Integrated and Sustainable Management of Shared Aquifer Systems and Basins of the Sahel Region

RAF/7/011

LIPTAKO-GOURMA AND UPPER VOLTA SYSTEM

2017

REPORT OF THE IAEA-SUPPORTED REGIONAL TECHNICAL COOPERATION PROJECT RAF/7/011

LIPTAKO-GOURMA AND UPPER VOLTA SYSTEM

COUNTERPARTS:

Mr Philippe Armand ADJOMAYI (Benin)

Mr Moussa BOUKARI (Benin)

Ms Ratoussian Aline KABORE KOMI (Burkina Faso)

Mr Alphonse GALBANE (Burkina Faso)

Mr Dickson ADOMAKO (Ghana)

Mr Shiloh Kwabena Dedeh OSAE (Ghana)

Mr Sidi KONE (Mali)

Mr Aly THIAM (Mali)

Mr Sanoussi RABE (Niger)

Mr. Ismaghil BOBADJI (Niger)

Mr Gounten MANOUABA (Togo)

Mr Kounadi DIABAKTE (Togo)

EXPERT:

Ms Laurence GOURCY (France)

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Table of Contents

1. INTRODUCTION

1.1. Short presentation of the studied area and previous studies undertaken

The Liptako-Gourma-Upper Volta system is not a transboundary aquifer with continuous groundwater flow in western Africa as in the case of the Iullemeden or Taoudeni sedimentary basins, but it is composed of various geological/hydrogeological units showing different groundwater dynamics, old sedimentary formations (sandstone) and fissured/weathered hard-rocks. Therefore, the limits of the aquifer systems could correspond more or less to the limits of hydrological basins (Upper Volta and Sourou) or natural regions (Liptako-Gourma). The Liptako-Gourma and Central Upper Volta are mainly crystalline basement aquifers. Two locally important sedimentary aquifers were identified in the Gondo-Sourou plain and the Pendjari/Oti basin. The countries concerned by these groundwater resources are Niger, Mali, Burkina Faso, Ghana, Benin and Togo. The Gondo-Sourou "piezometric depression" is composed of an unconfined aquifer that belongs to the Cenozoic intra-continental basins of Sahelian Africa (Koussoube, 2010; Dakouré, 2003). This specific area, prolonging the Taoudeni Basin is quite well studied, including 2 Ph D thesis and a major national Malian project "Programme d'Appui aux Collectivités Territoriales pour l'Eau potable et l'Assainissement (PACTEA)".

The Liptako-Gourma aquifer is one of the transboundary aquifers included in the ISARM (Internationally Shared Aquifer Resource Management) entries in the UNESCO/IHP program. This international project aimed at improving the understanding of scientific, socio-economic, legal, institutional and environmental issues related to the management of transboundary aquifers. However, the Liptako-Gourma is a natural geographic area with no precise limits.

Since the beginning of the ISARM project in Africa (2002) various activities have been carried out in order to compile the existing information, to build monitoring systems, to create platform and organize meetings to facilitate information/data exchange and to map the groundwater resources.

In 2005, under the WHYMAP (World-wide Hydrogeological Mapping and Assessment Program) and IGRAC (International Groundwater Resources Assessment Centre) the delineation of the transboundary aquifers in Western and Central Africa was established (Davies et al., 2012; Altchenko and Villholth, 2013). Within the 20 aquifers delineated, the transboundary aquifer of interest for the present study was identified as APWC17 (Liptako-Gourma). It encompasses the Gondo plain.

The recent GRAPHIC IHP program (Groundwater resources and climate) do not include any of the studied sectors as case studies.

In Niger, the BGR carried out a detailed study in an area close to capital city of Niamey showing the relationships between the alluvial, basement and Continental Intercalaire aquifers with the Niger River. The International Water Management Institute (IWMI), a non-profit, scientific research organization focusing on the sustainable use of water and land resources in developing countries proposed from 2009 to 2012 a large regional project "Groundwater in sub-Saharan Africa: Implications for food security and livelihoods" with the objective to address the key challenges and plug some of the major gaps. More detailed studies were carried out in Ghana. These projects focused in the North-eastern part of the country (part of the areas covered by the present study in the Upper Volta basin).

The CGIAR Research Program on Water, Land and Ecosystems (WLE) combines the resources of 11 CGIAR centers, the Food and Agriculture Organization of the United Nations (FAO) and numerous national, regional and international partners to provide an integrated approach to natural resource management research. Some activities concerned the Niger and the Volta basins, most of them related to irrigation and the implications for groundwater resources.

The Global Water Partnership (GWP) in West Africa help countries translates into action the principles of sustainable management of water resources. This institute is therefore strongly involved in Integrated Water resources managements. These international programs are supporting various activities leading to the better management of groundwater resources. However, few permit acquiring new technical data for improving hydrogeological knowledge. Various local studies may also be available. The Africa Groundwater Literature Archive is a searchable online database that so far catalogues nearly 7000 references for literature about groundwater in Africa and is being carried out by BGS in partnership with African hydrogeologists. Results and output of local and regional studies are being available through this portal.

1.2. Project objectives

The overall objective of the IAEA-supported project RAF/7/011 was to improve hydrogeological knowledge using geochemical (including isotopes) techniques of the transboundary aquifers Liptako-Gourma and Upper-Volta in order for local authorities to get high quality information to manage adequately the groundwater resource. Due to the large extend of the transboundary aquifer, the limits/functioning uncertainties and the wish of regional collaboration the sampling efforts were concentrated in three more specific studied areas: Liptako-Gourma basin (shared by Niger, Burkina Faso and Mali), Gondo-Sourou plain (Mali and Burkina Faso) and Central Upper Volta basin (Benin, Ghana, Togo, Burkina Faso) (Fig.1).

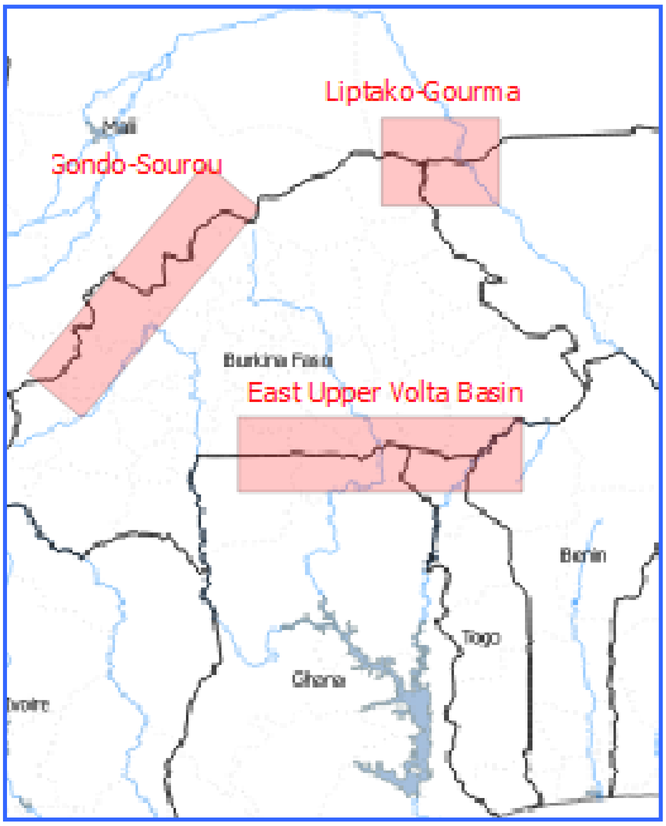

Figure 1: Upper Volta Basin, Liptako-Gourma region and the three pilot study areas

2. STUDY SITES

2.1. Location and over all topography

The Liptako-Gourma aquifer is estimated to 159,500 km^2 and includes about 7,758,500 inhabitants in 2013 (source: ISARM). It covers a great part of the North-eastern part of Mali and the North-east to East part of Burkina Faso as well as the southern part of Niger (Tillabery and Dosso regions as well as the Niamey urban community). The region is crossed by the Niger River.

The Liptako-Gourma is a geographical area characterized by its climate and vegetation. The region consists for the most part of a vast lateritic plateau in the West African savanna, approximately 198–305 m above sea level.

The Liptako-Gourma Authority was created in 3 December 1070 with the objective of the economic development of this low population density. The integrated water resources management is taken into account the environmental, economic and societal aspects. The specific objectives are to provide in sufficient quantity water of good quality for the development of irrigation and breeding, to evaluate water availability, to sustain the development of surface water works in order to regulate and improve surface water use. The Liptako-Gourma area presents today's security problems and therefore no samples were taken within the RAF/7/011 in the Niger-Mali border area.

The East Upper Volta Basin has 1,143,000 inhabitants within 47,800 km^2 (source ISARM). The area is comprised between 9°30' and 11°30' North and 0°45 and 2°03° East. In Togo the studied area concerns about 40% of the country (25,545 km^2) including the Kara and Savanes regions. It is also called the Oti basin. In Benin, the regional aquifer covers 12.1% of the country (13,590 km^2) and corresponds to the Pendjari basin. It included the Atacora, Donga and Alibori departments. In Ghana, the studied area includes the Upper East and the Upper West regions and covers a very large area of about 27,000 km^2. Only a small area of Burkina Faso is concerned by this studied area. The Southeastern part of the country is mostly entirely covered by the Arli national park in Centre Est (Boulgou, Koulpélogo provinces) and Centre Sud (Naouri province) regions. The altitude is progressively increasing from 160 m in the

Pendjari plains in the Western part to 650 m at the Atacora mountain chains. The Upper Volta aquifers are mainly of hard-rock and, for such lithologies, the aquifer systems characteristics are similar to those of the Liptako-Gourma. Some experts considered the hard-rock areas of Upper Volta Basin as part of the "Liptako-Gourma".

A sedimentary aquifer located in the East Benin-West Togo-Burkina Faso area (Pendjari/Oti basins) presents specific hydrogeological characteristics.

Another specific hydrogeological area, sedimentary aquifer, is located in the north-western part of the Upper-Volta basin, and concerned Mali and Burkina Faso. The plain, called Gondo or Gondo-Sourou plain has an extension of about 30,000 km^2 (source: Koussoube, 2010) of 90 km width and 400 km long (Fig.2). In Mali, it concerns small parts of the Mopti, Sikasso and Segou regions. In Burkina Faso, the Boucle du Mouhoun, Nord and Sahel regions are within the studied area. It is a flat area between the Bandiagara plateau (Mali) at more than 600 m high and some lateritic plateau in Burkina Faso less than 400 m high.

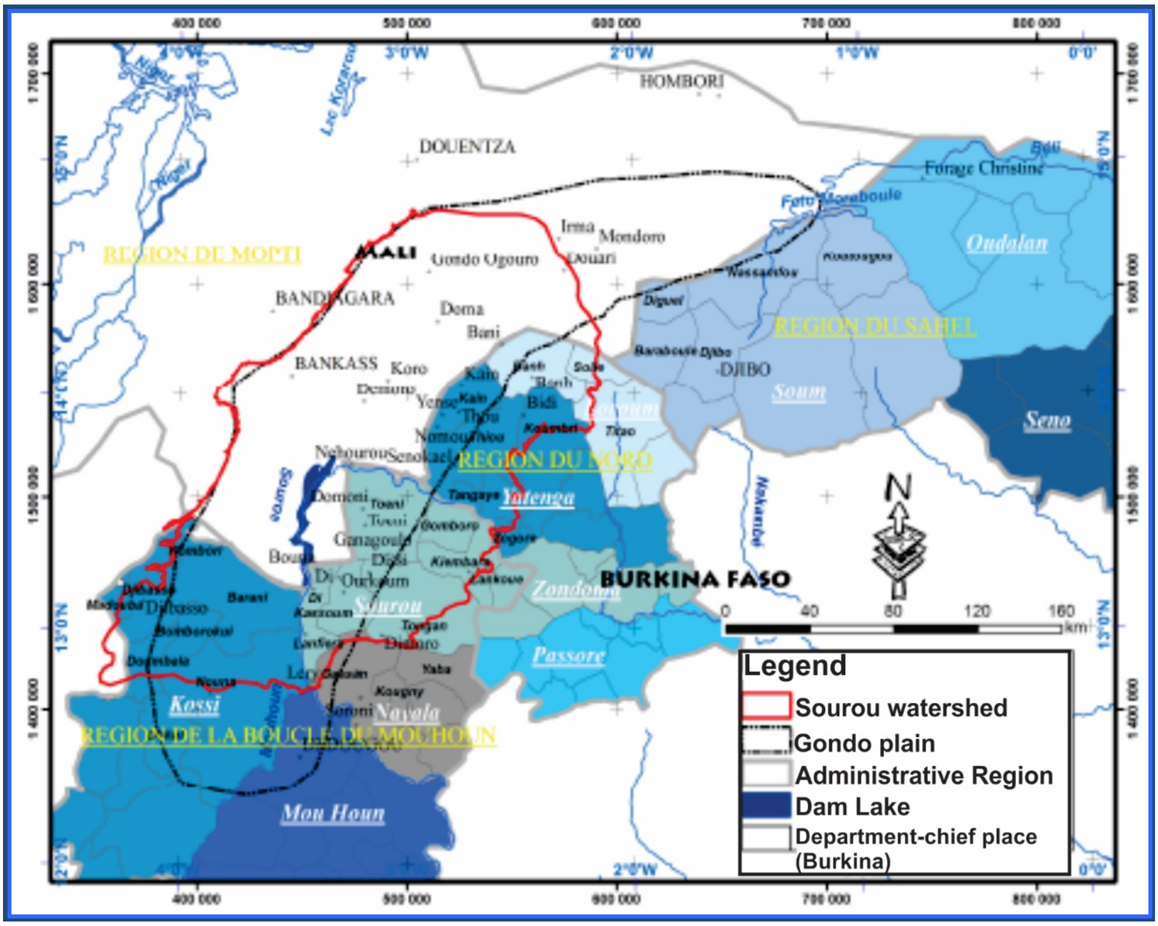

Figure 2: Gondo-Sourou plain in Mali and Burkina Faso (Koussoube, 2010)

2.2. Climatology

The Liptako-Gourma and Upper Volta areas are under various climate zones (from Köppen-Geiger classification); the Tropical Savanna (or Sudanese-Guinean, Aw) for the NE Upper Volta sector and subtropical steppe/ low-latitude semi-arid hot climate (BSh) for Gondo-Sourou and Liptako-Gourma sectors. The precipitation regime is controlled by to the movement of the Intertropical Convergence Zone (ITCZ) resulting in a seasonal precipitation oscillation between the Guinea Gulf and the Sahel (Fig.3). The studied areas present a unimodal diagram of precipitation with a clear rainy season in May-October (maximum around August). In the Liptako-Gourma plain (northern part of the study area) the climate is much drier than in the central part of the Upper Volta area. The Niamey meteorological station can be considered as representative of the climate of this sector. The average temperature is 29.3°C with an expected rainfall between 500 mm and 750 mm/year (from 1961-2015). The maximum precipitation is between June and September (Fig.4).

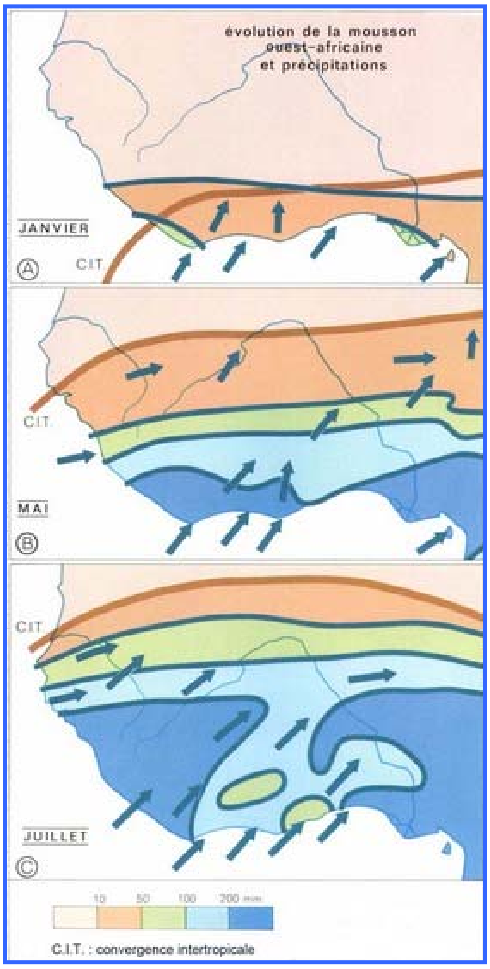

Figure 3: Evolution of the ITCZ in January, May and July (source: archives Larousse)

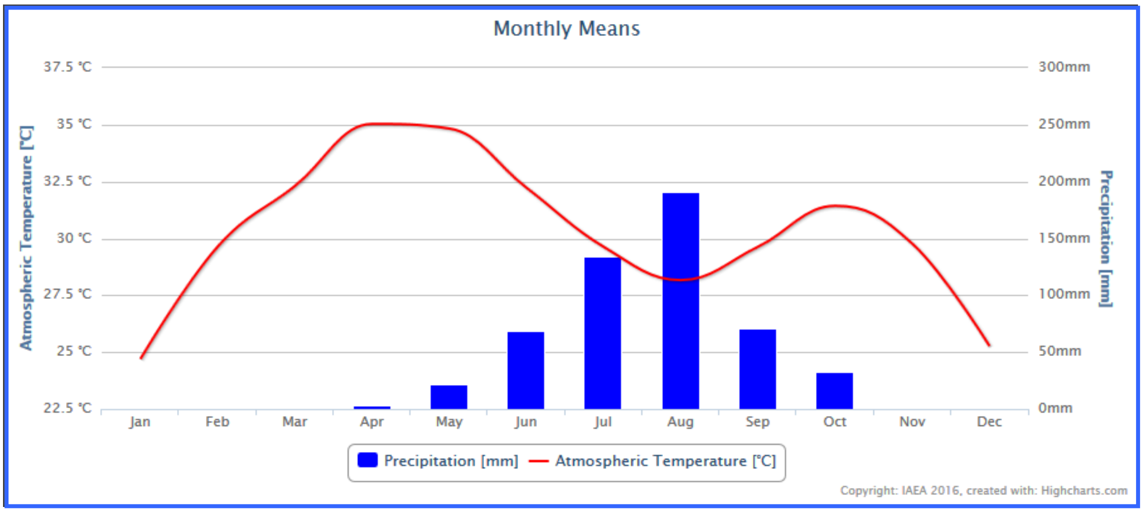

Figure 4: Monthly means of temperature and precipitation amount at the Niamey IRD/IRI IAEA GNIP station for the period 2009-2014 (source: WISER IAEA)

For the Gondo-Sourou plain, the precipitation varies from about 1100 mm in the southern part (Sikasso, Mali) to 500mm in Mopti (Mali). The average annual temperature is between 28°C and 30°C. At Bankass the annual precipitation is 528 mm for 27.4°C (Fig.5).

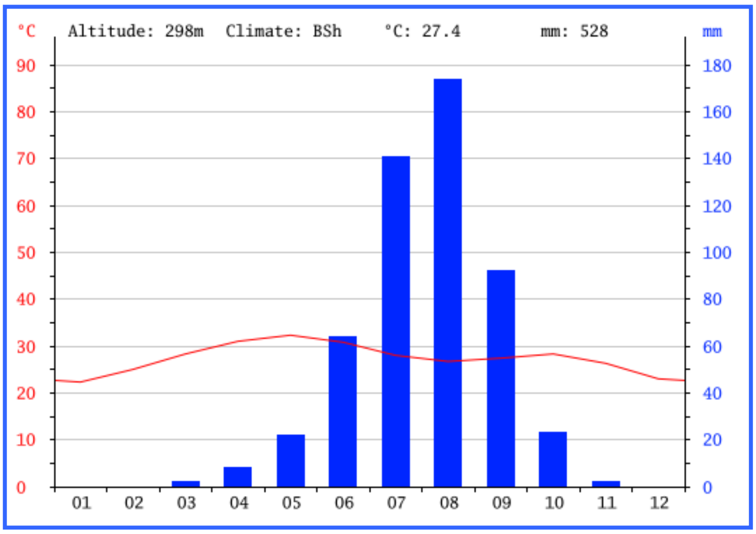

Figure 5: Monthly temperature and precipitation at Bankass (Mali). (climate-data.org)

The Sourou River is crossing the plain, mainly in Burkina Faso. This river has the particularity to have "inverse" flow direction during the annual high water level period. Various dams were built in this river. More specifically in the Central part of the Volta Basin, the total annual precipitation is between 1000-1350 mm (1981-2010).The average annual temperature is 27.4°C in Natitingou (Benin). An example of the monthly precipitation and temperature can be given for this sector by Mango station (Togo) data (Fig.6).

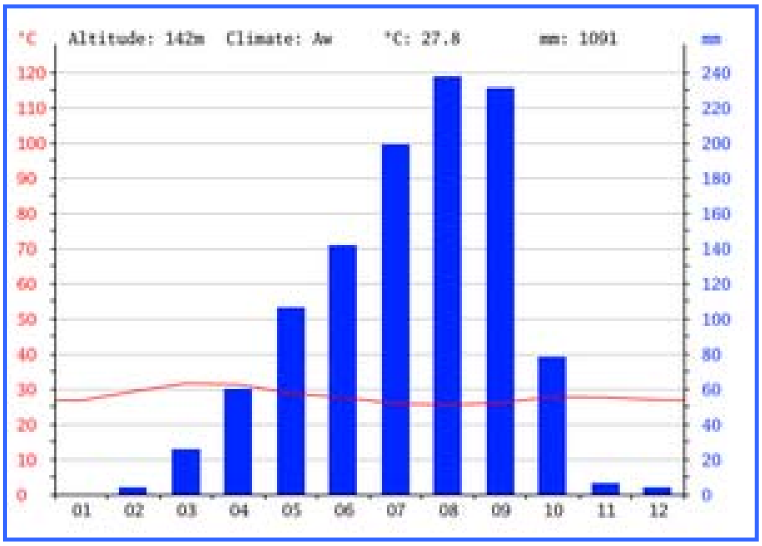

Figure 6: Monthly temperature and precipitation at Sansanné-Mongo station (Togo).
Source: climate-data.org

The vegetation consists predominantly of grassland, especially savanna with clusters of drought-resistant trees such as baobabs or acacias.

2.3. Geology and hydrogeology

The area is dominated by pre-Cambrian basement rocks and, for the Gondo-Sourou plain and Pendjari/Otibasin consolidated and unconsolidated sedimentary rocks. Therefore, the groundwater resource is mainly located in fractured areas and alterites (Fig.7).

Precambrian rocks comprise crystalline and metamorphic rocks. Un weathered basement rocks contain very little water resource. The main aquifers develop within the weathered overburden and fractured bedrock (McDonald and Davies, 2000).

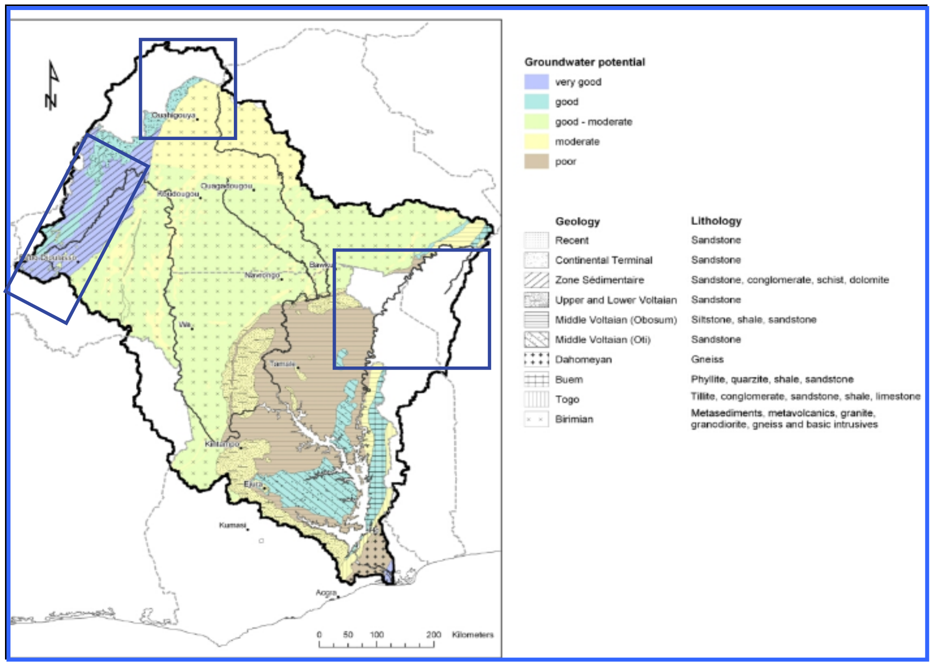

Figure 7: Geological map and groundwater potential of the Volta Basin, showing the three studied sectors (in Martin, 2006)

Liptako-Gourma:

About 95% of the Liptako-Gourma area consists of crystalline formations and 75% of them are of Birrimian age (Fig. 8). The Continental Terminal is found sometimes in geological unconformity, directly over the Birrimian basement (see Table below)

Age	Geological Formation	Lithology	Aquifer units
Quaternary	Niger valley	Sand, clays	alluvium
Middle Pliocene	Ouallam-Filingué	Sands, clayey silts/clayey sandstone	Continental Terminal
Neoproterozoic (Voltaian)		Sandstone, quartzite, mudstone	
Paleoproterozoic Precambrian (Birrimian)	Liptako-Gourma	Granitic, gneiss other crystalline metamorphic rocks (schist, green rocks, quartzite)	Basement discontinuous aquifer

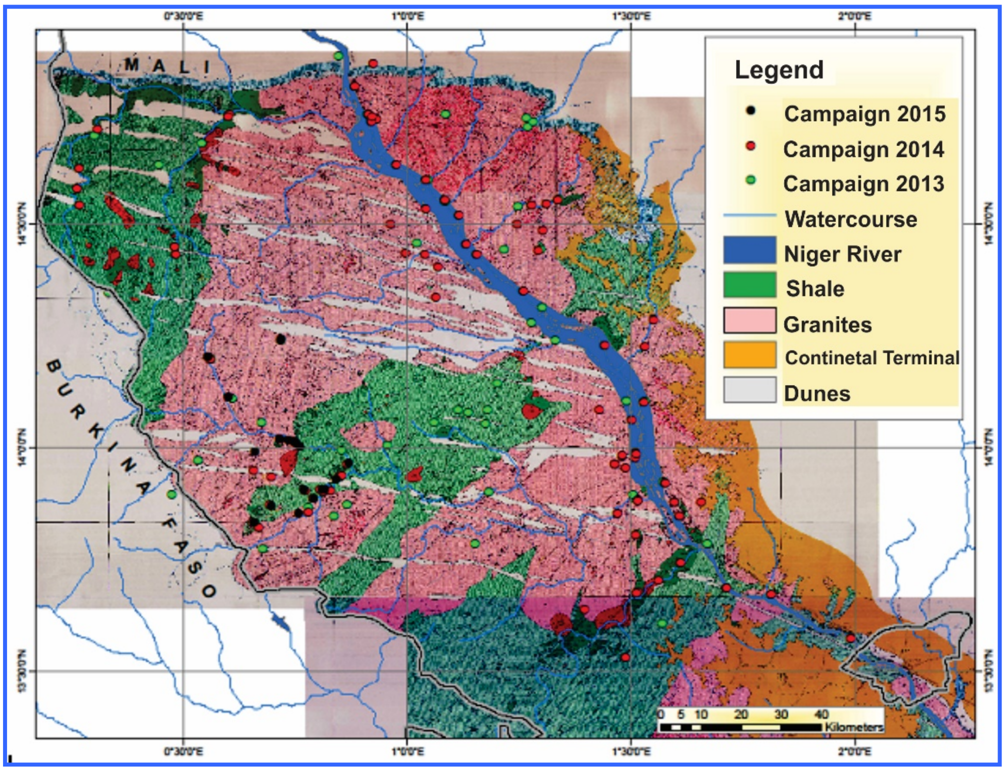

Figure 8: Geological map of the Liptako-Gourma in Niger (Sanoussi, RAF/7/011 report)

Gondo-Sourou plain (Fig.9):

Information of the geology of the area has obtained from Practica et al., 2010, United Nations 1988, Koussoube 2010.

Age	Geological formation	Lithology	Aquifer units
Quaternary		Sands and clays	Local aquifers only, Sourou alluvial aquifer
Neoproterozoic	Irma	Limestone, dolomite	Continental Terminal Quaternaire (CTQ) Multi-layered aquifer
Upper Eocene to Pliocene	Koro	Clays sand, with some lateritic intercalation, clays	
Precambrian	Sarnyéré	**Dolomite**, limestone	
Infracambrian	Toun	**Limestone**, limestone and, marble, sandstone, shale	Folded Infracambrian (ICP)
Infracambrian	Bandiagara (and Koutiala) Group	**Sandstone**, quartzite	Tabular Infracambrian (ICT)
Precambrian	Birrimian basement	sandstone, granites, volcanic rocks	Basement (Birrimian)

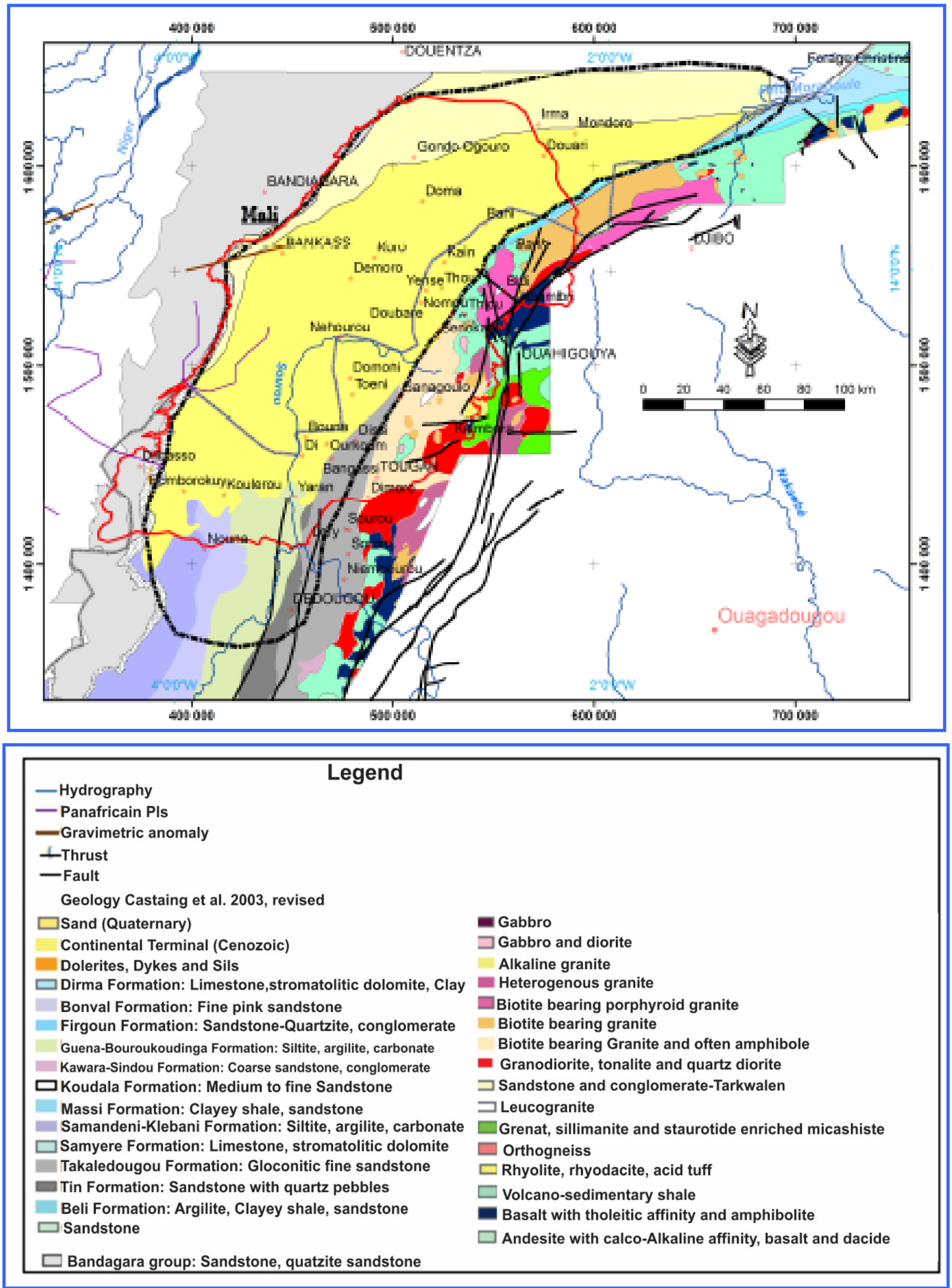

Figure 9: Geological map of the Gondo-Sourou plain (Castaing et al., 2003 and Meme 1992 in Koussoube, 2010)

Central Upper Volta:

The basin is composed of hard-rocks from the basement and sedimentary intergranular/fractured formations (Figs. 10 and 11). The synthesis is done using information from Affaton 1990, Affaton 2008, Carney et al. 2010, Martin, 2006(see table below).

Age	Geological Formation	Lithology	Aquifer units
Quaternary	Fluvial deposits	Sand, clays	Alluvial aquifers
Upper Voltaian (neoproterozoic)	Obosum/Tamale megasequence (of no interest for the study – only Ghana)		Voltaian basin aquifer
Proterozoic – lower Ordovician (Neoproterozoic) Middle Voltaian	Oti- Pendjari megasequences (called triad in Taoudenni basin)	***Sandstone**, argillites, tillites, dolomitic carbonates, shales, siltstone*	
Latest meso-proterozoic Lower Voltaian	Bombouaka megasequences (Gambaga) – includes Dapaong, Fosse-aux-lions, Yemboure) Panabako/Tossiego	***Sandstone,** quartz, arenite, shale, siltstone, limestone*	
Late Proterozoic – Early Paleozoic	Buem Volcanic-sedimentary structural unit	Sandstone, quartzite, rhyolite, andesite, shale, hematite, jasper, volcanic rocks	Sandstone structural units
	Togo series	Tillite, phylite, quartzite sandstone, shale, limestone	
Precambrian	Atacora structural units	Schist, micaschist, gneiss, quartzite, granite highly metamorphosed	Atacora structural units
Ante-Birrimian to Middle Proterozoic	Basement Birrimian formation	*orthogneiss, gneiss, micaschists*	Basement complex aquifer – Birrimian
Upper Birrimian		Basaltic and andesitic lavas, schist,	
Birrimian		Phyllites, greywackes, granites, gneiss, migmatites, granodiorite	

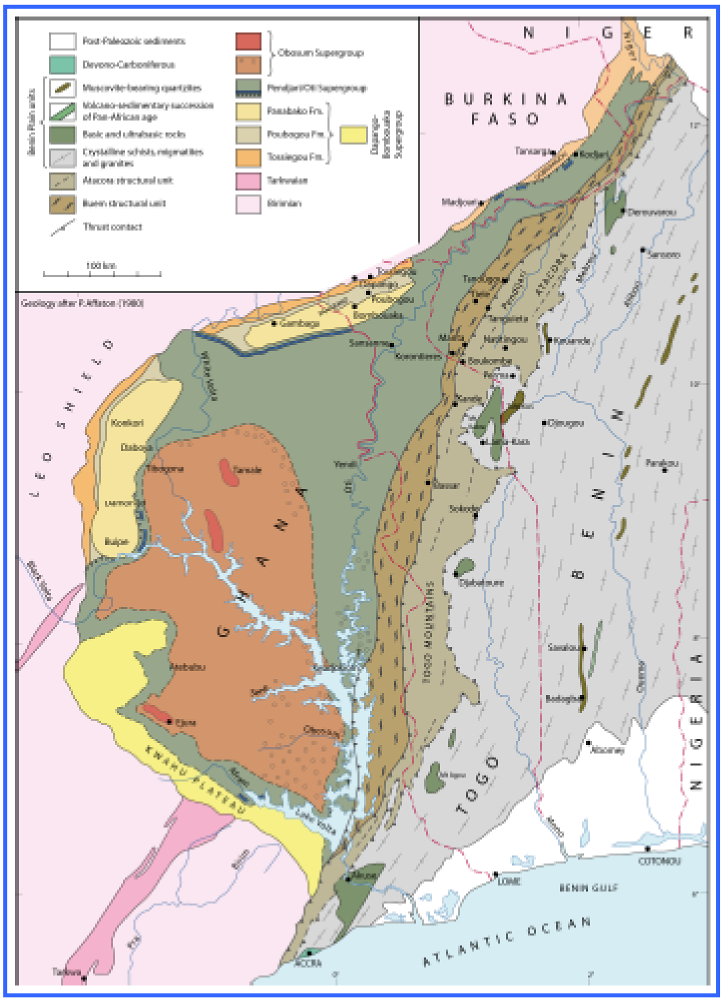

Figure 10: Geological map of the Volta basin (after Affaton, 1990)

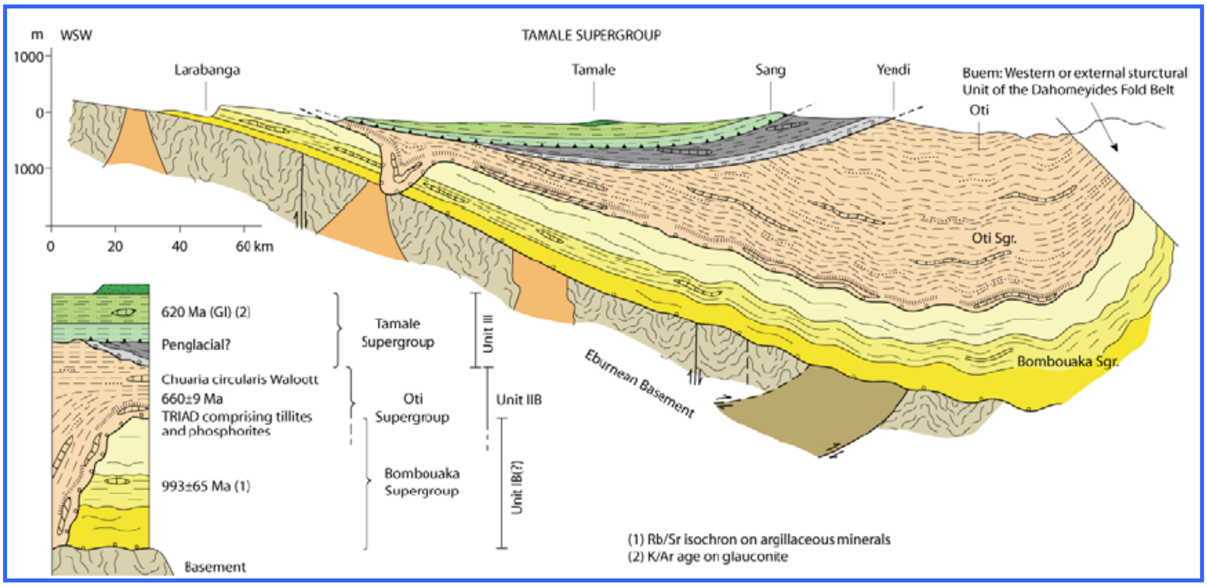

Figure 11: Cross-section of the Volta basin (modified after Affaton, 1990, in: Affaton, 2008)

3. DATA AQUISITION AND METHODOLOGY USED

A synthesis of data acquired within the IAEA-supported project RAF/7/011 by studied sector was established (see Table below).

Sector	Country	Sample type	Main hydrogeological formation	Number of sample/sampling sites/sampling campaign	Chemistry	$^{18}O/^{2}H$	^{3}H	$^{14}C/^{13}C$
LiptakoGourma	Niger	Rainfall	2013-2015	Niamey	N/A	17	0	0
		Surface Water		1 (Nera)	N/A	N/A	N/A	N/A
		Groundwater	basement	60/58/1	60	60	60	0
	Burkina Faso	Rainfall		No station	0	0	0	0
		Surface Water		3/2/2Gomdi reservoir, Yakouta	3	3	0	0
		Groundwater	Basement (granite, schist, orthogneiss, pegmatites)	80/80/2	80	80	38	0
Gondo-Sourou	Mali	Rainfall	2014-2015	Koutiala, Mopti/Sévaré, Bankass	N/A	27	0	N/A
		Surface Water		1/1/1 (Markala)	0	0	0	N/A
		Groundwater	CTQ, ICP, ICT	30/30/2	30	30	30	N/A
	Burkina Faso	Rainfall		No station				
		Surface Water		1/1/1 (Lery Dam)	1	1	0	N/A
		Groundwater		24/24/1	8	8	8	N/A
Central- Upper Volta	Benin	Rainfall	2014-2015	Natitingou	N/A	10	0	N/A
		Surface Water		12/12/1	12	12	11	0
		Groundwater	Basement, sandstone, Voltaian, Atacora	97/67/3	97	97	34	11
	Togo	Rainfall	2015	Dapaong Mango (no data yet)	0	14	0	0
		Surface Water		3/2/2 (Oti)	3	3		
		Groundwater	Basement, sandstone, Voltaian	66/42/2	66	66	41	20
	Ghana	Rainfall		Navrongo (no data yet)				
		Surface Water		12/12/1 - Tamini/White Volta	12	12	12	0
		Groundwater		73/73/2	72	73	73	27

4. RESULTS AND INTERPRETATION

4.1. Precipitation/Rainfall isotope signal

From the hydrochemical point of view, no new data was acquired during the duration of the project for the chemical composition of rainfall.

Tritium content of today's precipitation is not measured in the above-mentioned stations. Quite old data based on GNIP results and some publications were treated for West Africa (Lapworth et al. 2012). The ^{3}H values in precipitation are lower than 10 TU since more than 30 years. From isotope point of view the following stations have been installed during the implementation of the IAEA-supported project RAF/7/011: Niamey (Niamey), Dapaong, Mango (Togo), Natitingou (Benin), Navrongo (Ghana), Bankass, Koutiala, Mopti/Sevare (Mali). No data were yet available for Mango and Navrongo, the stations were installed late in the project. Also some stations belong to the GNIP network since some years: Bohicon, Kandi, Cotonou (Benin), Ouagadougou, Barogo, Hounde, Nasso and Bobo-Dioulassou (Burkina Faso), Bamako (Mali), Niamey (Niger) (Fig.12).

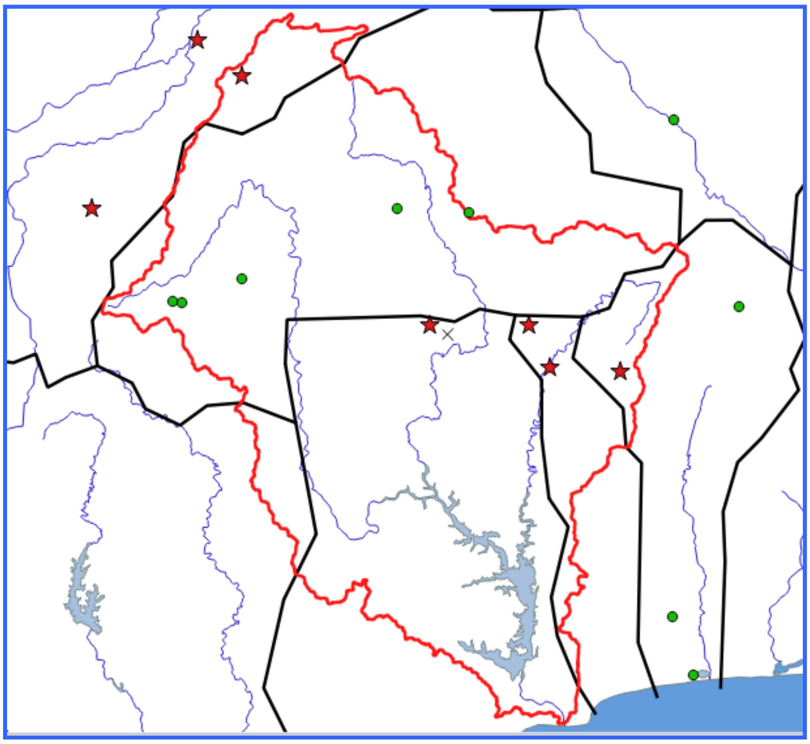

Figure 12: Location of the GNIP precipitation stations (green circles for on-going stations, X for closed stations) and those measured under RAF/7/011 (red star) in the area of interest.

As the region of interest is quite extended the precipitation signal for each studied sector was explored.

Liptako-Gourma:

Rainfall from Niamey station is perfectly representing the input signal for the Liptako-Gourma sector (Fig.13). As many years of information were available, it is possible to estimate the today's (2009-2014) weighted average of the stable isotopes input signal for this sector.

Niamey 2009-2014 (IAEA/GNIP): $\delta^2H = 6.55 \pm 0.24$ ‰ $\delta^{18}O + 4.62 \pm 0.97$ ‰

$$\delta^2Hw = 6.77 \pm 0.28 \times \delta^{18}Ow + 5.06 \pm 0.94$$

$$\delta^2Hpwlsr = 7.21 \pm 0.24 \times \delta^{18}Ow + 6.99 \pm 0.97$$

Weighted annual mean (2009-2015): $\delta^{18}O = -3.38$‰ and $\delta^2H = -16.96$ ‰

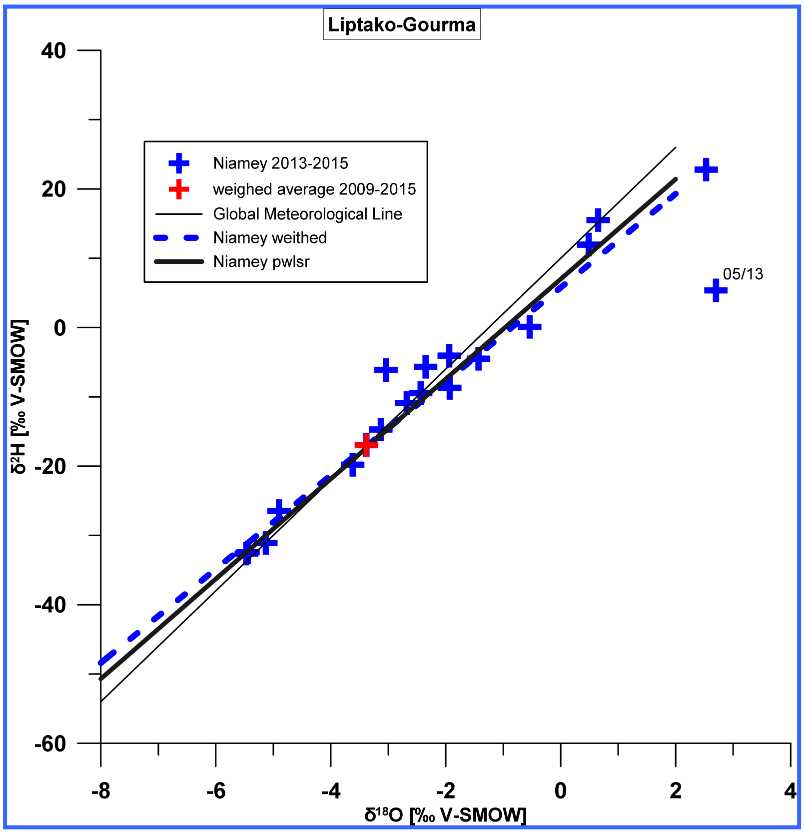

Figure 13: Water stable isotopes in precipitation for the Liptako-Gourma sector

This slope is quite different from the one determined in the 1989 rainy season by Girard et al. (1997). For these authors the best estimate of the local meteorological line is:

$$\delta^2H = 8 \times \delta^{18}O + 15.4$$

For the project period (2013-2015) and excepting May 2013 samples, the weighted mean of precipitation is δ^2H = -14.71‰ / $\delta^{18}O$ = -3.13‰. The data from Taupin et al. (1995 and 2002) indicates an interannual mean of precipitation in Niamey of -4.2‰ $\delta^{18}O$ for the period 1992-1999 and δ^2H = -33.9‰ / $\delta^{18}O$ = -4.54‰ for 1988-1989.

Gondo-Sourou:

In this sector, three meteorological stations were installed in 2014 and two years of data are already available (Fig.14). Bamako station, having a long data record, may be used to compare with data from the other stations having only two years of information.

Bamako 1962-1999 (IAEA/GNIP): $\delta^2H = 6.39 \pm 0.11 \times \delta^{18}O + 0.88 \pm 0.62$

$$\delta^2Hw = 6.56 \pm 0.13 \times \delta^{18}Ow + 1.33 \pm 0.62$$

$$\delta^2Hpwlsr = 6.88 \pm 0.16 \times \delta^{18}Ow + 2.22 \pm 0.89$$

Weighted annual mean: δ^2H = -31.18‰ / $\delta^{18}O$ = -4.58‰

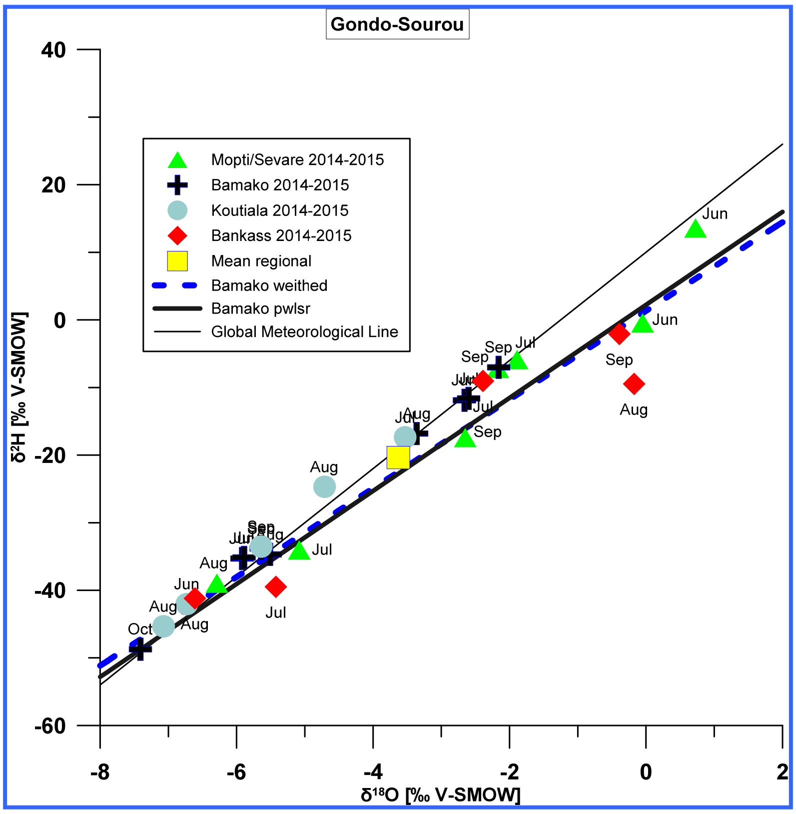

Figure 14: Water stable isotopes in precipitation for the Gondo-Sourou sector

The local meteorological line (LMWL) defined by Dakouré (2003) and with equation δ^2H = 7.7 x$\delta^{18}O$ + 12 does not fit well with the most recent precipitation data. Bamako meteorological line appears to be quite evaporated (slope of 6.6) as well as some monthly samples in Mopti/Sevare and Bankass. As rain amount is not available it is not possible to evaluate whether the most evaporated samples correspond to lowest rain amount/relatively dry month. The other monthly samples are falling onto the GML. Not considering the most evaporated samples (Bankass 07-08/15), the 2013-2015 mean for the three stations (Bankass, Koutiala, Mopti/Sevare) of the Gondo plain is: δ^2H = -20.37‰ / $\delta^{18}O$ = -3.63‰. The weighted mean cannot be calculated as no information on monthly rainfall amount was given.

Central Upper Volta:

There is no long-term station of the GNIP network in this sector (Fig.15). The Cotonou station, quite far from the studies area and having most probably an oceanic effect, showed, however, data that fit quite well to the stable isotopes signal for stations located in the studied area. The input signal for isotope information may be presented by the data from North Ghana (Akiti, 1980) or other local meteorological line proposed for North Ghana (Yidana et al., 2016; Pelg-Ba, 2009, Yidana, 2013). There is not yet data from the precipitation stations in Ghana for the period 2014-2015 collected during the implementation of the IAEA-supported project RAF/7/011. Data from Natitingu (Benin) station is available for two year period (2014-2015)

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North Ghana at Bolgatanga 1978-1979 (from Akiti, 1980): $\delta^2H = 7.86 \times \delta^{18}O + 13.61$

North Ghana composite (from Yidana et al, 2016): $\delta^2H = 7.5 \times \delta^{18}O + 5.53$

North Ghana at Tamale 1997-1998 (from Pelig-Ba, 2009): $\delta^2H = 6.9 \times \delta^{18}O - 0.19$

North Ghana at Tamale 2012 (from Yidana, 2013): $\delta^2H = 7.3 \times \delta^{18}O + 4.77$

Cotonou 2005-2013 (IAEA/GNIP): $\delta^2H = 7.10 \pm 0.10 \times \delta^{18}O + 9.09 \pm 0.67$ ‰

$\delta^2Hw = 7.29 \pm 0.19 \times \delta^{18}Ow + 9.66 \pm 0.66$

Natitingu 2014-2015: $\delta^2H = 7.41 \pm 0.36 \times \delta^{18}O + 9.89 \pm 0.98$

$\delta^2Hw = 7.43\ \delta^{18}Ow + 9.74$

Cotonou weighted annual mean: δ^2H = -12.59 ‰ / $\delta^{18}O$ = -3.00 ‰

Natitingu weighted annual mean: δ^2H = -12.55 ‰ / $\delta^{18}O$ = -3.02 ‰

Kandi station is located in the east northern part of Benin and, even located quite far from the studies area, may also be used. The results are indeed quite in accordance with Natitingou data (Fig.15). The most enriched precipitation corresponds to the beginning (March, May) and the end (October/November) of the rainy season. Also, months with low rain amounts are notably evaporated.

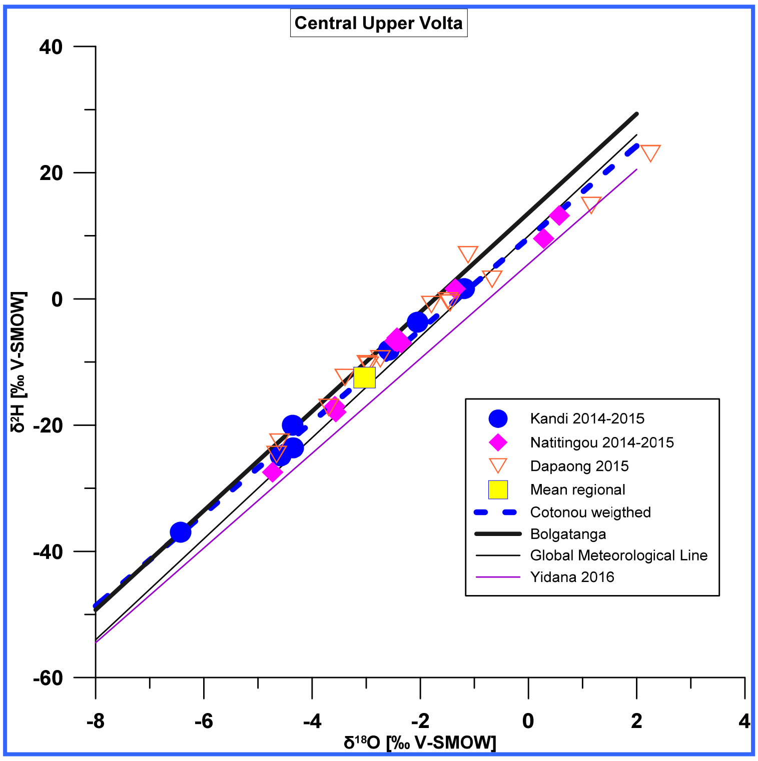

Figure 15: Stable isotopes in precipitation for the Central Upper Volta sector

Considering Dapaong and Natitingou for 2014-2015, except March/May and Oct/Nov samples, the average value of the precipitation is δ^2H = -8.84 ‰/ $\delta^{18}O$ = -2.66.‰. The weighted average would be δ^2H = -12.46 ‰ and $\delta^{18}O$ = -3.03 ‰.

However there were only a few data to calculate the average and no reliable information on the rain amount. Yidana 2013 proposed a mean average value for precipitation in North Ghana of δ^2H = -23 ‰ and $\delta^{18}O$ = -4.00 ‰ that fit better with groundwater data obtained within the IAEA-supported project RAF/7/011 (see below).

4.2. Presentation of groundwater chemical data

In order to have a consistent regional approach in the data treatment and having only little information on the geological formation/lithology of sample sites, broad hydrogeological classes were used: i) for Gondo-Souro- Quaternary/alluvial, Continental terminal/Quaternary, folded Infracambrian, tabular Infracambrian, ii) for Upper Central Volta - Voltaian (Oti/Pendjari, Triad), sandstone structural units (Buem, Togo), Atacora, Birrimian basement (see geological description) and iii) Liptako-Gourma only Birrimian/basement units. Additional information, when available, may also have been used.

An important number of chemical results should be handled carefully as the ionic balance is higher than 5%. The synthesis by country is given below:

Country	Number of chemical data	N. of data with ionic balance ≤│5│%	N. of data with ionic balance >│5│% and ≤│10│%	N. of data with ionic balance >│10│%
Mali	30	13	5	12
Burkina Faso	94	94	-	-
Niger	60	60	-	-
Ghana	86	76	9	1
Togo	69	58	2	9
Benin	109	109	-	-

In Togo, the ionic balance >10% is due, except for 1 sample, to an excess of anions or deficit of cations. The results with error balance >│10│% were not used. In Mali, only 18 (of 30) set of chemical data can be used. For a great majority of the samples there is a cation excess. The chemical data interpretation will therefore be limited.

4.3. Liptako-Gourma:

Location of the sampling points in the Liptako-Gourma area is shown in Fig. 16.

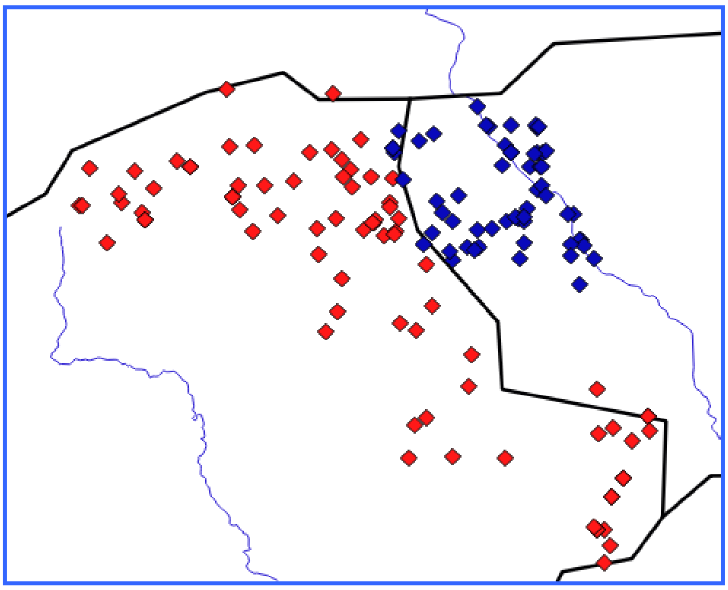

Figure 16: Location of the sampling points in the Liptako-Gourma sector (Burkina Faso (red) and Niger (blue)

Groundwater of this sector is of Ca-Mg-HCO_3 and Ca-Mg-Cl (NO_3)-SO_4 type (Fig.17). One of the main factors for anion variability is the nitrate content. NO_3 concentrations vary from <LQ (0.5 $mg.l^{-1}$) up to 1483 $mg.l^{-1}$ (Famale, Niger). Sulfate and chloride are often of much less important (in meq/l) than nitrate.

Only one sample in Burkina Faso (C80) has high SO_4 content. Ca, Mg and Na are of similar importance. Potassium represents usually less than 5% of total cations.

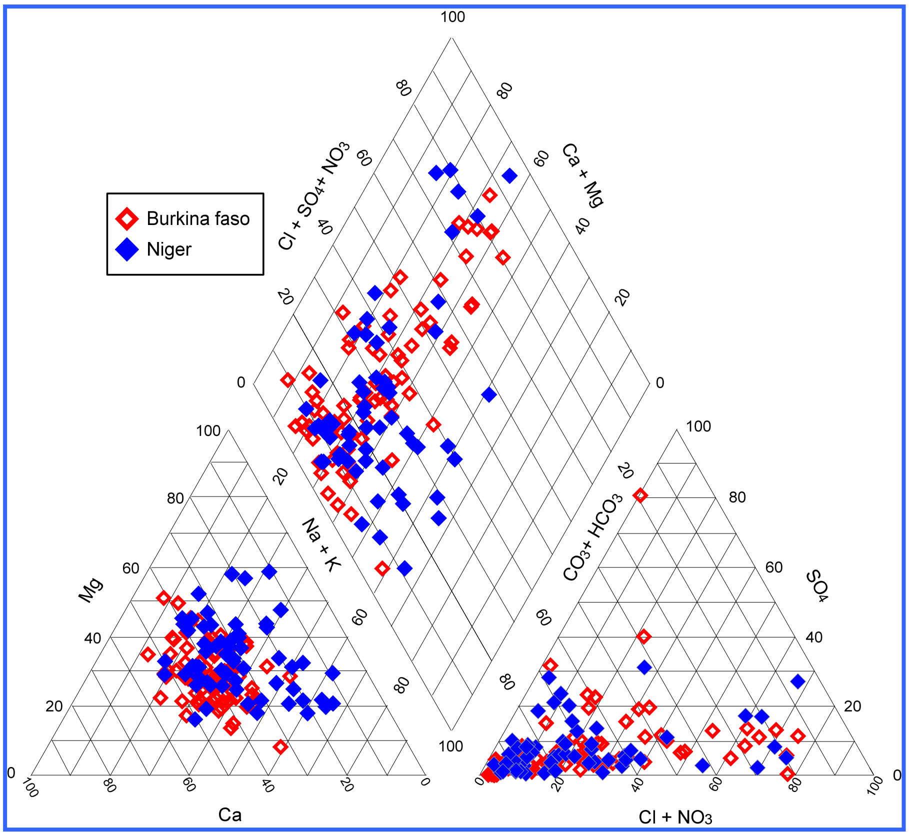

Figure 17: Piper diagram for the Liptako-Gourma sector

In Burkina Faso and Niger only groundwater from basement/crystalline rocks were sampled. Birrimian and granitoids formations were not identified in Burkina Faso or in Niger. Only 3 river samples were taken in Burkina Faso. On Fig. 18 the ratios (Na+Mg)/ (Na+K) vs total cations are presented. There is a great dispersion of the sampling points thus confirming that the cation exchange process is not dominating in the studied area.

Part of the chemical variability can be attributed to the impact of human activities and mainly waste water and fertilization input reflected in the nitrate content variability. As there is no source of chloride identified in the geological formation, the Cl is mainly issued to domestic waste water and therefore correlated quite well to nitrate except for C80 sample sites.

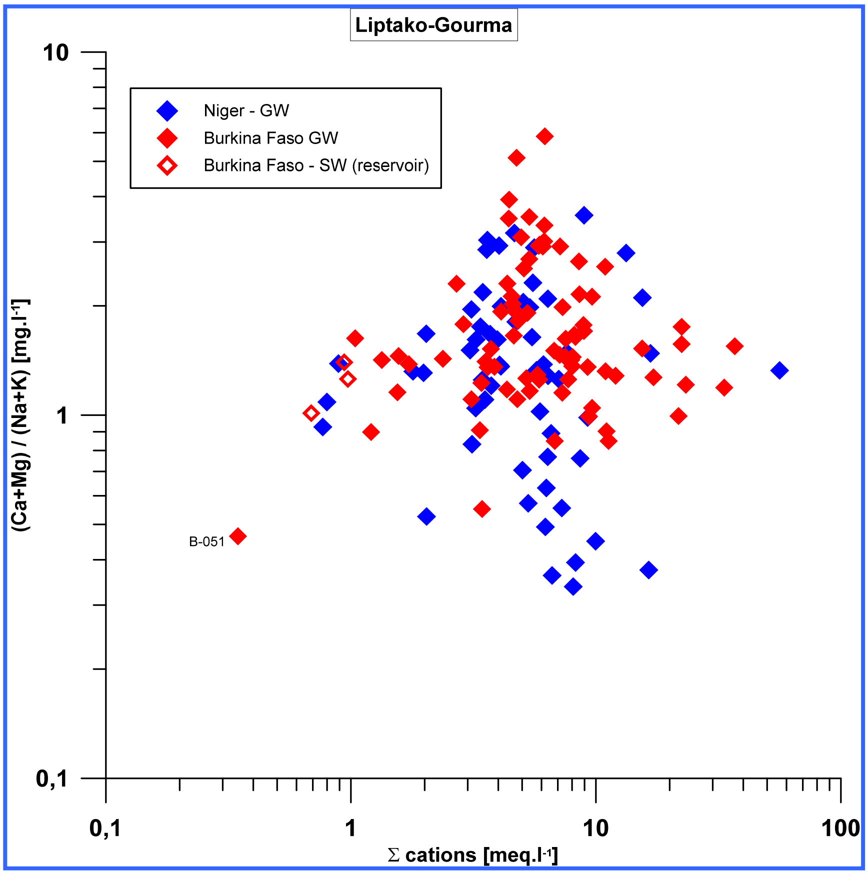

Figure 18: Cationic exchange evidence in the Liptako-Gourma sector

The two water drinkable limits are plotted in the figure and it can be seen that a great majority of the water collected have higher NO_3 and Cl concentrations. The highest concentrations in Cl are related to high Ca, Mg, Na, K (except C80) indicating long residence time and multiple pressure source. The nitrogen contamination can be at sampling points (wells, borehole) scale due to lack of protection measures but it is possible that, in some sectors, the contamination is more diffuse and extend to a larger scale. Local studies may be carried out to confirm the extent of the contamination (Fig.19).

As the area of concern is quite urge and there is a lack of information on the characteristics of sampled wells, it is difficult to show the possible surface/groundwater influence or any differences between samples taken from the colluvium materials, the weathered part of the basement or from fractured basement.

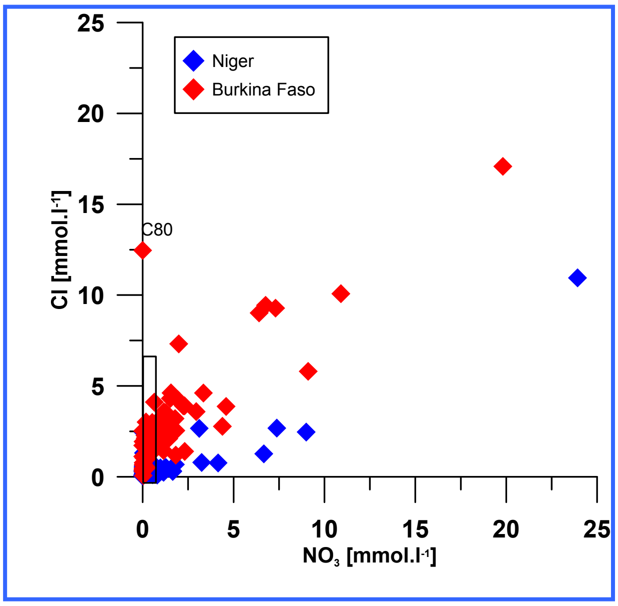

Figure 19: Cl vs NO_3 relationship in the Liptako-Gourma sector

In the stable isotopes graph (Fig.20) the surface water samples plotted along an evaporation line with a slope of 4.83. Most of the groundwater samples are also falling onto this evaporation line. Evaporation of the water can occur during precipitation, infiltration of water through the soil and unsaturated/weathered zone. Evaporation may take place after sampling if conservation procedures are not strictly followed. We considered here that the water sample storage was adequate and no isotope fractionation occurred after sampling. The intercept between evaporation line and the Niamey precipitation line is much closer to Niamey's rainfall weighted average determined using Niamey GNIP station for the more recent data.

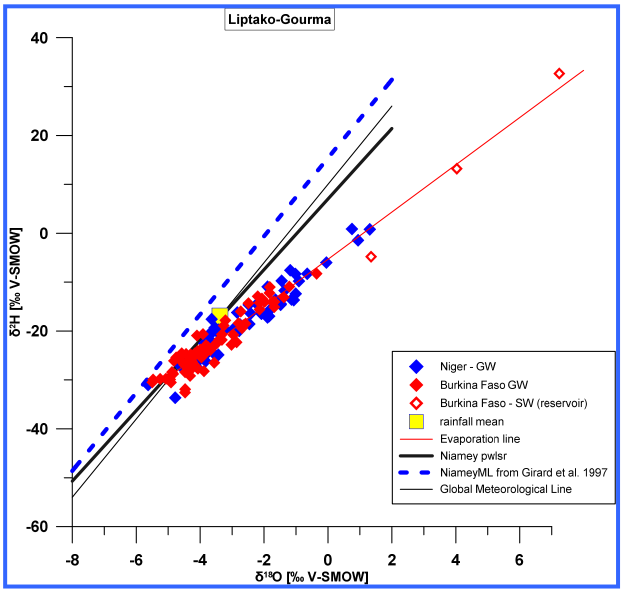

Figure 20: Global distribution of the stable isotope data in the Liptako-Gourma sector

The d-excess of groundwater is highly variable from -9.7 to +14.04 ‰. It has not been possible to link d-excess to the maximum depth of boreholes/wells or to the spatial distribution of the samples. Dray et al. (1978) showed that the "old" groundwater in this sector may have isotope composition of $-8<\delta^{18}O<-6$‰. No water samples have tritium content below detection limit in the present study and $\delta^{18}O$ lower that -6‰confirming that no groundwater may be considered as pure "old" groundwater. However, groundwater with lowest isotope values and no/low evaporation may be considered as quite protected and/or with part of the oldest component.

The water samples with $\delta^{18}O$ contents ranging between -5‰ -1‰ present low nitrate content (Fig. 21). For most of the isotopically depleted samples, groundwater may be considered as more protected against a direct infiltration of contaminant or, less probable, under denitrification process. Groundwater in these sectors is most probably of greater mean residence time. This may correspond to fractured basement but not enough information is available on sampling wells to confirm this hypothesis. For the most isotopically enriched samples ($\delta^{18}O > -1$‰) nitrate concentrations may be much lower due to surface water dilution such. Most of the sampling points are located closed to Niger River. In some of the isotope depleted samples (in both Niger and Burkina Faso) some relatively high nitrate concentrations (max. 23.2 $mg.l^{-1}$) and tritium higher than detection limits were observed. A mixture of relatively old and young water may explain such pattern. Also, present-day recharge during the rainy season (where monthly average of $\delta^{18}O$ may be lower than -5‰) may occur. This would mean a very low flow within the aquifer around the sampling well or sampling not properly carried out (not pumped and only the superficial and recently recharge water was sampled). In addition, ephemeral rivers or hand-made ponds may directly infiltrate during intense rainfall events.

The tritium content of today's precipitation is not known by direct measurement of rainfall. Data of one year (2012) rainfall water taken at Cotonou indicates that tritium is ranging 1.3-2.3 TU. The highest values (max 9.1 TU at B220) indicate post-1960s recharge (or possible terrigenic production from the presence of U, Th, Li and B, Andrews and Kay, 1982). Rain in Kobio (Niger River, closed to Niamey) was 8.9 UT in 1989 which represent about 3 TU in 2015 corrected for radioactive decay. Considering that tritium content higher than 3 would indicate the presence of part of the "tritium pic" component (1960-1970), more than 60% of the samples collected would be a mixture of such water and today's precipitation. This is quite classical in the fractured zone of hard-rocks formations while the weathered zone may contain younger water.

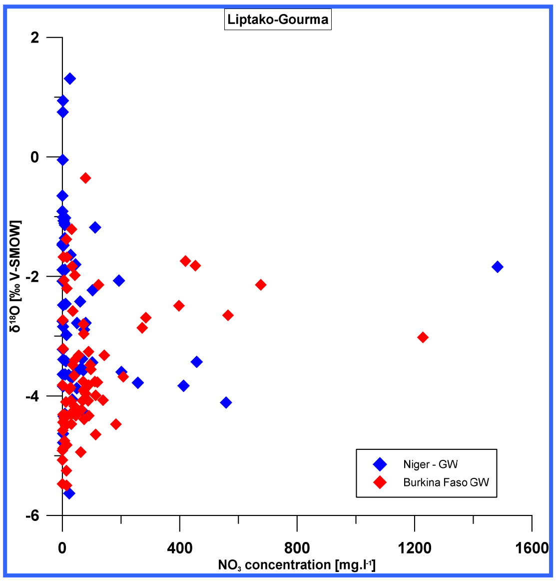

Figure 21: $\delta^{18}O$ *vs* NO_3 in the Liptako-Gourma sector

We could not find any correlation between any chemical elements and isotope data. Also statistical analyses (PCA, CFA) do not show correlations between measured parameters. Previous studies (expert mission report by Gourcy, 2015) showed that, in Niger, the most significant parameter that may explain great part of the isotope variability is the distance to the Niger River. Also, it was demonstrated that water samples taken in wells exploiting both alluvial and basement formations are diluted.

4.4. Gondo-Sourou:

The location of sampling points is shown in Fig. 22. There are only 11 samples from Burkina Faso with chemical and isotope data. The only lithological information on these samples is "sédimentaire" or "crystalline" and this indication is missing for some samples. Samples were not identified as part of the Sourou basin and has been identified from the whole set of samples from Burkina Faso by a geographical approach.

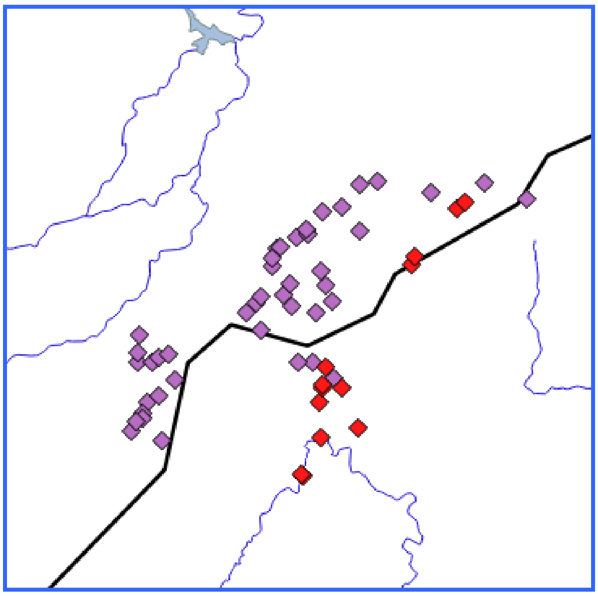

Figure 22: Location of sampling points with chemical analyses for Gondo-Sourou sector (Burkina Faso (red) and Mali (violet)

Hydrochemical information for Mali's samples is available for the Tabular Infracambrian formations ICT (5 samples), Infracambrian plissé ICP (5 samples) and Continental Terminal Quaternary CTQ (20 samples).

As indicated before some chemical data from Mali samples could not be used due to analytical problems. The Piper diagram was built without the data with an ionic balance higher than 10%.

Groundwater is mainly of Ca-Mg-HCO_3 type. Few samples from Mali are enriched in sulfate, others in chloride. The great variability of samples from Mali may be due to analytical problems (Fig.23). For Burkina Faso, 2 samples were enriched in sodium. Groundwater at these points presented high NO_3 concentrations.

The high content of sulfate has been identified in the Gondo plain as a groundwater management problem. The origin of high SO_4 content in groundwater may be presence of sulfur mineral in the geological formations (carbonated rocks) in some sectors (Groen et *al.,* 1988; Bethemont et al., 2003). Water of crystalline formation in Mali has low mineralization (conductivity varies between 12 to 130 $\mu S.cm^{-1}$) except Kouri.

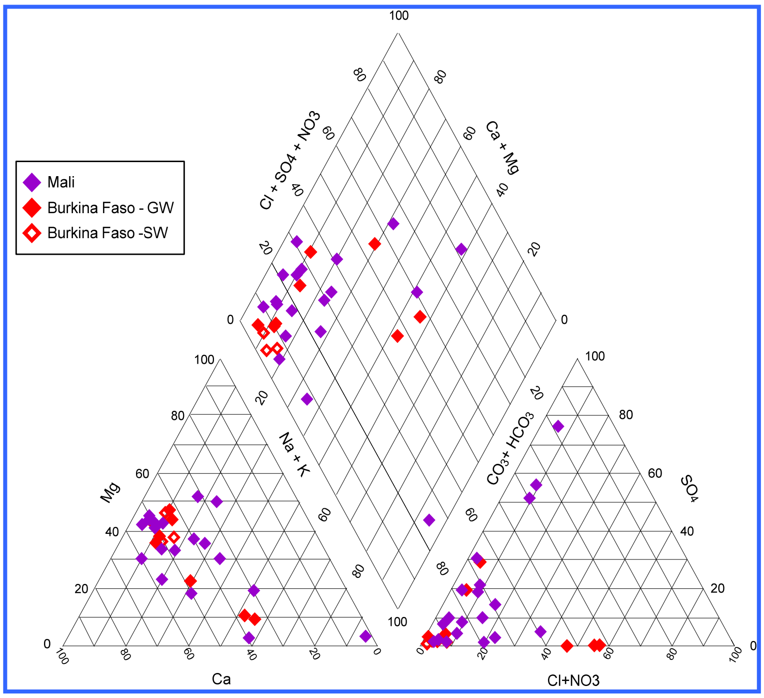

Figure 23: Piper diagram for the Gondo-Sourou sector

Fig. 24 is showing the possible existence of cation exchange for a few samples collected in Mali and Burkina Faso. The more chemically evolved sample, Gangafani is located in the north-eastern part of the studied area. The samples from the ICP have the highest Ca+Mg / Na+K ratio due to the dominance of limestone for this formation.

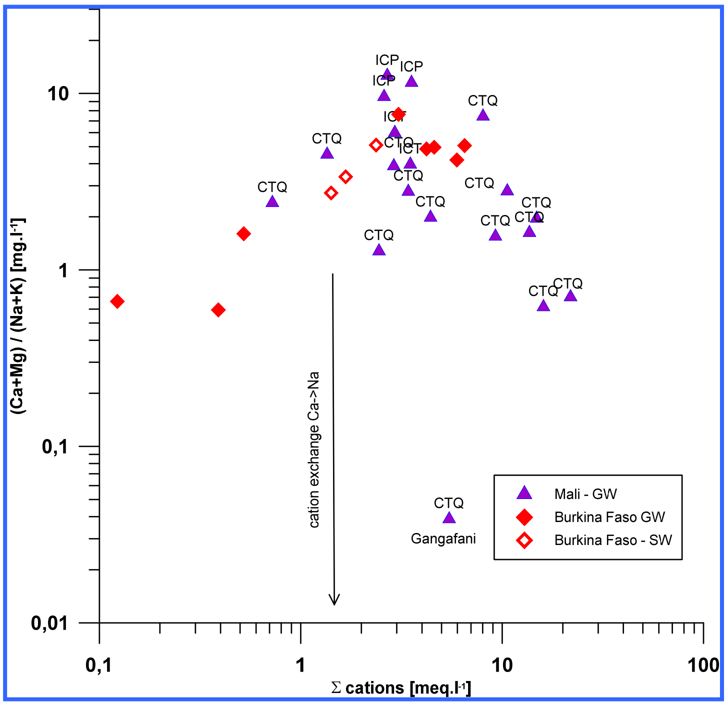

Figure 24: Cationic exchange evidence in the Gondo-Sourou sector

In Burkina Faso nitrate concentrations are not very high in the Sourou plain. Two samples have NO_3 concentrations higher than 10 $mg.l^{-1}$ and low Cl concentrations indicating most probably organic origin of nitrogen (waste water or organic animal dejection).Surface water as well as two groundwater samples have both low content of Cl and NO_3 (Fig.25).

In Mali three samples present very high NO_3 concentrations (>49 $mg.l^{-1}$), Koulongon –Peulh, Thiondougou, Sirakele. Koussoube (2010) suggested that SiO_2 is a good indicator of possible drainage of water from deepest aquifer (Infracambrian). This cannot be seen using the sampling point selected for this study. Three samples (Souhe, Thiondougou, Diallasagou) have high conductivity linked to high SO_4, Na and Cl concentrations (Fig.26). The wells are located in the central southern part of the Gondo-Sourou plain. As discussed earlier, isotope data from Mali could be classified in the three hydrogeological formations dominated the studied area; CTQ (Continental Terminal Quaternaire), ICP (Infracambrien plissé) and ICT (Infracambrien tabulaire). Unfortunately, the wells/boreholes sampled in Burkina Faso could not be identified in terms of the dominant lithology.

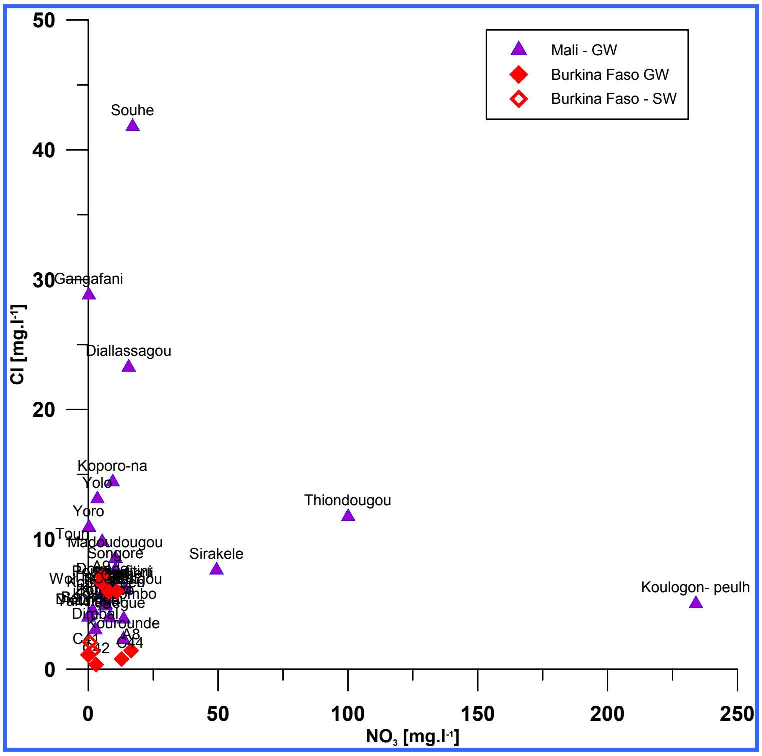

Figure 25: Cl *vs* NO_3 in the Gondo-Sourou sector

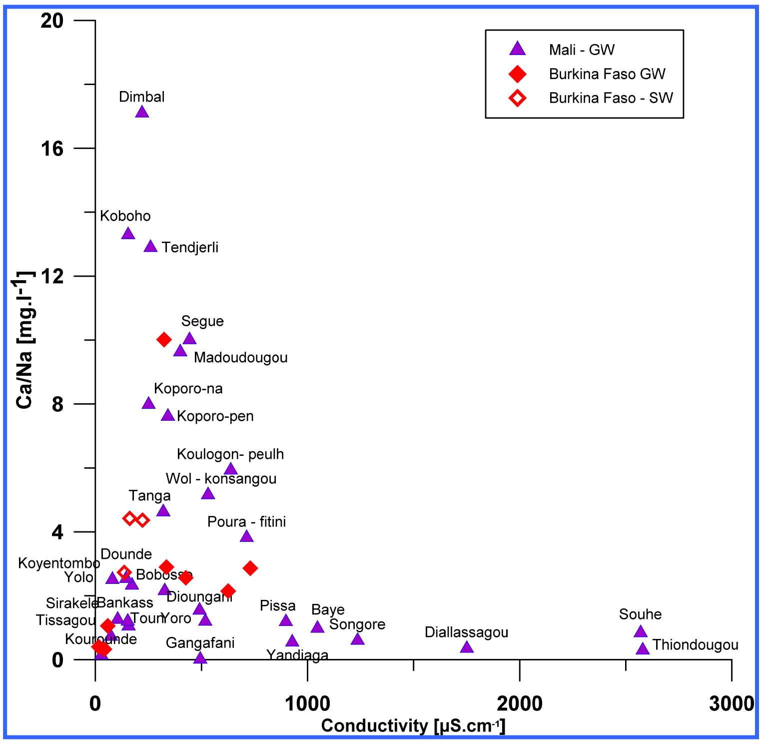

Figure 26: Ca/Na vs conductivity in the Gondo-Sourou sector

The Global Meteoric Water Line and the Local Meteoric Water Line (LMWL) rainfall lines already established are presented in Fig. 27. Surface water data plots along an evaporation line of slope 4.78. The rainfall mean isotopic value calculated for the period 2014-2015 is quite enriched comparing to groundwater samples not evaporated. The input signal calculated by Dakouré (2003) may be used instead.

Four sampling points from Mali from the CTQ are more strongly evaporated or are falling in a different precipitation line, Baye, Songore, Pissa and Souhe. Three samples having a d-excess around -7‰ were taken in the same sector. These samples are in the CTQ, the upper and therefore more vulnerable aquifer. These samples also present high conductivity. No chemical information is available for these samples. Two of these samples (Pissa and Songore) have very low tritium content (<0.3 TU) so may have part or are mainly old (recharge before 1960).

For stable isotopes (Fig.27) there is no difference between the ICP, ICT and CTQ except for the four samples mentioned above.

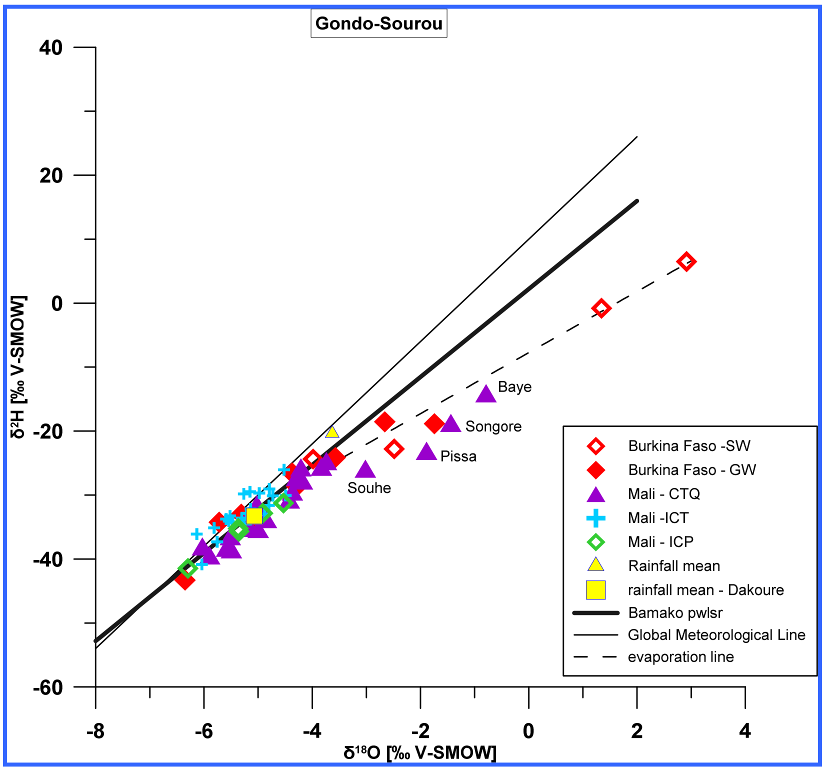

Figure 27: Global distribution of the stable isotopes data in the Gondo-Sourou sector

A PCA carried out using Burkina Faso and Mali data is showing a correlation between all chemical elements and the stable isotopes data (Fig.28). The x axis is defined by the mineralization, the samples Songore, Baye, Pissa, Souhe, Thiondougou, Dialassagou (Mali) being well represented in the right part of this axes.

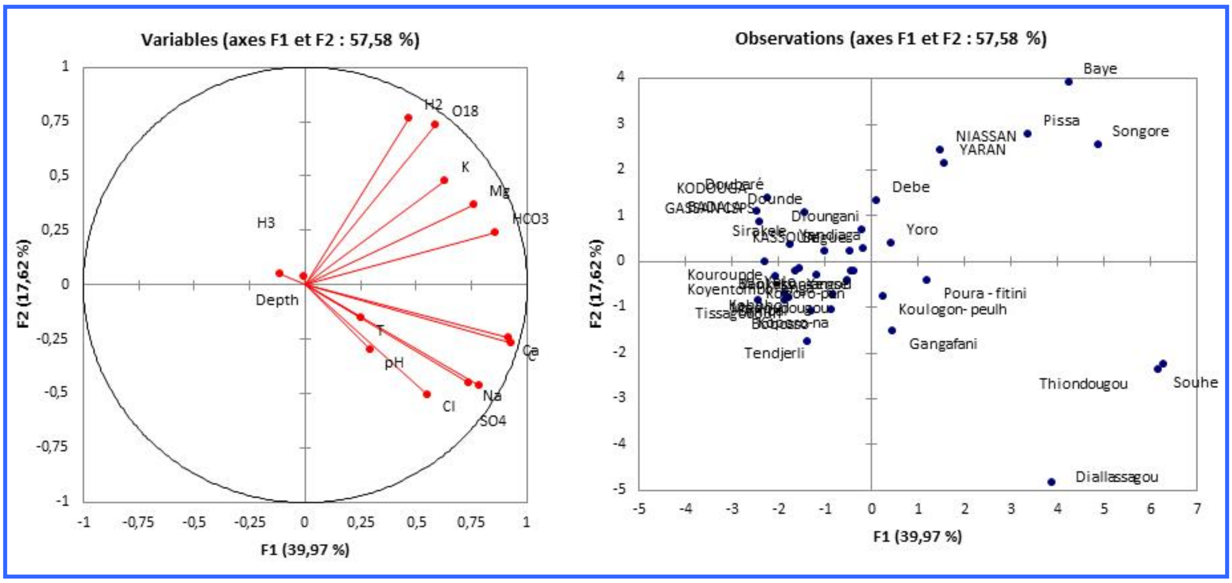

Figure 28: PCA for samples of the Gondo-Sourou sector

Considering only the data from Mali, where sample location is better identified, it is clear that the samples with highest$\delta^{18}O$ are from the CTQ (superficial layer) and corresponds to shallow wells (Fig.29).

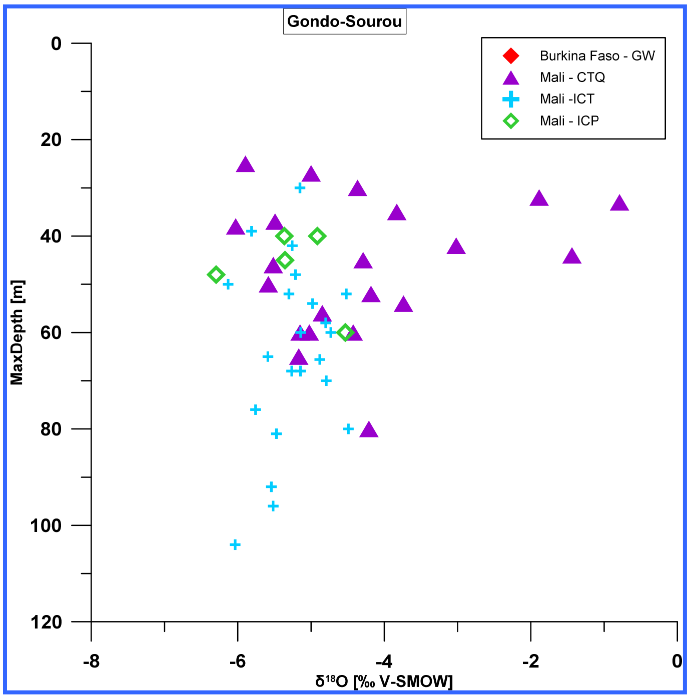

Figure 29: Relationship between the max depth of wells and the $\delta^{18}O$ content of groundwater in the Gondo-Sourou sector

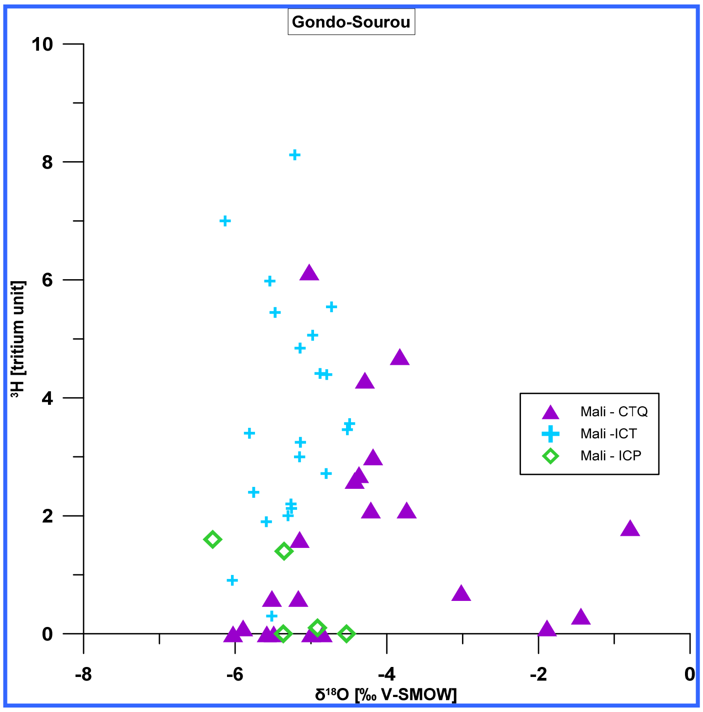

Figure 30: Tritium *vs* $\delta^{18}O$ contents of groundwater in the Gondo-Sourou sector

Groundwater may be quite old as tritium values vary from 0 to 1.6 TU (Fig.30). Groundwater may be in semi-confined aquifer with low recharge. The sector of concern is between Madoudougou and Wol-Kansangou.

Samples from the deepest aquifer (ICT) show the highest range of ^{3}H values. The four samples with highest conductivity have the lowest ^{3}H values (Fig.31). Very old water with long transit time and therefore intense water-rock interaction may explain this negative correlation. In addition some geological lithologies that can be preferentially dissolved should be present (limestone, evaporites).

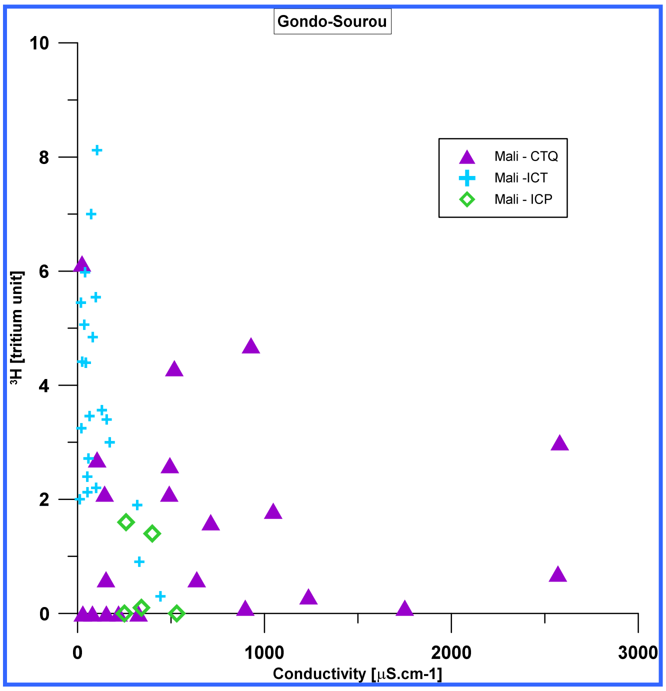

Figure 31: Tritium *vs* conductivity of groundwater in the Gondo-Sourou sector

In 2003 Dakouré (Dakouré, 2003) considered that samples with tritium content higher than 5 TU would represent present-day precipitation. The reservoir water (Doubare, BKF) could be considered as representative of present day's precipitation. The ^{3}H of one sample taken in February 2016 is 1.6 TU.

In parallel, monitoring of the Kou River (BKF) from December 2013 to December 2015 indicated ^{3}H values varying from < DL (0.4 TU) to 0.6 TU. In 2013, some highest values (up to 4 TU) were detected. However, no information of the sampling sites and the importance (and its variation) of the groundwater participation in the surface water flow is available and this information is therefore difficult to use.

Having no other tritium data from precipitation and considering the difficulties in interpreting the Kou River data, we could consider that 1.6 is a good approximate for today's input signal. Most of the ICT samples are water from the 1963 pick up to now with mixing ratios. The samples with highest ^{3}H are located in the southern part of the studied area (Mafoune-Tene). For this studied area, it is difficult to go further in detail in the data interpretation due to lake of information on water samples.

4.5. Central Upper Volta sector:

Location of sampling points having chemical data is shown in Figure 32.

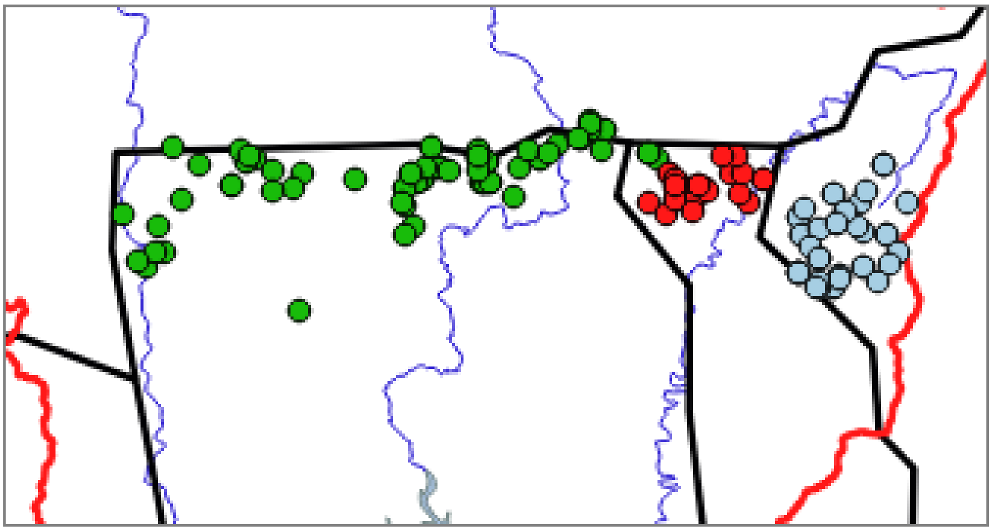

Figure 32: Sampling points for Central Upper Volta sector (Ghana (green), Togo (red), Benin (blue)

In order to prepare the syntheses of the existing data it has been first necessary to homogenize the information related to the information on "Aquifer Name". In Togo the samples are classified in Socle (basement), Triade (Oti/Pendjari) and grès (Sandstone). In Ghana only the basement was sampled.

A simplified "common" description for the lithology was proposed and used in the present document. The corresponding information is given in the table below.

Aquifer Name (used for data interpretation)	Lithology (as described in literature)
Basement	Birrimian
Sandstone	Buem
	Togo
Atacora	Atacora
Voltaian	Tamale
	Oti/Pendjari (Triade)
	Dapaong

Groundwater of the Central Upper Volta sector presents a great variability of chemical facies (Fig.33).

Ghana's water is more homogeneous as sampling concerned only basement aquifer. It has a chemical evolution along the Ca: Mg mixing line for cations and variability in anions' due mainly to $Cl+NO_3$.

In Togo, except three samples enriched in sulfate, the anion's triangle in the Piper diagram does not show evidence of a strong geochemical evolution. For cations, Na+K may represent nearly 100% of the total cations and 91.6% for Na, K being of less importance. Groundwater evolves from $Ca\text{-}Mg\text{-}HCO_3$ to Na (K)-HCO_3 type. In Burkina Faso, two samples are also quite enriched in SO_4, compared to the relative abundance of other anions.

In Benin, cation dispersion in the Piper diagram is high, while anions are more homogeneous. One sample (B831) from Atacora, with NO_3 concentration of $113.6 mg.l^{-1}$, is at the extreme right of the $Cl+NO_3$ axis. The two other sampling points from Benin having an important proportion of nitrate are from the Atacora aquifer.

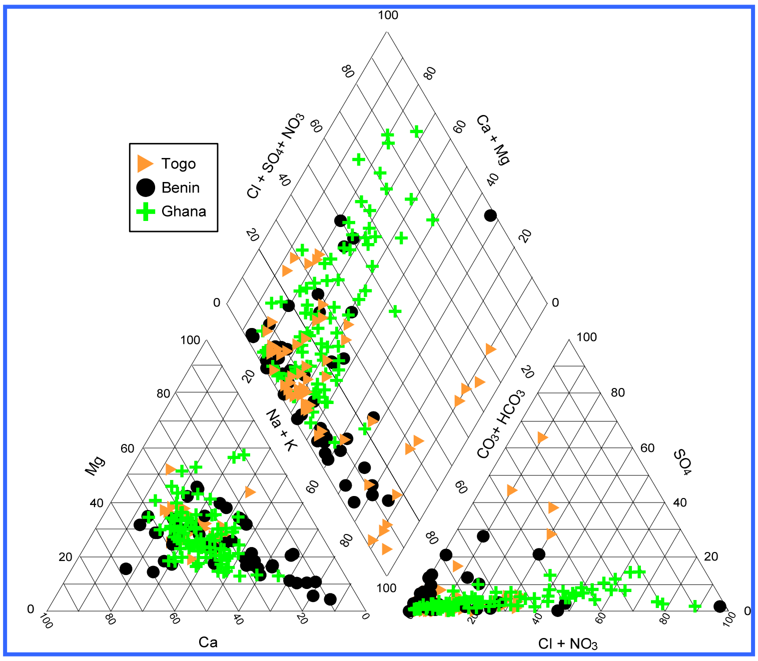

Figure 33: Piper diagram for the Central Upper Volta sector

Fig. 34 provides clear evidence of cation exchange affecting some samples of the Voltaian formation in Benin and Togo. The samples are located in the North-Eastern part of Togo (Oti region) and north-western part of Benin corresponding to the Pendjari formation (for most of samples). Therefore, the cation exchange is affecting the sedimentary aquifers more than the hard-rock aquifers and more the Voltaian than the sandstone (sandstone s.s. and Atacora).

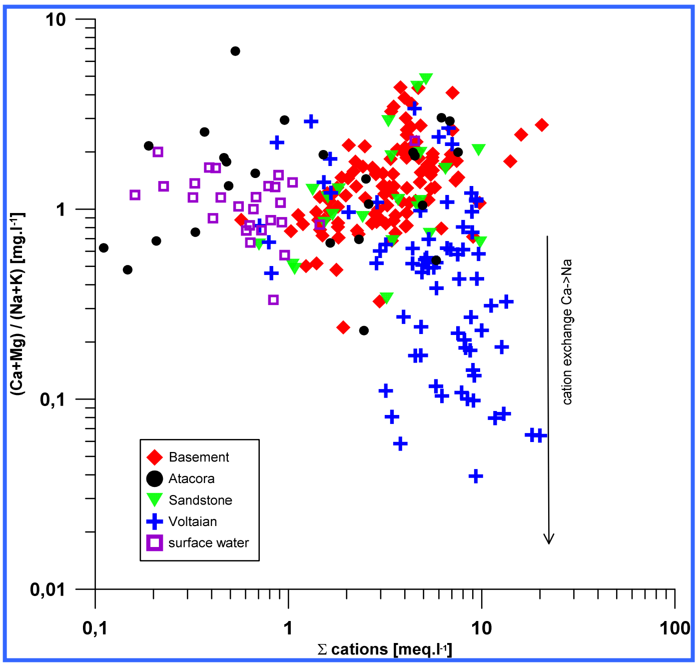

Figure 34: Cationic exchange evidence in the Central Volta sector

Looking at the hydrochemical vulnerability index as described by Meyzonnat et al. (2015) we see a quite regular evolution from groundwater in the basement formations being highly vulnerable, to aquifers in the Voltaian sedimentary aquifer (Fig.35). The same samples that are showing cation exchange process (Fig. 34) are the ones being less vulnerable. Two samples from the sampling point Adbadia EA Islamic (sampling campaigns 1 and 2) have the highest chemical vulnerability index.

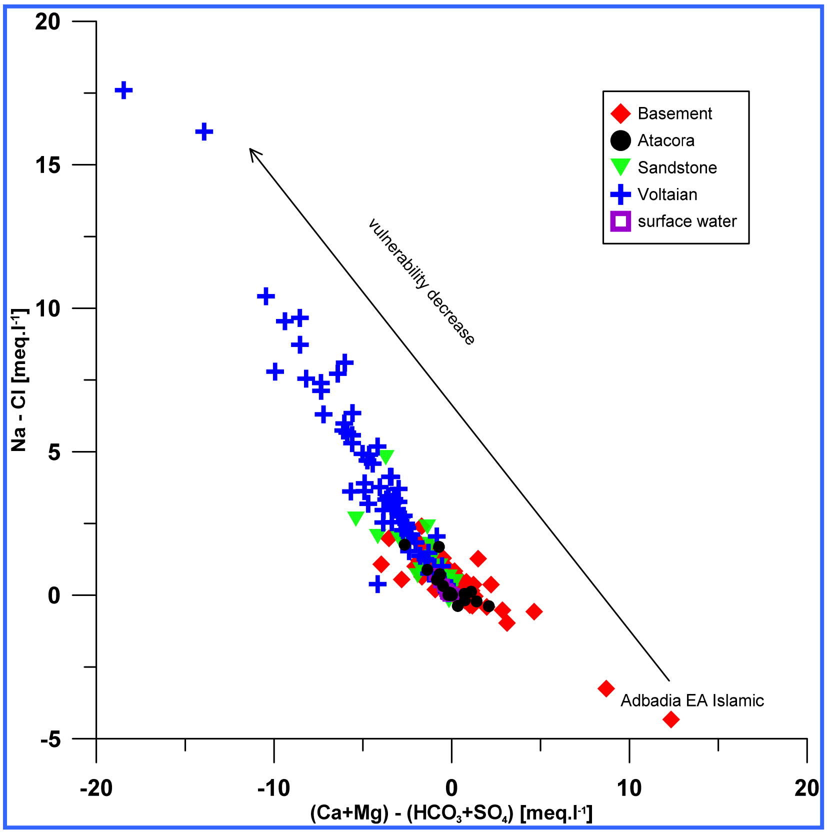

Figure 35: Hydrogeochemical Vulnerability Index in the Central Volta sector

A hydrogeochemical vulnerability Index (HVI) has been attributed to each groundwater sample from its orthogonal projection on the linear regression line. The number of HVI classes was kept to 5 and used thereafter.

The relation between nitrate and chloride is showing that the high nitrate content is related also to high Cl concentration (Fig. 36). This is usually due to anthropogenic impact from urban and agriculture origin (organic N). The highest concentrations of NO_3 are always for

HIV category 5. Some highly vulnerable groundwater from the geochemical point of view can present low nitrate content, partly due to denitrification processes.

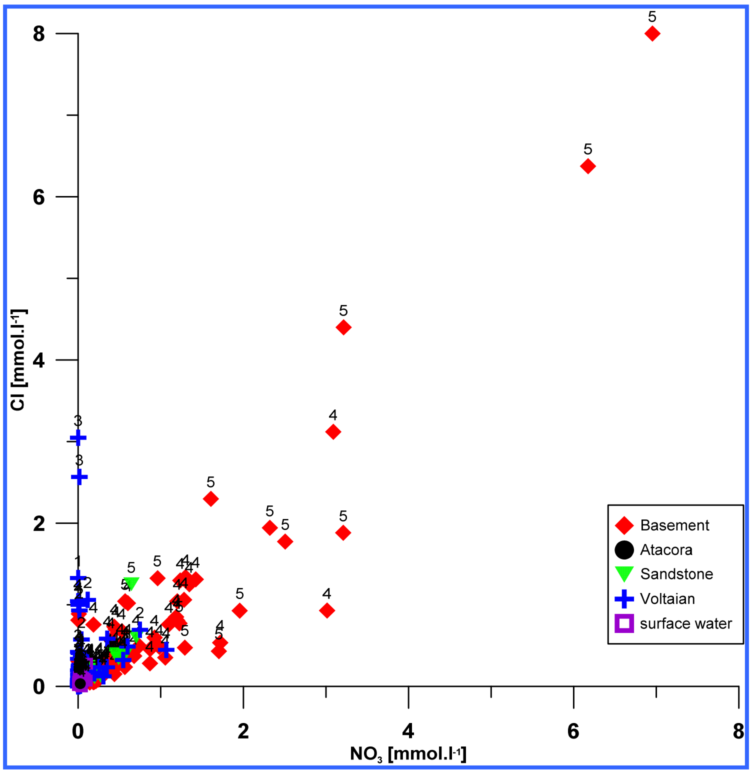

Figure 36: Cl *vs* NO_3 contents in the Central Volta sector

The HVI categories 1, 2 and 3 are located eastern part of Benin and North western part of Togo where are the sedimentary formations. However, sandstones and Atacora formations are mainly of HVI 4. Therefore, only the Voltaian formation of the sedimentary aquifers is of low chemical vulnerability.

The presence of cation exchange processes and the indications of lower chemical vulnerability indicates that the groundwaters of the Voltaian aquifer is of longer residence time. Looking at the geographical position of the sampling points and the Ca/Na (indicating cation exchange) it is possible to determine the flow direction within this geological formation. For some points (usually of HVI 4), along the flow line, local/direct recharge is possible.

For stable isotopes, the surface water samples fall on an evaporation line with a slope of + 5‰ (Fig. 37). As for the other sectors, we see that the average value of precipitation samples from 2014 and 2015 is quite enriched comparing to the major part of groundwater samples. Two years of data is not well representing the input signal. For the majority of groundwater samples values ranged from -6‰ to -2‰ for $\delta^{18}O$ and from -40‰ to -20‰ for $\delta^{2}H$.

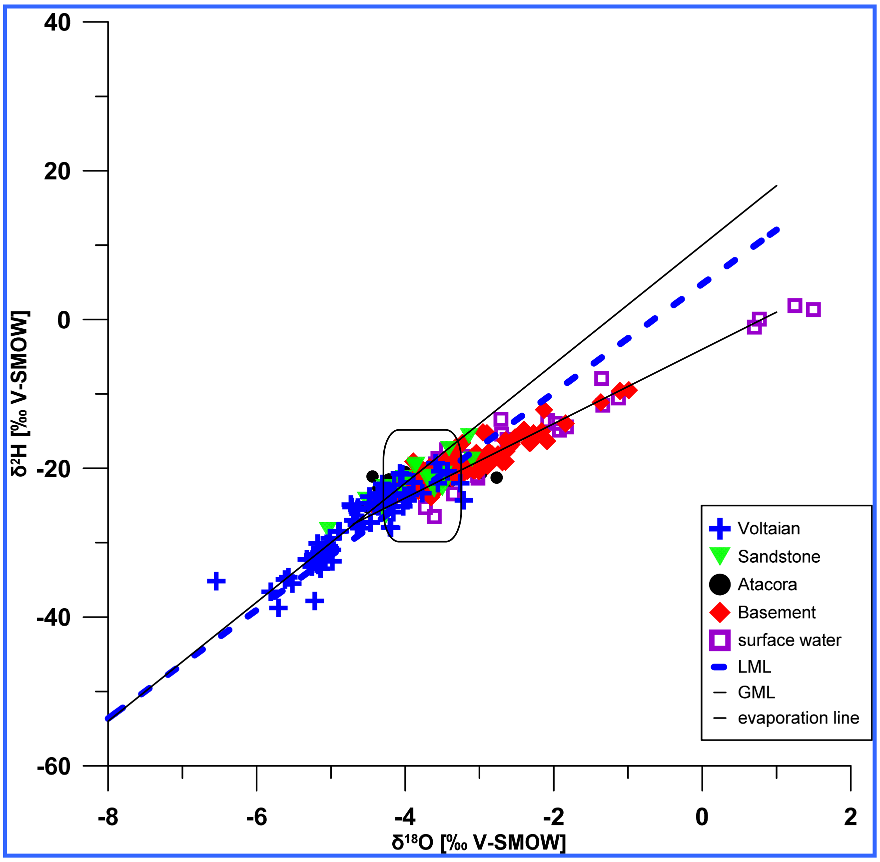

Figure 37: Global distribution of the stable isotope contents in the Central Upper Volta sector

Dispersion of $\delta^{18}O$ and $\delta^{2}H$ values around the LMWL is quite high for the Voltaian formation however few groundwater samples are showing high evaporation (Figs. 37 and 38). In Togo groundwater samples plot perfectly on the LMWL and only surface water is showing evaporation process. On the contrary nearly all Ghana groundwater samples are evaporated being all in the basement formation. The "starting" point of groundwater isotopic composition is closed to -4‰.

Groundwater from the Voltaian formations is the most depleted isotopically while the water from basement hard-rocks formation are the most evaporated (Fig. 37). Water from sandstones and Atacora is falling closer to the precipitation average signal with few exceptions. In Ghana, the sampling was carried out only in the basement formation at low depth therefore the isotope data is reflecting evaporation and today's precipitation signal.

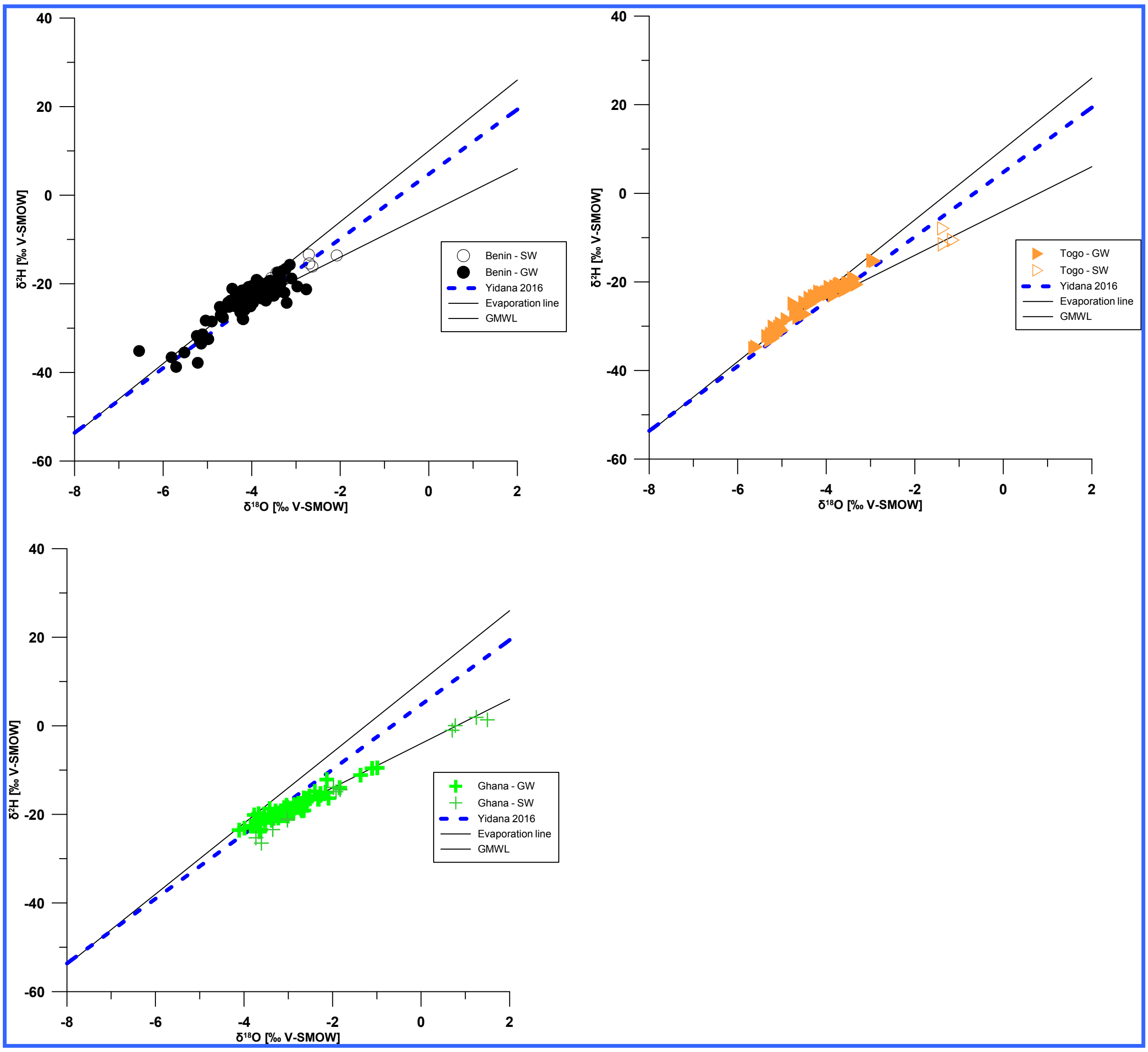

Figure 38: Global distribution of the stable isotopes data in the Central Upper Volta sector for each country

Tritium data is confirming that the Voltaian groundwater is the oldest and then the less influenced by evaporation and today's precipitation (Fig. 39).

As for the other studied sectors, there is no tritium data for recent regional rainfall. Then the tritium input signal could be deduced from data from surface water. Tritium values range 1.6 to 3.4 TU for surface water sampled during the implementation of the IAEA-supported project RAF/7/011. The lowest values (1.6 and 1.7 TU) belong to samples from reservoirs in Ghana. It is possible that groundwater influences the isotope composition of this surface water. We may consider that the average tritium value for the input signal is comprised between 2.4 and 3.4 TU. Few samples from the basement (and one from Voltaian) are showing highest values indicating a recharge from 1963 up to now with different mixing ratio. Much of Voltaian water has very low tritium values, indicating groundwater of more than 60 years old (or great part of very old water). For lower ^{3}H values, the stable isotopes content ranges between -4 and -6‰ for $\delta^{18}O$. This variability may be due to the paleoclimate effect.

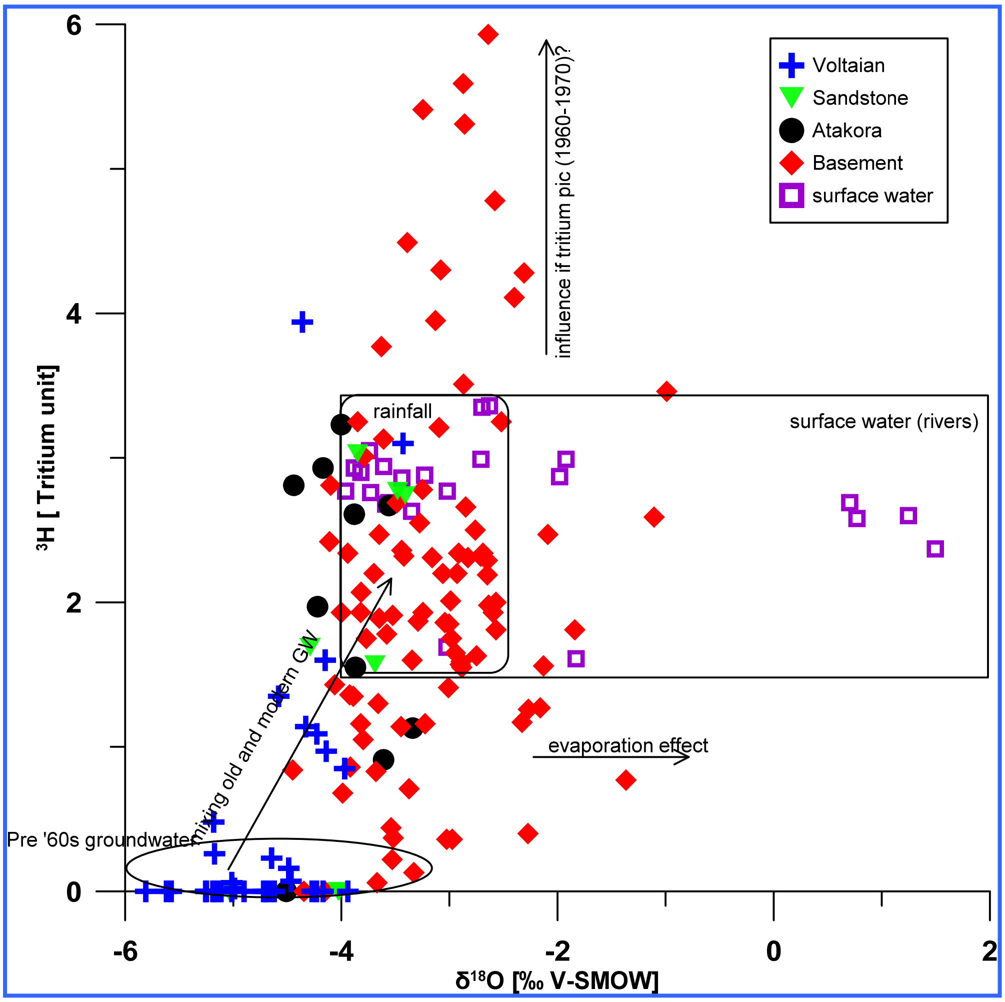

Figure 39: ^{3}H *vs* $\delta^{18}O$ contents according to the main lithological units in the Central Upper Volta sector

The geographical distribution shows an evolution from the eastern part of the studied area (NW Benin) moving from today's precipitation to oldest groundwater (no tritium water) in

NE Togo. The tritium values are spatially varying in North Ghana and West Togo indicating more recent recharge (Fig.40).

The Atacora and Sandstone formation have an intermediate position with significant tritium values indicating present days (1960-2016) recharge but lower range of tritium values due to a slower dynamic. This indicates that recharge by infiltration of surface water during rainy season (and intense rainy events) may occur for basement aquifers but would take more time through the unsaturated zone to reach groundwater.

As a synthesis, the dynamic of the recharge of the different aquifers could be classified from the faster to the slower: Basement/Birrimian> sandstone and Atacora>Voltaian. It is difficult to distinguish sandstones and Atacora formations in terms of hydrodynamic behavior partly due to the relatively small number of samples taken in this sedimentary context.

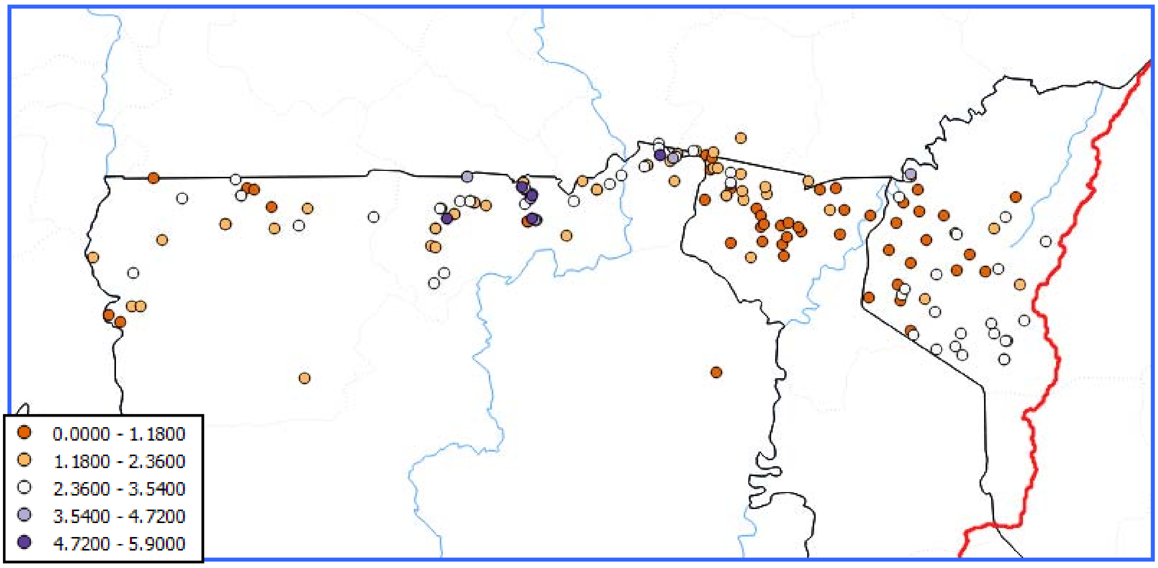

Figure 40: Spatial distribution of ^{3}H contents in the Central Upper Volta sector

For some samples the analyses of $A^{14}C$ and $\delta^{13}C$ was performed in order to estimate groundwater ages. For activity ^{14}C higher than 85 percent modern carbon (pmc) tritium values were systematically higher than 1 TU indicating the presence of "modern" water mixing with old groundwater. One sample (Nabame, Togo) with $A^{14}C$ of 51 pmc has also a tritium content of 1.6 TU as a result of mixture between old and more recent water.

For age dating, it is necessary to estimate the $\delta^{13}C$ of soils that is influenced directly by natural vegetation or crop. The selected sector is under Guinea and Sudan savannah agro-ecological zones dominated by crops and grazing of livestock. The major food crops cultivated include sorghum, maize, millet, groundnut, (Obuobie and Barry, 2010; Obuobue and Barry, 2012). The soil occupation can be considered to be dominated by C4 plants. Mean of $\delta^{13}C$ of C4 plants may be considered as -12‰ (average -15 to -20‰).

The main evolution of $A^{14}C$ vs $\delta^{13}C$ is done along the Y axis indicating few chemical processes (Fig.41). Using the graphical method proposed by Han et al. 2012, sample having tritium content (mainly basement) can be considered under open system conditions. Weathering of silicates is possible.

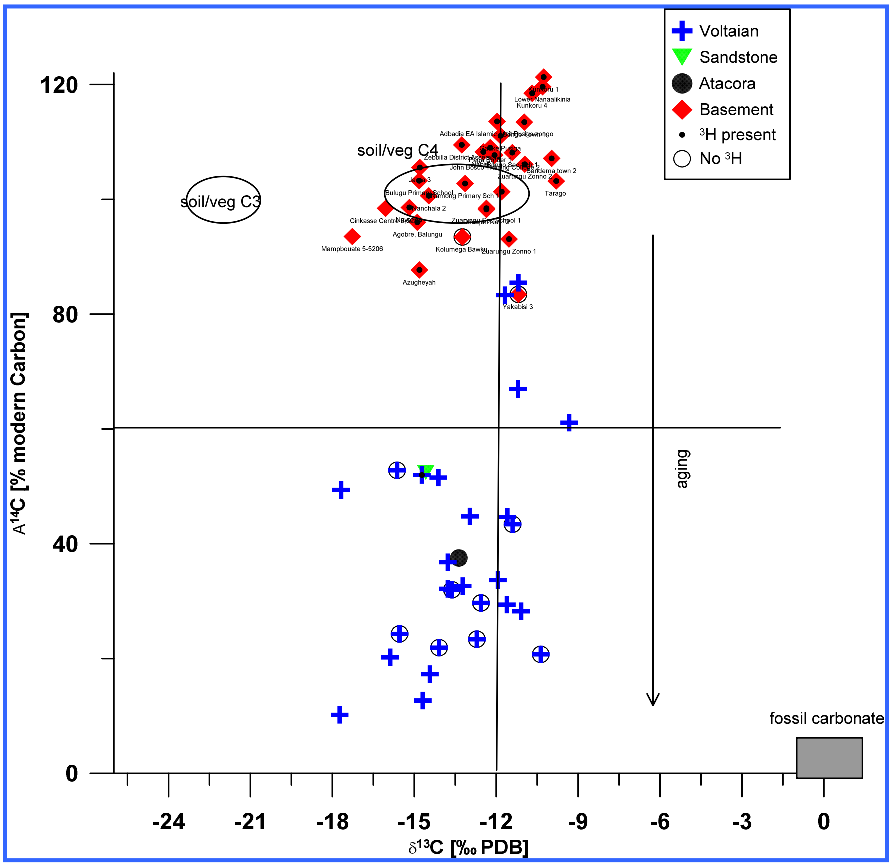

Figure 41: $A^{14}C$ versus $\delta^{13}C$ in groundwaters of the Central Upper Volta sector

For age estimation, the missing temperature data was replace by 31°C while samples with no pH or chemical information could not be treated. The typical $\delta^{13}C$ content of organic matter in the soil was estimated as -12‰, while $\delta^{13}C$ of the mineral phases was chosen as +0.8‰.

The oldest groundwater, using Evans model, are ranging 800 to 22,400 years. The "youngest" groundwater is usually mixed with modern water. There are about 30 groundwater samples presenting very old water. All are located in Voltaian formation in Togo and in Benin (also one sample in Atacora and one in Sandstone).

Groundwaters without tritium and/or with low ^{14}C activity (less than 84 pmc) are considered as "old" waters and are not influenced by modern precipitation, show the most depleted isotopic values ($\delta^{18}O$ lower than -4.95‰ and $\delta^{2}H$ lower than -31.1‰) (Fig. 42). The oldest groundwaters may provide information on paleo recharge conditions (recharge under lower air temperature). Some old groundwaters may show an evaporated signal (based on stable isotope contents), showing that evaporation can take place during recharge and it is therefore not related always to a direct influence of surface waters or high vulnerability to pollution.

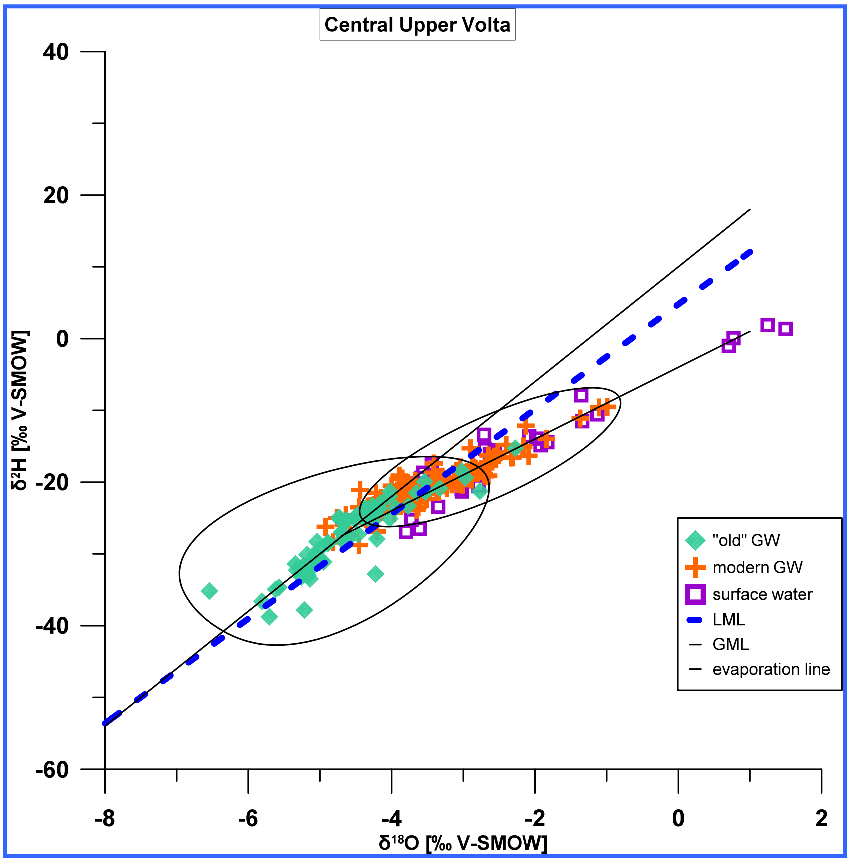

Figure 42: Global distribution of the stable isotope data for groundwater having age information in the Central Upper Volta sector

Finally, a statistical data analysis was performed for groundwater samples from Central Upper Volta sector having common information (n=234). The PCA is showing that stable isotope data are opposite to Na and HCO_3 in the Y/F2 axes, indication of long residence time and ionic exchange. A PCA using only the samples having ^3H data (n=146) is confirming this pattern (Fig. 43).

The CFA (corresponding factor analysis) confirmed that the hydrogeochemistry of Voltaian and basement samples are the more differentiated while Atacora and Sandstone water have less chemical specificity (also there is less water samples from these two geological formation).

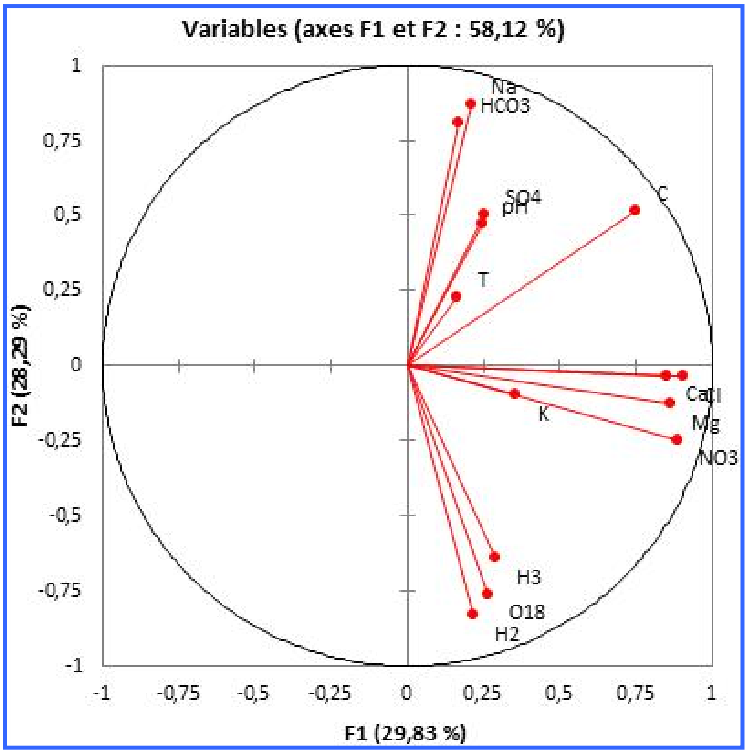

Figure 43: PCA for GW samples having complete dataset including ^3H (n=146) for the Central Upper Volta sector

5. CONCLUSIONS

Hard rock/ basement aquifers

The hard rock aquifers studied within the IAEA-supported project RAF/7/011 are covering a large part of the Upper Volta Basin from North Benin, Togo and Ghana up to south-western part of Niger, area sometimes identified as the Liptako-Gourma.

In these geological formations, two main aquifer systems can be identified: the weathered zone aquifer system (regolith aquifers) and the fractured zone aquifer system. Recharge in basement was assessed to be 100-160 mm/an (or 10-16% of annual precipitation) in West Benin and Ghana (Seguis et *al.,* 2011; Obuobie and Barry 2012). The source of recharge to the aquifers in Ghana, particularly aquifers in the north of the country is mainly through precipitation (Obuobie, 2008; Martin, 2006). In Niger, groundwater recharge is lower, around 1-13 mm/a (Barry and Obuobie, 2012).

Groundwater abstraction is usually carried out through dug wells or collector wells quite superficial (10 to 60 m depth) as well as some artificial ponds, permitting water accumulation during rainy season. Thus the yield may be quite low and water may be missing at the end of the dry season. In North Ghana, current estimates indicate that there is today enough water for irrigation and other human activities (Akudago et al., 2009; Barry et al., 2010). However, the recent practices, based on the use of very shallow aquifers which get dry in part of the year, and the anthropogenic pressure, reflected in the presence of nitrate contamination, limit the use of groundwater resources.

The chemical and isotope data is confirming the existence of a recharge by precipitation or superficial (rivers) water infiltrating in specific areas during intense rainfall events or rainy season (August-September rainfall in the northern part of the Liptako-Gourma). Most of the groundwater samples were showing evaporated evidence, confirming a probable infiltration of surface water all over the studied area. In various sectors, ponds or small water retention areas were created for domestic use. These water infiltration points may also facilitate the transfer of contaminant such as nitrate. Most groundwater samples collected during the implementation of the IAEA-supported project RAF/7/011 presented high to very high (up to 1450 $mg.l^{-1}$) nitrate concentrations. Nitrate concentration occurs around the ponds and dug wells but, in some sectors, groundwater contamination may extend over larger aquifer area. Some data indicates a possible double origin of nitrate from sewage and from agriculture fertilizer.

The chemical variability of groundwater is therefore mainly driven by the importance of the human pressure reflected in nitrate contents. Surface water infiltration was clearly identified around the Niger River. Groundwater resources were located in the alluvial and basement aquifer. The river infiltration contributes to lowering nitrate concentrations.

Thus, the basement aquifers are highly vulnerable to global change (anthropogenic and climatic). However, various wells showed the existence of cation exchange and low tritium contents, indicating also mean residence time of groundwater of a few decades. Mixture between quite young and oldest groundwater was also highlighted. Additionally "old" groundwater may be evaporated during recharge and keep this signature with time.

The selection of sampling points and the great number of wells located in the weathered zone of the basement aquifers do not allow an overall evaluation of the groundwater resource in the Liptako-Gourma aquifer system. Furthermore, aquifers in hard-rock formations may be considered more as small and independent units than as extended uniform aquifers.

Sedimentary aquifers

In two sectors, sedimentary aquifers were studied; the Gondo-Sourou (Mali-Burkina Faso) and the Oti/Pendjari areas (Togo, Benin, Burkina Faso).

In the sedimentary consolidated aquifers, various chemical processes could be highlighted, such as cation exchange (usually Na replaces Ca in groundwater evolving along a given flow path), mineralization (water-rock interaction increasing with time). Also, isotope tools (stable water isotopes, tritium and ^{14}C) showed than part of the groundwaters are quite old (estimated to reach up to 22400 years).

Groundwater resources in the two sedimentary basins may be quite important but the main problems encountered for water management were the presence of some highly mineralized (saline) waters, and the low success rate of drilling productive water wells. In some cases, as groundwater can be very old, recharge should be carefully evaluated in order to ensure sustainable use of these water resources.

The Gondo-Sourou is an endorheic basin located in a large plain where agricultural activities expanded after various dams were built in the Sourou River. Other projects were planned and building of irrigation systems will permit a greater use of the land. This will also induce an increase of the population and therefore a higher pressure on groundwater resource. Only a few samples collected during the implementation of the IAEA-supported project RAF/7/011 presented high nitrate concentrations. Three samples out of 42 showed NO_3 concentrations higher than 20 $mg \cdot l^{-1}$. The sedimentary aquifers, except in the recharge area, are better protected against anthropogenic pressure. However, due to the lack of drilling equipment, the existing wells were usually quite shallow, and therefore more sensitive to pressure and variability in the recharge conditions.

Water conductivity increases from Mali to Burkina Faso along the flow lines due to the increase of water-rock exchange. High mineralized water (SO_4, Na, Cl) were found in some sectors leading to abstraction of groundwater with chemical characteristics not compatible to drinking water or irrigation standards. The origin of the solutes could not be determined at this stage.

Tritium data showed that 25% of the groundwater sampled were older than 1960 (pre bomb test). No ^{14}C analyzed were carried out. It was also not possible to evaluate the exchange between the deepest and the more superficial aquifer. However, there is not a clear difference in ^{3}H content of groundwater from the three identified aquifer layers, all showing old (>60 years) and young data. Therefore, recharge sectors or areas of exchange between deepest (and oldest) and more superficial aquifers exist.

In the Pendjari/Oti sedimentary aquifer system is composed of various layers, the Voltaian, the sandstones and the Atacora formation.

The sedimentary aquifers presented a great aquifer potential. However, boreholes were not always productive and it is important to locate the more promising sectors for exploitation. The less vulnerable sectors present highest groundwater quality (low nitrate concentration) but also the older groundwater and the renewable rate should be evaluated to estimate sustainable exploitation of this water resource.

Carbon-14 analyses were carried out on various samples and could confirm the presence of quite old water (800 to 22,000 years) mainly in the Voltaian aquifer. Very old (more than several hundreds of years) groundwaters are often depleted in stable isotope contents, a feature that can be considered as a paleo recharge fingerprint. Also, tritium measurements are important in the case of the expected very old groundwaters, as it permits underlying the presence of mixing processes between very old and younger groundwaters in some sectors.

Voltaian aquifer recharge takes place mainly in the geographic depressions. Three sampling points presented the highest tritium values. These boreholes were located in depressions. However, well productivity in these cases is quite low. These sectors should be well protected in order to avoid transfer of various pollutants to the Voltaian aquifer.

Buem and Togo sandstones presented both young and quite old groundwater age data. The vulnerability of these formations is medium to high. Localized recharge was highlighted for theses formations that showed, for 17% of the sampled points, concentrations of nitrate higher than 30 $mg \cdot l^{-1}$.

And finally, the Atacora sandstones formation is the more vulnerable of the sedimentary formations. This is clearly an important recharge area and therefore should be protected. Already 30% of the sampling points showed nitrate concentrations higher than 40$mg \cdot l^{-1}$, some points reaching up to 260 $mg \cdot l^{-1}$.

The hydrochemical data (such as cation exchange) permitted the delineation of groundwater flow directions and to highlight some localized recharge areas.

Recommendations

Very interesting results were obtained within the scope of the IAEA-supported project RAF/7/011. For the basement aquifer, an extended survey of nitrate concentration in groundwater would help in determining if the infiltration of the pollutants is mainly occurring at the places occupied by dug wells and ponds, i.e. very localized areas that may be protected, or if the observed pollution in some sectors is the result of diffuse pollution. It could be very interesting to explore if groundwater in some sectors characterized by the presence of gold mineralization of Birrimian volcano-sedimentary rocks, is still affected by pollution levels higher than the drinking-water standards as reported in the past (i.e. Smedley et al., 2007).

Exploration of the deepest layers of the hard-rocks aquifers would be also recommendable as groundwater resource may be available and less vulnerable.

It is important to continue the monitoring of groundwater water levels and quality, surface water and precipitation for stable isotopes and to collect additional tritium data in order to ensure a good baseline database allowing various, detailed and more focuses groundwater studies.

In the sedimentary aquifer, the sectors identified as recharge areas should be protected in order to avoid increasing level of groundwater pollution. Transboundary studies should continue between Burkina Faso and Mali to delineate the hydrogeological conceptual model of the Gondo-Sourou aquifer and evaluate the impact of the incoming global changes due to the development of irrigated agriculture. In the transboundary area between Togo, Benin and Burkina Faso, international collaboration would permit to establish the hydrogeological map of the sedimentary aquifers (Pendjari/Oti sectors), to obtain better water balance estimates (including groundwater recharge) in order to propose sustainable management plan that avoids a lowering of groundwater levels.

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ACRONYMS

BGS: British Geological Survey

BKF: Burkina Faso

CFA: corresponding factor analysis

CGIAR: Consultative Group for International Agricultural Research

CTQ: Continental Terminal Quaternaire

FAO: Food and Agriculture Organization

GNIP: Global Network of Isotopes in Precipitation

GWP: Global Water Partnership

GRAPHIC: Groundwater Resources Assessment under the Pressures of Humanity and Climate Change

HVI: hydrogeochemical vulnerability Index

IAEA: International Atomic Energy Agency

ICP: Infracambrian Plissé

ICT: Tabular Infracambrian

IGRAC: International Groundwater Resources Assessment Centre

IHP: International Hydrology Project

ISARM: Internationally Shared Aquifer Resource Management

ITCZ: Intertropical convergence zone

IWMI: The International Water Management Institute

LG: Liptako-Gourma

PCA: Principal Component Analysis

PACTEA : Programme d’Appui aux Collectivités Territoriales pour l’Eau potable et l’Assainissement

TU: Tritium Unit

UNESCO: United Nations Education Science and Culture Organizations

UV: Upper Volta

WLE: Research Program on Water, Land and Ecosystems

WHYMAP: World-wide Hydrogeological Mapping and Assessment Program