

LAKE CHAD

SUSTAINABLE WATER MANAGEMENT



Project Activities - Report N° 3

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Lake Chad Commission
Rond Point de l'Etoile,
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Federal Institute of Geosciences and
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List of acronyms

- AHT = Agro- Hydro-Technik, Essen, Germany
- BGR = Federal Institute for Geosciences and Natural Resources, Hannover, Germany
- BMZ = Federal Ministry of Economic Cooperation and Development, Bonn, Germany
- LCBC = Lake Chad Basin Commission, N'Djamena, Chad
- SRTM = Shuttle Radar Topographic Mission
- USGS = US Geological Survey

Report on the BGR Project Activities for the Period September 2009 – January 2010

This report summarizes the project activities performed during the project leader's mission at the LCBC from September 2009 to January 2010 under the umbrella of the LCBC¹/BGR² project.

The LCBC/BGR project is financed by the BMZ³. Its first phase, which was started on Mai 2007, will finish on the 31st December 2010.

The main objective of the project is to **strengthen the LCBC** so that it is able to **coordinate the exchange of groundwater data** between the member states, **integrate them in a management system** and **elaborate sustainable water resources strategies**.

1. The Lake Chad basin

The Lake Chad basin has been limited by AHT⁴ using HYDRO1K. HYDRO1K is a geographic database developed by USGS⁵ to provide global topographic coverage derived from the USGS' 30 arc-second digital elevation model of the world.



Figure 1.1 Lake Chad basin (yellow area) design based on HYDRO1K, a geographic database that provides coverage derived from the USGS' 30 arc-second digital elevation model of the world.

¹ LCBC = Lake Chad Basin Commission, N'Djamena, Chad

² BGR = Federal Institute for Geosciences and Natural Resources, Hannover, Germany

³ BMZ = Federal Ministry of Economic Cooperation and Development, Bonn, Germany

⁴ AHT = Agro- Hydro-Technik, Essen, Germany

⁵ USGS = US Geological Survey

The basin (Figure 1.1) occupies a surface of 2,381,635 km² distributed into the southeast part of Algeria (3.8% of the basin), some small areas of Libya (0.1%), the eastern part of Niger (29%), north-western Nigeria (7.6%), the extreme north of Cameroon (2.1%), the north of the Central African Republic (9.3%), almost the whole of Chad except the extreme north (43.9%), and the Darfur region in Sudan (4.2%).

2. The surface waters

Two main rivers supply most of the water to the Lake Chad. They are the Chari-Logone, which is the most important as it brings about 95% of the annual volume of surface water that reaches the lake, and the Komadugu-Yobe that supplies some 3%. In addition, the precipitation on the lake's surface provides about 2% of the annual volume of water that reaches the lake.

Within the basin there are very important and well-known swamps regions, as the Yaérés in the extreme north of Cameroon, the Lake Chad itself, the Lake Fitri, the Massénya to the south of Chad, the Salamat to the southeast of Chad and the Komadugu-Yobe to the north-east of Nigeria (see

Figure 2.1).

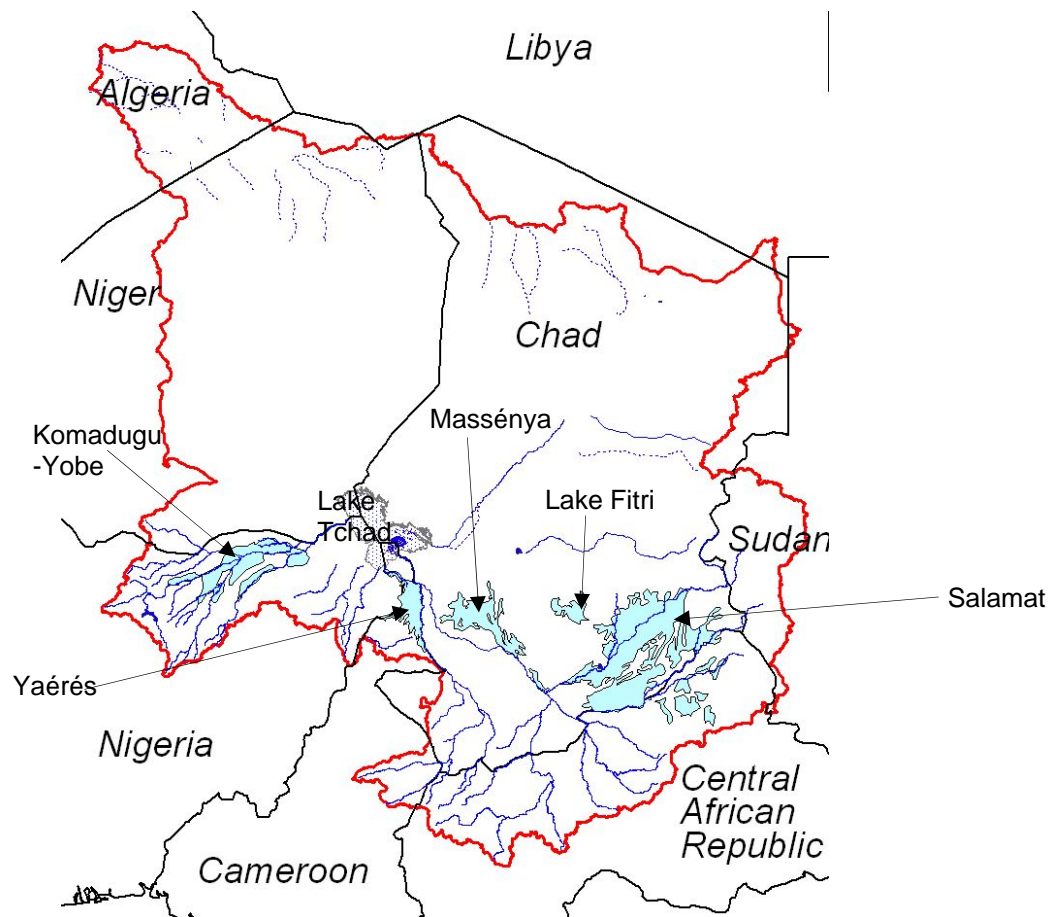


Figure 2.1 Surface water and swamps within the Lake Chad basin.

3. Geology of the basin

Following Figure 3.1 shows the geology of the Lake Chad basin. Most of it is covered by Quaternary sands. Below the sands, at about 75 m depth, appear the clays of the Pliocene with a mean thickness of approximately 280 m (compare with the hydrogeological cross-section represented in Figure 3.2). Further down, a layer of sand of about 30 m thickness is encountered that belong to the Lower Pliocene. These sands give place to the real Pliocene aquifer, as the clays are generally considered as impermeable. Further down appear the sandstones of the Continental Terminal (Tertiary) with a thickness of about 150 m. The deepest aquifer is the Continental Hamadien (Cretaceous), which also consists of sandstone.

The granitic and gneiss rocks of the basement at the bottom are considered as the base of the system.

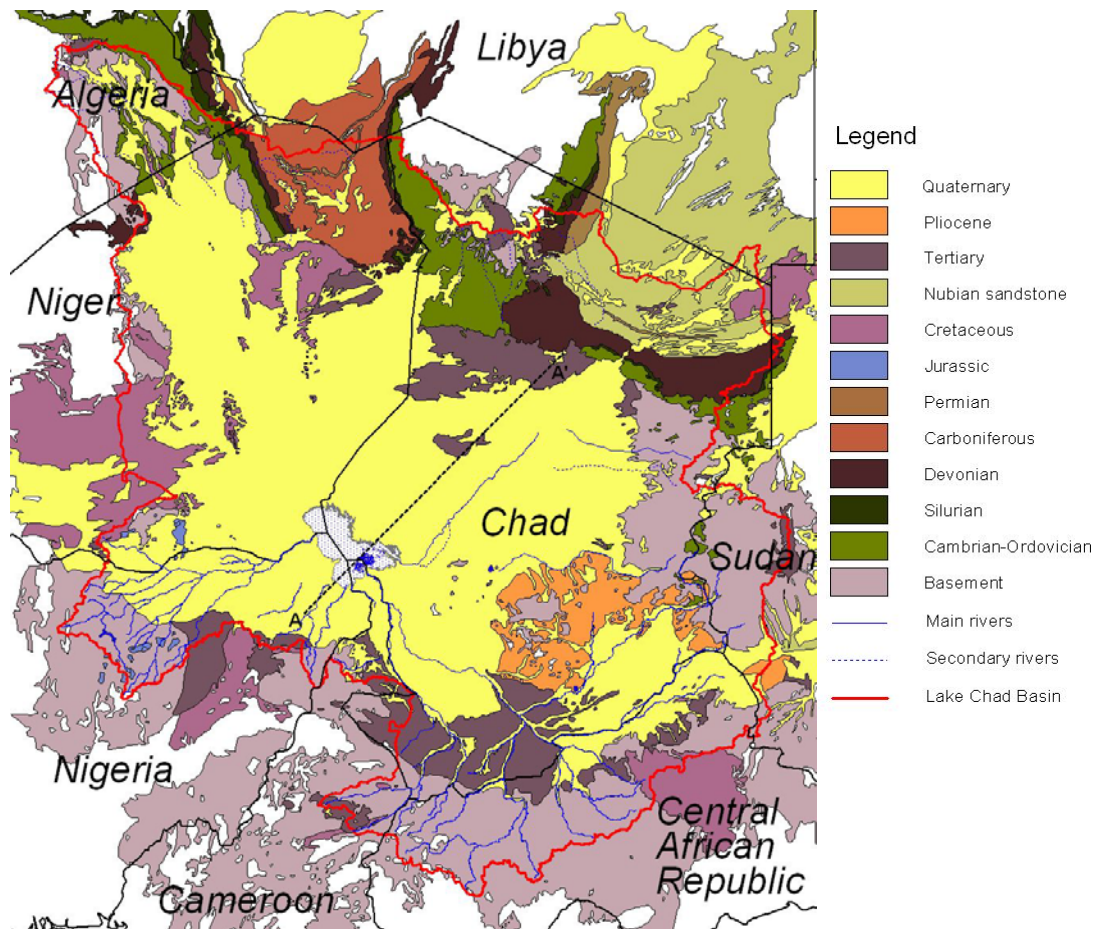


Figure 3.1 Geology of the Lake Chad basin. The next figure shows a cross-section drawn along the line AA'.

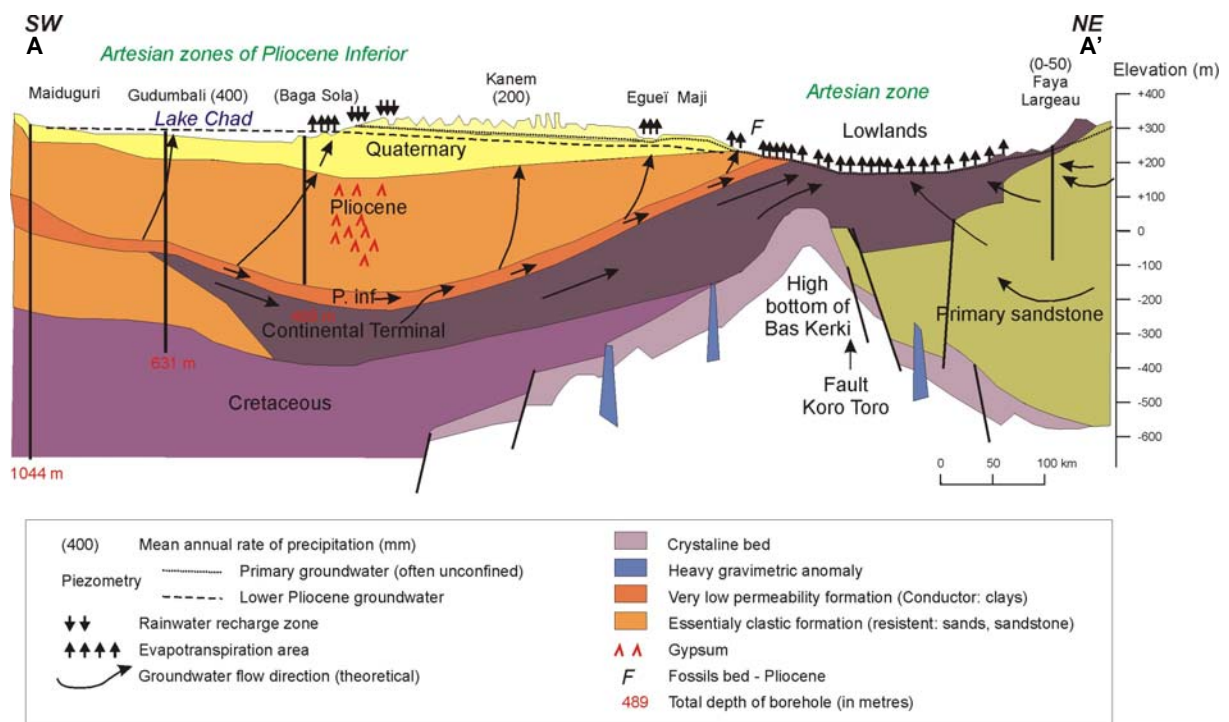


Figure 3.2 Hydrogeological cross-section showing the geology and general flow directions in depth (after Schneider, 1992).

4. Groundwater flow in the Quaternary aquifer (phreatic aquifer)

The project has collected a number of data available in various water-related ministries and government institutions related to hand-dug wells, boreholes and wells (Figure 4.1). Most of these data correspond to the data bases of Niger and Chad, while data for Cameroon and Nigeria were collected from publications available at the LCBC (Eberschweiler, 1993; UNESCO, 2003).

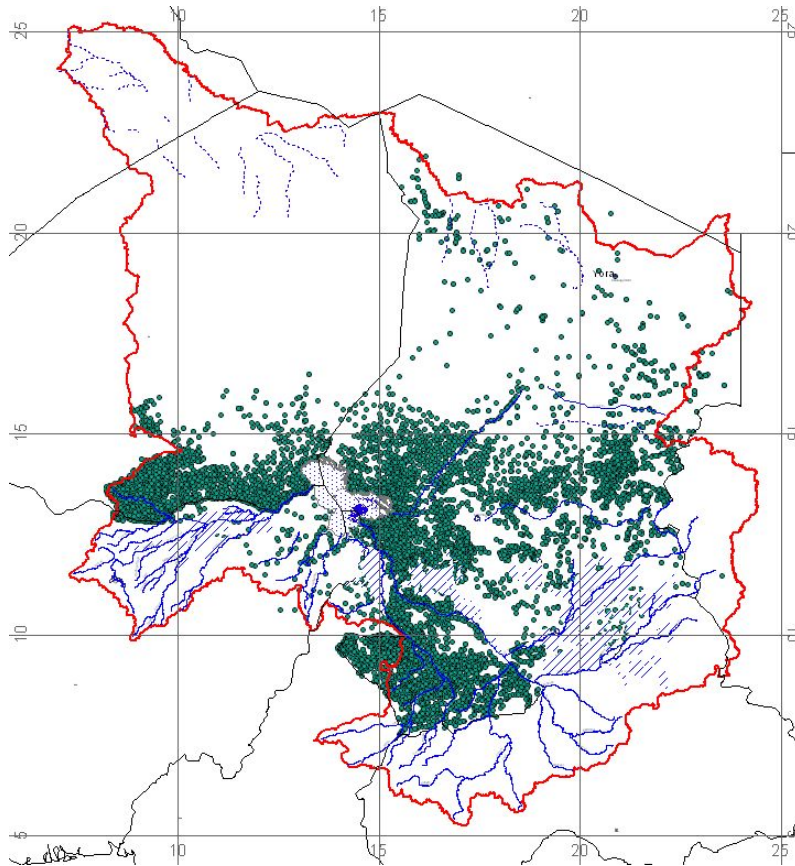


Figure 4.1 Data available at the LCBC on borehole location. Most of the 18,694 borehole data concerns the data bases of Niger and Chad. Data for Cameroon and Nigeria were obtained from publications.

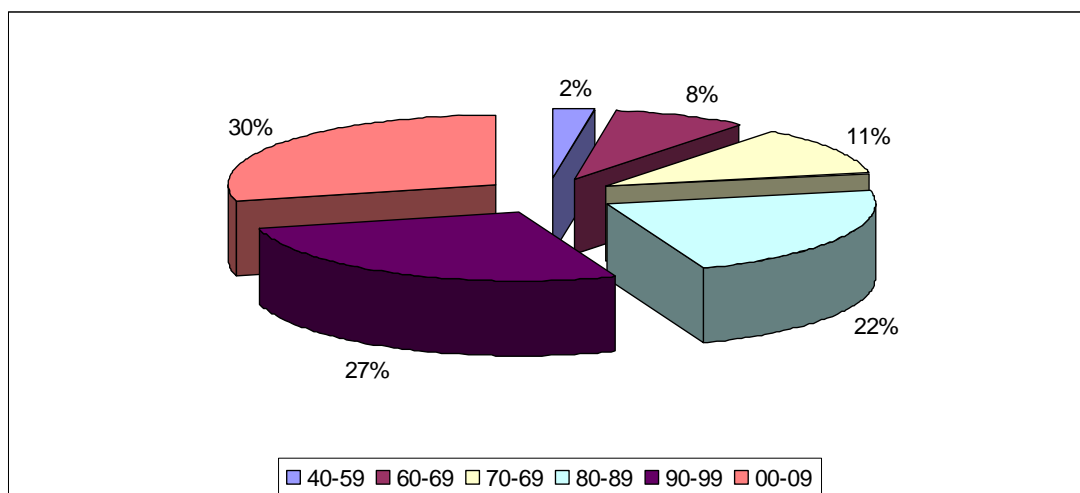


Figure 4.2 Analysis of the data from the database of the Ministère de l'Hydraulique, Chad, which contains 12,425 boreholes. The pace at which boreholes were constructed picked up in the 80's, due to the severe drought that the country was suffering. This trend, although somehow weakened, has continued in the last 2 decades.

The database for Chad was handed over to the LCBC in January 2010 and contains 12,425 boreholes. An analysis of these data shows that borehole construction pace picked up in the 80's, due to the severe drought that the country was suffering. However, this tendency did not revert but even continue to increase in the last 20 years (Figure 4.2).

There are 18,694 boreholes listed in the LCBC database, about 11,395 of them do get water from the Quaternary aquifer (Figure 4.3).

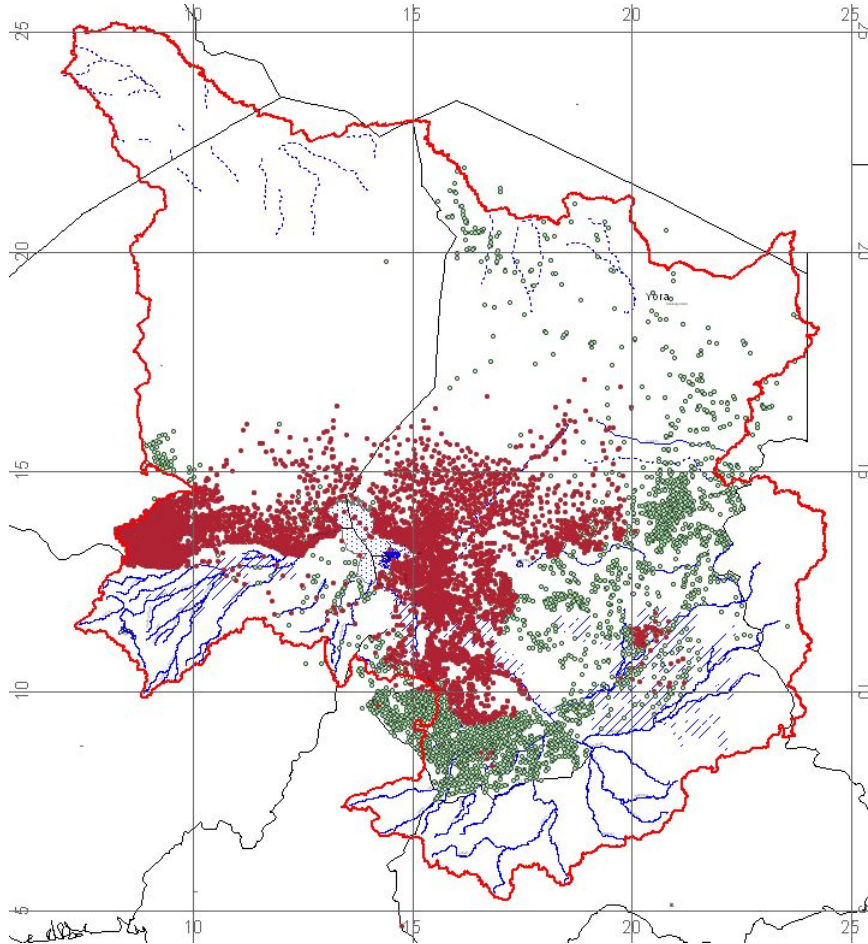


Figure 4.3 The red dots indicate the 11,395 boreholes that tap groundwater from the Quaternary aquifer. The green dots belong to other aquifers like Lower Pliocene, Continental Terminal or fractured basement.

It is possible to use the available data on rest water level from the databases to draw the groundwater contour lines. Although elevation data are seldom recorded in the databases, they were estimated using the SRTM (Shuttle Radar Topographic Mission) elevation model. Figure 4.4 presents the groundwater contour lines for the Quaternary aquifer. The upper graph shows the whole Lake Chad basin, while the lower graph is a zoom of the area covered by quaternary sands.

The groundwater contour lines show groundwater depressions to the south-east and south-west. They also give indication of regional recharge from the Chari, Logone and Komadugu-Yobe rivers as well as from the Yaéré and Massénya swamps. However, the Komadugu-Yobe swamp seems to act as discharge from the aquifer. The Bodélé area to the north of the lake is the lower part of the quaternary groundwater and is separated from the Lake Chad by a height in the Kanem that acts as water divide.

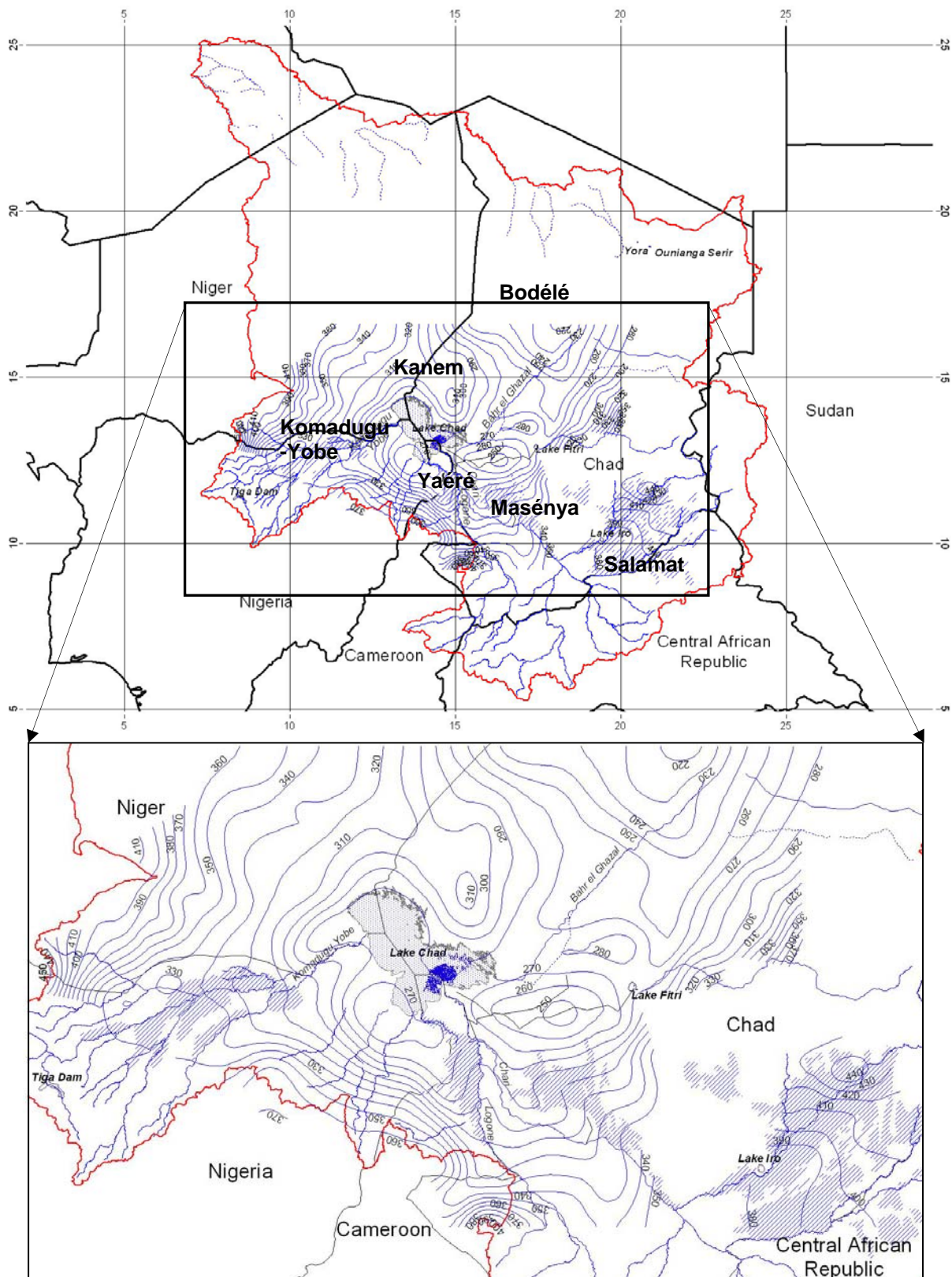


Figure 4.4 Groundwater contour lines obtained using the data available in the LCBC database. The STRM elevation model was applied for the estimation of the borehole elevations.

To improve the data situation within the LCBC, the project has run various field-trips in the Chadian part of the basin mainly for:

- Hydro-census of water points in a more or less homogeneously distributed way. A distance between boreholes of some 25 km was adopted for those boreholes located to

the south of the lake. However, due to the scarcity of boreholes to the north of the lake, the distance between measurements had to be expanded to 50 km.

- Measurement of rest water level.
- Sampling for full chemical analysis and isotopes (^{18}O , ^2H and tritium).

During the last months of 2008 and the beginning of 2009, the analysis was concentrated in the southern part of Chad, especially the Chari-Baguirmi area, where 192 water points were visited (Figure 4.5). These campaigns were run in cooperation with the University of N'Djamena and the results will be the basis of the PhD Thesis of Mr. Abderamane Hamit, a Chadian candidate that will defend his work at the University of Poitiers, France.

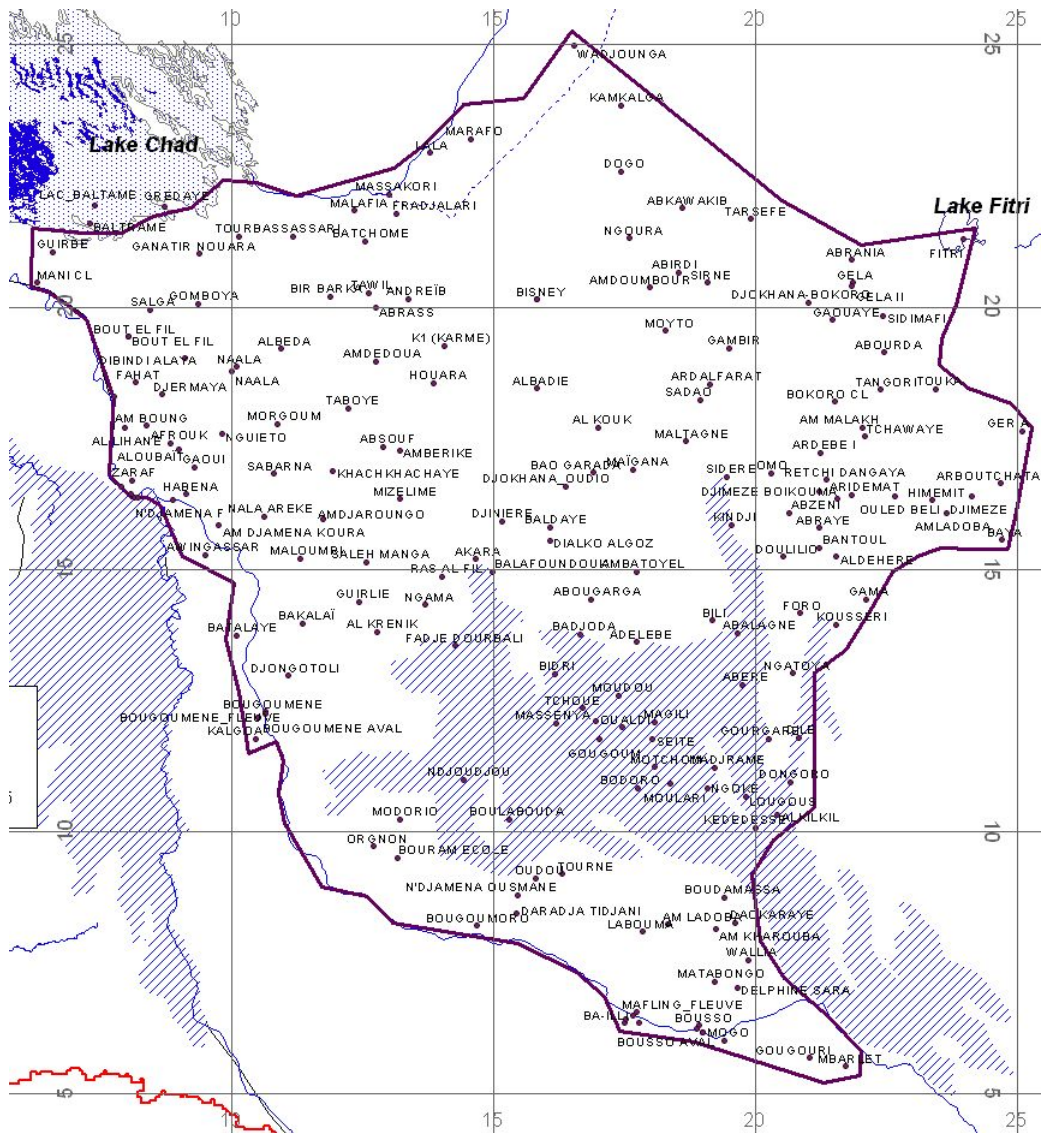


Figure 4.5 The study area covers a surface of 52,000 km² in which 192 water points were localised and sampled.

Additional field-trips, still in cooperation with the University of N'Djamena, started during the last months of 2009 and are still on-going. Here the northern part of the lake was involved in order to investigate the groundwater situation in that area. At the time of reporting a total of 116 water points have been identified, sampled, and analysed.

Figure 4.6 shows the location of all water points included in our study up to now. The points visited in the last field-trips are plotted with blue dots while the red dots indicate those boreholes localised in the first trips.

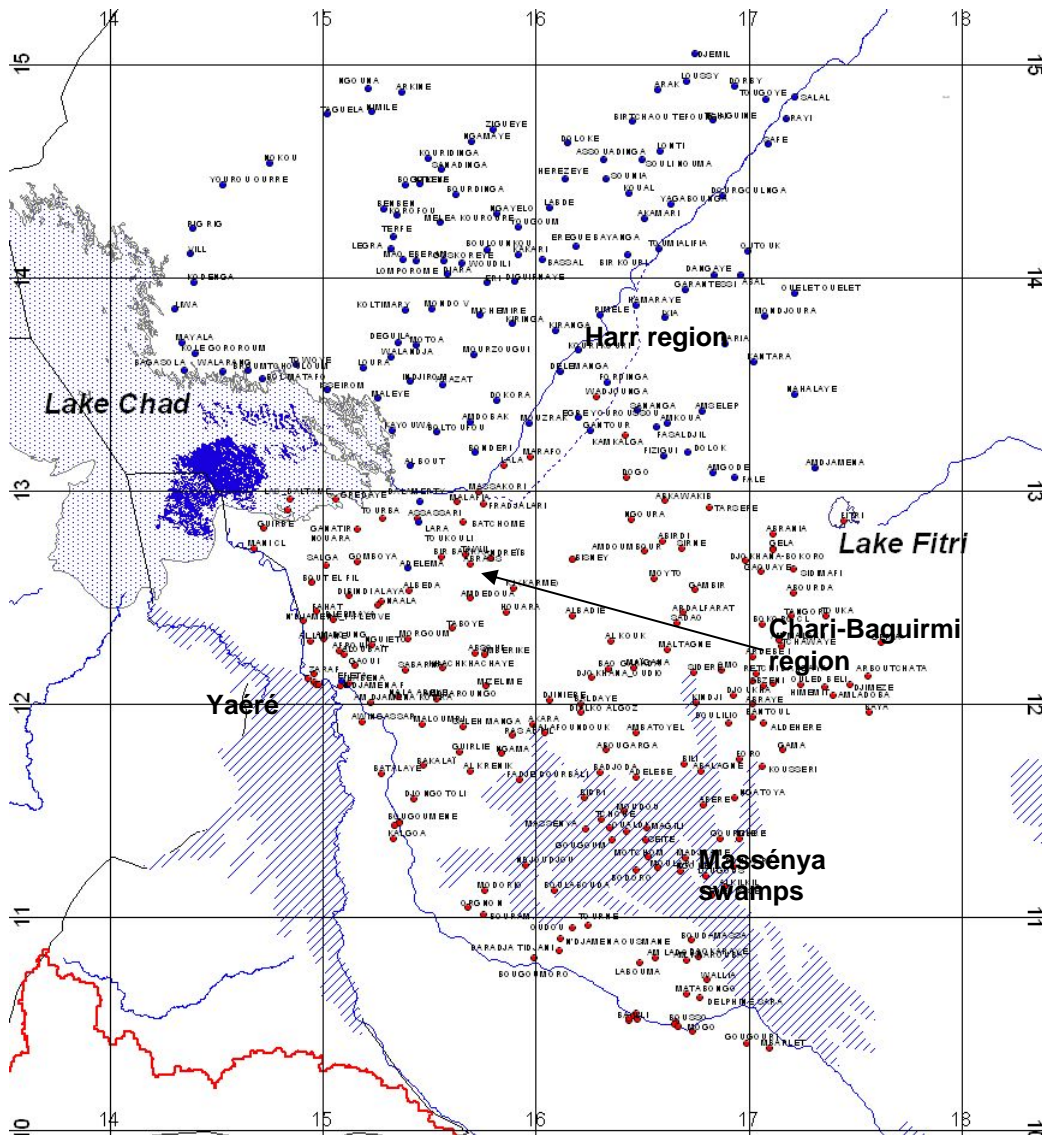


Figure 4.6 Location of all water points visited and sampled under the umbrella of the LCBC/BGR project. The points visited during the on-going field trip are indicated with blue dots while the red dots show the sampling of the old field trips (end of 2008-beginning of 2009).

5. Results obtained

5.1 Depth to groundwater for the Quaternary free aquifer

A map indicating the depth to groundwater (in m below ground) for the Quaternary aquifer was compiled using the rest water level data measured in the field trips (Figure 5.1).

The curves show groundwater close to the surface in the area around the lake, especially to the north where groundwater is encountered at depths not lower than 5 m below ground. Along the southern rim of the lake groundwater is encountered at about 10 m below ground. Further, groundwater appears also close to the surface underneath the swamps of Massénya (10 m below ground) to the south of the studied area as well as along the Chari River.

The apparent higher level of groundwater to the south-eastern of the area in the vicinity of Lake Fitri is due to a change in the composition of the aquifer. These water points are located in areas with granite of the basement, where groundwater is confined to the upper weathered region.

Groundwater is deep in those areas distant to surface water bodies. This is the case in the Chari-Baguirmi area where groundwater can be as deep as 50 m below ground.

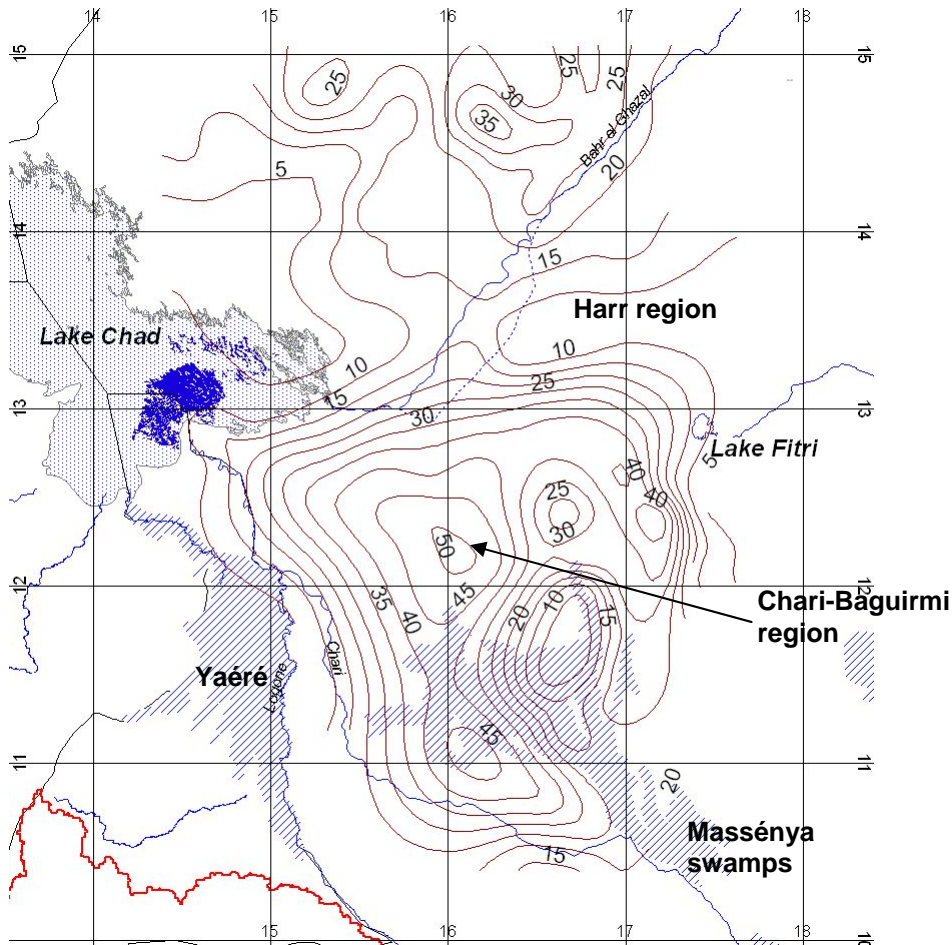


Figure 5.1 Depth to groundwater for the Quaternary aquifer (m below ground). The curves show groundwater close to the surface in the area around the lake, especially to the north where groundwater is encountered at depths not lower than 5 m below ground. Along the southern rim of the lake, groundwater is encountered at about 10 m below ground. Further, groundwater appears also close to the surface underneath the swamps of Massénya (10 m below ground) to the south of the studied area as well as along the Chari River. Groundwater is deep in areas far from surface water bodies as in the Chari-Baguirmi region.

5.2 Groundwater contour line map for the Quaternary aquifer

The groundwater contour line map (Figure 5.2 Groundwater contour lines (m above mean sea level). This map was produced using the SRTM90 elevation model for surface heights and the groundwater level measurements obtained in the BMZ/BGR project.) was constructed using surface height from the elevation model SRTM90 and the groundwater levels measurements obtained during the field campaigns. It confirms the picture described above, especially the recharge to the aquifer from the southern part of the lake, the Chari River and the Massénya swamps; and the depression in the Chari-Baguirmi.

The picture also shows groundwater domes in the Harr region and to the north of the lake, as well as a discharge to the northeast of the study region towards the low lands through the Bahr el Ghazal. This presently dry river acts as a discharge of the Lake Chad whenever the lake's level is higher than 285 m above mean sea level.

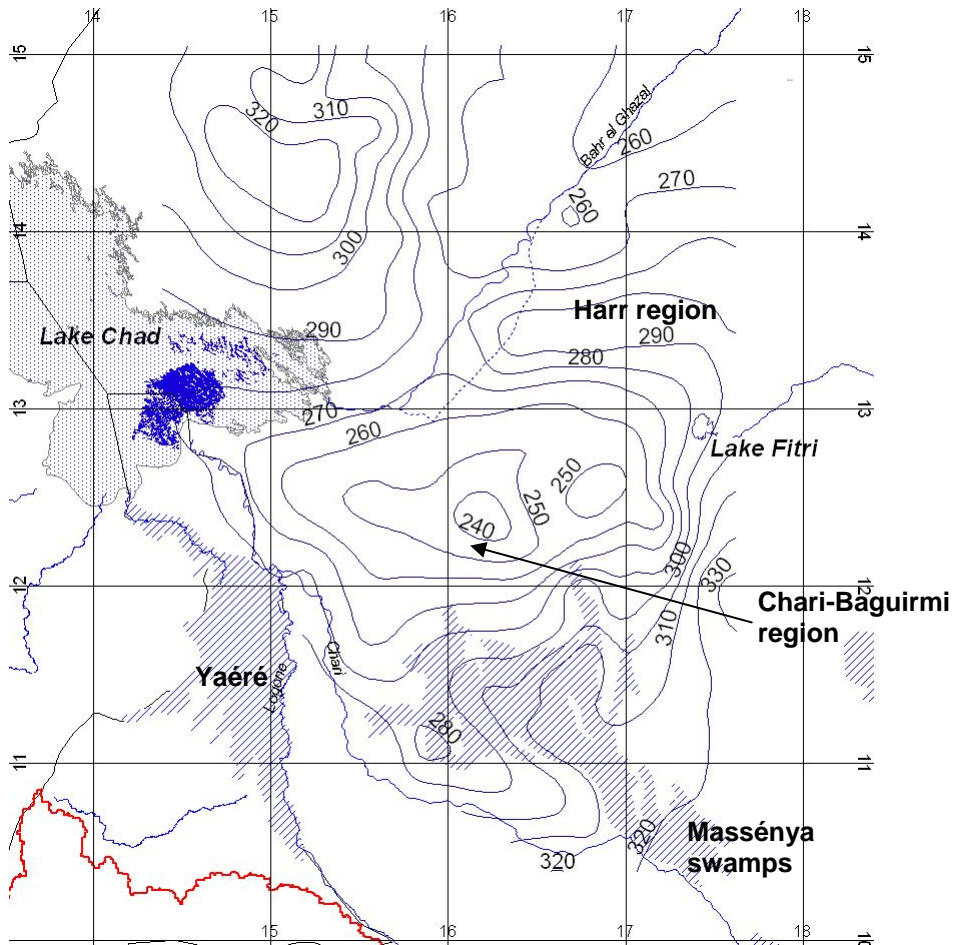


Figure 5.2 Groundwater contour lines (m above mean sea level). This map was produced using the SRTM90 elevation model for surface heights and the groundwater level measurements obtained in the BMZ/BGR project.

5.3 Hydrogeochemistry

The results of the chemical analyses are used to characterise the groundwater of the area and thus of the different aquifers. Waters close to the recharge zone have a weak mineralisation, similar to that of precipitation (Figure 5.3). Along the underground passage, groundwater absorbs minerals from the sediments and rocks. Therefore, samples taken from a region far from the recharge area would always show higher mineralisation.

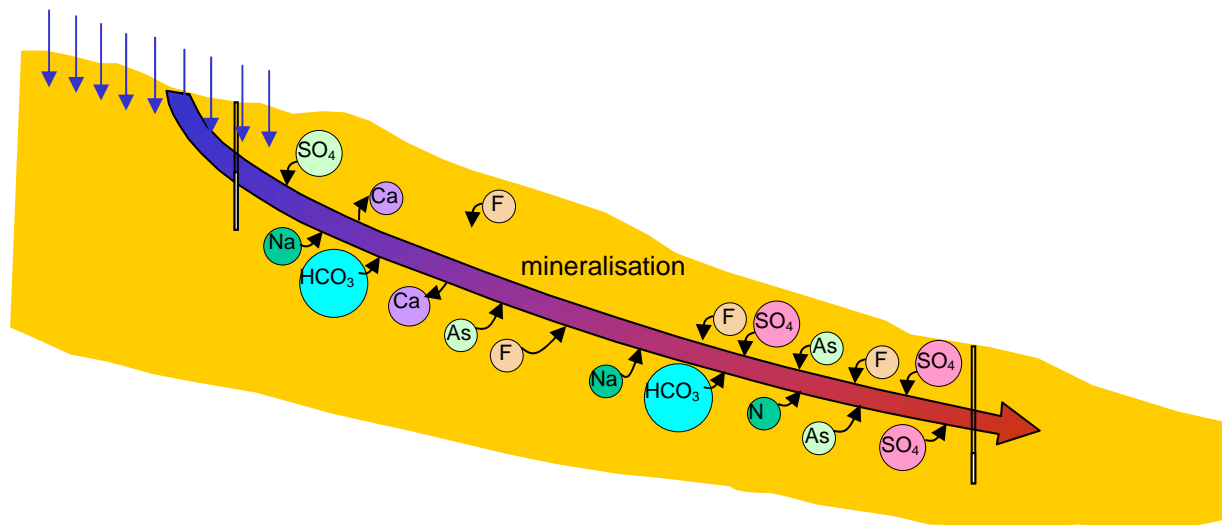


Figure 5.3 Groundwater mineralisation during the flow in the underground.

The sampling for chemical analyses included hand-dug wells and boreholes as well as surface water: Lake Fitri (1) and Chari River (15), Lake Chad (1). In the case of dug-wells, due to their large diameter, sampling was performed using a bucket. If a pump was installed, the sample was taken after constant in-situ parameters were reached. The in-situ measurements included:

- pH.
- Electrical conductivity.
- Water temperature.
- Total alkalinity.

All samples were sent to the BGR laboratory, Germany, for analysis (total cations and anions, trace elements). The next chapters summarize the results obtained.

5.3.1 Water characterization

The Piper diagram (Figure 5.4) is a common way of plotting chemical results to distinguish between waters of different characteristics and often between aquifers. The chemical composition of groundwater from the recharge zone to the discharge point is characterized mainly by three zones areas in the piper diagram.

- If the analysis falls in the sector defined as "bicarbonate calcium", it means that the water is weakly mineralised typical for groundwater located nearby the aquifer recharge area. Surface water, if originated by precipitation, should show this quality.
- The sector named "bicarbonate sodium" is defined by waters that were recharged relatively long ago and have flown a certain distance within the aquifer to allow for sodium to replace calcium. These waters have thus a higher mineralisation.
- The sector indicated as "hyper-chloride sodium" (also "sulphate chloride sodium") shows waters with high mineralisation. They are located far away from the recharge zone and have flown a long distance in the aquifer. In this process, bicarbonate has been replaced by sulphate and chloride is added to sodium.
- Samples of chloride-sulphate-calcium-magnesium type are affected by evaporation, are stagnant, or are stored in sediments containing gypsum.

The arrows in the figure show the direction of mineralisation, from blue to red, or from bicarbonate-calcium to hyper-chloride sodium through bicarbonate-sodium.

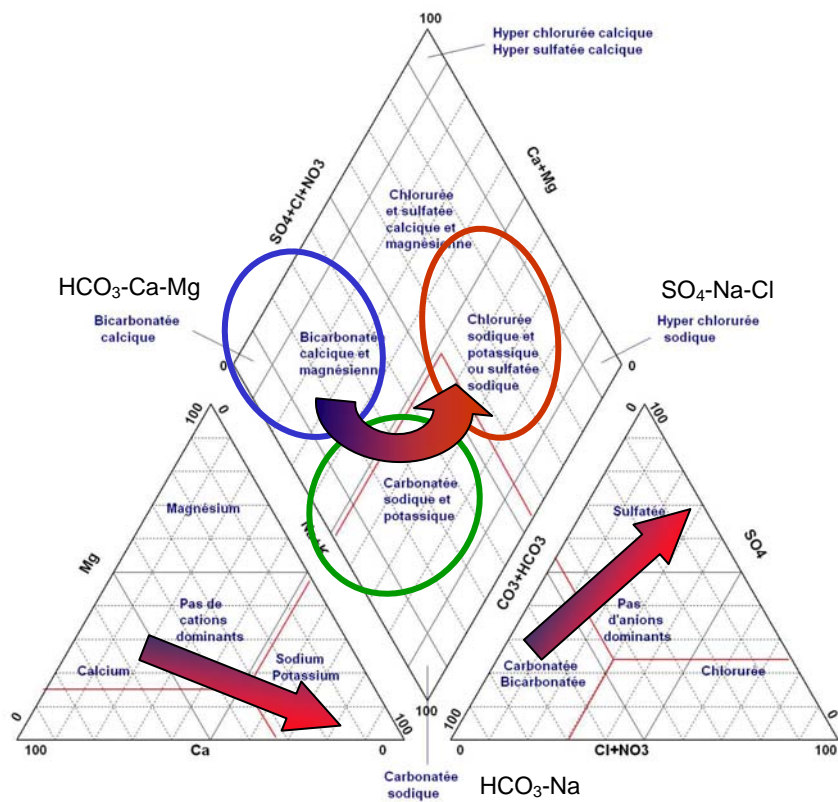


Figure 5.4 Piper diagram for explaining water quality.

Figure 5.5 shows the location of the sampling points (a) and the Piper-diagram (b) for the results the chemical analyses for all 17 surface water samples. They all indicate water of bicarbonate-calcium type and are thus originated by meteoric water or precipitation.

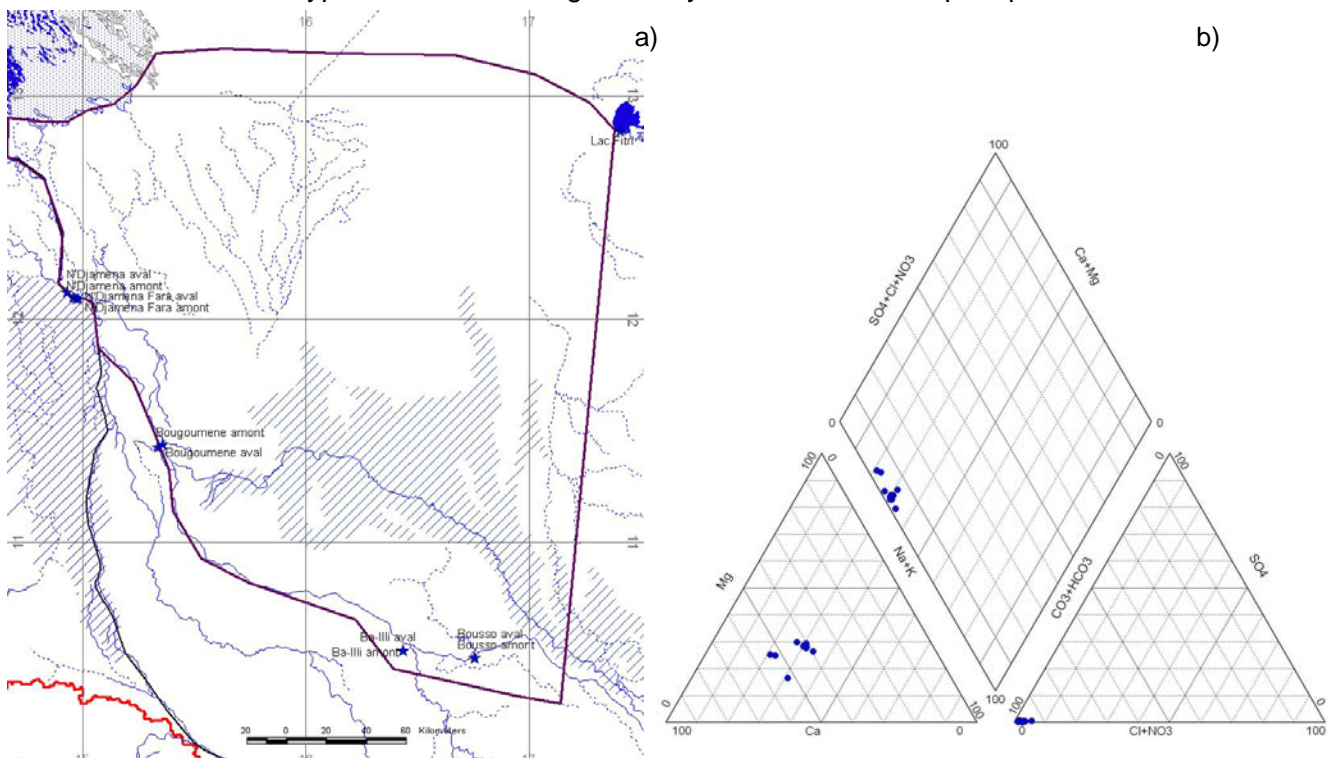


Figure 5.5 Location of water points sampled during the field campaigns (a) and chemical analyses results (b) for surface waters (BGR laboratory).

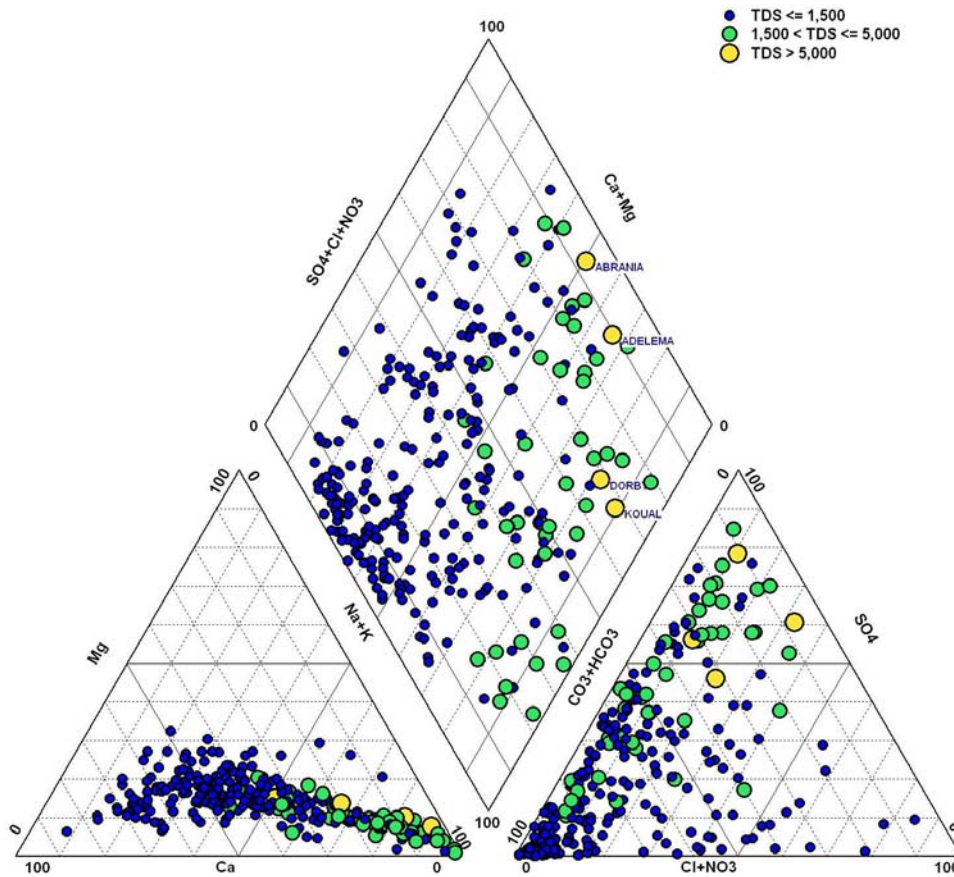


Figure 5.6 Chemical analysis for groundwater (results from BGR laboratory).

When drawing the same Piper diagram for groundwater samples, the representation changes (Figure 5.6). Although most of the samples indicate the presence of groundwater of bicarbonate-calcium type, also water of bicarbonate-sodium type is present and even water of sulphate-chloride-sodium type.

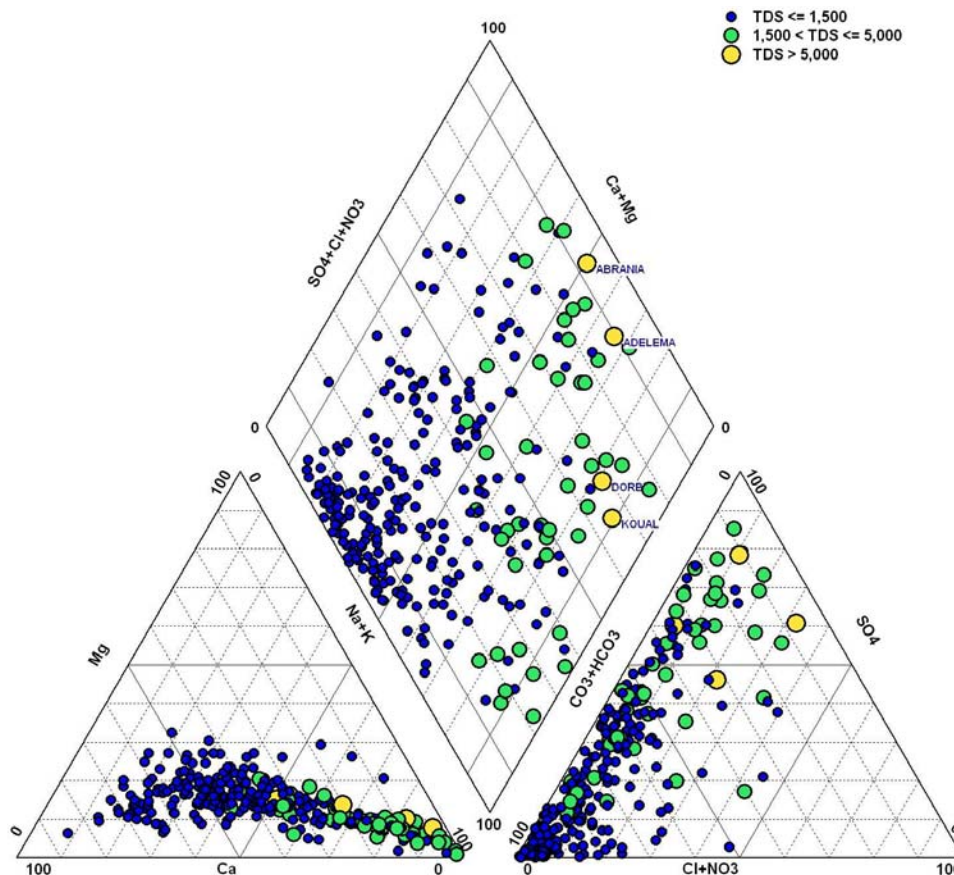


Figure 5.7 Chemical analyses results for groundwater without considering nitrate (BGR laboratory).

The picture in Figure 5.6 shows on the anion side the sum of chloride and nitrate. Assuming that nitrate pollution of groundwater in the Lake Chad area is local (see Chapter 5.3.8) and due to direct input of faeces into de borehole, nitrate can be eliminated from the anions. In this case, many of the low TDS points move towards the left in the Piper diagram and in the anions-diagram (compare Figure 5.6 and Figure 5.7).

It is also possible to draw a distribution map of water-types using the results of the chemical analyses (Figure 5.8). The classification used corresponds to that used in Figure 5.4. Water of calcium-magnesium-bicarbonate type is encountered in the Massénya region. As already explained this type of water corresponds generally to areas close to the recharge regions and thus confirms the conclusions from the groundwater contour map.

On the other side, water of sodium-calcium-sulphate-chloride type is found in the vicinities of the Lake Fitri. Here the underground is composed of granitic and gneiss rocks of the basement covered by a thin layer of recent sand deposits. Groundwater is mainly confined to the upper weathered region of the granite what leads to the different chemical composition.

The Chari-Baguirmi area presents water of sodium-calcium-sulphate type, which indicates either a long flow path through sediments or the exposition to rocks of the basement.

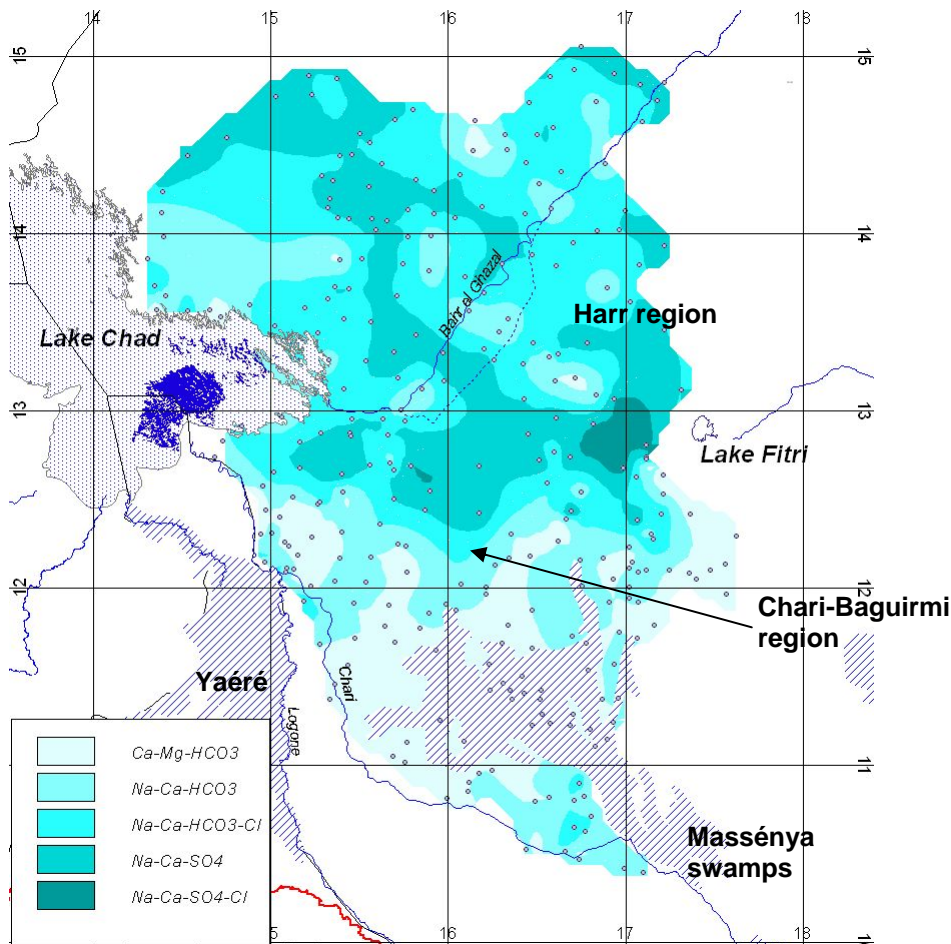


Figure 5.8 Groundwater-type distribution map. Water of calcium-magnesium-bicarbonate appears in the Massénya swamps and to the NE of N'Djaména. The Chari-Baguirmi region is characterized by water of the sodium-calcium-sulphate to sodium-calcium-sulphate-chloride.

5.3.2 Total dissolved solids (TDS)

Figure 5.6 and Figure 5.7 also indicate that groundwater presents different salt contents depending on the area, which is graphed by means of concentrations of total dissolved solids (TDS). Water with TDS concentrations higher than 500 mg/l tends to scaling and clogging of pipes and has salty taste or is corrosive. According to the World Health Organisation (WHO), TDS concentrations higher than 1,500 mg/l make water unpalatable, although higher TDS values do not seem to cause health problems. Therefore, waters with TDS concentrations up to 5,000 mg/l can still be used for livestock supply.

Waters can be classified by the amount of TDS in mg/l:

- Fresh water < 1,500 mg/l TDS
- Brackish water 1,500 to 5,000 mg/l TDS
- Saline water > 5,000 mg/l TDS

Of the 290 groundwater samples available to date, 242 or 84% present TDS values below the WHO limit, 43 or 15% have values between 1,500 and 5,000 mg/l, and only 4 samples have values of TDS higher than 5,000 mg/l (yellow circles in Figure 5.9).

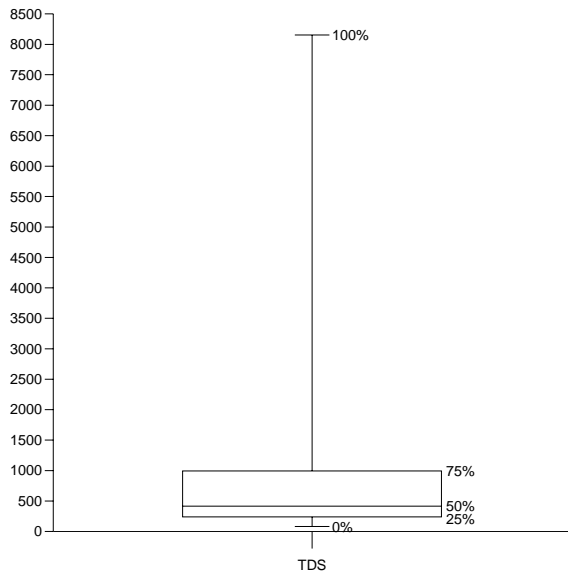


Figure 5.9. Statistical representation of TDS values. Of the 290 groundwater samples available to date, 84% present TDS values below 1,500 mg/l and 43% between 1,500 and 5,000 mg/l.

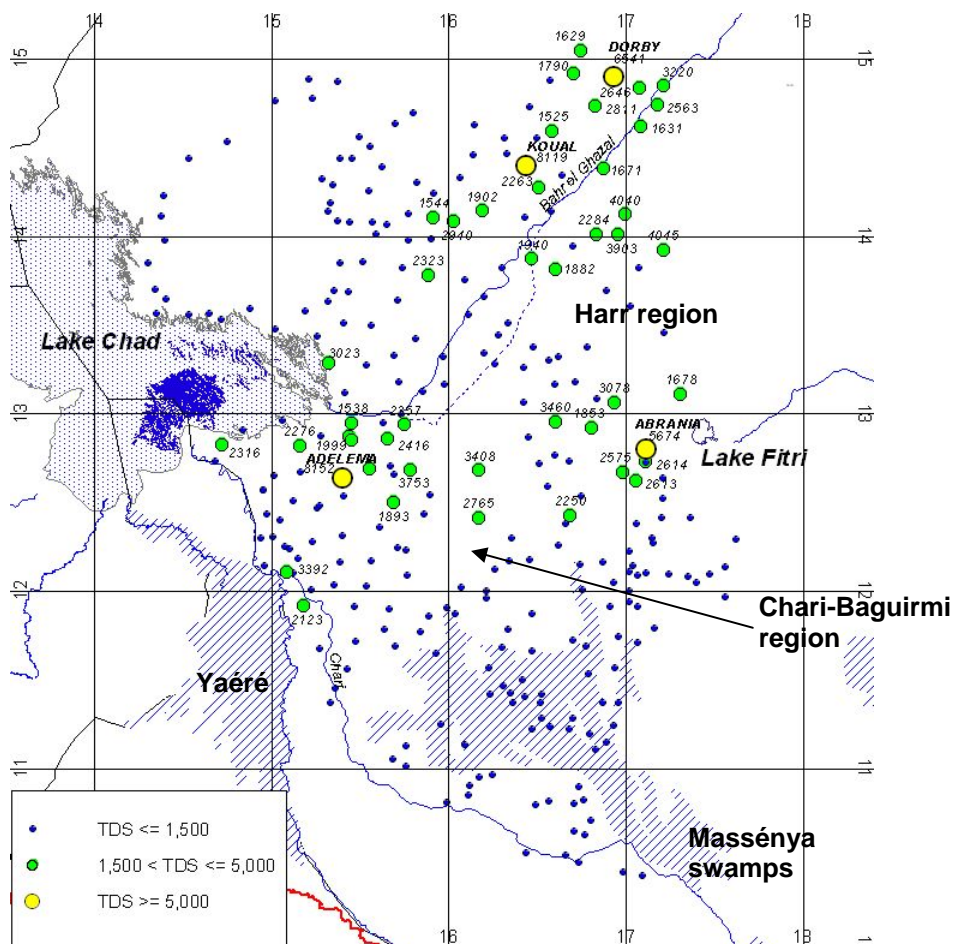


Figure 5.10 Groundwater TDS distribution map (mg/l). The 4 labelled water points represented by yellow circles have TDS-concentrations higher than 5,000 mg/l, what means that the water is not suitable for drinking.

The low TDS values present in the the Massénya swamps and in the Kanem area is an indication of newly recharged groundwater. Water with TDS values above 1,500 mg/l are only encountered in the Chari-Baguirmi region, where the groundwater depression is found,

and along the Bahr el Ghazal (Figure 5.10). The TDS concentration at Dorby (6,541 mg/l), Koual (8,119 mg/l), Adelema (8,152 mg/l), and Abrania (5,674 mg/l) is higher than 5,000 mg/l meaning unsuitable water for all drinking purposes.

The analysis of the correlations between TDS and the main anions and cations dissolved in the water (Figure 5.11) shows a clear correlation of TDS with the cation sodium ($R^2 = 0.9$), a relatively good association with the anions chloride ($R^2 = 0.6$) and sulphate ($R^2 = 0.8$), and a poor correlation with the cation calcium ($R^2 = 0.3$). Therefore, the aquifer in the region is characterized especially by the presence of sodium and sulphate.

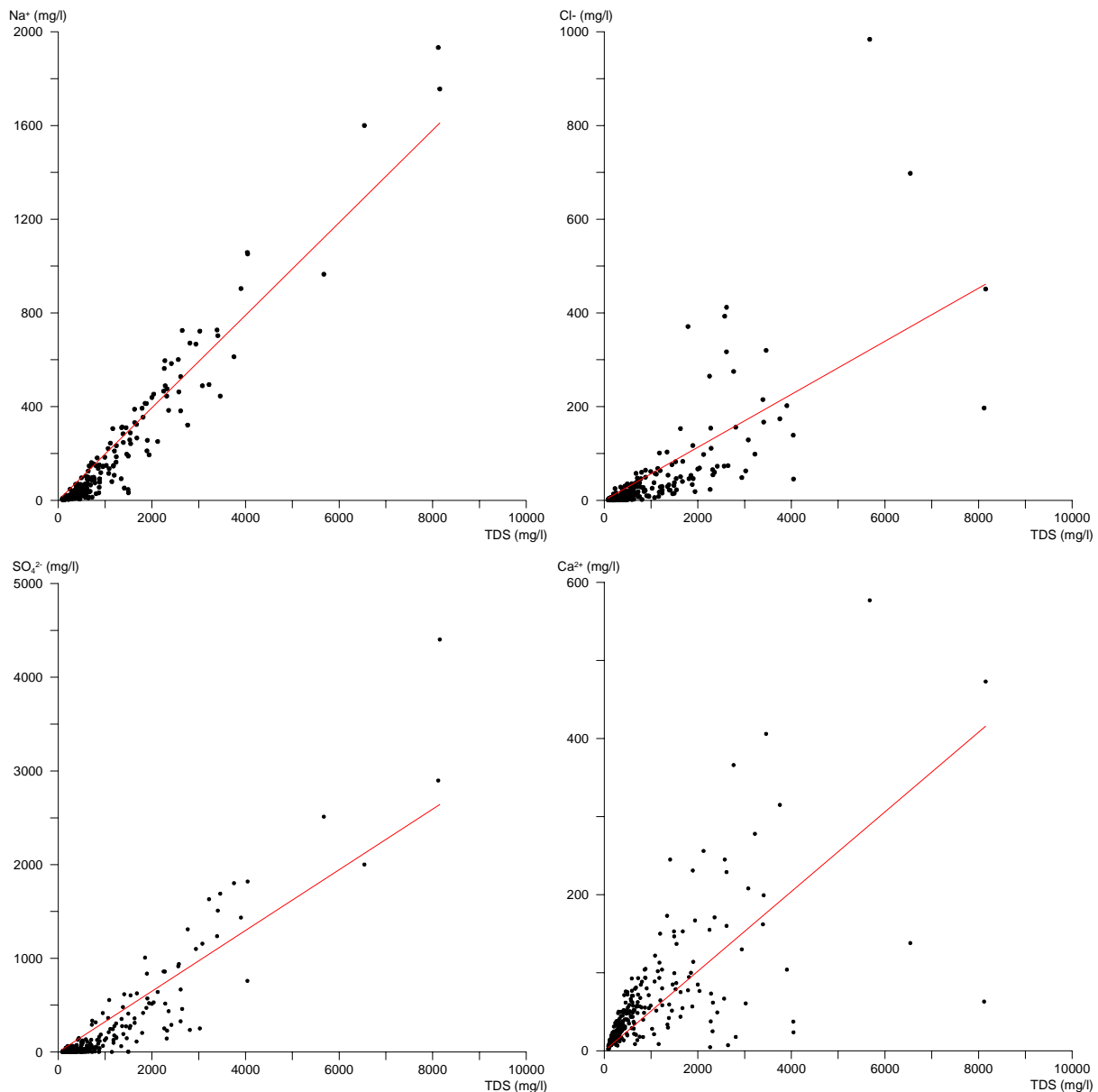


Figure 5.11. Correlation between TDS and the main dissolved anions and cations. The correlation is good with sodium, relatively good with sulphate and chloride, and poor with calcium.

5.3.3 pH

Although the pH value does not have health implications, it is one of the most often measured parameters. A pH value of 7 indicates neutral water. Higher values correspond to alkaline waters, which tend to scale, while pH values lower than 7 correspond to acid waters that are corrosive.

In general, the pH value of groundwater in the study region lies within the range of 6.5 to 8.5, as provided by the WHO. However, the water is slightly alkaline because more than 75% of the samples have values above 7. Of the 290 available samples, 5 show a pH value lower than 6.5 and 1 has a pH value higher than 8.5 (Figure 5.12).

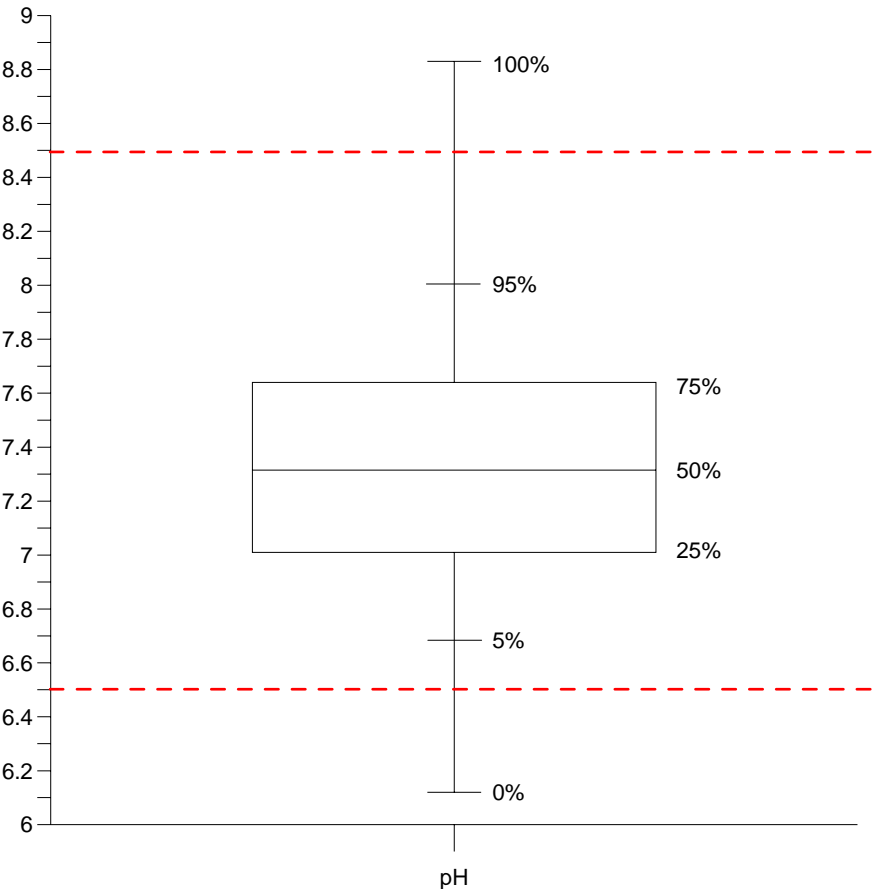


Figure 5.12 Statistical representation of pH values for groundwater in the study area. Five samples present a pH lower than 6.5 and 18 samples a value higher than 8.

Figure 5.13 shows the pH distribution in the study area. The most alkaline water with pH values above 7.8 is encountered along Bahr el Ghazal. Values between 7.5 and 7.8 are present in the surroundings of Lake Fitri and Lake Chad, as well as along the northern segment of the Chari River. Neutral water with pH values between 6.5 and 7.5 is found in the Massénya swamps and in the Kanem area to the north of the Lake Chad. Acid waters with pH values lower than the recommended minimum of 6.5 are present in five singular cases scattered in the study area (big blue circles in Figure 5.13).

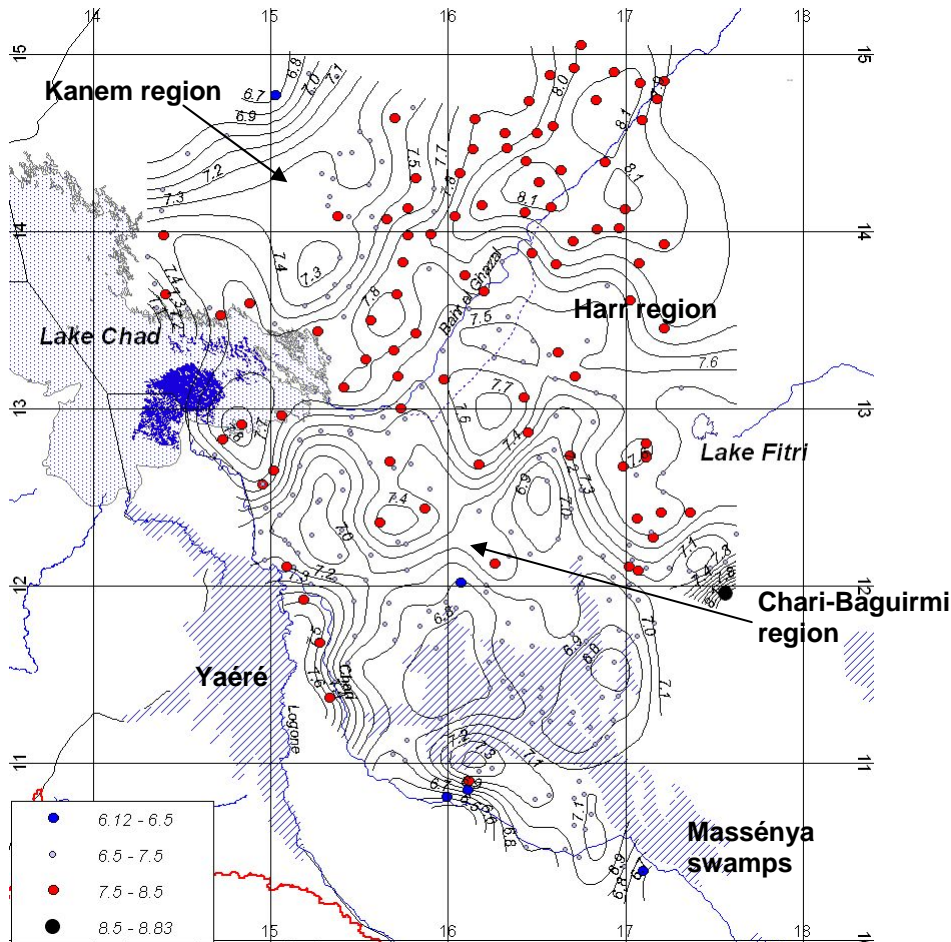


Figure 5.13 Groundwater pH distribution map. The most alkaline water with pH values above 7.8 is encountered along the Bahr el Ghazal. Values between 7.5 and 8.5 are present in the surroundings of the lakes Fitri and Chad, as well as in the northern segment of the Chari River. Neutral water with pH values between 6.5 and 7.5 are typical for the Massénya swamps and the Kanem region to the north of the Lake Chad. Acid water with pH values lower than 6.5 are singular cases.

5.3.4 Water hardness

Hardness indicates primarily the content of calcium and magnesium, and to a lesser extent, iron, in the water. It is generally estimated by adding up the concentrations of calcium and magnesium and converting this sum into calcium carbonate (CaCO_3) equivalent. Although hardness does not present any hazard to health, extreme high or low hardness are undesirable. Hard water causes precipitation of carbonate and thus scaling. On the other hand, soft water is very aggressive and corrosive to iron pipes and cement. There are various scales to define water hardness like the German hardness, which calculates:

$$d^{\circ}\text{H} = \frac{(\text{CaO} + 1.4 \text{ MgO}) \text{ mg/l}}{10}$$

and considers:

d°H	Water type
0 - 4	very soft
4 - 8	soft
8 - 12	medium hard
12 - 18	somewhat hard
18 - 30	hard
> 30	very hard

The whole water hardness scale is present in the study area with 25% of the samples containing soft water (Figure 5.14).

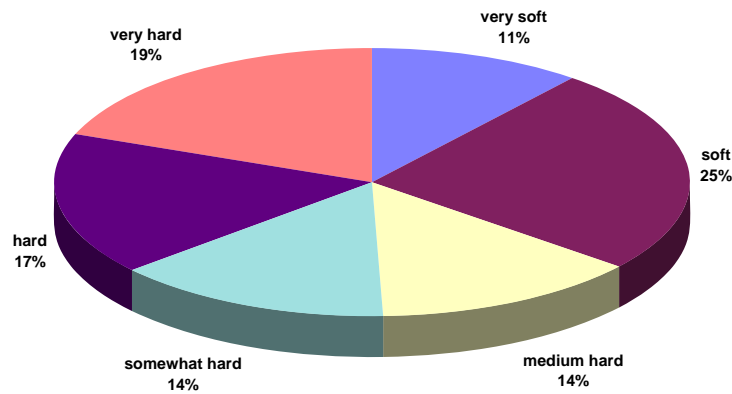


Figure 5.14 Percentages of water hardness, defined as German hardness, in the study area.

Figure 5.15 shows the distribution of the hardness in the study area. Very hard and hard waters are encountered along Bahr el Ghazal and the Chari-Baguirmi area. Soft and very soft water is characteristic for the Massénya swamps, the Harr region and the Kanem region.

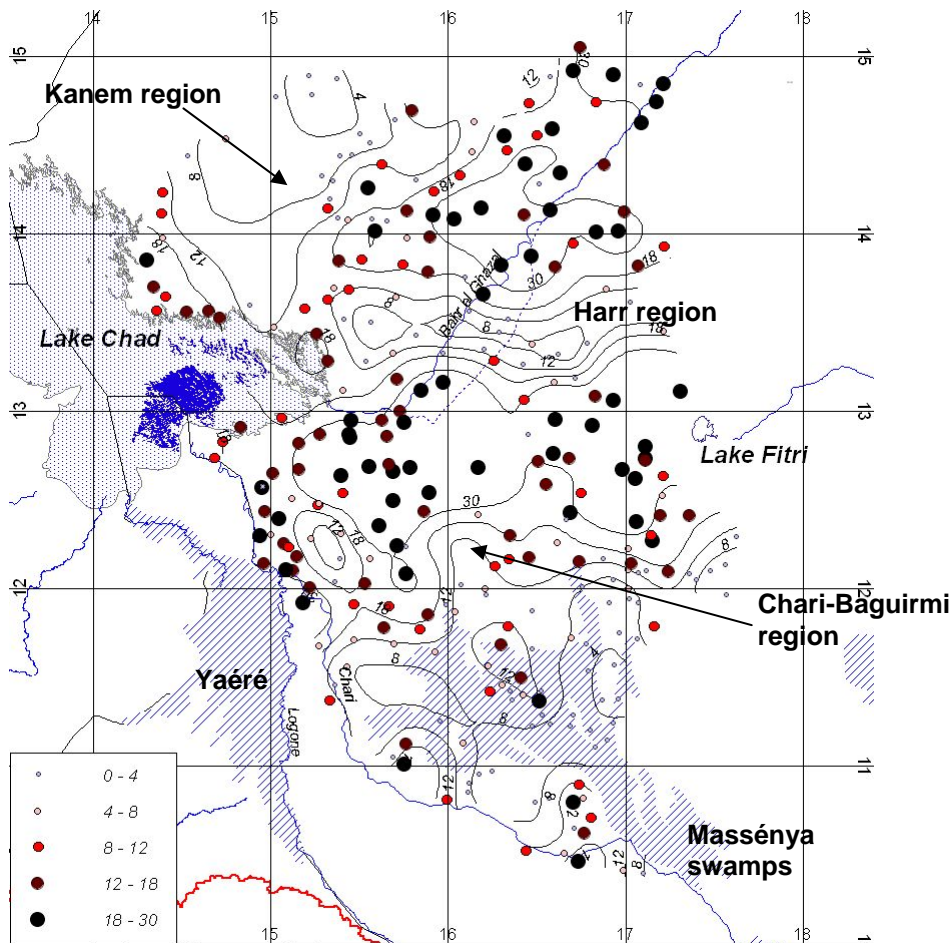


Figure 5.15 Groundwater hardness distribution map (mg/l). Hard and very hard water is encountered along the Bahr el Ghazal and in the Chari-Baguirmi region. Very soft and soft water is typical for the Massénya swamps, the Harr region, and the Kanem region.

5.3.5 Bicarbonate

As already mentioned, the water hardness is calculated as CaCO_3 equivalent. Thus the generally soft water of the area is due to the relatively low concentration of carbonates (Figure 5.16).

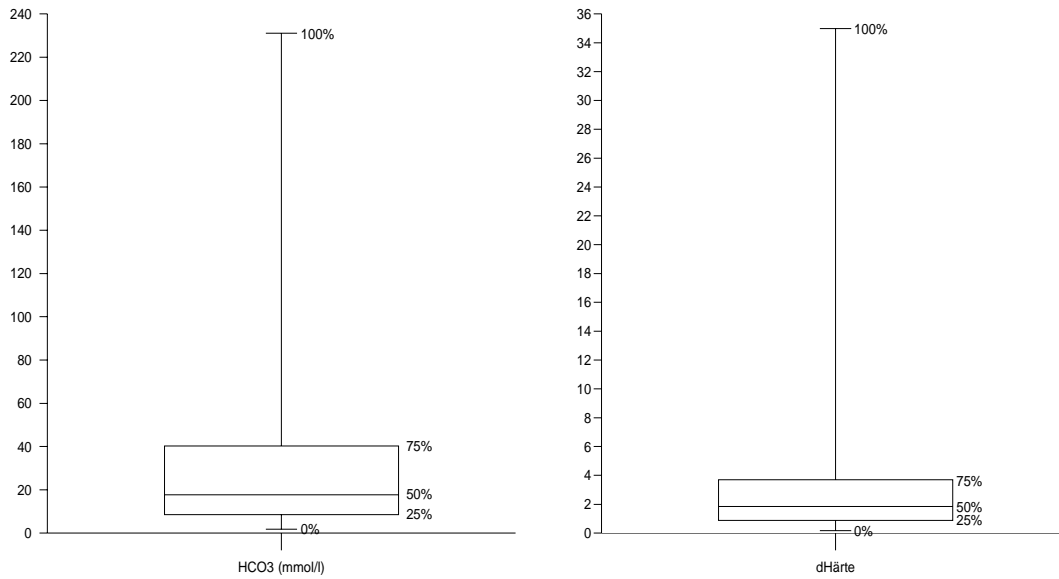


Figure 5.16 Presence of hydrogen carbonate in the study area and the associated hardness.

The distribution of bicarbonate in the study area (Figure 5.17) shows enhanced contents along the Bahr el Ghazal, along the lowest segment of the Chari River, to the north of the Chari-Baguirmi region, and in the proximities of Lake Fitri. Lower bicarbonate contents are encountered in the Massénya swamps and in the Kanem region.

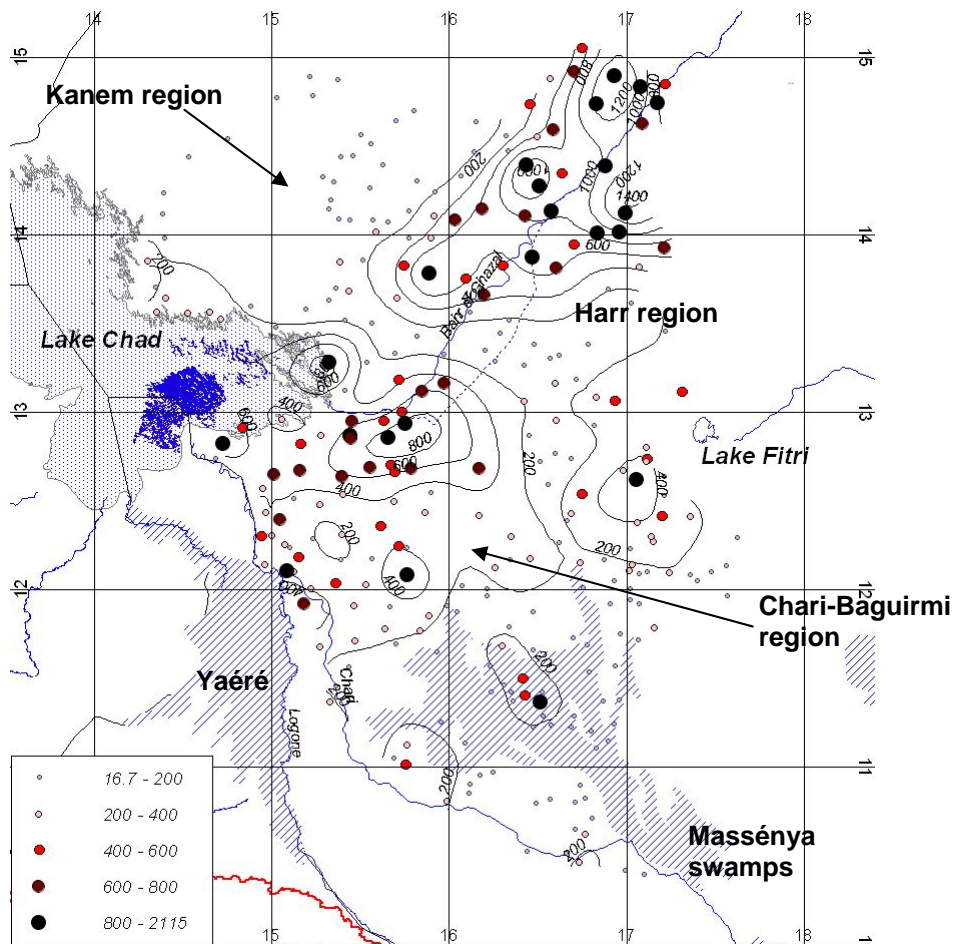


Figure 5.17 Groundwater bicarbonate distribution map (mg/l). Enhanced contents of bicarbonate appear along the Bahr el Ghazal, along the lowest segment of the Chari River, to the north of the Chari-Baguirmi region, and in the surroundings of Lake Fitri. Lower values appear in the Massénya swamps and in the Kanem region.

5.3.6 Chloride

Chloride contents above 200 mg/l give water a salty taste. However, chloride is not considered hazardous to health.

In general, the chloride distribution map (Figure 5.18) shows high chloride concentrations along the Bahr el Ghazal, to the north of the Chari-Baguirmi region, and in the proximities of the Lake Fitri. Enhanced concentrations of chloride between 20 mg/l and 200 mg/l are measured also in the surroundings of Bousso to the south of the investigation area.

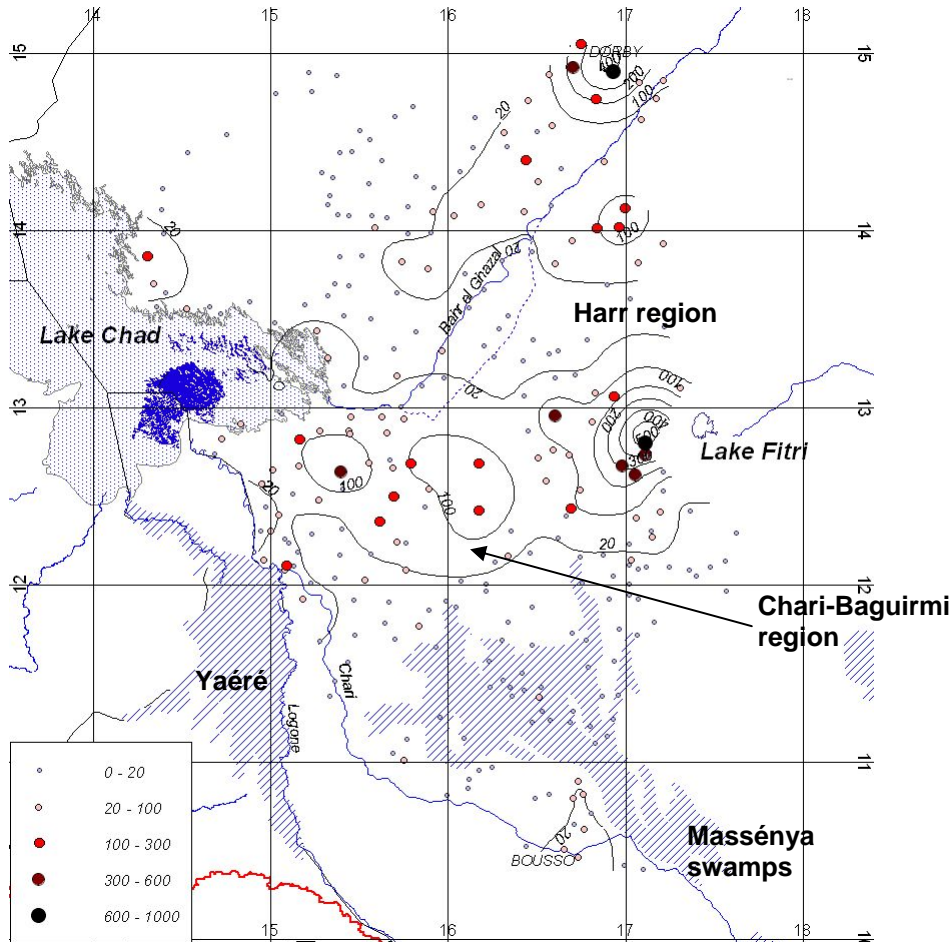


Figure 5.18 Groundwater chloride distribution map (mg/l). High chloride concentrations are measured in the Chari-Baguirmi area and along the Bahr el Ghazal, especially in the surroundings of Derby. Also enhanced chloride values are encountered in the proximities of Bousso.

5.3.7 Sulphate

The presence of sulphate in drinking water can be noticed by taste. Very high concentrations have laxative effect in unaccustomed users. However, sulphate in water does not have serious health implications and WHO has not set any limitation for this anion.

The Massénya swamps and the Kanem region present very low sulphate concentrations. Similar to the chloride and TDS distribution maps, the sulphate map (Figure 5.19) shows high concentrations along the Bahr el Ghazal, to the north of the Chari-Baguirmi area, and in the proximities of the Lake Fitri. The samples with the highest concentrations of TDS (Dorby, Koual, Adelema, and Abrania, see Figure 5.10) also show the highest concentrations of sulphate.

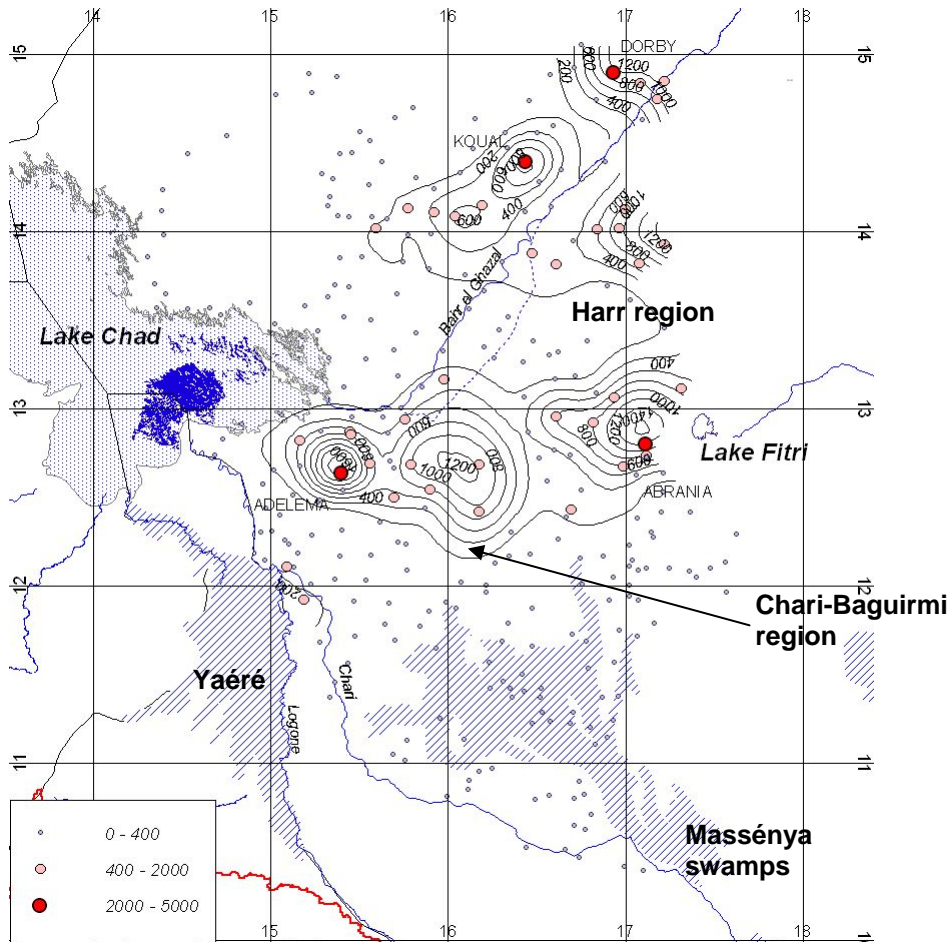


Figure 5.19 Groundwater sulphate distribution map (mg/l). The samples with the highest TDS have also the highest sulphate concentrations.

5.3.8 Nitrate

Nitrate is generally an indicator of groundwater contamination, mostly caused by inadequate use of nitrogenised fertilizers, inefficient or defect sanitation plants, or even direct pollution with human or animal faeces.

High nitrate concentration is considered as carcinogen for adult persons, if exposure is permanent. It is also known as the cause for the so called "blue death" of babies, due to lack of oxygen in blood. For this reason, the upper limit accepted by the WHO norms (and also EU and EPA in the USA) is fixed at 50 mg/l (expressed as nitrate NO_3^-). However, the EU norms consider a concentration of 25 mg/l as the figure from which measures of groundwater protection should be adopted.

The nitrate distribution map is presented in Figure 5.20. In total 41 of the 290 samples, or 14%, present levels of nitrate above the limit of 50 mg/l accepted by the WHO. It is assumed that most of the cases are due to local contaminations caused by direct input of animal faeces in the wells. The drinking troughs for the animals are generally located next to the well; therefore the surrounding area is excessively contaminated with faeces. To extract the water, a bucket hanging from a cord is used, which is pulled by a bull. Whenever the cord falls on the ground, it gets contaminated with dirt and faeces that will fall into the water when the bucket is pushed back into the well. However, the enhanced nitrate concentrations measured in the proximities of Bousso could also be the result of the intensive agricultural activities in the area.

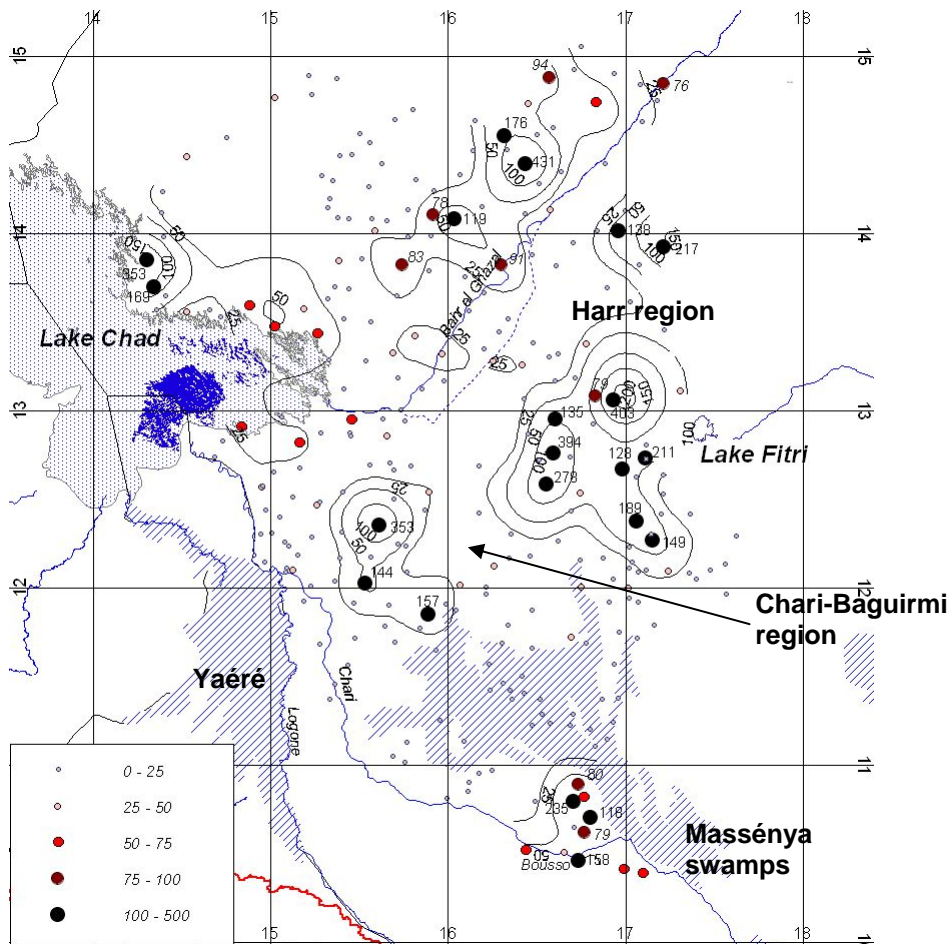


Figure 5.20 Groundwater nitrate distribution map (mg/l). In total 41 of the 290 samples, or 14%, show nitrate concentrations higher than the WHO limit of 50 mg/l.

5.3.9 Phosphate

The natural concentration of phosphate in groundwater is caused by the presence of phosphoric minerals like apatite and phosphorite. However, natural concentrations generally do not exceed values of 0.1 mg/l. Although it is not considered as harmful for health, they are a good indicator for pollution. The presence of phosphate in higher concentrations is always an indicator of human pollution due to an excessive use of fertilizers, intensive animal practices and manure as well as industrial or sewage discharge.

The results obtained so far indicate the presence of phosphate in 113 of the 290 samples, or 39 %. Even concentrations higher than 10 mg/l were measured in five samples: Guirbe on the southern edge of the lake with 21.3 mg/l as well as Mizelime (10.6 mg/l), Modorio (16 mg/l), Oualdi (23.8 mg/l) and Seite (24.7 mg/l) in the Massénya swamps (Figure 5.21). These high figures are probably due to agricultural contamination.

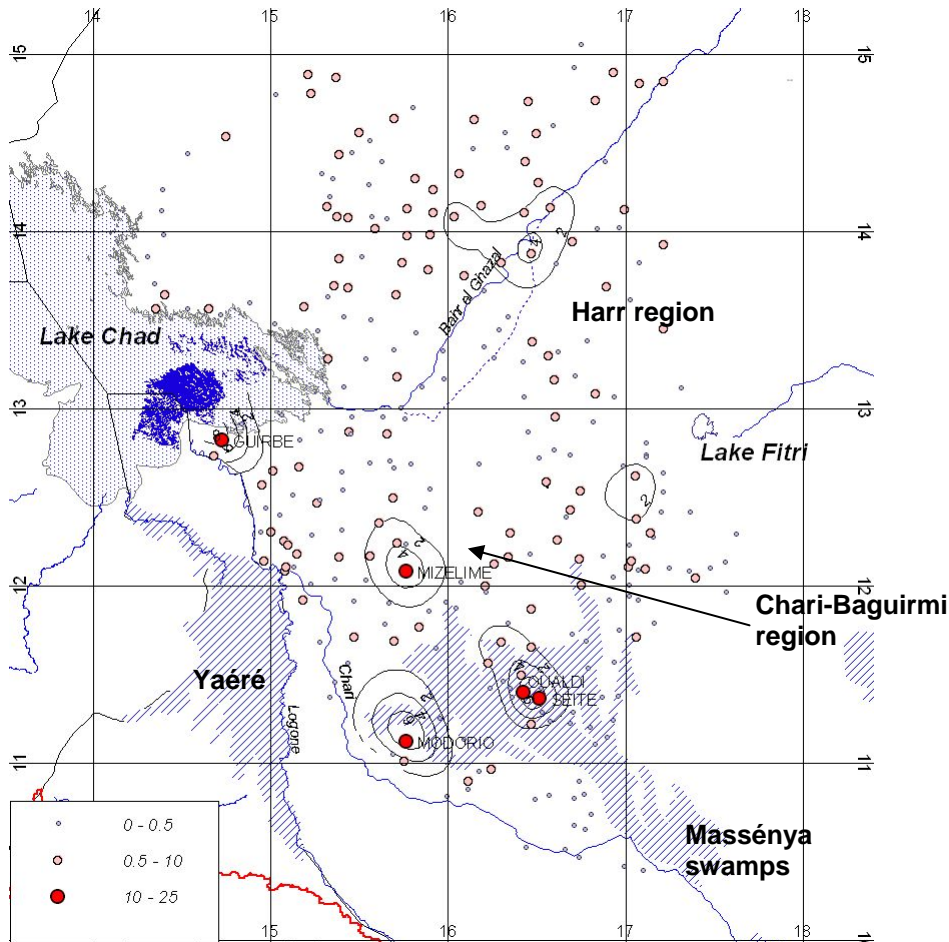


Figure 5.21 Groundwater phosphate distribution map (mg/l). 39 % of the samples show high levels of phosphate. Concentrations exceed 10 mg/l in the five labelled locations, probably the result of intensive use of fertilizers for agriculture.

5.3.10 Fluoride

Fluor is considered necessary at certain levels to avoid caries. However, concentrations above 0.5 mg/l to 1 mg/l can lead to changes in the skeleton (fluoride-osteosclerosis) as well as blotches on the teeth (fluorosis).

High-fluoride groundwater is often linked to deep groundwater. It is also associated with water of sodium-bicarbonate type and relatively low calcium and magnesium concentrations. These water types present high pH values (above 7). Therefore, information on chemical composition of groundwater can be used as an indicator of potential fluoride problems.

The most common minerals containing fluoride are:

- (Fluor)Apatite ($\text{Ca}_5[(\text{F},\text{Cl})(\text{PO}_4)_3]$).
- Fluorite (CaF_2).
- Mica, with the formula $\text{X}_2\text{Y}_{4-6}\text{Z}_8\text{O}_{20}(\text{OH},\text{F})_4$ in which X is K, Na, or Ca or less commonly Ba, Rb, or Cs; Y is Al, Mg, or Fe or less commonly Mn, Cr, Ti, Li, etc.; and Z is chiefly Si or Al but also may include Fe^{3+} or Ti.

Groundwater in the study area shows fluoride contents above the upper WHO limit of 0.5 mg/l (Figure 5.22) especially along the Bahr el Ghazal, to the south of the Lake Chad, and in the vicinity of Lake Fitri. Especially the zone along Bahr el Ghazal presents alkaline water (pH above 7) and enhanced concentrations of bicarbonate, potassium, and sodium as well as magnesium and lithium (Figure 5.23). Thus, the presence of mica could be the cause for the high fluoride content.

However, high fluoride concentrations are also typical for groundwaters contained in granitic/gneiss rocks of the basement complex. Therefore, a high content of fluoride could also be an indication of upwelling groundwater from the basement into the shallow aquifers.

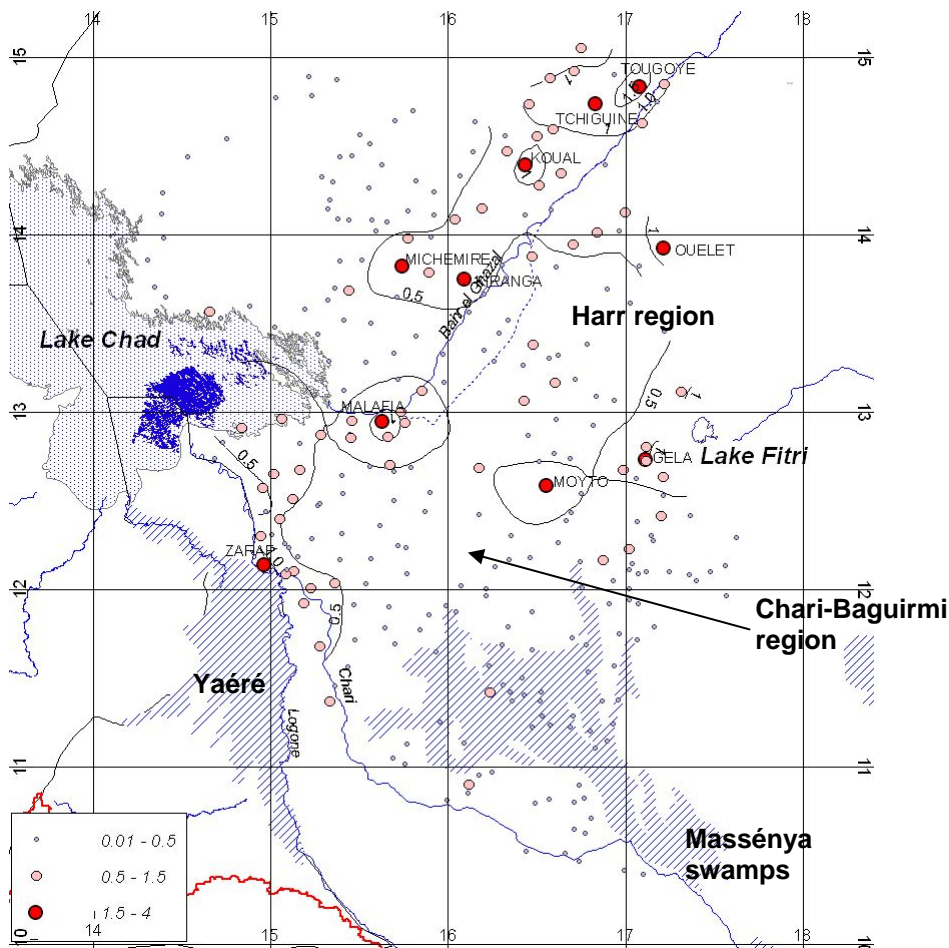


Figure 5.22 Groundwater fluoride distribution map (mg/l). Fluoride concentrations above the WHO limit of 0.5 mg/l are encountered along the Bahr el Ghazal, to the south of the Lake Chad, and in the proximities of the Lake Fitri.

5.3.11 Lithium

Lithium is generally linked to deep groundwater e.g. the igneous/gneiss rocks of the basement. It generally appears in concentrations between <0.005 and 0.5 mg/l. It is beneficial for the immune system and, in small quantities, it is considered as an anti-depressive. There are no limits for lithium contents from the WHO.

The lithium distribution map (Figure 5.23) shows enhanced lithium concentrations with values above 0.1 mg/l along the Bahr el Ghazal and to the north of the Chari-Baguirmi area. As described above, the presence of lithium could be due to the presence of mica in the underground or the upwelling of groundwater from the basement complex into the shallow aquifers.

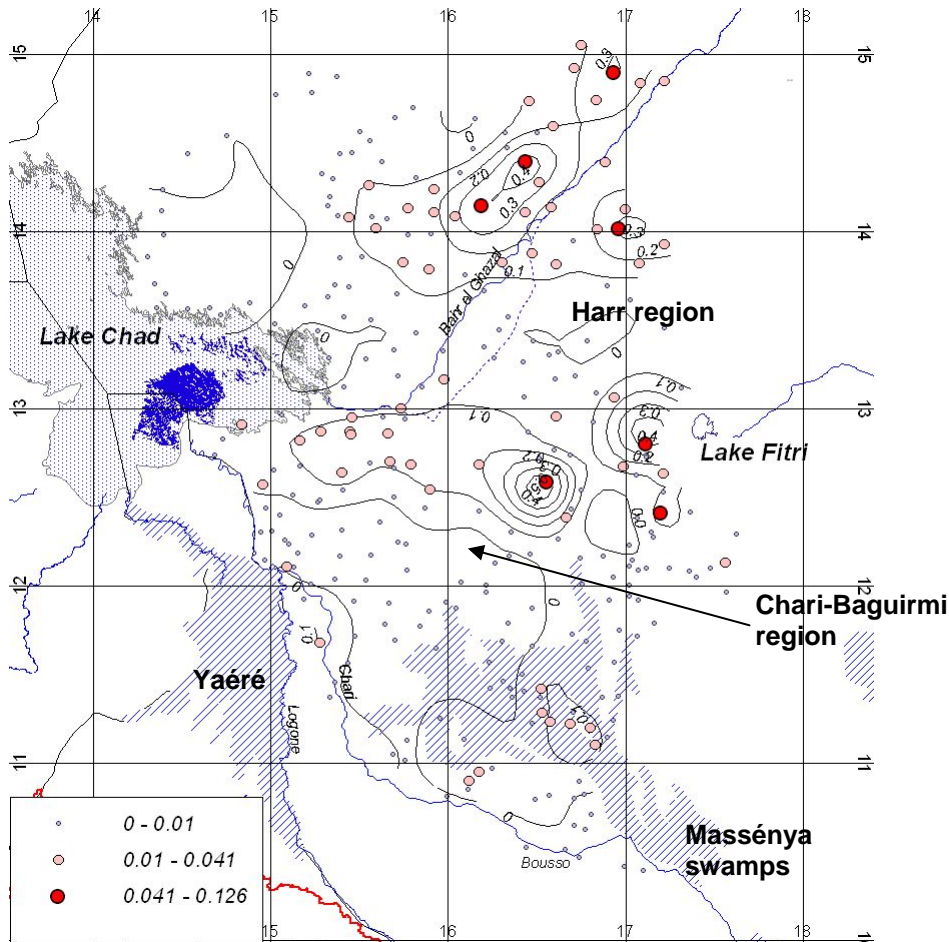


Figure 5.23 Groundwater lithium distribution map (mg/l). Enhanced concentrations of lithium above 0.1 mg/l appear along the Bahr el Ghazal.

6. Isotopy

Due to natural fractionating processes, it is possible to employ the environmental isotopes ^{18}O and ^2H to determine recharge characteristics to the aquifers. Rainwater, depending on the effects it suffers before reaching the soil surface, has a particular composition of these isotopes.

A different number of neutrons in the nucleus of an atom mean a change in the molecular mass or atomic weight. A water molecule is generally written as H_2O , but there are different masses of this molecule, due to different numbers of neutrons in the molecules of hydrogen or oxygen atoms. For example, water composed as $^2\text{H}_2^{16}\text{O}$ has a mass of 20 and is heavier than water as $^1\text{H}_2^{16}\text{O}$ with a mass of 18. In the clouds, the first raindrops contain generally heavier molecules that tend to fall earlier. On the other side, when there is evaporation, it is the light molecules that tend to leave first. These effects are used for defining possibilities of evaporation in surface and groundwater.

The measurement of an absolute ratio of isotopes would lead to difficulties in the comparison of results from different laboratories. That is why the results are always expressed as the ratio between the ratios measured for the given sample and that of a reference sample which, in the case of oxygen leads to (the same procedure is valid for hydrogen):

$$\delta^{18}\text{O}_{\text{sample}} = \frac{(^{18}\text{O}/^{16}\text{O})_{\text{sample}} - (^{18}\text{O}/^{16}\text{O})_{\text{reference}}}{(^{18}\text{O}/^{16}\text{O})_{\text{reference}}}$$

The International Atomic Energy Agency (IAEA) has published a Global Meteoric Water Line (GMWL) with a relationship of $\delta^2\text{H} = 8 \delta^{18}\text{O} + 10$, which is an average of the rainwater composition worldwide. Although no rainwater isotope was measured in the project, the

database of IAEA contains enough values for N'Djamena to be able to determine the local water line (Figure 6.1) that will be adopted for the study area.

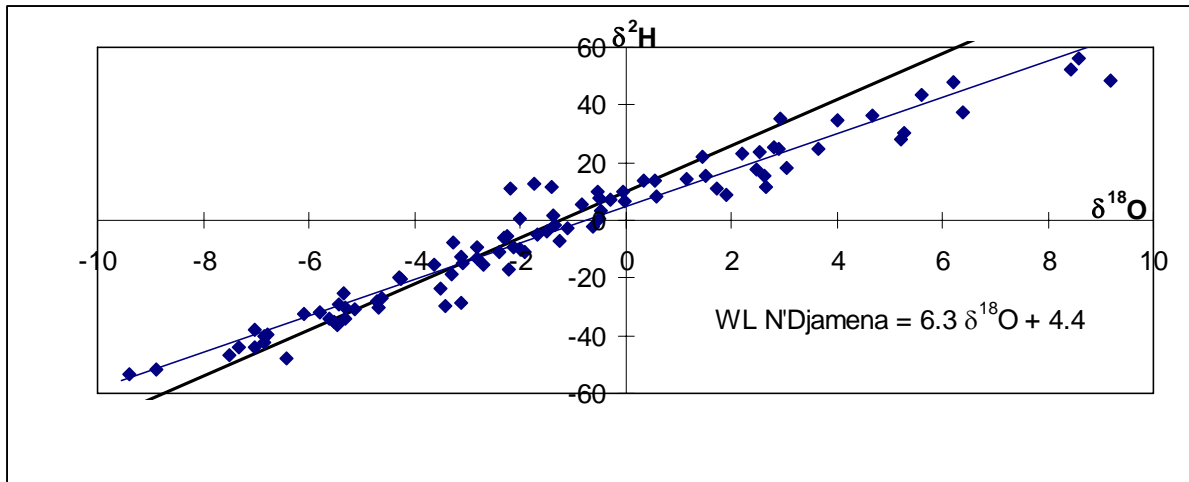


Figure 6.1 Local water line for Ndjamen (thin blue line) using data from IAEA compared to the Global Meteoric Water Line (bold black line).

The local line has a slope of 6.3 and thus smaller than the GMWL, due to the evaporation of water in the clouds, in the atmosphere, and in the unsaturated zone of the soil before reaching the groundwater table. Further, the positive side of the graph indicates enrichment of ^{18}O and ^2H rainwater. This is common in arid areas for small precipitation events because the water molecules of the heavier isotopes tend to fall first (Figure 6.2). The composition changes for long precipitation events or downpours towards lighter water. Further, in arid regions with sandy soils isolated small precipitation events of less than 10 mm do not produce groundwater recharge because of superficial crusting and pore-air that needs to be released for percolation to take place (Döll and Flörke 2005). This means that groundwater recharged by precipitation has mostly negative values of $\delta^{18}\text{O}$ and $\delta^2\text{H}$.

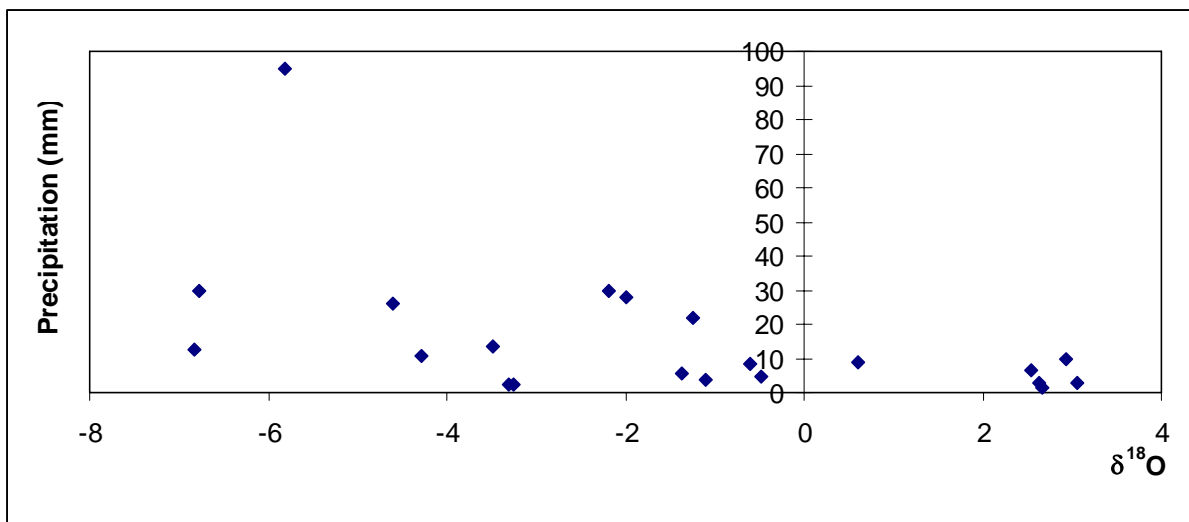


Figure 6.2 Measurement for $\delta^{18}\text{O}$ in N'Djamena during 1995 (Djoret 2000). Small precipitation events tend to draw in the positive side of the graph because the heavier isotopes are predisposed to fall first.

The project has taken groundwater and surface water samples to be analysed for environmental isotopes. Figure 6.3 shows the locations where the isotopes ^{18}O and ^2H have

been measured up to now. All analyses correspond to groundwater from the Quaternary aquifer and to the Lake Fitri.

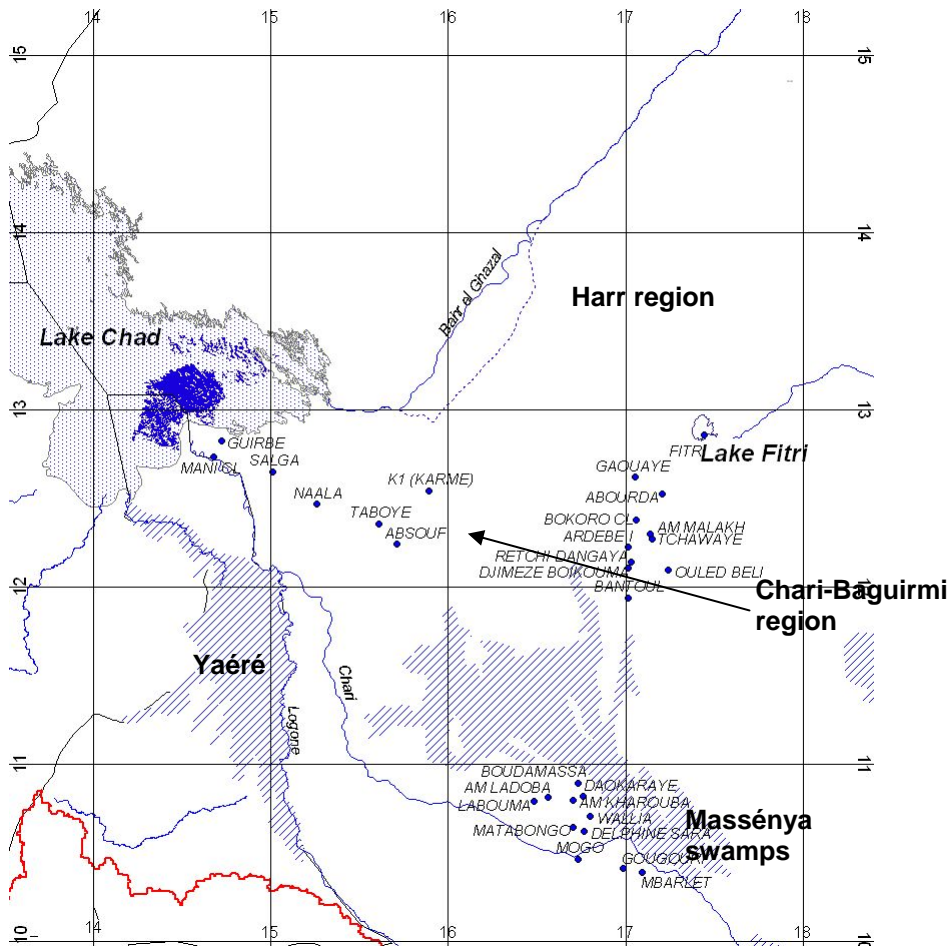


Figure 6.3 Location of the wells with results for ^{18}O and ^2H .

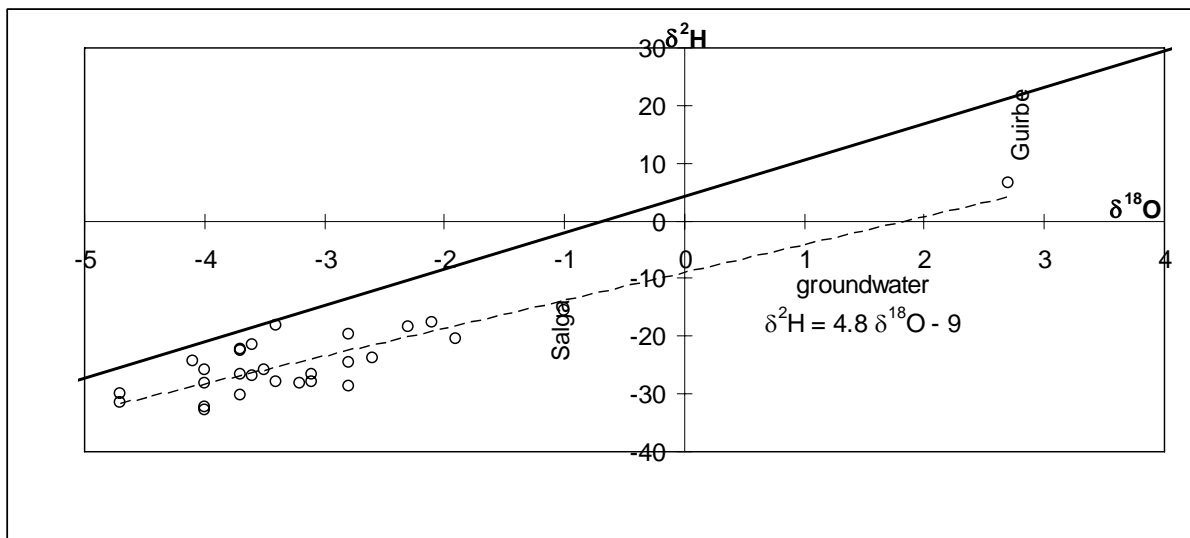


Figure 6.4 Evaluation of the environmental isotopes for groundwater. All data lie below the local water line and the trend-line has a slope smaller than that of the local water line. This is an indication of water evaporation in the unsaturated zone. The fact that the results for Guirbe plot on the positive side of the graph is probably due to recharge from the lake into the aquifer.

Figure 6.4 shows that all isotope results for groundwater fall below the local water line (bold black line) and that the trend-line of the data has a smaller slope than the local water line. This is due to the evaporation that takes place in the unsaturated zone. Further, it is evident that the groundwater at Guirbe has a different isotopic composition than the rest of the area as its result plots in the positive side of the graph. Taking into consideration that this well is located relatively close to the Lake Chad (some 15 km) and knowing that the lake has an enriched isotopic composition with $\delta^{18}\text{O} = 5$ and $\delta^2\text{H} = 23$ (Goni 2006), it can be postulated that groundwater in Guirbe is affected by recharge from the lake into the aquifer. Further, Salga, the next well some 50 km away from the lake, also shows relatively heavy isotopic composition although already in the negative part of the graph. This is probably the result of a weakened influence from the lake, due to the increased distance.

The proposed these does not contradict earlier publications on the issue. Fontes et al. (1969) studied the northeast coast of the Lake Chad by means of isotopic analyses. The investigation was aimed to evaluate the recharge of the lake into the aquifer. They concluded that there is no important discharge in that direction because already at a distance of some couple of meters the groundwater presents the characteristics of rainfall recharged water. In a later work concerning the same area, Fontes et al. (1970) conclude that the lake actually discharges towards the northeast, but groundwater is composed by waters originated by precipitation on the top and waters leaked by the lake at deeper depths.

Further, Isiorho and Matisoff (1990) investigated the south-western part of the lake, in Nigeria. With measurement of water levels in 12 existing open wells and electrical resistivity profiling in 13 locations, they produce a map of the potentiometric surface that shows outflow from the lake even as far as to 50 km from the shore. Additionally, they measured leakage from the Lake Chad into the Quaternary aquifer in 6 locations in the surroundings of Duro and concluded that lake water flows into the aquifer at a median velocity of $1.15 \cdot 10^{-3}$ m/d.

Djoret (2000) in his doctoral thesis investigated the northern part of the Chari-Baguirmi area and published values for the isotopes ^{18}O and ^2H for 23 water points, including samples from the Chari River.

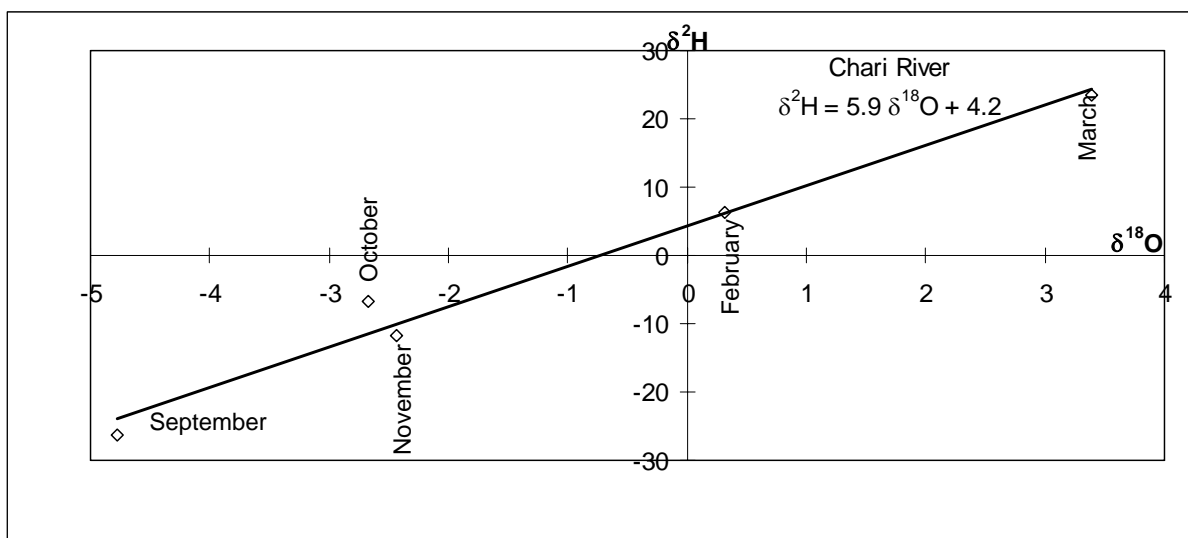


Figure 6.5 Evaluation of the isotopic composition of Chari River water published by Djoret (2000). Immediately after the rainy season, in September, the river water shows a light composition that moves toward more heavy water as long as the time passes through the year. The heaviest water was measured in March, at the end of the dry season. This is caused by the evaporation suffered by the river water.

The isotopic composition of the water from the Chari River shows the effect of evaporation (Figure 6.5). The lightest water was measured in September, immediately after the rainy

season. As long as the months pass the river water becomes heavier reaching the heaviest composition in March, at the end of the dry season.

Figure 6.6 shows the location of the wells measured by the project as blue circles. The locations of the wells included in Djoret's (2000) publication are presented as red dots. The pairs of data close to the wells correspond to the measured values of $\delta^{18}\text{O}$ and $\delta^2\text{H}$.

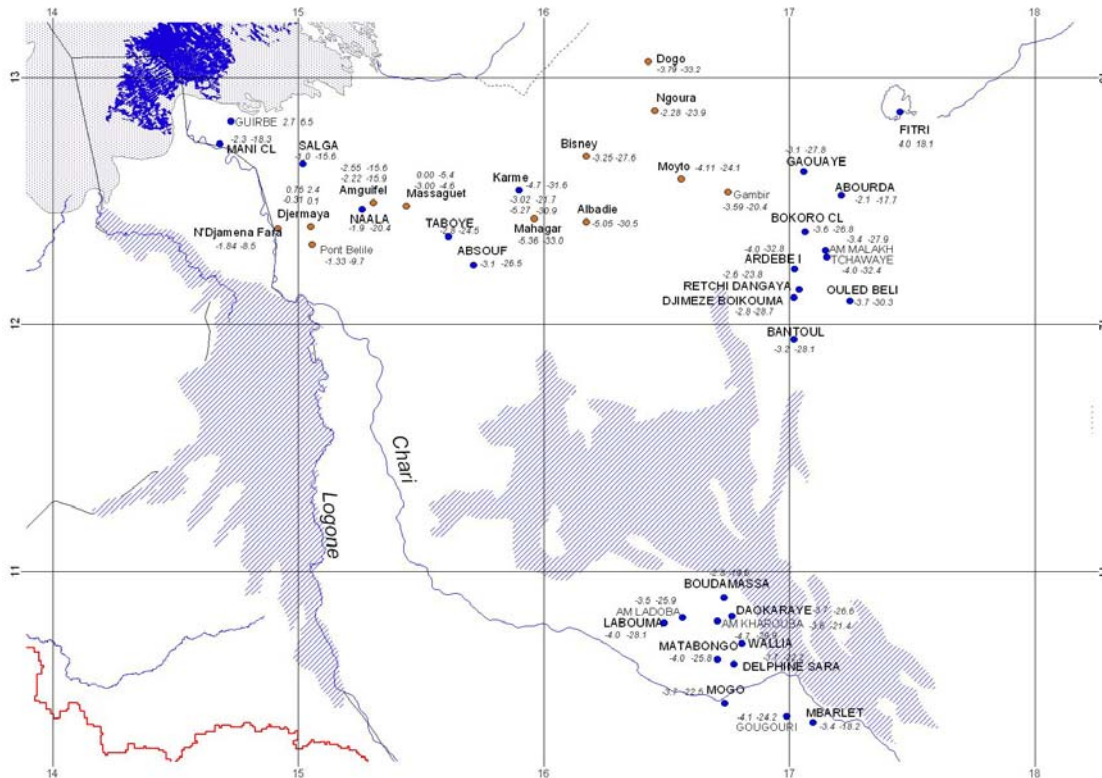


Figure 6.6 Location of wells with isotope measurements in the Chari-Baguirmi area. The blue dots indicate the wells measured by project and the red circles correspond to the locations investigated by Djoret (2000). The pairs of values are the measurements for $\delta^{18}\text{O}$ and $\delta^2\text{H}$ for each well.

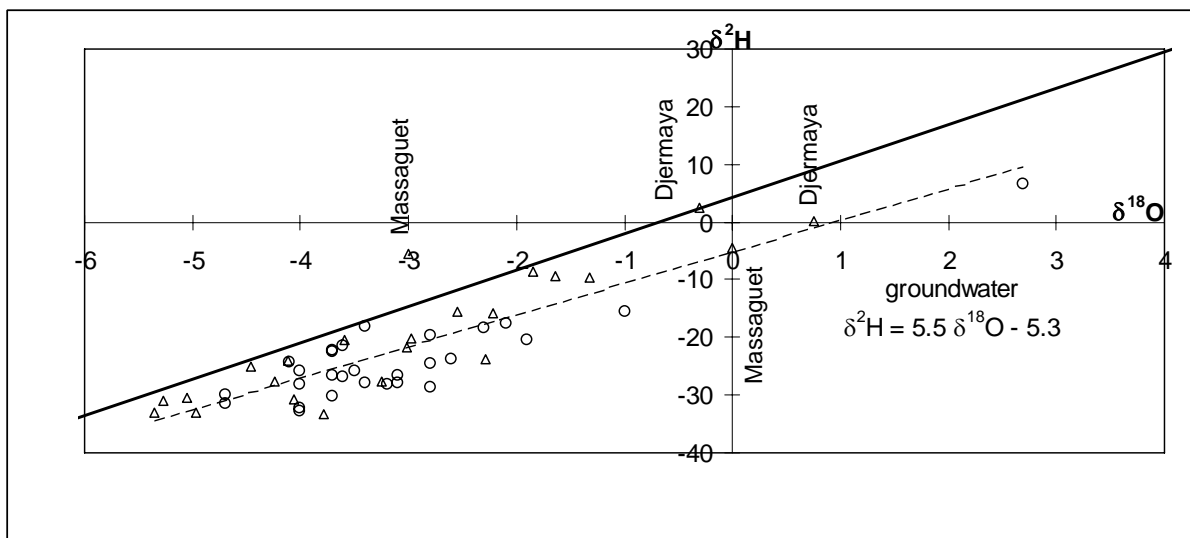


Figure 6.7 Location of wells with isotope measurements for groundwater with additional data published by Djoret (2000) plotted as triangles. All data lie below the local water line (bold black line) and the trend-line of the data has a slope smaller than that of the local water line. This is an indication of water evaporation in the unsaturated zone. According to Djoret the values for Massaguet and Djermaya plot on the positive side of the graph because they receive direct recharge from the Chari River.

If Djoret (2000) results are included in the evaluation of the isotopes of the Chari-Baguirmi area (Figure 6.7), the slope of the trend-line is slightly higher (5.5 instead of 4.8), but this is a minor difference. The measured isotopes still draw below the local water line (bold black line) and the trend-line of the data has a smaller slope than the local line, what indicates evaporation of recharge water in the unsaturated zone.

The results for Djermaya and Massaguet show on the positive side of the graph and Djoret (2000) concludes that this is the effect of direct recharge from a palaeo-channel of the Chari River that is located between Massénya and Massaguet.

A profile of $\delta^{18}\text{O}$ and $\delta^2\text{H}$ content was drawn using the isotope data from the project and those published by Djoret (2000), all of them measured in the period november-december. The profile starts from the Lake Chad and crosses the Chari-Baguirmi region up to the Lake Fitri (Figure 6.8). The decline of the isotope values with increase of distance to the lakes is an indication of recharge or leakage from these water bodies into the aquifer. A simple calculation based on mass conservation results in a mix of 20% to 30% of groundwater and 80% to 70% of Lake Chad water at Guirbe, some 15 km from the lake. At Salga, come 52 km from the lake shore, the proportion changes to 80% of groundwater to 20% of lake water. Finally at Naala, some 85 km from the lake shore, only 10% of the mix corresponds to lake water. The sudden increase in $\delta^2\text{H}$ values at Massaguet shows probably the effect of a surface water source, probable a palaeo-channel of the River Chari, as proposed by Djoret (2000).

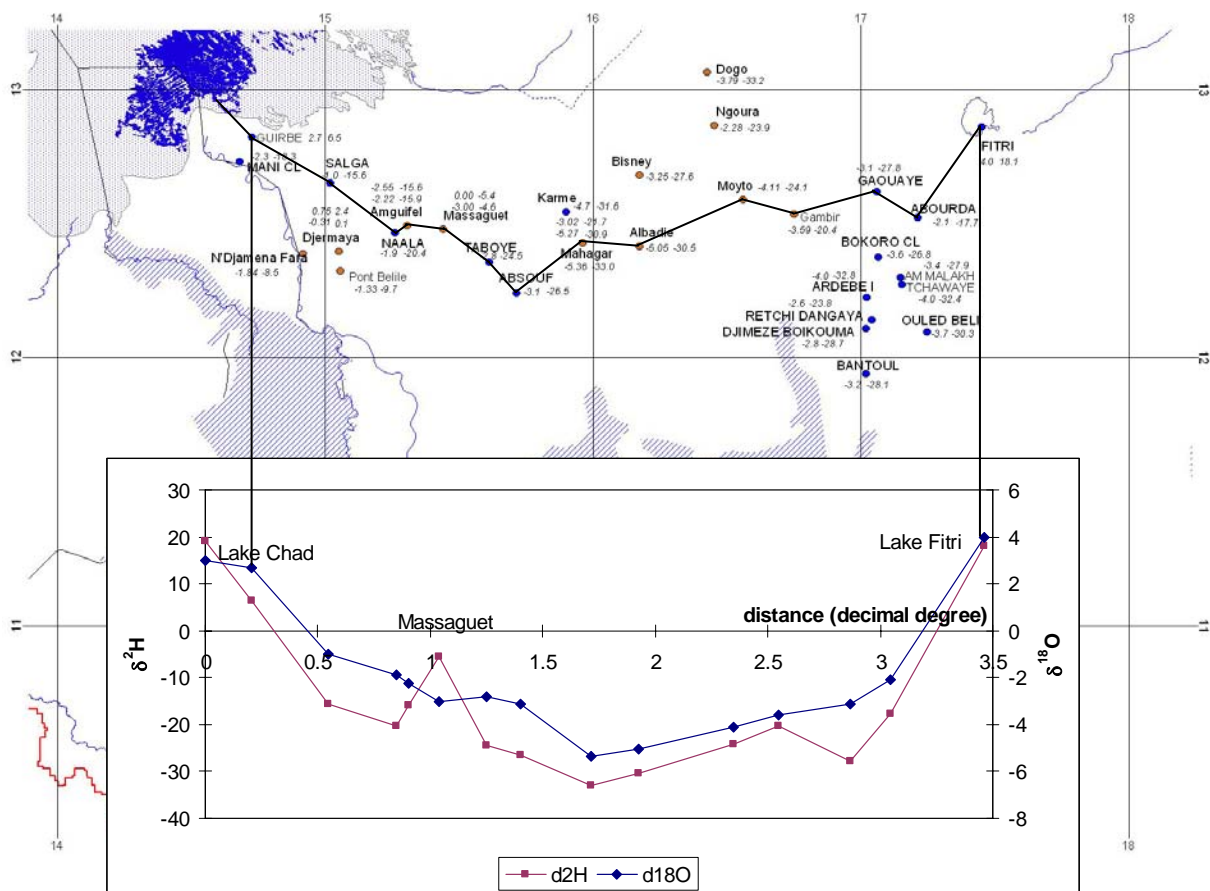


Figure 6.8 Location of the wells and profile of isotope measurements. There is recharge from the Lake Chad as well as from the Lake Fitri into the aquifer, as shown by the decline of $\delta^{18}\text{O}$ and $\delta^2\text{H}$ with increasing distance to the lakes. The sudden increase of the isotope values at Massaguet is an indication of recharge by surface water, probably a palaeo-channel from the River Chari (Djoret 2000).

Goni (2006) published 117 values of ^{18}O and ^2H for groundwater and surface water, including a sample from the Lake Chad, for the Nigerian part of the basin. Figure 6.9 shows the location of the wells with the published results. The red dots correspond to wells with very

heavy isotopic composition. Due to their proximity to the lake, it can be assumed that groundwater at Chadi Bakari and Minari does contain water from the Lake Chad or in other words, that the lake recharges the aquifer. The case of Dala Alamdari is a clear indication of recharge from Lake Alo located close by, which isotopic composition is $\delta^{18}\text{O} = 5.27$ and $\delta^2\text{H} = 23.6$ (Goni 2006).

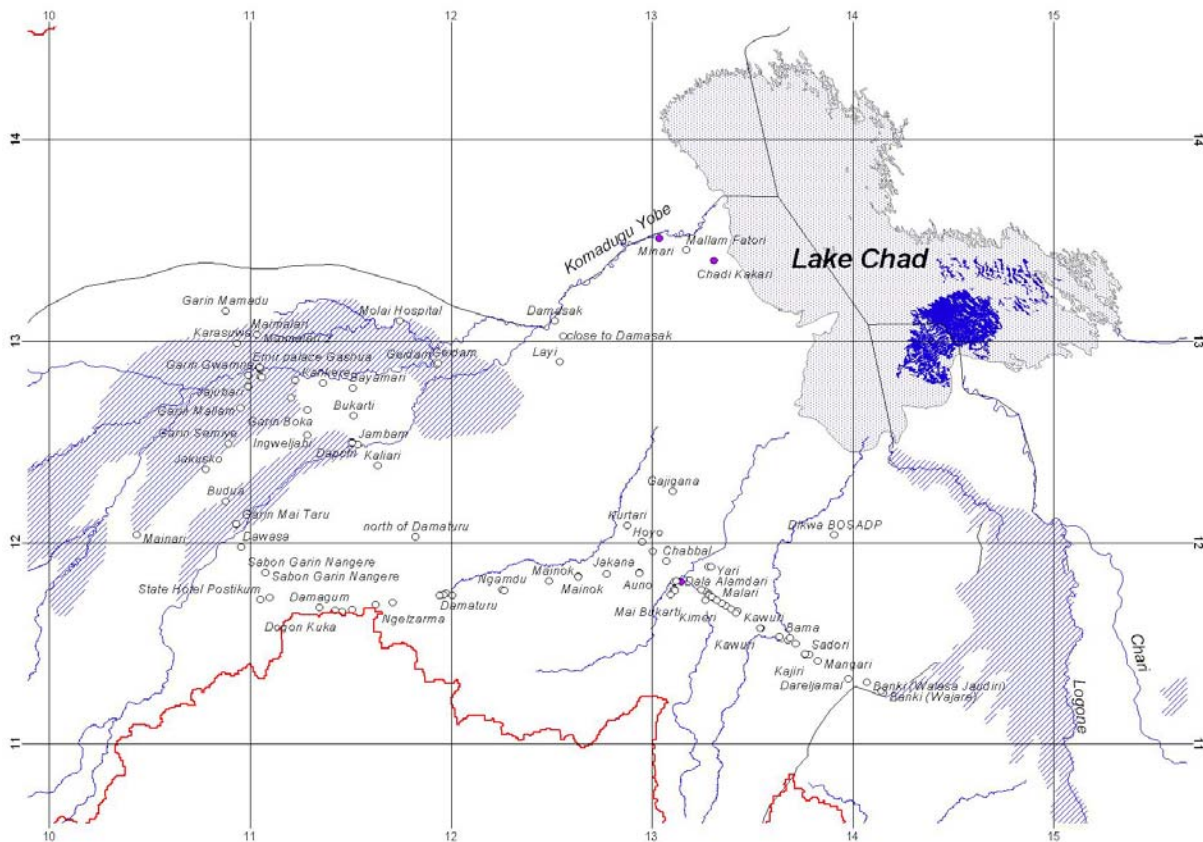


Figure 6.9 Location of wells with isotopic results published by Goni (2006). The red dots correspond to wells with very heavy isotopic composition. Due to their proximity to the lake, Chadi Bakari and Minari could show recharge from it. The case of Dala Alamdari is clearly a direct recharge from the Lake Alo located close by, which isotopic composition is $\delta^{18}\text{O} = 5.27$ and $\delta^2\text{H} = 23.6$ (Goni 2006).

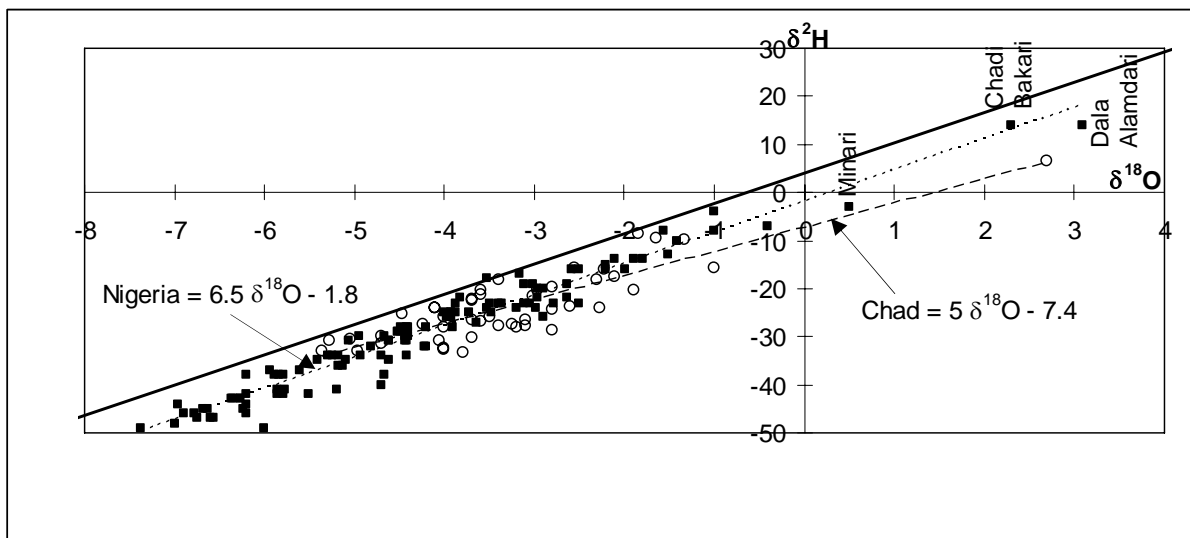


Figure 6.10 Comparison of Nigeria data from Goni (2006) represented with black squares and the Chad data shown with open circles. The data corresponding to Nigeria has a trend-line with a higher slope, which is an indication of less evaporation in recharge water. Further, the squares are farther to the left of the graph towards less enriched values, which means that recharge takes place with colder water.

Figure 6.10 shows the local water line as a bold black line, Goni data as black squares and the Chad data with open circles. The Nigeria data shows a higher slope of the trend-line (6.5 instead of 5.5) meaning that recharge water experiences less evaporation. Further, the data plot more to the left of the graph towards the less enriched water indicating recharge with cooler water than in Chad.

7. Summary and conclusions

Various field trips aimed to investigate the groundwater of the eastern part of the Lake Chad Basin have been performed. Measurement of rest water level in 290 water points has allowed the construction of a depth-to-water map and a groundwater contour map, which gives hints on the flow direction in the study area.

A total of 290 groundwater samples and 17 surface water samples have been taken and analysed in the BGR laboratories in Germany. The chemical results show that:

- Surface waters present a very weak mineralisation, which indicates that they are produced of precipitation, at least short after the wet season.
- In general, groundwater quality is good enough to be used for human consumption, especially in the Massénya region and the Kanem region. However, high values of salts expressed as enhanced TDS and water hardness are encountered along the Bahr el Ghazal, to the north of the Chari-Baguirmi region and in the vicinities of Lake Fitri. The TDS concentration at Dorby (6,541 mg/l), Koual (8,119 mg/l), Adelema (8,152 mg/l), and Abrania (5,674 mg/l) is higher than 5,000 mg/l meaning in these cases unsuitability for all drinking purposes.
- pH value is generally within the range given by the WHO, although groundwater is slightly alkaline (75% of the samples have pH values above 7).
- High nitrate concentrations appear scattered throughout the whole study area. The contamination is probably local and linked to a wrong management of the wells used for watering livestock that allows animal faeces and dirt to enter directly into the well. It is recommended that a better well management is implemented to avoid the local pollution becoming a regional hazard. The pollution in the vicinities of Bousso is probably due to intensive agriculture and the use of nitrogenous fertilizers.
- Relatively high phosphate concentrations are an indication of extensive use of fertilizers by the agriculture. It is recommended that better practices are assumed to avoid further contamination.
- Further, along the Bahr el Ghazal and in the proximities of the Lake Fitri there are enhanced concentrations of fluoride and lithium in groundwater, due mainly to the presence of mica in the clays that compose the aquifer. The presence of these ions could be an indication of up flow of deep groundwater.
- The isotopic analyses indicate recharge from the Lake Chad into the quaternary aquifer to the south-east (Chad) and in Nigeria at the vicinities of the Komadugu-Yobe River. The presence of enriched water in Massaguet has been interpreted as caused by recharge from a palaeo-channel from the Chari River.

It must be kept in mind that some of these conclusions, especially for the Kanem area, might change with the results of the field campaign presently on-going. Further, outstanding isotopic analyses might bring more light on the recharge and discharge characteristics, as well as the influence of the Lake Chad and the Chari River as recharge bodies for the Quaternary aquifer.

8. Literature

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