04599353 | 0,40144675 | -1,5279812 | -9,9354639 | 52.242731 | 0,50209985 | -0,2368033 | 78,3503461 | 46,0769352 | 0,35356085 | 26,11871773 |
| GR006 | 69,736 | 9,22627105 | 0,02425822 | -14,460904 | -29,807787 | 66.0227972 | 0,36291424 | 0,45833607 | 133,615225 | 34,5882743 | 0,31554741 | 31,73329102 |
| GR007 | 75,886 | 5,30570652 | 0,0564932 | -6,43912 | -45,985736 | 8.64864088 | 0,48366795 | 0,41327869 | 124,866886 | 36,3670948 | 0,40761346 | 30,39691354 |
| GW009 | 182,737 | 0,62104451 | 0,80353872 | -0,4451228 | -13,993067 | 60.6120908 | 0,33601008 | -0,8386066 | 34,5332749 | 30,7622698 | 0,19093851 | 38,32405353 |
| GW010 | 150,973 | 1,07545582 | 0,44290901 | -1,0914194 | -1,9589898 | 38.4710047 | 0,64454092 | -0,1658197 | 79,0711327 | 46,243725 | 0,44235922 | 32,64261761 |
| GW011 | 152,342 | 0,66785117 | 0,53551682 | -0,7619094 | -13,13222 | 46.7158697 | 0,23342406 | -0,6259016 | 43,7127387 | 26,8658526 | 0,13924402 | 37,37113402 |
| GW012 | 48,947 | 2,69099572 | 0,21627672 | -8,1523426 | -245,44446 | 29.8771008 | 0,17780611 | -0,0635328 | 117,581301 | 46,9002362 | 0,25969476 | 37,9236786 |
| GW013 | 75,710 | 1,27560187 | 0,60927827 | -2,7079675 | -52,259844 | 47.39407 | 0,28793056 | -0,1794262 | 71,4609372 | 48,0192523 | 0,31779869 | 40,30681305 |

**Appendix 5** (Continued)

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| GW014 | 111,308 | 0,82045356 | 0,58960855 | -0,8032886 | -62,377479 | 51.0815161 | 0,19721516 | -0,4419672 | 42,5456447 | 23,5013764 | 0,13977466 | 43,74069787 |
| GR008 | 63,170 | 1,37290519 | 0,16440854 | -1,9186236 | -28,169615 | 18.0273566 | 0,28706877 | 0,19614754 | 135,638962 | 37,9078985 | 0,28718107 | 32,94757218 |
| NW001 | 8,384 | 5,32233883 | 0,03559786 | -5,8917464 | -76,917946 | 10.3775368 | 0,09146049 | 0,03102459 | 351,059804 | 23,746159 | 0,24049435 | 20,4865557 |
| NR001 | 9,647 | 25,7246377 | 0,00673711 | -27,758826 | 375,455191 | 16.8621091 | 0,11721094 | 0,07859016 | 413,875482 | 26,1039944 | 0,31598329 | 33,13793516 |
| NR002 | 22,441 | 27,8332145 | 0,00575765 | -32,802109 | -112,42769 | 9.65249475 | 0,13169755 | 0,14572131 | 190,173037 | 18,047027 | 0,18132618 | 42,75037836 |
| NW002 | 95,906 | 1,80861563 | 0,63070092 | -0,8756284 | -198,07198 | 37.8968017 | 1,79908532 | -0,0206475 | 107,352161 | 66,8984898 | 1,94880324 | 32,06227034 |
| NL001 | 12,680 | 4,45623645 | 0,05715361 | -3,4562364 | -593,32203 | 23.9262752 | 0,19510872 | 0,08304918 | 278,929289 | 28,4680908 | 0,39797751 | 21,77933018 |
| NW003 | 5,549 | 16,6862515 | 0,01890174 | -18,146404 | -47,724387 | 27.2598882 | 0,15178888 | 0,03409836 | 572,742701 | 43,1836594 | 0,66239607 | 23,82445141 |
| NR003 | 54,438 | 60,8695652 | 0,00261119 | -71,408027 | -175,00536 | 7.05613627 | 0,21091207 | 0,39143443 | 126,356446 | 17,8533274 | 0,18270174 | 44,09653064 |
| NR004 | 9,949 | 11,673365 | 0,03096064 | -12,968129 | -71,844937 | 10.0769236 | 0,21786501 | 0,05891803 | 350,260138 | 42,053361 | 0,60649928 | 28,70264064 |
| NW004 | 7,985 | 2,28663446 | 0,07911803 | -2,2980305 | -16,357757 | 19.1100377 | 0,09660885 | 0,03202459 | 383,098013 | 27,9028088 | 0,2683315 | 12,82580399 |
| NW005 | 12,469 | 2,55120374 | 0,04030998 | -4,1841768 | -113,92999 | 15.9762324 | 0,07252286 | 0,06629508 | 317,400572 | 23,5047993 | 0,1512125 | 16,53069987 |
| NR005 | 22,131 | 29,3995859 | 0,00614789 | -34,178992 | -170,97286 | 10.1192877 | 0,14817441 | 0,14838525 | 195,839508 | 20,1131636 | 0,21040836 | 44,14534773 |
| NW006 | 7,943 | 7,62211487 | 0,0265658 | -8,8696616 | -80,866945 | 21.2226775 | 0,10229414 | 0,04110656 | 407,632325 | 28,0343928 | 0,30084264 | 26,48158035 |
| NR006 | 11,552 | 9,32302305 | 0,03101106 | -10,155754 | -25,128104 | 12.2655371 | 0,20477189 | 0,08214754 | 357,758034 | 39,0659405 | 0,53579172 | 32,90697019 |
| NR007 | 12,513 | 19,2934783 | 0,02302285 | -24,930765 | -104,27266 | 12.6145536 | 0,29135677 | 0,0732541 | 336,115148 | 52,2303917 | 0,81351733 | 35,2914755 |
| NW007 | 89,529 | 2,28325187 | 0,53837115 | -1,3317271 | -1,1470274 | 14.3814919 | 3,1188591 | 0,25169672 | 129,775927 | 82,0452213 | 4,47454976 | 35,57543262 |
| NR008 | 13,727 | 5,14492754 | 0,07911803 | -6,7123174 | -168,42025 | 10.8286239 | 0,293912 | 0,08336885 | 317,357321 | 53,3907993 | 0,7641685 | 39,83642585 |
| NS001 | 14,960 | 16,8379447 | 0,01689283 | -23,285497 | -230,70542 | 22.1371473 | 0,28070245 | 0,13032787 | 393,196877 | 52,1324484 | 0,75510785 | 27,63549732 |
| NR009 | 56,865 | 57,8804348 | 0,00281474 | -68,25864 | -183,78458 | 6.21470969 | 0,22273779 | 0,41786066 | 125,439719 | 18,5379572 | 0,19017981 | 44,52138016 |
| NW009 | 16,742 | 12,7109974 | 0,08364927 | -14,209741 | -326,45843 | 20.7063369 | 0,54497745 | 0,03818852 | 252,179551 | 66,0574727 | 1,62643086 | 27,85617417 |
| NW010 | 7,589 | 16,6220736 | 0,02184994 | -17,022468 | -299,12251 | 19.3413658 | 0,19416774 | 0,04846721 | 398,043774 | 40,1755451 | 0,61937542 | 31,82446296 |
| NS002 | 14,383 | 112,252964 | 0,00186793 | -127,80308 | -633,4497 | 15.06 | 0,14525767 | 0,09007377 | 295,524869 | 25,8175755 | 0,30330949 | 34,16288375 |
| NW011 | 8,209 | 9,07928389 | 0,01910218 | -10,756509 | -46,994937 | 18.9193254 | 0,09386003 | 0,04986066 | 384,652623 | 24,6967453 | 0,25327901 | 29,3668155 |

**Appendix 5** (Continued)

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| NW012 | 7,791 | 29,8737728 | 0,01144735 | -34,746395 | -485,38754 | 21.5963168 | 0,18747646 | 0,04540984 | 463,95577 | 44,6316999 | 0,67365892 | 22,52922423 |
| NW013 | 21,793 | 6,22728981 | 0,04809949 | -6,014255 | -2821,5496 | 15.66 | 0,19346522 | 0,07694262 | 193,428112 | 25,722597 | 0,3074508 | 41,15611262 |
| NR010 | 54,520 | 66,4281783 | 0,00304121 | -76,950411 | -160,43869 | 1.64 | 0,27383763 | 0,4265082 | 137,127608 | 22,9362076 | 0,25363265 | 48,01276575 |
| NR011 | 76,242 | 88,9462049 | 0,00152448 | -103,37428 | -304,34255 | 0.5532546 | 0,213855 | 0,54852459 | 107,946427 | 15,3632405 | 0,1546884 | 43,49323917 |
| NW014 | 12,825 | 4,39598239 | 0,0979591 | -3,6840382 | 524,816868 | 20.2616871 | 0,19093931 | 0,03146721 | 264,301057 | 33,1718631 | 0,46584992 | 39,87947971 |
| NW015 | 28,138 | 3,40473146 | 0,03830762 | -3,5202418 | -14,752385 | 9.28233769 | 0,10501353 | 0,12852459 | 181,890202 | 15,759597 | 0,14091132 | 42,38292828 |
| NW016 | 16,027 | 19,9874883 | 0,05380793 | -20,95207 | -245,93065 | 22.8518851 | 0,39206137 | 0,01385246 | 215,671786 | 51,8901376 | 0,98204964 | 30,98373354 |
| NW017 | 6,865 | 2,85829308 | 0,10110032 | -3,5439531 | -41,32726 | 28.1820745 | 0,13508823 | 0,02909836 | 494,627138 | 45,4763093 | 0,52465387 | 24,58100559 |
| NW018 | 28,815 | 2,96822742 | 0,15033532 | -2,1432767 | -753,14847 | 21.5562733 | 0,23339886 | -0,0009262 | 135,465699 | 24,9082401 | 0,31323142 | 40,02401441 |
| NW019 | 30,15 | 13,6498077 | 0,01346969 | -21,938138 | -80,434421 | 16.4549813 | 0,16055825 | 0,13377869 | 199,499922 | 27,7050685 | 0,22804457 | 31,61294072 |
| NR012 | 43,54 | 13,025133 | 0,01094517 | -14,713654 | -146,73185 | 10.0247951 | 0,16796054 | 0,30177869 | 138,624853 | 16,3665578 | 0,16221177 | 43,75712493 |
| NB001 | 20,447 | 180,072464 | 0,00068685 | -239,75622 | -5,0252761 | 13.5137598 | 0,09221433 | 0,11940164 | 211,975325 | 15,7382773 | 0,13970008 | 41,93466126 |

**Appendix 6:** TDS, molar ratio computed to assess ion origin (Na/Cl, Cl/(Cl+$HCO_3$), CAI-1, CAI-2), suitability of water for irrigation (SAR, KR, %Na, PI) and consumption (WQI) for the dry season samples

| ID | TDS | Na/Cl | Cl/(Cl+HCO3) | CAI1 | CAI2 | WQI | SAR | RSBC | PI | SSP | KR | MAR |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| AW01 | 13 | 7,7173913 | 0,044765166 | -9,23110504 | -0,0061405 | 23.72741295 | 0,12100884 | -0,00336885 | 247,539 | 25,1403239 | 28,0660148 | 18,7722755 |
| AW02 | 28 | 14,2474916 | 0,008086638 | -19,84723856 | -0,00251915 | 24.7404349 | 0,08198131 | 0,09459016 | 218,7237 | 15,2157466 | 12,8817932 | 35,8057305 |
| AR03 | 23 | 0,68599034 | 0,971114216 | -22,91135048 | -0,29026188 | 5.387690169 | 0,11545788 | -0,0375459 | 71,45534 | 92,7611721 | 38,3252497 | 15,5982189 |
| AR04 | 25 | 13,5575793 | 0,019186956 | -17,24363899 | -0,00516645 | 10.04738286 | 0,2049316 | 0,12311475 | 248,328 | 32,0944213 | 37,1511566 | 40,8439275 |
| AR05 | 22 | 54,4757033 | 0,002555843 | -65,1841234 | -0,00266993 | 14.51260858 | 0,09358854 | 0,09338525 | 252,5839 | 16,7276504 | 16,7877291 | 39,8299811 |
| AW06 | 12 | 10,2898551 | 0,014935118 | -12,31137949 | -0,00278663 | 34.04739823 | 0,06929289 | 0,03010656 | 360,1387 | 18,0489054 | 18,4057676 | 24,5056764 |
| AR07 | 22 | 16,6220736 | 0,010330498 | -20,82142602 | -0,00336855 | 11.85236618 | 0,11660978 | 0,09340984 | 269,5416 | 21,866155 | 22,3393106 | 39,8115145 |
| AR08 | 18 | 40,617849 | 0,004642332 | -45,40813697 | -0,00339204 | 31.08926979 | 0,12311094 | 0,0767541 | 428,6414 | 28,0426105 | 34,8595004 | 39,0655932 |
| AW09 | 14 | 4,40993789 | 0,026609335 | -7,874623609 | -0,0029959 | 30.62 | 0,06258459 | 0,03819672 | 342,264 | 21,1485873 | 15,0145202 | 19,4220748 |
| AD10 | 16 | 35,0790514 | 0,005296142 | -47,49101908 | -0,0039983 | 15.15855008 | 0,10171472 | 0,05639344 | 320,8781 | 24,3658987 | 23,7955347 | 34,3243243 |
| AW11 | 10 | 6,61490683 | 0,0306819 | -9,213667602 | -0,00412946 | 29.43295516 | 0,08161724 | 0,02479508 | 409,5728 | 26,2399666 | 25,5352686 | 26,5861027 |
| AD12 | 37 | 52,5439408 | 0,003886314 | -64,16291145 | -0,00402415 | 8.684590168 | 0,19184839 | 0,18584426 | 196,1018 | 24,4168457 | 26,4541714 | 41,6272173 |
| AW13 | 64 | 6,22370266 | 0,005351771 | -9,156520708 | -0,00070881 | 14.9233399 | 0,03837547 | 0,04918033 | 124,7015 | 4,74847794 | 3,38715613 | 6,5144909 |
| AS14 | 21 | 176,397516 | 0,001251366 | -202,4046444 | -0,00413468 | 25.46843705 | 0,14349078 | 0,07837705 | 283,314 | 25,3515741 | 29,5975555 | 32,7765522 |
| AW15 | 13 | 1,67769376 | 0,101460804 | -6,119668702 | -0,00873792 | 24.45074459 | 0,10983418 | 0,05680328 | 474,3914 | 55,8937522 | 34,6826997 | 30,2010669 |
| AR16 | 33 | 71,6614907 | 0,002622214 | -94,41711221 | -0,00402632 | 18.4455089 | 0,16877941 | 0,172 | 215,1729 | 24,9259518 | 25,1995865 | 42,9326288 |
| AW17 | 14 | 10,0661626 | 0,013677397 | -14,02250336 | -0,00296069 | 32.92571568 | 0,06740618 | 0,04744262 | 362,4687 | 19,5267265 | 17,4171075 | 38,5756677 |
| AR18 | 25 | 41,4103924 | 0,005560237 | -54,73006295 | -0,00490986 | 9.09 | 0,17001704 | 0,11405738 | 243,7373 | 28,5411686 | 30,2196948 | 41,552363 |
| AW19 | 10 | 6,01355167 | 0,037457036 | -8,375685016 | -0,00460111 | 31.53067874 | 0,09874757 | 0,0292377 | 519,69 | 34,2430713 | 37,3791523 | 24,0580223 |
| AR20 | 14 | 30,8695652 | 0,010262696 | -38,6707771 | -0,00638494 | 12.32645877 | 0,16837997 | 0,04908197 | 353,7287 | 36,8489284 | 46,5779832 | 29,6007054 |
| AW21 | 10 | 10,4642594 | 0,02156394 | -13,54821237 | -0,00452343 | 27.14792894 | 0,10608495 | 0,03490984 | 410,4445 | 29,52583 | 32,3552958 | 24,652605 |
| AW22 | 10 | 3,10767435 | 0,076289041 | -6,15802888 | -0,00583382 | 31.56576265 | 0,08451471 | 0,01881967 | 392,9967 | 35,1882173 | 27,3804874 | 32,8265377 |
| AW23 | 107 | 1,59994698 | 0,722936841 | -1,215679962 | -0,00565594 | 54.47244087 | 1,45538798 | -0,16595082 | 92,42473 | 60,0393104 | 143,286899 | 33,50645 |

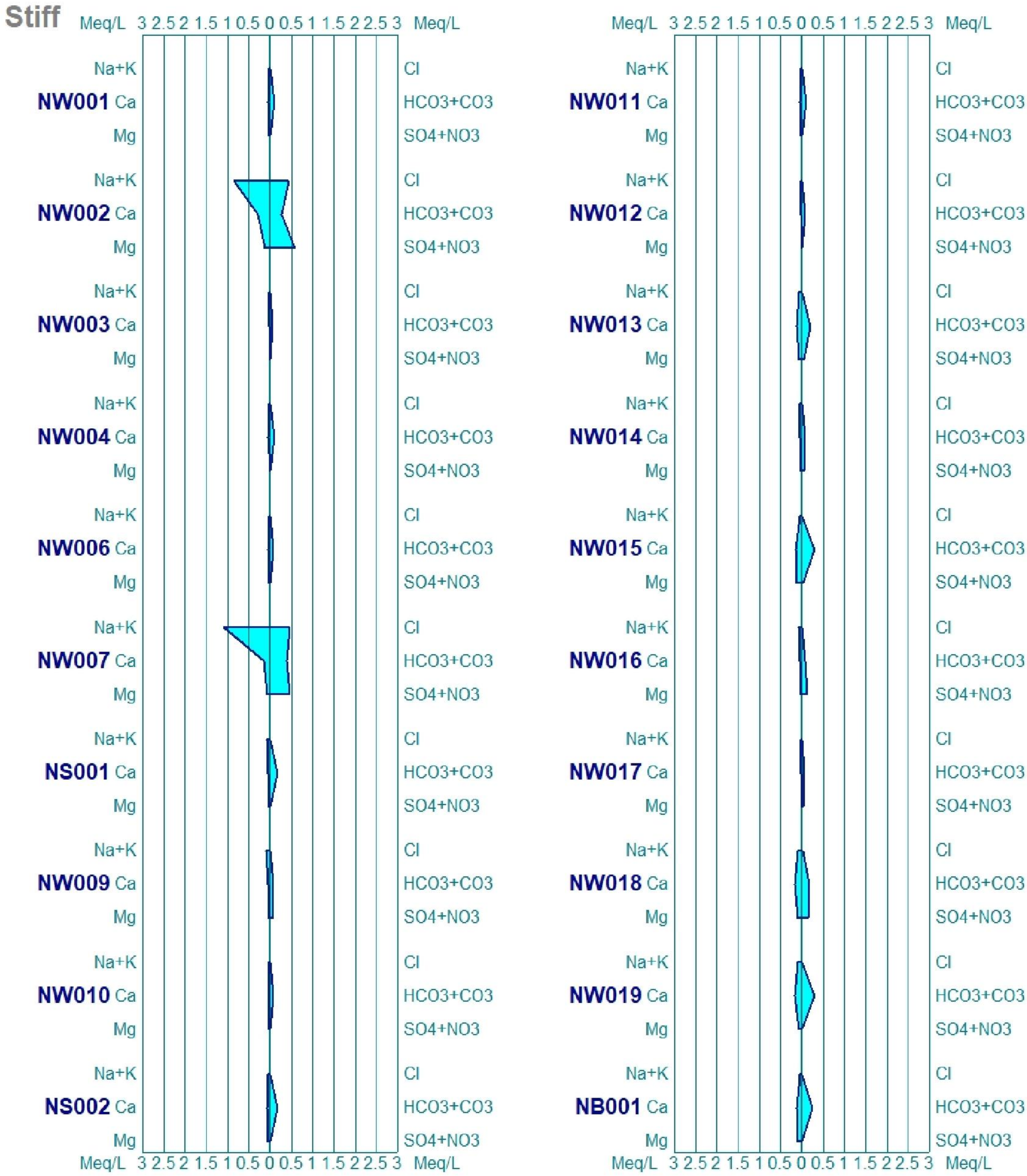
**Appendix 6** (Continued)

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| AR24 | 22 | 28,3496007 | 0,007880534 | -33,92121886 | -0,0042605 | 8.914137003 | 0,14292042 | 0,08327049 | 241,1944 | 23,7985002 | 26,1002035 | 39,6360293 |
| AW25 | 17 | 6,17391304 | 0,265650517 | -8,210722361 | -0,01556514 | 27.26225764 | 0,44713844 | -0,00335246 | 208,5633 | 65,6796072 | 143,701686 | 28,7329451 |
| AW26 | 143 | 13,3717176 | 0,008528829 | -16,74000221 | -0,00216911 | 3.999486719 | 0,19454529 | 0,53795082 | 94,65881 | 13,4789611 | 12,4357286 | 35,8494056 |
| AW27 | 17 | 4,44521739 | 0,257297115 | -4,864534834 | -0,00775179 | 39.20459364 | 0,40460943 | 0,00331967 | 198,3807 | 53,4606896 | 104,59173 | 36,5186306 |
| AW28 | 47 | 12,5146886 | 0,006214658 | -23,1722225 | -0,00227223 | 96.69684442 | 0,10722973 | 0,3135 | 244,2948 | 21,3884144 | 14,6921649 | 29,9755097 |
| AR29 | 115 | 51,4492754 | 0,002292195 | -65,66932755 | -0,00239605 | 10.61113136 | 0,19448838 | 0,60704918 | 105,2829 | 14,7859016 | 13,5936213 | 44,3086325 |
| NR51 | 88 | 4,87591172 | 0,038214813 | -11,59269264 | -0,00677006 | 26.18177594 | 0,28836766 | 0,39931967 | 183,4632 | 44,0013876 | 32,9756178 | 34,2250133 |
| NW52 | 171 | 1,38548442 | 0,91990738 | -2,303530393 | -0,00624268 | 203.4474219 | 0,79913619 | -0,48885246 | 53,13204 | 55,3059987 | 64,4220573 | 32,4133504 |
| NW53 | 57 | 1,56857547 | 0,689899315 | -4,755481487 | -0,01202709 | 46.87447883 | 0,50517174 | -0,02885246 | 141,6786 | 78,3119596 | 117,391304 | 35,2 |
| NW54 | 78 | 2,80632411 | 0,043489935 | -11,05969224 | -0,00596244 | 34.81931268 | 0,13525608 | 0,17404918 | 161,3035 | 37,2406876 | 15,0273846 | 25,1958264 |
| NW55 | 107 | 1,34215501 | 0,460525676 | -2,20793727 | -0,00433621 | 38.87042809 | 0,40494116 | -0,26658197 | 75,78625 | 38,2712424 | 34,9211009 | 29,8700226 |
| NW56 | 106 | 3,23738025 | 0,786623682 | -5,707910118 | -0,01247081 | 109.5973681 | 1,38286439 | -0,08593443 | 99,38159 | 80,0311316 | 222,137476 | 37,0386102 |
| NB57 | 60 | 18,1585678 | 0,007074297 | -107,8436809 | -0,01194967 | 70.17502885 | 0,16637486 | 0,20835246 | 452,7903 | 70,2665856 | 39,7908524 | 30,7887861 |
| NW58 | 185 | 0,6194222 | 0,80072542 | -1,065578419 | -0,0021369 | 67.33191449 | 0,31350158 | -0,76844262 | 34,87269 | 30,8831614 | 18,5288079 | 38,8701215 |
| NR59 | 169 | 6,41377791 | 0,047496291 | -8,083256255 | -0,00582033 | 21.62538548 | 0,71799159 | 0,93213115 | 111,1633 | 38,0308642 | 48,1982694 | 33,3061346 |
| NW60 | 219 | 2,66838615 | 0,085815112 | -3,134740028 | -0,00313147 | 23.99 | 0,47743877 | 0,5304918 | 81,78955 | 24,1230191 | 25,6999946 | 28,1407994 |
| NW61 | 100 | 3,04633867 | 0,377878306 | -9,531018398 | -0,00756107 | 45.22791176 | 0,2643469 | -0,2510082 | 64,13329 | 45,7066517 | 26,7870578 | 33,9743671 |
| NR62 | 69 | 2,57246377 | 0,080855388 | -4,896876914 | -0,00544053 | 56.12674515 | 0,24855269 | 0,21882787 | 163,2288 | 35,3013439 | 28,4180812 | 31,6317803 |
| NR63 | 85 | 2,64596273 | 0,044876511 | -9,11821677 | -0,00612243 | 22.28961127 | 0,17931714 | 0,3720082 | 189,8177 | 41,5284779 | 20,5432405 | 32,4070323 |
| NW64 | 190 | 0,64474408 | 0,721110321 | -0,891007644 | -0,0014401 | 69.63809147 | 0,32784405 | -0,87286885 | 38,5798 | 27,9585862 | 18,7278754 | 31,7993205 |
| NW65 | 273 | 1,70314843 | 0,189353124 | -1,908778285 | -0,00481508 | 22.69137679 | 0,88862508 | 0,66836066 | 87,82937 | 39,9827659 | 47,2970165 | 18,9792254 |
| NW66 | 223 | 5,33786232 | 0,041772477 | -8,873354976 | -0,00443194 | 15.18060247 | 0,41740975 | 0,26581967 | 86,55218 | 28,7928827 | 24,140426 | 14,0397242 |
| NW67 | 101 | 0,80281587 | 0,387318092 | -1,948385786 | -0,00506057 | 15.18 | 0,29480007 | -0,01092623 | 117,5953 | 45,9418369 | 32,2397235 | 33,8617672 |
| NW68 | 179 | 0,91162667 | 0,603200177 | -1,738067165 | -0,00301906 | 64.87154625 | 0,31929308 | -0,66803279 | 45,25891 | 30,8783208 | 20,2138416 | 31,8654132 |
| NR69 | 103 | 1,71987578 | 0,105855521 | -3,051687158 | -0,00400255 | 78.10508819 | 0,37261276 | 0,56428689 | 185,3786 | 42,853721 | 40,9400796 | 35,1729586 |

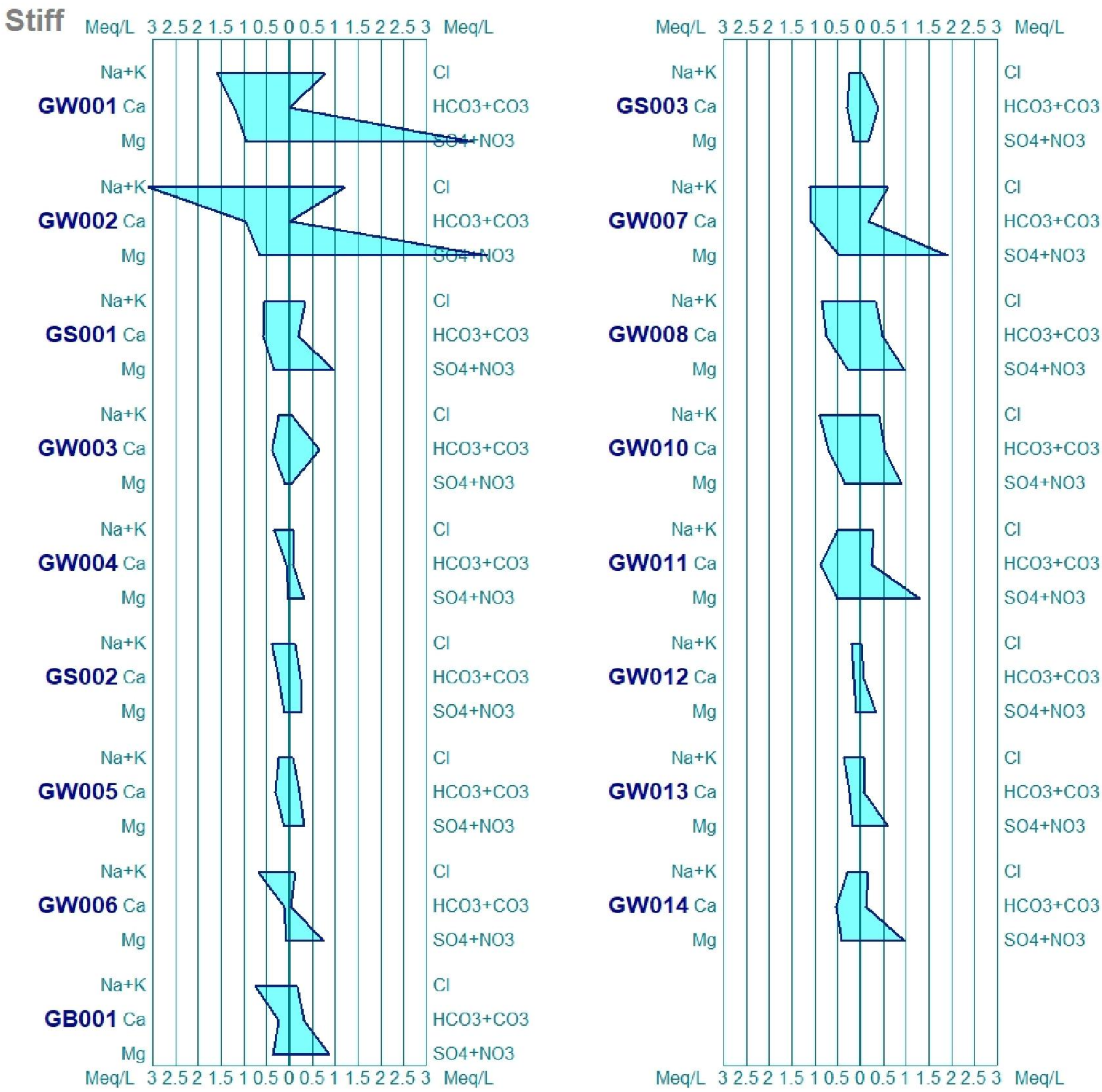
**Appendix 6** (Continued)

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| NW70 | 502 | 40,4986039 | 0,005747509 | -44,05881947 | -0,00403757 | 23.14123054 | 0,88303189 | 3,13147541 | 68,10925 | 25,4473702 | 31,3533959 | 45,0328927 |
| NW71 | 220 | 3,58307453 | 0,085440584 | -4,221802414 | -0,00441757 | 22.66871565 | 0,6484805 | 0,41852459 | 89,4488 | 31,2571514 | 37,2004621 | 16,4134233 |
| NR72 | 79 | 6,59712482 | 0,050573667 | -8,397389623 | -0,00635468 | 20.97 | 0,4786509 | 0,3222377 | 149,8915 | 38,8531461 | 49,7118285 | 28,0538527 |
| NB73 | 746 | 9,06009191 | 0,040790919 | -8,861622204 | -0,00541908 | 16.38 | 1,86518214 | 4,34254098 | 68,0756 | 36,0274898 | 55,4119122 | 32,8341621 |
| NR74 | 610 | 2,45302795 | 0,046124141 | -3,47041045 | -0,00202351 | 34.31214081 | 0,43761344 | 2,12959016 | 47,35016 | 16,0336204 | 12,3725477 | 29,7371356 |
| NR75 | 225 | 6,7719559 | 0,043070863 | -7,554812519 | -0,00449642 | 17.12766573 | 0,70201412 | 0,82672131 | 86,45015 | 29,3752824 | 36,8017796 | 24,6997354 |
| NW76 | 311 | 0,47774327 | 0,529995863 | -0,584225183 | -0,00111923 | 85.52373095 | 0,2905888 | -1,2804918 | 36,97358 | 25,2186693 | 12,4497599 | 29,8823138 |
| NW77 | 336 | 1,03038739 | 0,967772614 | -0,631531829 | -0,00364778 | 147.7110025 | 1,03118346 | -1,23557377 | 39,09341 | 44,6500442 | 49,9118463 | 40,4928559 |

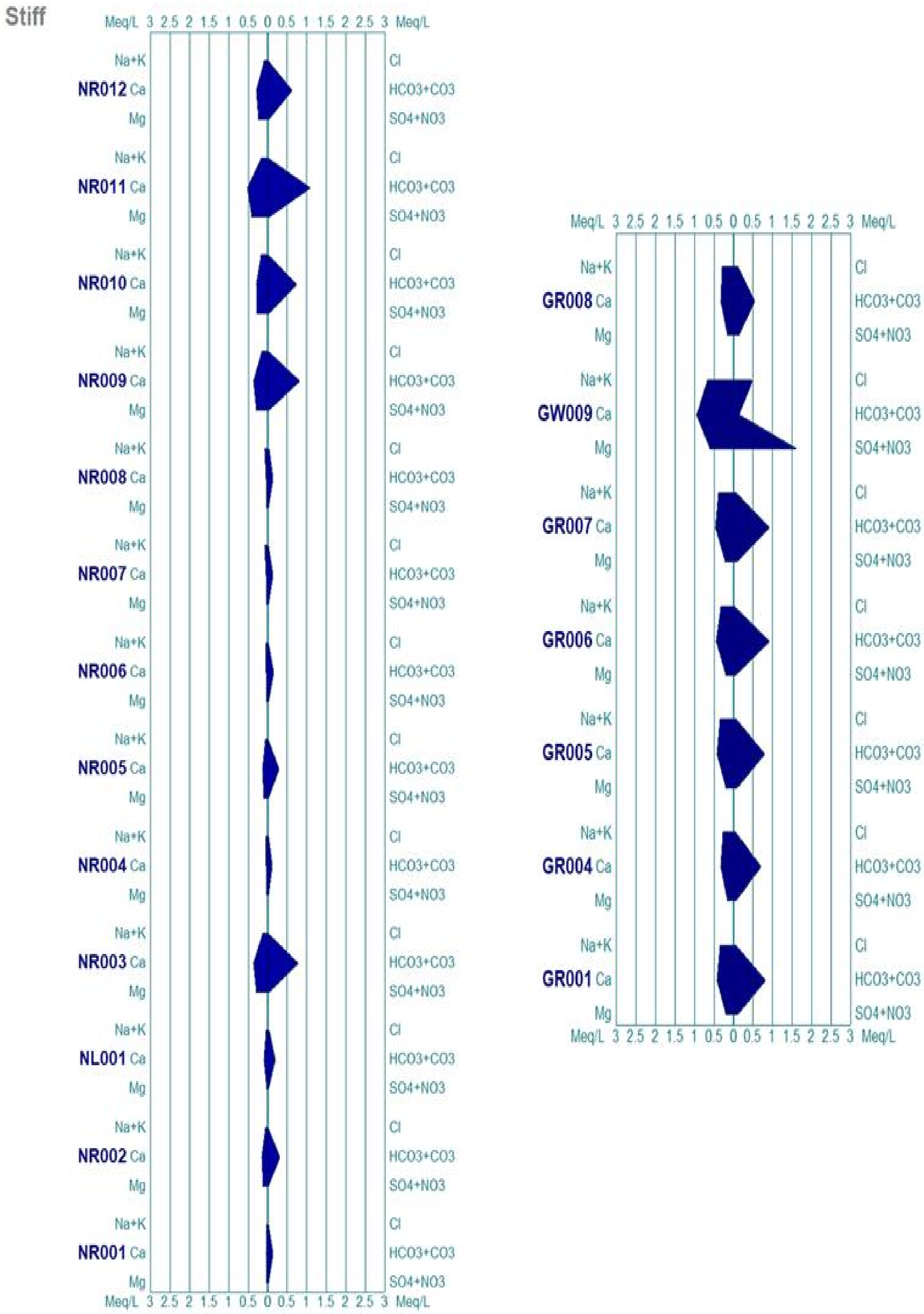
**Appendix 7:** Stiff diagrams of the water samples collected in the rainy season



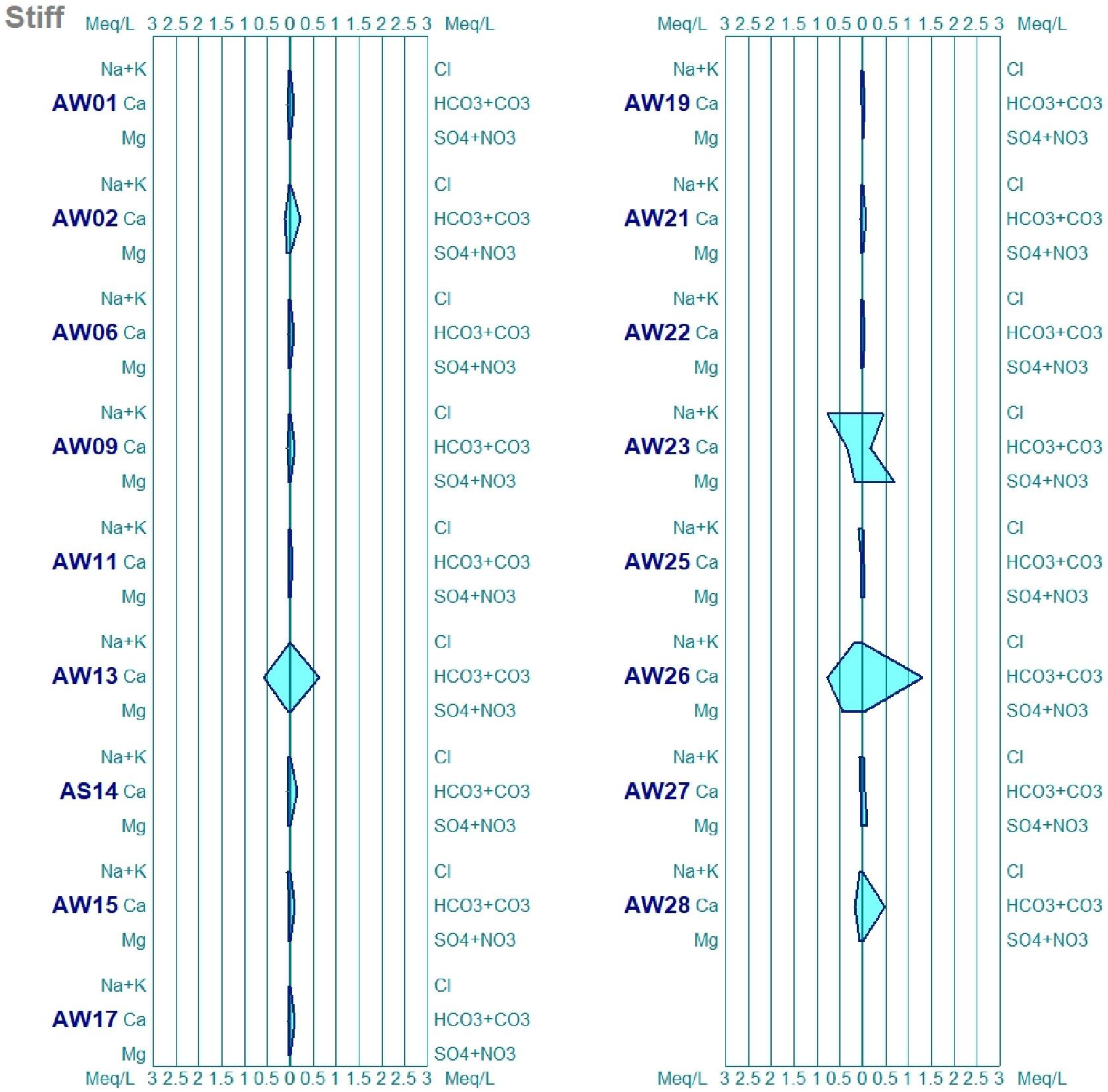
**Appendix 7** (Continued)



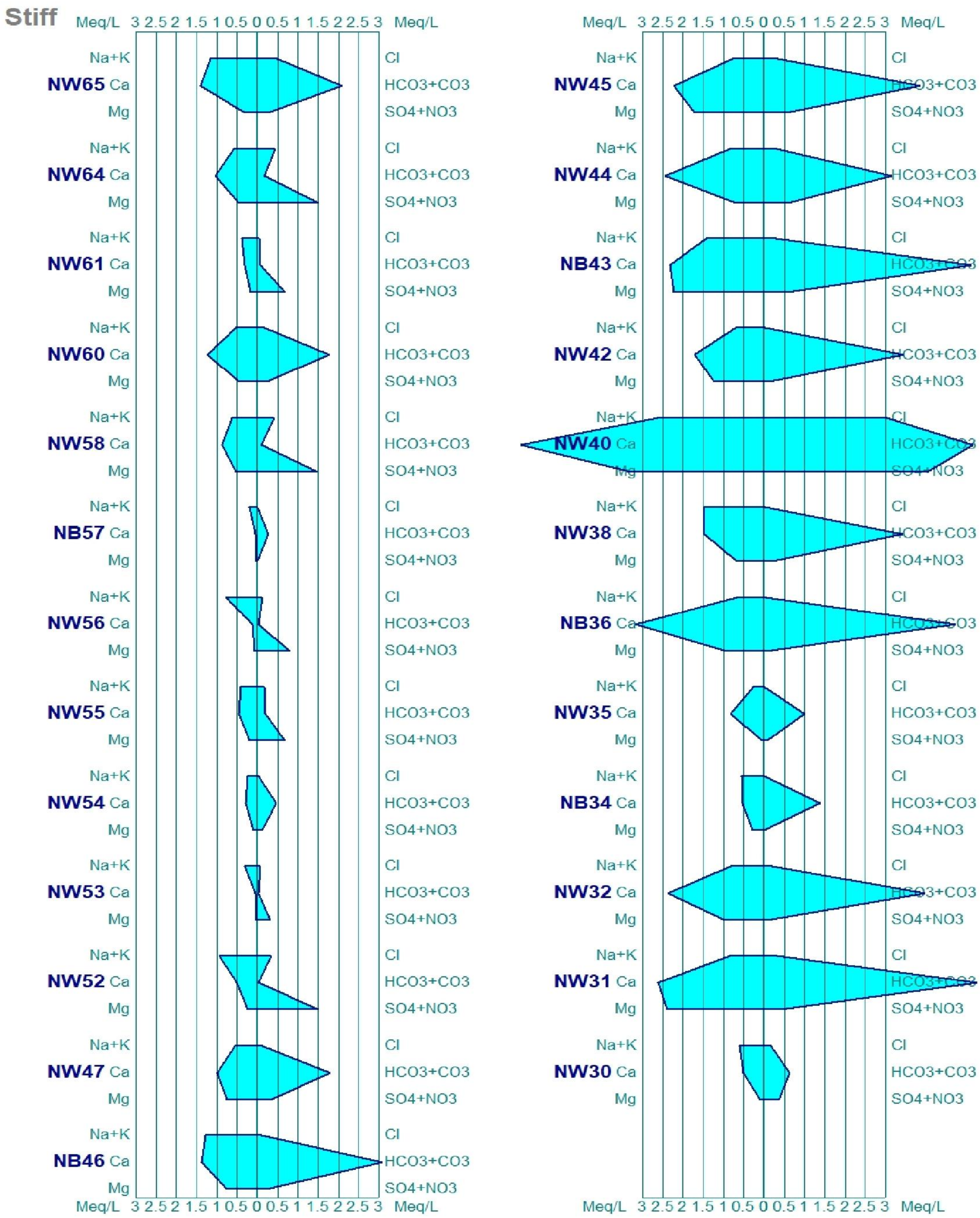
**Appendix 7** (Continued)



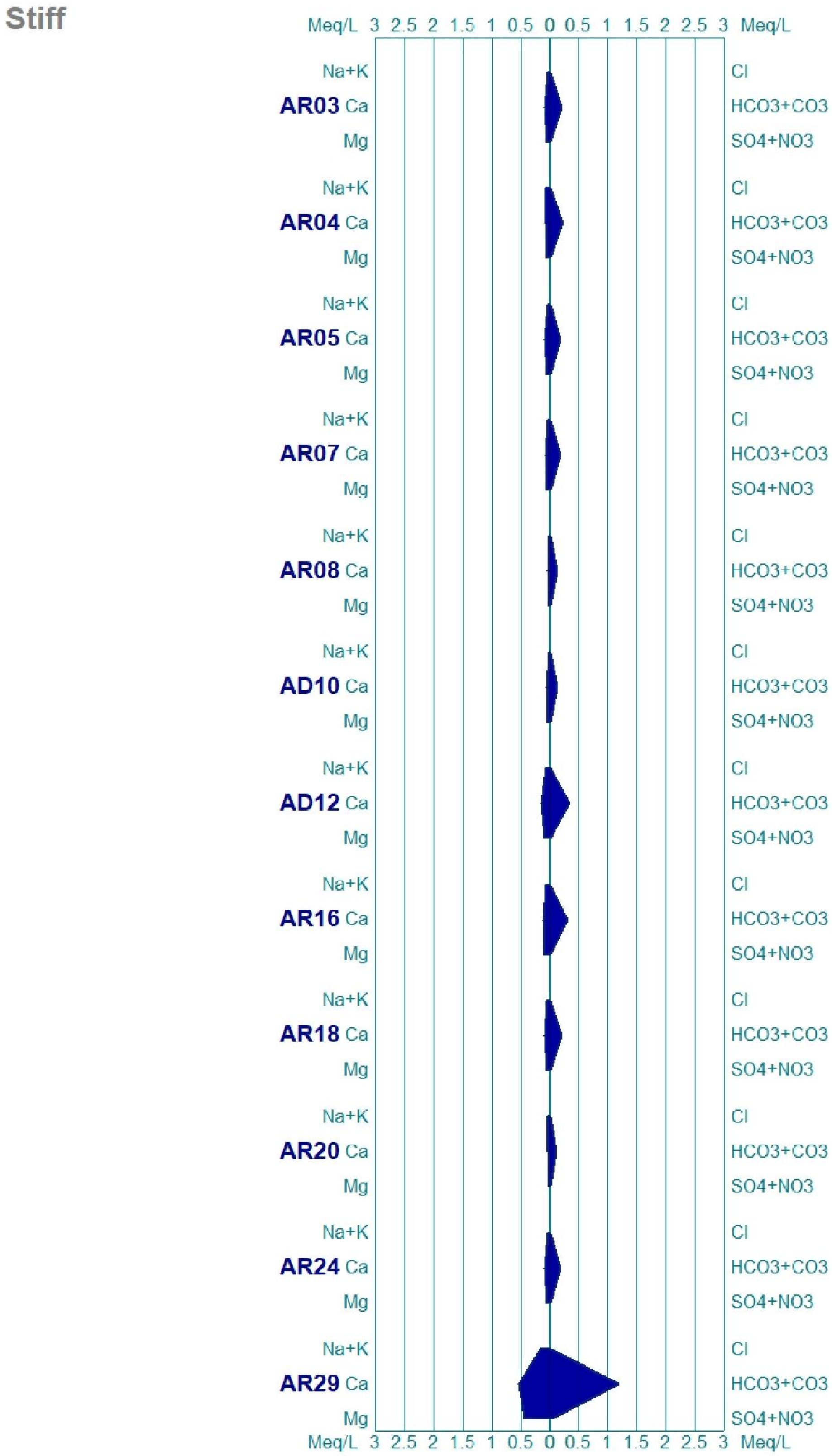
**Appendix 8:** Stiff diagrams of the water samples collected in the dry season



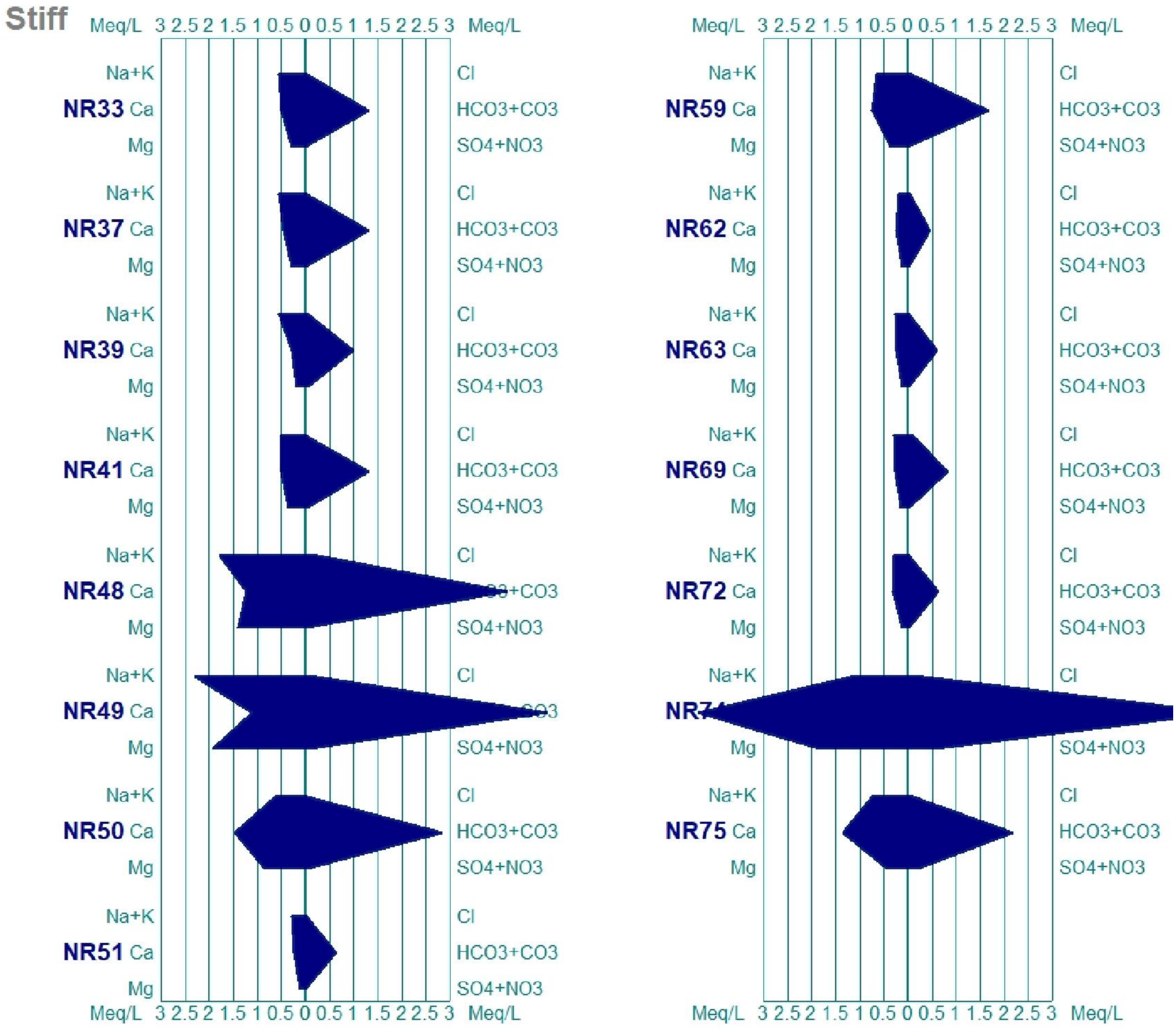
**Appendix 8** (Continued)



**Appendix 8** (Continued)



**Appendix 8** (Continued)



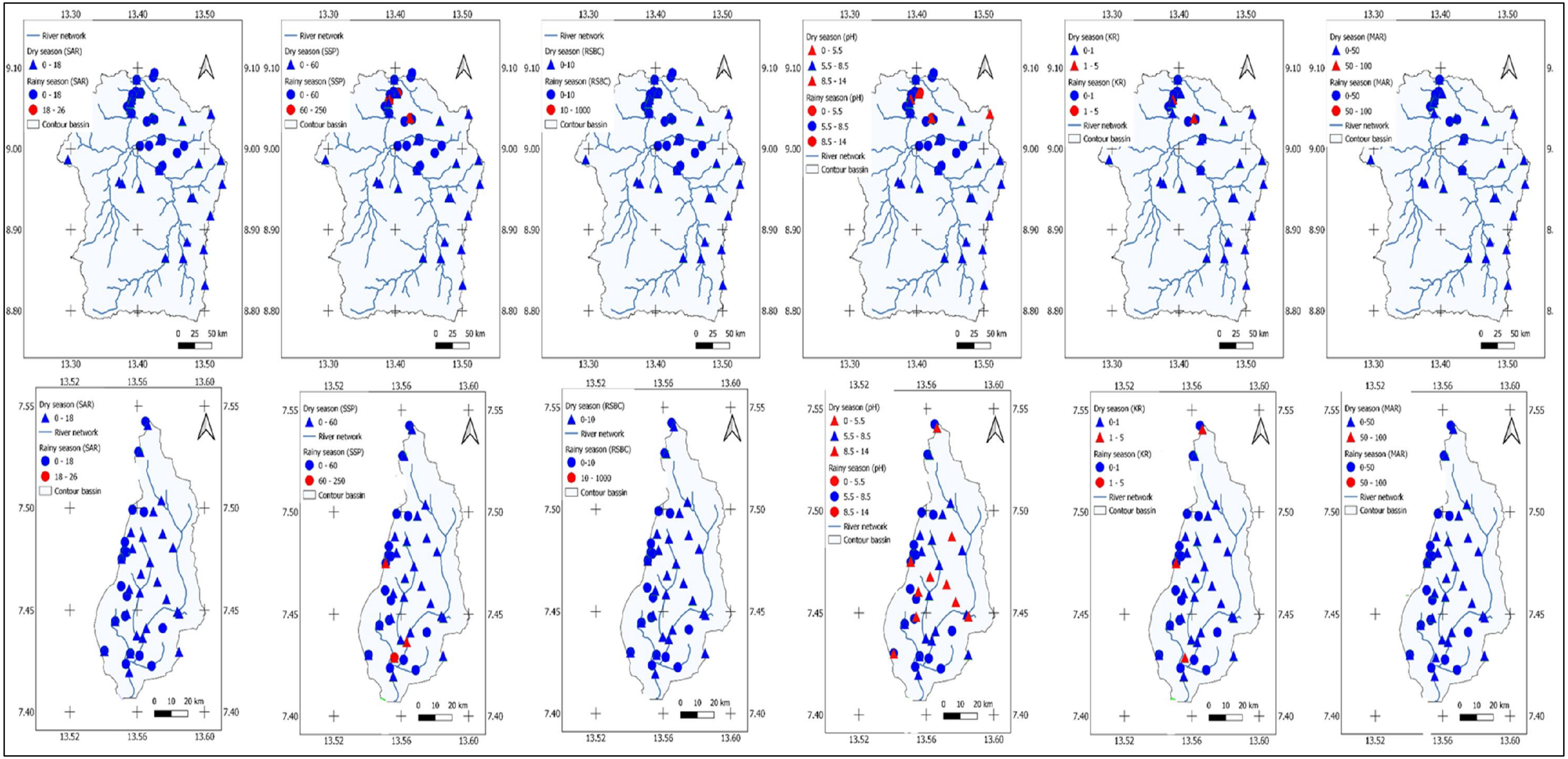
**Appendix 9:** Piezometric measurements of the rainy season (mean depth of **7.47m** in DLSW and **11.04m** in BIW)

| ID | Depth (m) | Static (m) |
|---|---|---|
| GW001 | 12 | 9,7 |
| GW002 | 10,6 | 6,98 |
| GW003 | 8,72 | 4,49 |
| GW004 | 1,69 | 1,31 |
| GW005 | 4,6 | 2,97 |
| GW006 | 9,5 | 7,5 |
| GB001 | 60 | 27 |
| GW007 | 5,23 | 3,1 |
| GW008 | 5,97 | 2,71 |
| GW010 | 7,69 | 2,9 |
| GW011 | 8,5 | 6,22 |
| GW012 | 6,64 | 2,94 |
| GW013 | 6,63 | 2,23 |
| GW014 | 9,38 | 5,35 |
| NW001 | 5,18 | 3,14 |
| NW002 | 4,03 | 2,32 |
| NW003 | 13,43 | 9,65 |
| NW004 | 12,53 | 8,49 |
| NW005 | 14,27 | 9,62 |
| NW006 | 14,81 | 9,72 |
| NW007 | 5,86 | 4,47 |
| NW009 | 17,36 | 6,94 |
| NW010 | 9 | 5,56 |
| NW011 | 13,52 | 5,32 |
| NW012 | 11,83 | 4,95 |
| NW013 | 9,97 | 3,01 |
| NW014 | 6,19 | 2,29 |
| NW015 | 6,14 | 5,64 |
| NW016 | 11,73 | 6,31 |
| NW017 | 13,99 | 6,69 |
| NW018 | 11,27 | 5,05 |
| NW019 | 17,61 | 13,56 |
| NB001 | 42,4 | 7,15 |

**Appendix 10:** Piezometric measurements in the dry season (mean depth of

| ID | Depth (m) | Static (m) | ID | Depth (m) | Static (m) |
|---|---|---|---|---|---|
| **1** | 5.9 | 5.4 | **26** | 14.22 | 10.1 |
| **2** | 15.79 | 12.76 | **27** | 16.65 | 12.47 |
| **3** | 20.71 | 16.54 | **28** | 10.7 | 9.4 |
| **4** | 16.94 | 14.62 | **29** | 12.5 | 11.8 |
| **5** | 9.31 | 6.17 | **30** | 11.3 | 9.7 |
| **6** | 18.33 | 11.38 | **31** | 14.2 | 11.5 |
| **7** | 16.05 | 13.32 | **32** | 4.6 | 4.5 |
| **8** | 18.78 | 15.07 | **33** | 7.5 | 6.7 |
| **9** | 13.64 | 13.13 | **34** | 13.9 | 12.4 |
| **10** | 16.47 | 16.09 | **35** | 12.15 | 12.09 |
| **11** | 14.19 | 13.89 | **36** | 16.8 | 12.1 |
| **12** | 6.99 | 6.41 | **37** | 9.5 | 8.95 |
| **13** | 17.25 | 15.63 | **39** | 9.9 | 6.9 |
| **14** | 12.56 | 11.05 | **40** | 8.9 | 8.45 |
| **15** | 19.22 | 16.36 | **41** | 7.9 | 7.85 |
| **16** | 15.91 | 14 | **42** | 6.5 | 5.9 |
| **17** | 9.77 | 7.95 | **43** | 8.1 | 7.5 |
| **18** | 12.37 | 11.25 | **44** | 4.3 | 2.6 |
| **19** | 12.24 | 10.9 | **45** | 5.3 | 4.8 |
| **20** | 4.45 | 4.11 | **46** | 11.4 | 9.8 |
| **21** | 17.53 | 12.25 | **47** | 11.55 | 10.9 |
| **22** | 12.09 | 10.19 | **58** | 10.78 | 9.77 |
| **23** | 12.1 | 8.76 | **59** | 1.57 | 1.35 |
| **24** | 7.42 | 7.34 | **60** | 9.63 | 5.86 |
| **25** | 3.53 | 3.22 | **61** | 8.74 | 6.36 |

**Appendix 11:** Indices used to determine suitability of water sources for irrigation



**Appendix 12:** Indices used to determine suitability of water sources for drinking