***L**AKE **C**HAD*
***S**USTAINABLE **W**ATER **M**ANAGEMENT*

Project Activities - Report N° 4

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Lake Chad Commission
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N'Djamena

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Figure 21. Spatial distribution of nitrate concentrations. A total of 59 samples (or 13%) show concentrations above the limit of 50 mg/l given by the WHO. Pollution has different sources. To the north of 12° latitude north pollution is thought to be the result of animal faeces from livestock watering directly from the borehole. In the south, pollution is due to agricultural use as the result of excessive application of nitrogenised fertilizers.

Figure 22. Spatial distribution of sulfate. Sulfate in concentrations above 1,000 mg/l is present in 14 samples, and 18 samples have concentrations between 500 mg/l and 1,000 mg/l. All these samples are located to the east and west of the Bahr el Ghazal, to the SE of the Lake Chad and in the vicinities of the Lake Fitri.

1. Generalities

This report summarizes the results obtained under the umbrella of a BGR project in collaboration with the Lake Chad Basin Commission (LCBC). The project “Lake Chad: Sustainable Water Management” was financed by the Federal Institute for Economic Cooperation and Development (BMZ) and the first phase extended over 4 years from Mai 2007 to June 2011.

During this first phase of the project, a total of 441 water samples (Figure 1) were taken from surface water (19) and groundwater (422) to investigate their chemical composition. Groundwater comprised mainly the upper quaternary aquifer (417), but 5 samples were taken from deep boreholes that get water from the lower Pliocene. The samples were analyzed at the BGR laboratory in Germany. Analyses comprised complete anion and cation species, and trace elements. In-situ parameters (temperature, pH and electric conductivity) were measured by means of a multi-sensor set from the Wissenschaftlich-Technische Werkstättem (WTW). Oxygen content was not measured due to the sampling method used (bailer).

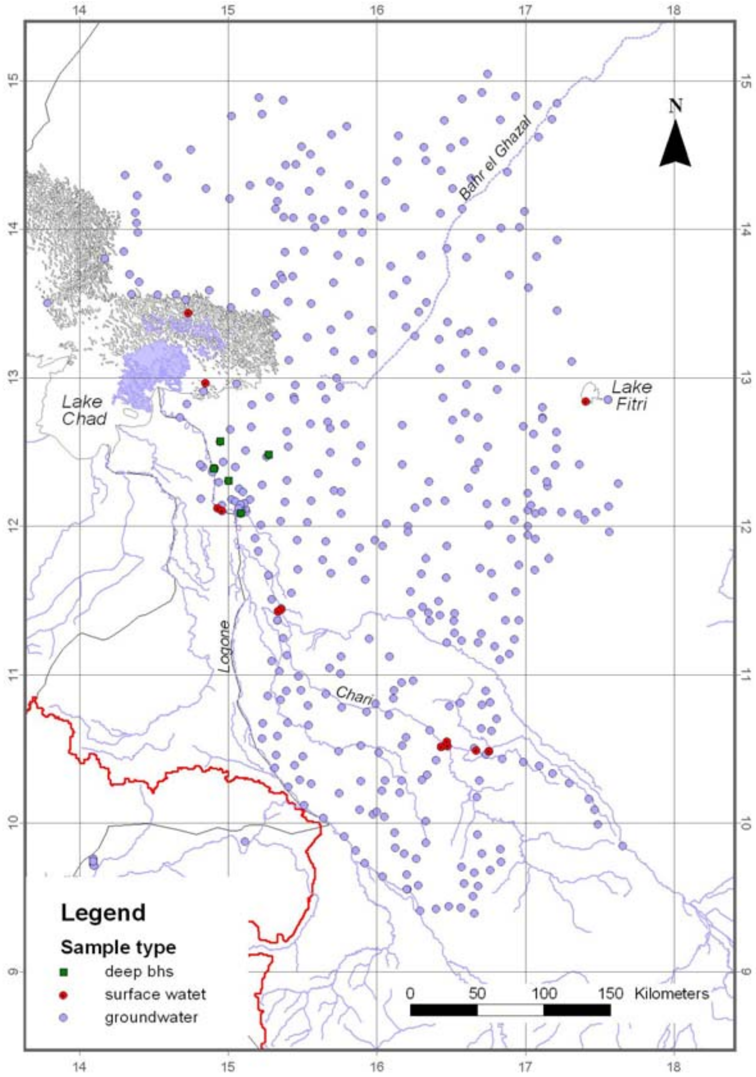

Figure 1. Location of the 441 water samples taken during the first phase of the LCBC/BGR project.

Sampling trips took place in three different periods: November 2008 to April 2009, November 2009 to March 2010, and November 2010 to February 2011. Aim of the sampling was to assess the groundwater quality. The results were used to investigate zonation of the aquifer and define areas of groundwater recharge.

2. Results

2.1. Ion balance

An easy way to assess the quality of chemical analyses is the calculation of the ion balance. For an analysis to be acceptable, the ion balance has to be lower than 1% for samples with total cations or anions of less than 1 mmol(eq)/l. For higher salt contents, it has to be lower than 5% (Figure 2).

The ion balance is based on the equilibrium between anions and cations. According to the DIN norm DEV A0-5, the ion balance can be calculated as follows:

$$ion\ balance\ (\%) = \frac{\sum cations - \sum anions\ \ (\mathrm{mmol(eq)/l})}{\left(\sum cations + \sum anions\ \ (\mathrm{mmol(eq)/l})\right) * 0.5} * 100$$

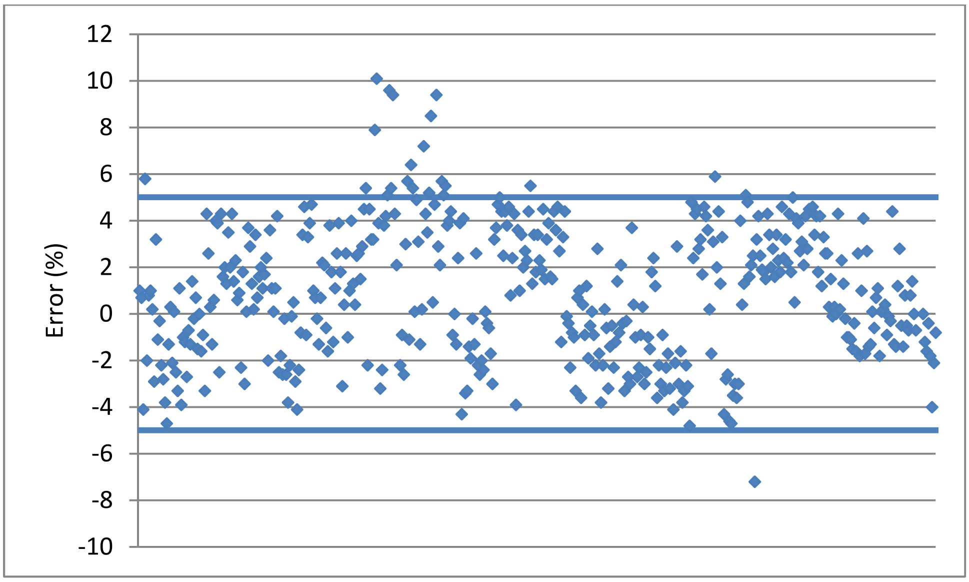

Figure 2. Ion balance for 441 water analyses. A total of 22 samples presented ion imbalance, probably due to organic carbon dissolved in groundwater.

Although 22 samples (5% of all results) presented ion imbalance, due probably to the presence of dissolved organic carbon in groundwater, it is concluded that the laboratory has worked adequately.

2.2. Groundwater quality

Regional groundwater quality depends among others on the processes suffered by the recharge water during infiltration. Mineralization of recharge water is controlled by the flow properties and thickness of the unsaturated zone. Precipitation in areas away from oceans contains almost no minerals, but it can be mineralized along the through-flow in the unsaturated zone to reach the aquifer as more or less saline water.

In the case of aquifers with shallow water table, newly recharged water will have low mineral content because on one side it percolates quickly through the unsaturated zone and on the other hand it has had no time to acquire minerals from the underground. Recently recharged groundwater is always of Ca-Mg-HCO_3-type.

Regional groundwater quality also depends on the aquifer composition, recharge quantity, and flow velocity. Mineralization increases with residence time of groundwater in the aquifer if reactive material is present in the matrix. Groundwater experiences exchange of cations and anions, depending on their availability in the underground. Ca and Mg will be exchanged by Na (or vice versa); HCO_3 by SO_4 and/or Cl, although anion exchange is rather seldom. Groundwater of Na-HCO_3, Na-SO_4, or Na-Cl-types, this last case for aquifers far away from coastal areas, is always the result of very long residence time when the groundwater has been able to absorb minerals from the surrounding rocks.

Groundwater in the Lake Chad region displays regionally different chemical compositions as shown in Figure 3. Groundwater of Ca-Mg-HCO_3-type (light color) appears in the proximities of the Chari and Logone rivers in the southern part of the region, as a result of direct recharge either from surface water or from precipitation. Further, poor mineralized water is present to the north of Lake Chad, surely as a result of direct recharge from precipitation because no surface water is present in this area.

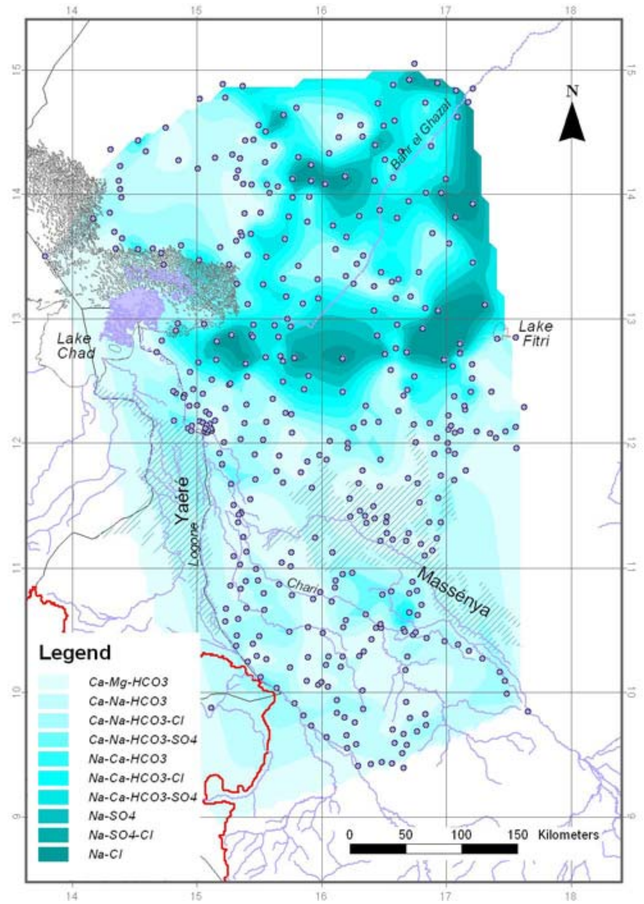

Figure 3. Distribution of water quality. Salinity of groundwater increases with color darkness. The dots indicate the location of water sampling.

Groundwater of the Na-SO_4-Cl-type appears to the south-east of the Lake Chad and east and west of the Bahr el Ghazal. These regions are characterized by very low hydraulic conductivity that leads to extremely low flow velocity, or in other words, to very long residence time. It is assumed that this groundwater is of very old age (was recharged long time ago) and has had time to mineralize.

Another way of visualizing water quality is by means of a Piper Diagram (Figure 7). The chemical composition of groundwater along the flow path from the recharge zone to the discharge point is described mainly by three zones in the 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 in the study area, 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 present 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.

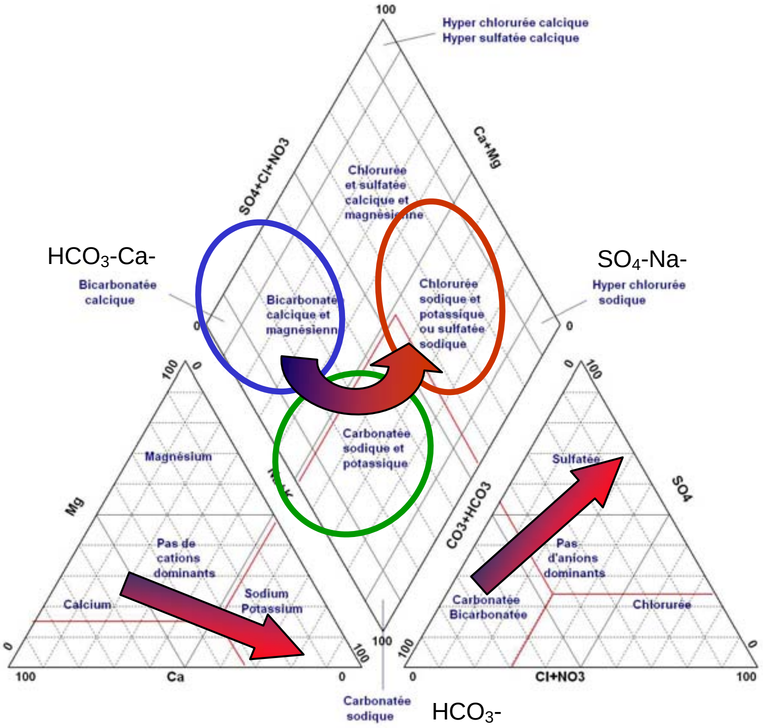

Figure 4. Piper Diagram for the representation of water quality.

Figure 5 shows the water quality of surface water. All samples have low mineralization with TDS less than 1,500 mg/l (see chapter 2.4 below) and fall into the “bicarbonate calcium” zone. These waters are directly originated by precipitation.

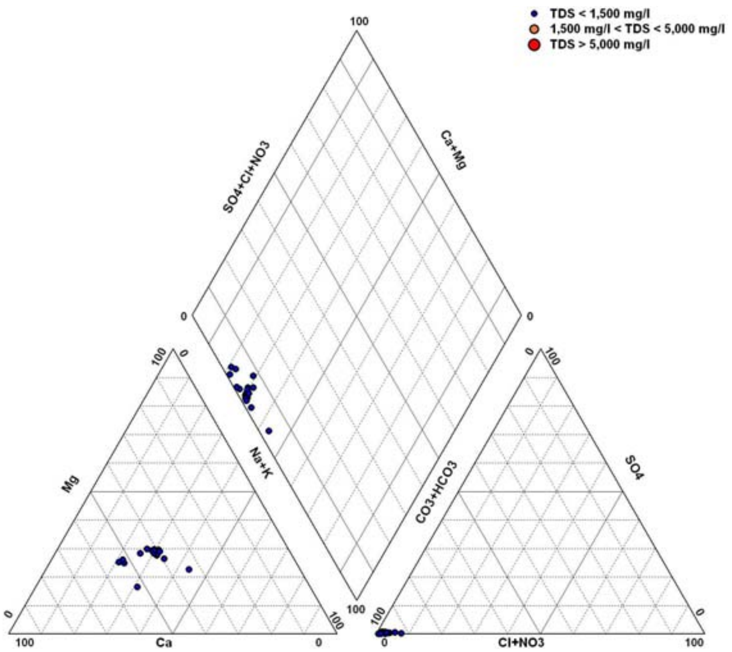

Figure 5. Piper Diagram for surface water. As expected, all points fall in the “bicarbonate calcium” zone.

The Piper Diagram for the 5 deep boreholes from the Lower Pliocene aquifer is presented in Figure 6 below. Groundwater mineralization is relatively weak with TDS lower than 1,500 mg/l. Further, groundwater is of “bicarbonate sodium” type that indicates a long path in the underground during which calcium has been replaced by sodium.

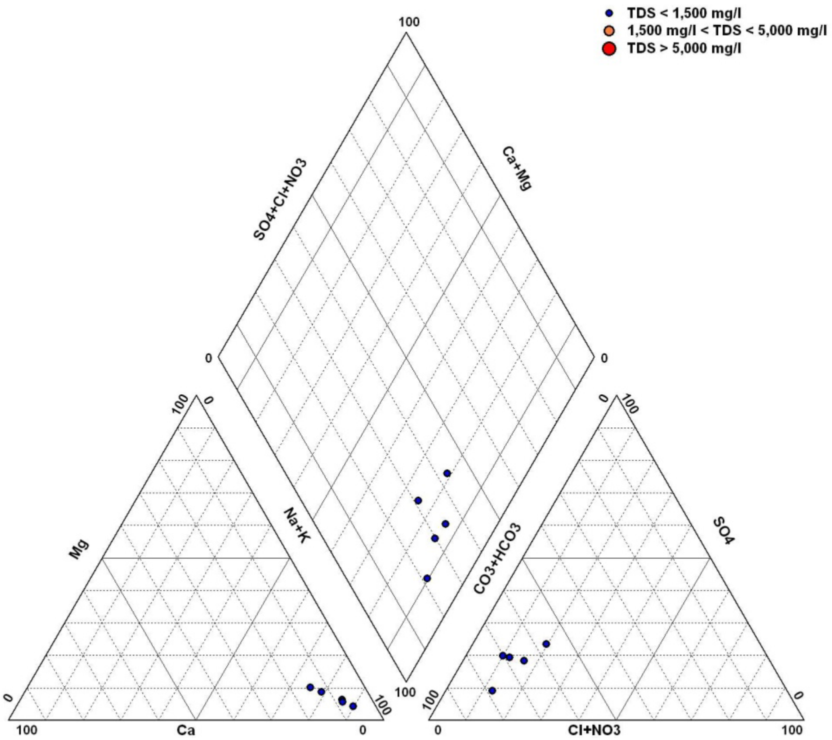

Figure 6. Piper Diagram for deep boreholes that extract water from the Lower Pliocene aquifer. Groundwater is of “bicarbonate sodium” type with relatively low mineralization (TDS < 1,500 mg/l).

Groundwater in the Quaternary aquifer presents often large amounts of nitrate. Assuming that nitrate is a human induced pollution, Piper diagrams can be plotted without this anion und thus get a better idea of the groundwater natural characteristics (compare values for the Kanem region in Figure 7).

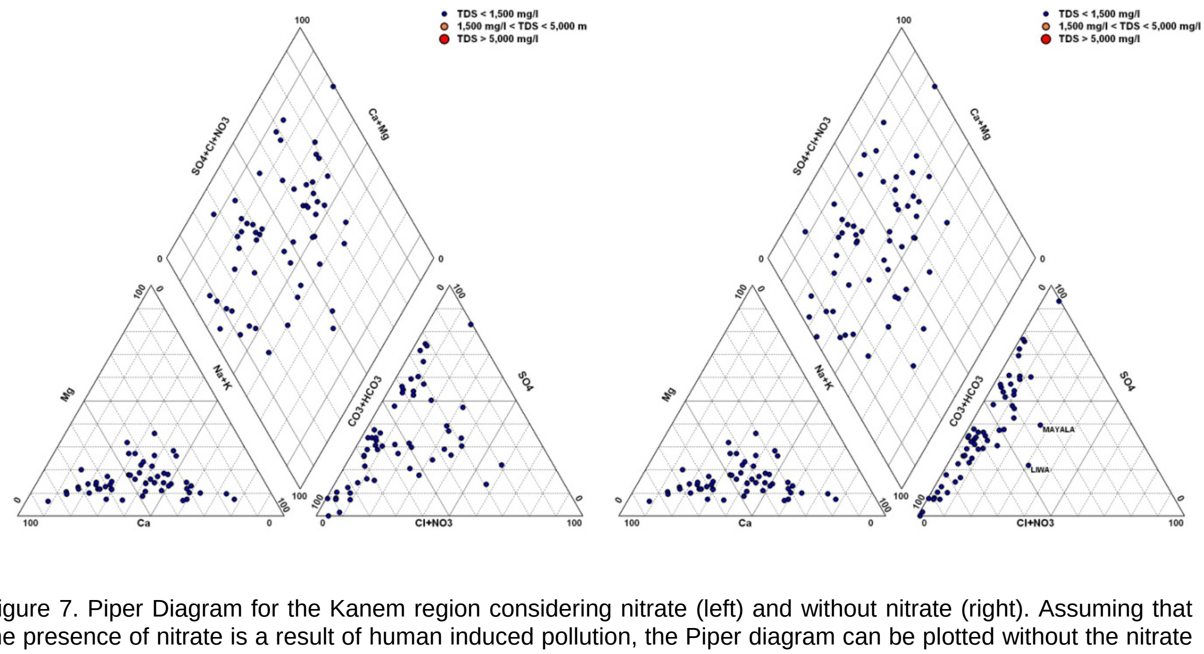

Figure 7. Piper Diagram for the Kanem region considering nitrate (left) and without nitrate (right). Assuming that the presence of nitrate is a result of human induced pollution, the Piper diagram can be plotted without the nitrate ion for a better perception of the natural groundwater composition.

To be able to better understand what is happening in the quaternary aquifer, results were distributed according to zones of sampling: Kanem, Bahr el Ghazal, Harr, depression, palaeo Chari delta, and Chari Logone region. The piper diagrams for each of these regions, always without including nitrate, are represented in Figure 8.

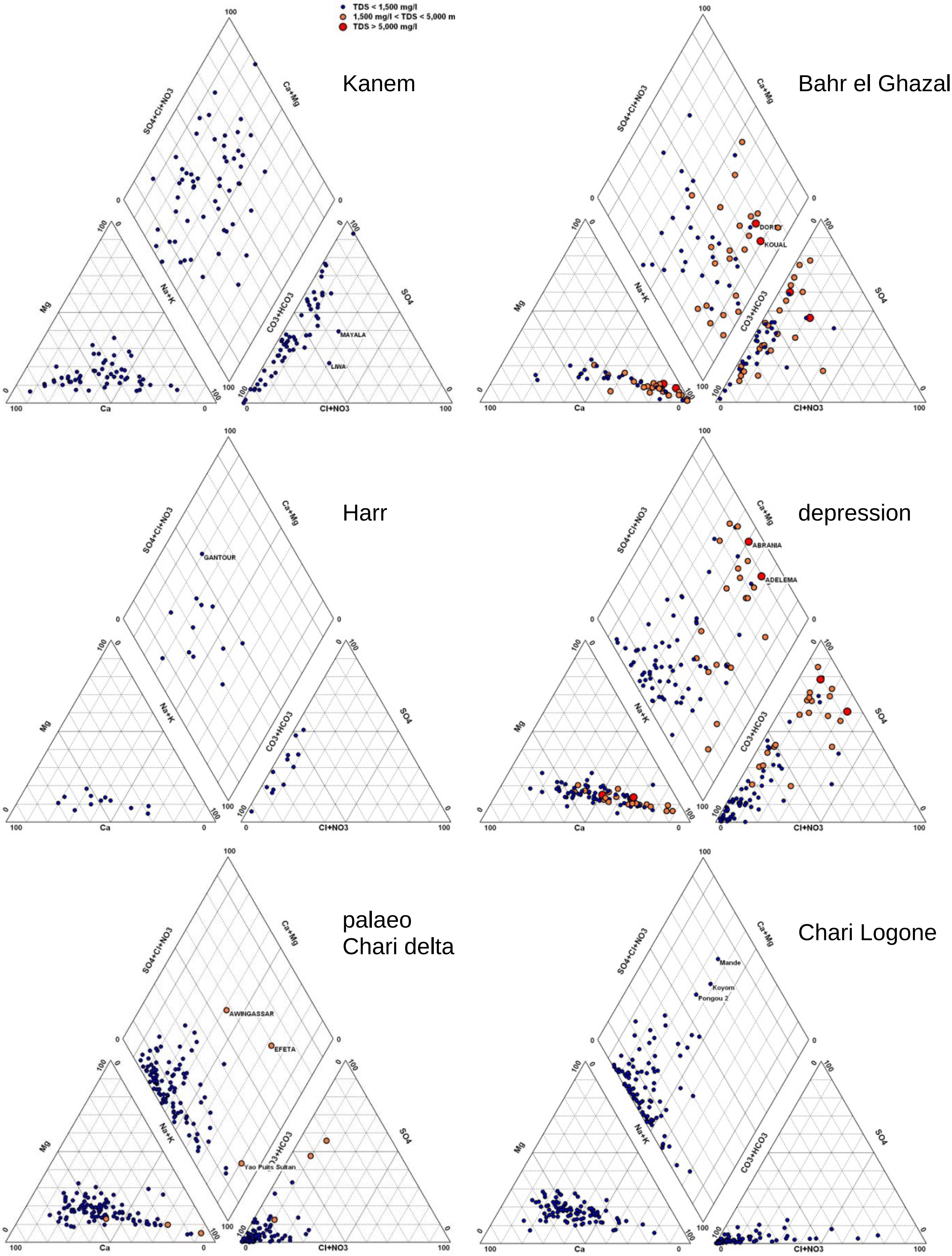

Figure 8. Piper Diagrams for different regions in the Quaternary: Kanem, Bahr el Ghazal, Harr, depression, palaeo Chari delta, and Chari Logone (from upper left to bottom right). The nitrate anion has been eliminated in all plots. Groundwater in Kanem, Bahr el Ghazal, and the depression show ion exchange from bicarbonate to sulfate and from calcium to sodium. High TDS values are encountered in Bahr el Ghazal and the depression.

According to the plots, groundwater experiences ion exchanges in the Quaternary aquifer especially in the Kanem, Bahr el Ghazal, and depression regions. In all cases, calcium is replaced by sodium and bicarbonate by sulfate.

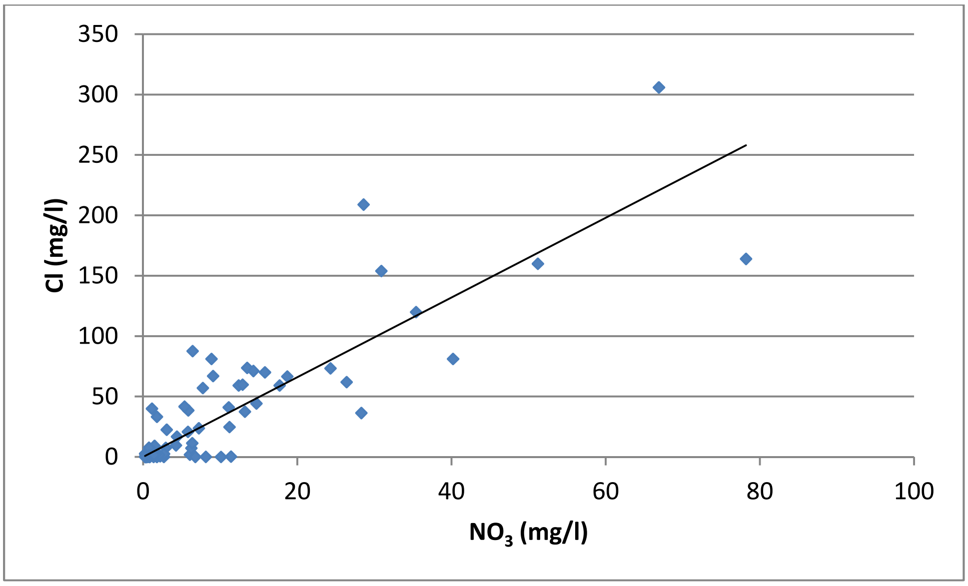

Figure 9. The good correlation of chloride and nitrate in the Chari Logone area indicates the contamination of groundwater by agriculture caused by the excess of chlorinated fertilizers that infiltrates up to the aquifer together with the recharged water.

The Piper Diagram corresponding to the Chari Logone region presents high values of chloride. This region also has high concentration of nitrate. A comparison between both anions shows a good correlation (Figure 9), what leads to the conclusion that the intensive use of chlorinated fertilizers in the agriculture is contaminating the groundwater during the recharge processes.

2.3. pH

pH is one of the most often measured parameters, although the usual groundwater pH values have little implication for human health. According to the World Health Organization (WHO, 2008) norms, drinking water should have pH values between 6.5 and 8.5. These values are mainly based on technical considerations (corrosion), but the range can be extended to 9.5 in the absence of distribution systems.

The map of Figure 10 shows that most of the water complies with the WHO recommendations, except in 7 samples (or 1.6%) where water is slightly acidic (pH < 6.5). However, only at Royono the acidity could be of concern (pH = 4), the other samples show pH values higher than 6.

Rather alkaline water is found in 12 samples (or 2.7%) with pH values higher than 8.5, although lower than 9.5 in all cases. However, due to the fact that none of these samples belong to a distribution system, water still is within the range recommended by the WHO.

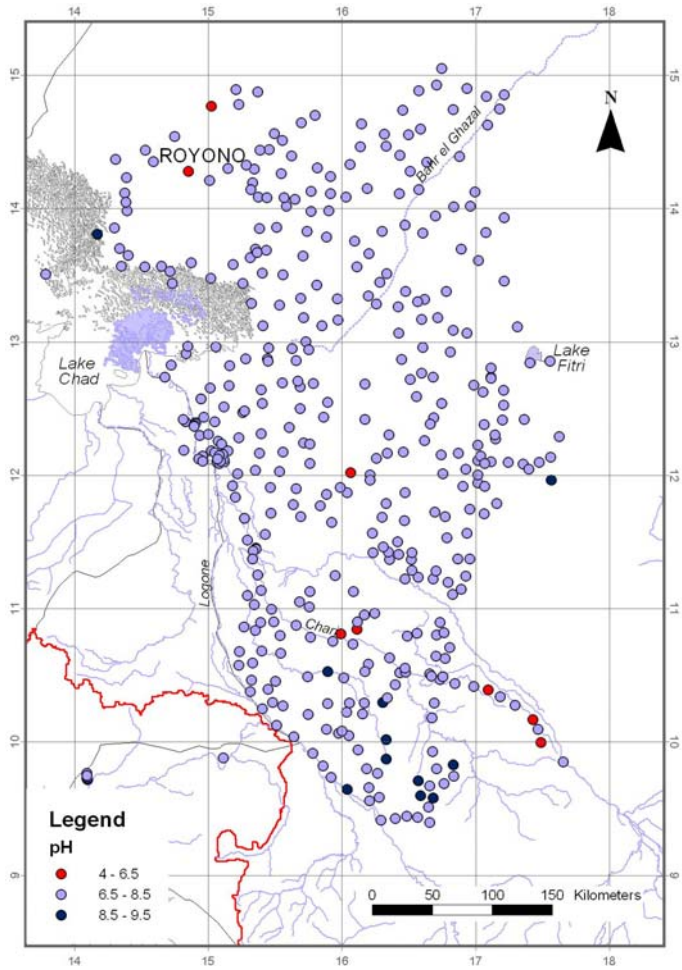

Figure 10. Spatial distribution of pH. Values generally lie within the range suggested by the WHO, although 8 samples show slightly acidic water (ph lower than 6.5). However, only at Royono groundwater is acid (pH = 4), the other 7 samples have values higher than 6.

2.4. Total Dissolved Solids (TDS)

TDS is an indicator for the mineralization of the water and implies mainly inorganic salts (calcium, magnesium, potassium, sodium, bicarbonate, chloride, and sulfate). WHO suggests that TDS concentrations higher than 1,500 mg/l would impair the palatability of water and low values would turn water insipid. Although higher TDS values do not seem to cause health problems, waters with TDS concentrations up to 5,000 mg/l are too saline for human consumption, but it can still be used for livestock supply.

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

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

Water in the study area generally is of low TDS (Figure 11) with 90% of the samples showing TDS of less than 1,500 mg/l. Forty-three samples (10%) have TDS between 1,500 mg/l and 5,000 mg/l and only 4 samples (less than 1%) present TDS higher than 5,000 mg/l (at Dorby, Koual, Adelema, and Abrania).

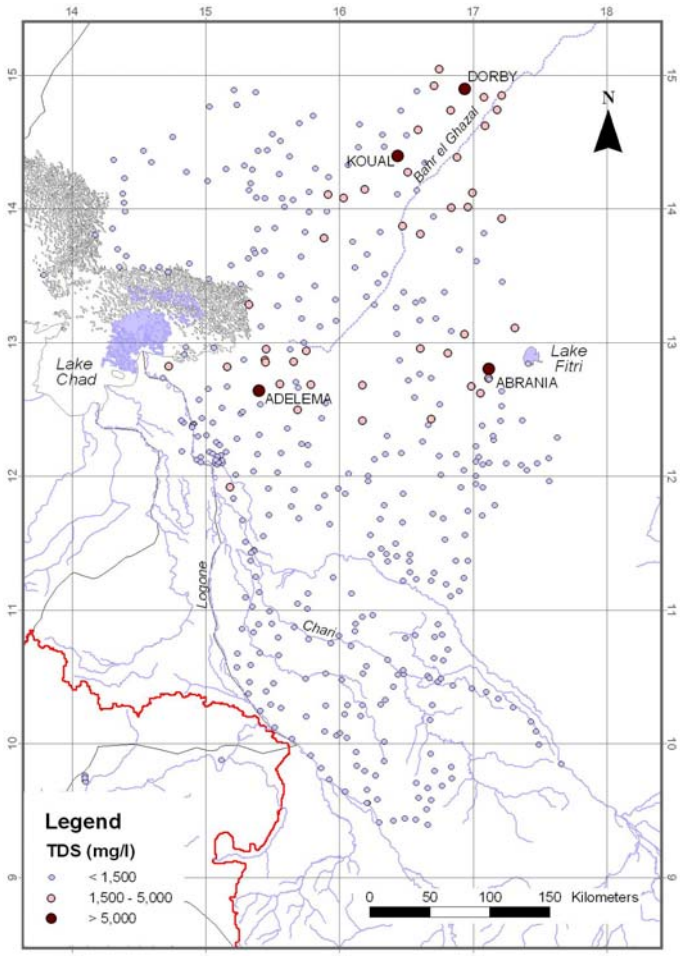

Figure 11. Spatial distribution of TDS. Generally water is of low TDS and thus apt for human consumption. Only 4 samples present TDS concentrations higher than 5,000 mg/l.

A study of correlation between TDS and the main dissolved anions and cations (Figure 12) shows:

- Very good correlation with sodium and sulfate,
- Good correlation with magnesium and bicarbonate,
- Less pronounced correlation with calcium and chloride,
- Low correlation with potassium.

It can be concluded that high TDS figures correspond mainly by elevated concentrations of sodium and sulfate.

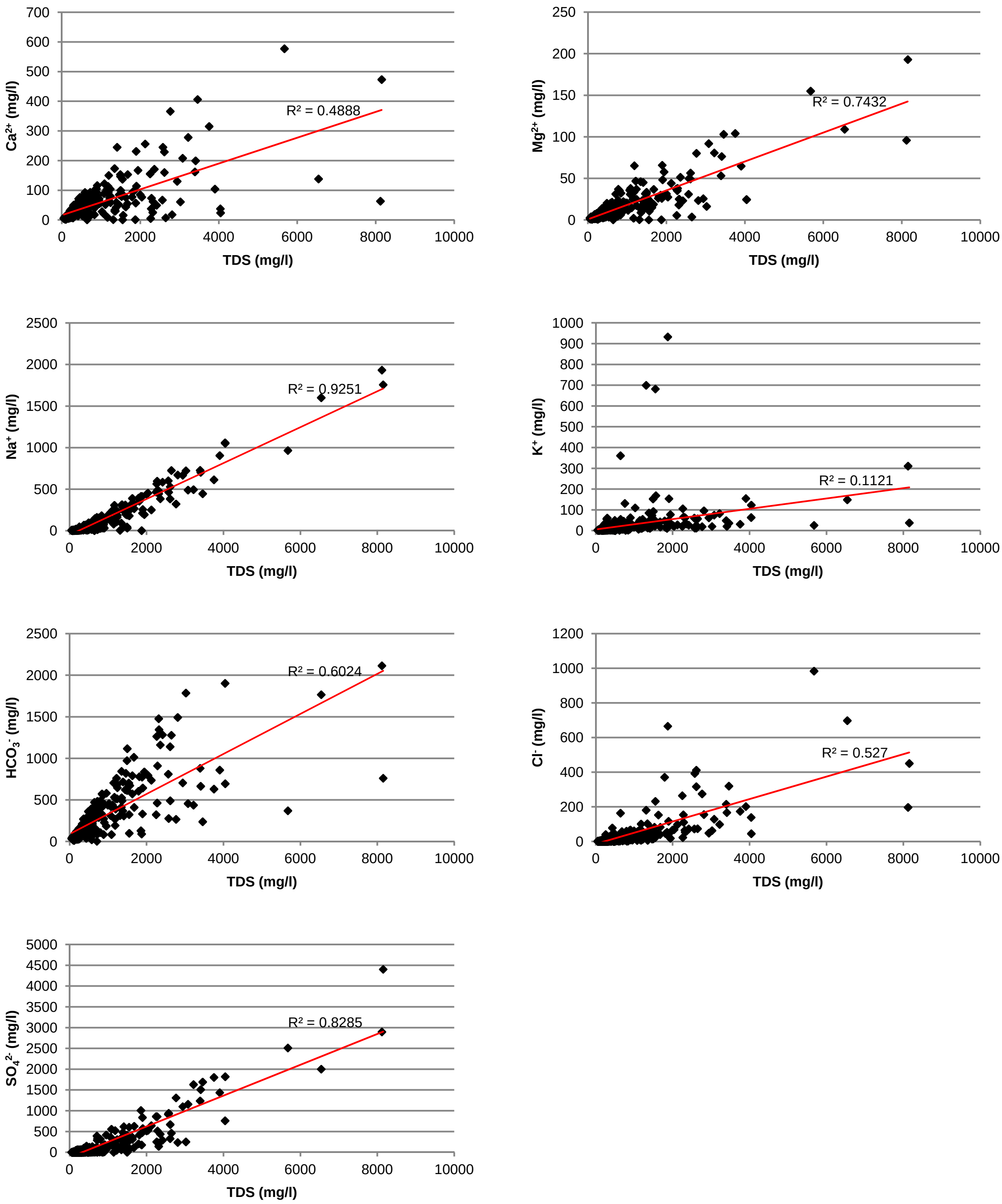

Figure 12. Correlation of TDS with the main dissolved cations and anions. Correlation is very good for sodium and sulfate, good for magnesium and bicarbonate, relatively good for calcium and chloride, and low for potassium.

2.5. Fluoride

Fluor uptake is considered necessary for the human body at certain levels to avoid caries. However, long exposure to concentrations above 0.5 mg/l to 1 mg/l can lead to blotches on the teeth (fluorosis) that may weaken the tooth, and to changes in the skeleton (fluoride-osteosclerosis).

High-fluoride groundwater appears in active volcanic zones associated with geothermal activities, crystalline basement aquifers (Fantong et al, 2009) and arid sedimentary basins (Pauwels & Ahmed, 2007). It is often associated with water of sodium-bicarbonate type and relatively low calcium and magnesium concentrations because high calcium concentrations limit the fluoride mobility through precipitation as CaF_2. Sodium-bicarbonate waters typically present high pH values (above 7). Therefore, information on chemical composition of groundwater can be used as an indicator of potential fluoride problems (Brunt et al, 2004).

The most common minerals containing fluoride are:

- (Fluor)Apatite ($Ca_5[(F,Cl)(PO_4)_3]$.
- Fluorite (CaF_2).
- Mica, with the formula $X_2Y_{4–6}Z_8O_{20}(OH,F)_4$ 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 Fe3+ or Ti.

Groundwater shows fluoride contents above the upper WHO limit of 1.5 mg/l in 12 of 441 or 3% samples (Figure 13), especially along the Bahr el Ghazal, to the south of the Lake Chad, in the vicinity of Lake Fitri, and in the Mayo-Kebbi region. Elevated fluoride concentrations between 0.5 mg/l and 1.5 mg/l are present all along the Logone River and along the Chari River to the north of parallel 11° north.

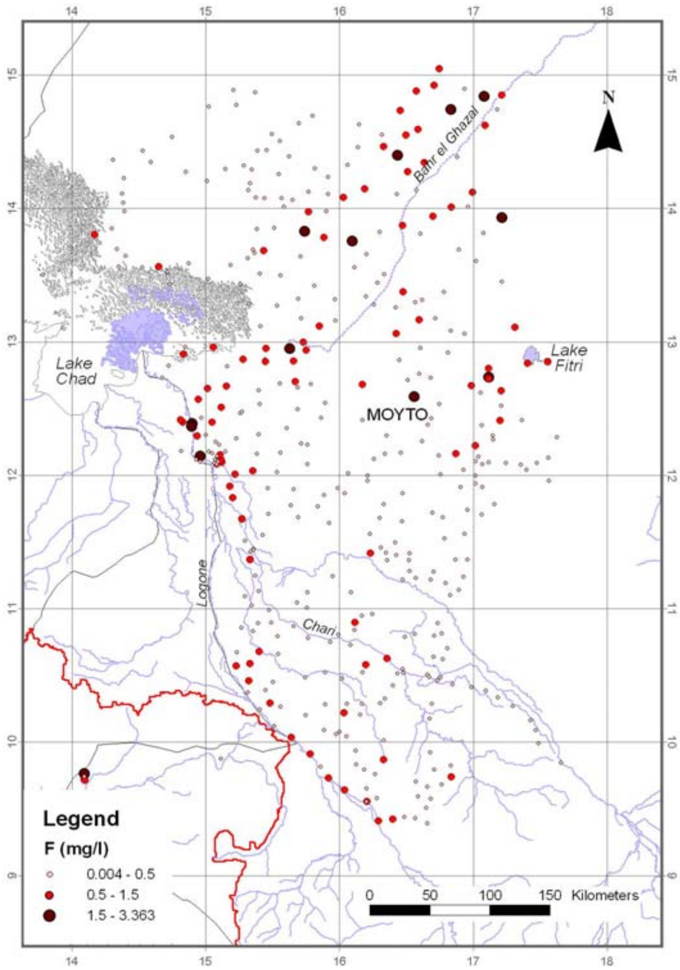

Figure 13. Spatial distribution of fluoride concentrations. Concentrations above 1.5 mg/l appear in 12 samples, especially along the Bahr el Ghazal, to the south of the Lake Chad, in the vicinities of the Lake Fitri, and in the Mayo-Kebbi region. Elevated concentrations between 0.5 mg/l and 1.5 mg/l are encountered along the Logone River and along the Chari River to the north of parallel 11° north.

The zones to the south of the Lake and east and west of the Bahr el Ghazal are characterized by alkaline water (pH above 7) and enhanced concentrations of bicarbonate, potassium, and sodium as well as magnesium and lithium (Figure 14). Thus, the presence of mica would be the cause for the high fluoride content in this region.

There are post-tectonic granite intrusions in Moyto, in the proximities of the Lake Fitri, and in the Mayo Kebbi region. The groundwater flow through weathered granite could be the explanation of high fluoride in these areas.

The Logone River is known to be flowing along a structural feature (fault zone). Thus, upwelling groundwater from the basement into the shallow aquifers is probably the cause of high fluoride here.

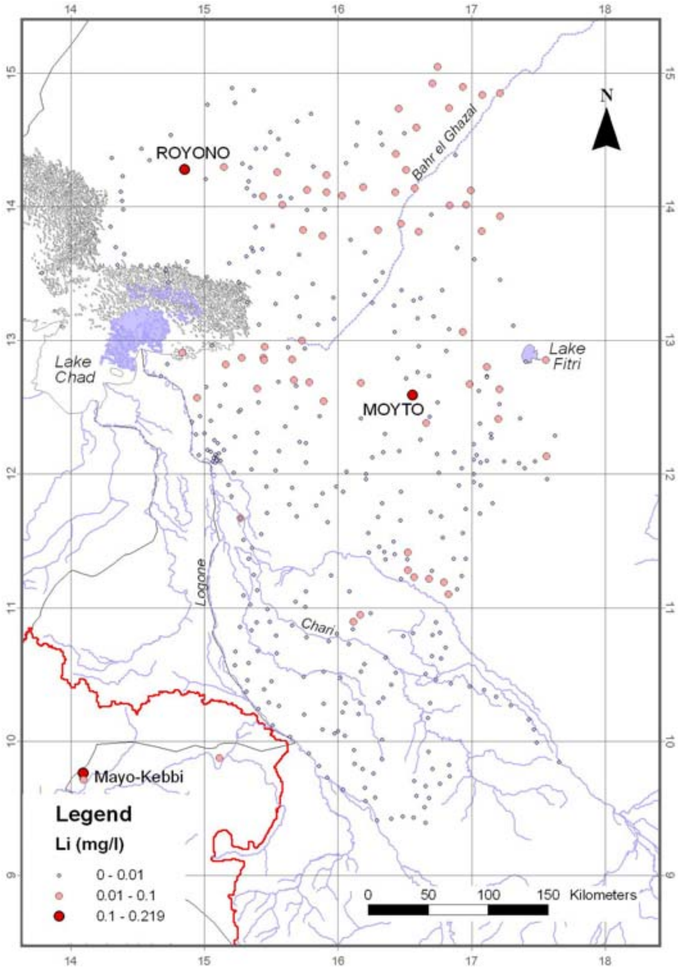

Figure 14. Spatial distribution of lithium concentrations. Enhanced values appear in the proximities of the Bahr el Ghazal, to the SE of the Lake, and in a fringe between Lake Chad and Lake Fitri. The largest concentrations were encountered at Moyto and the Mayo-Kebbi region (intrusion of post-tectonic granite), as well as at Royono.

2.6. Sodium

According to the WHO (2008), there is no firm conclusion that sodium excess in water can cause hypertension, therefore no health limit can be proposed. However, concentrations of sodium chloride concentrations above 200 mg/l can change the taste of water.

The presence of enhanced sodium in the region is mainly due to the high temperatures and consequently high evaporation rates that the area supports. Generally, it appears in excess compared to chloride, indicating either the effect anion exchange or the absence of NaCl salts (Figure 15). Only 13 samples (or 0.03%) show slightly more chloride than sodium and all of them belong to the Chari-Logone region, where the presence of pollution by means of chlorinated fertilizers has already been shown (see chapter 2.2).

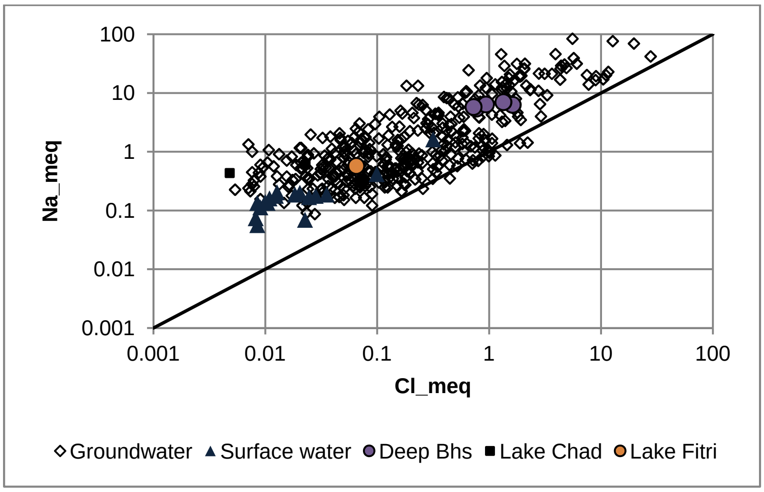

Figure 15. Correlation of sodium and chloride (molar). Sodium appears generally in excess compared to chloride, indicating either the effect of anion exchange or the absence of NaCl salts.

The highest sodium concentrations are present along the Bahr el Ghazal and to the SE of the Lake Chad as well as in the proximities of the Lake Fitri (Figure 16). All other samples have concentrations of sodium below 50 mg/l, probably as the result of direct recharge from precipitation with low sodium content. Therefore, these zones can be considered as recharge areas and should be protected to avoid pollution from the surface.

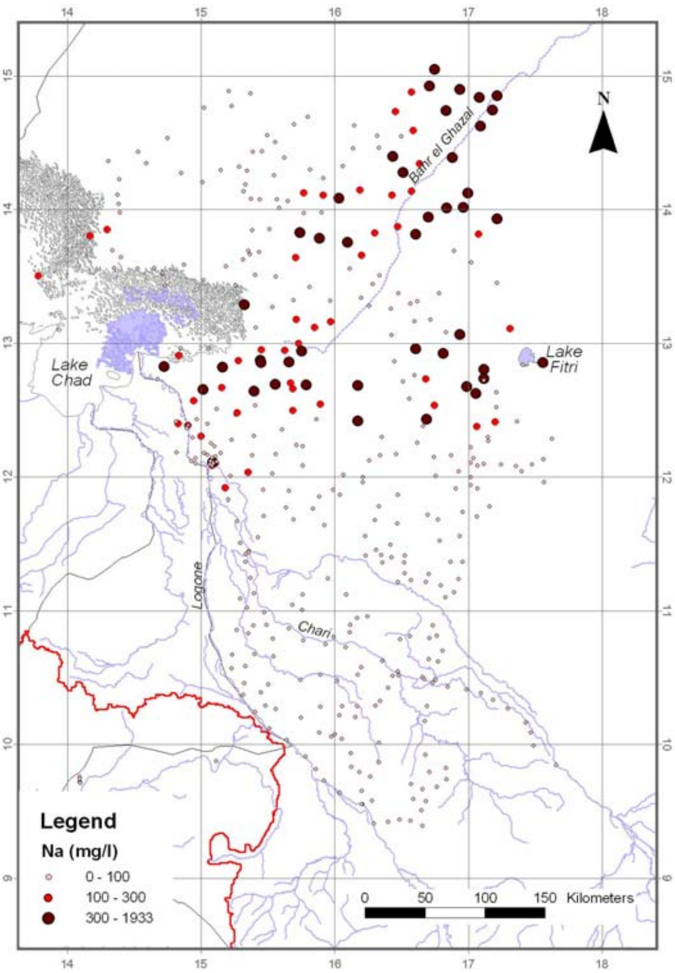

Figure 16. Spatial distribution of sodium concentrations. The highest concentrations appear along the Bahr el Ghazal, to the SE of the Lake Chad and in the proximities of the Lake Fitri.

2.7. Irrigation Suitability

High concentrations of sodium limit the use of water for irrigation purposes. Sodium adsorbs into cation exchange sites in the soil causing aggregates of some soils to break down (disperse). In this way, pores are sealed and consequently soil permeability reduced, especially in the case of montmorillonitic clays. Affected clayey soils will become either anaerobic (lacking oxygen), saline, or compacted (Bauder et al, 2008).

Also salinity, as electric conductivity, limits the suitability of water for irrigation. Saline conditions inhibit the ability of the plant to take up water from the soil, independent whether salinity comes from irrigation water or soil water that became saline because of salt addition, poor drainage, evaporation from a shallow water table.

To map the regions where groundwater is suitable for irrigation, three different indexes were used: Wilcox (Wilcox, 1948), Sodium Adsorption Ratio (SAR) (Richards, 1954) and Magnesium Hazard (Szabolcs & Darab, 1964).

Wilcox: calculates the percentage of sodium within the cations (as Na in percentage) following the formula below and relates it to the EC in µS/cm (Figure 17).

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

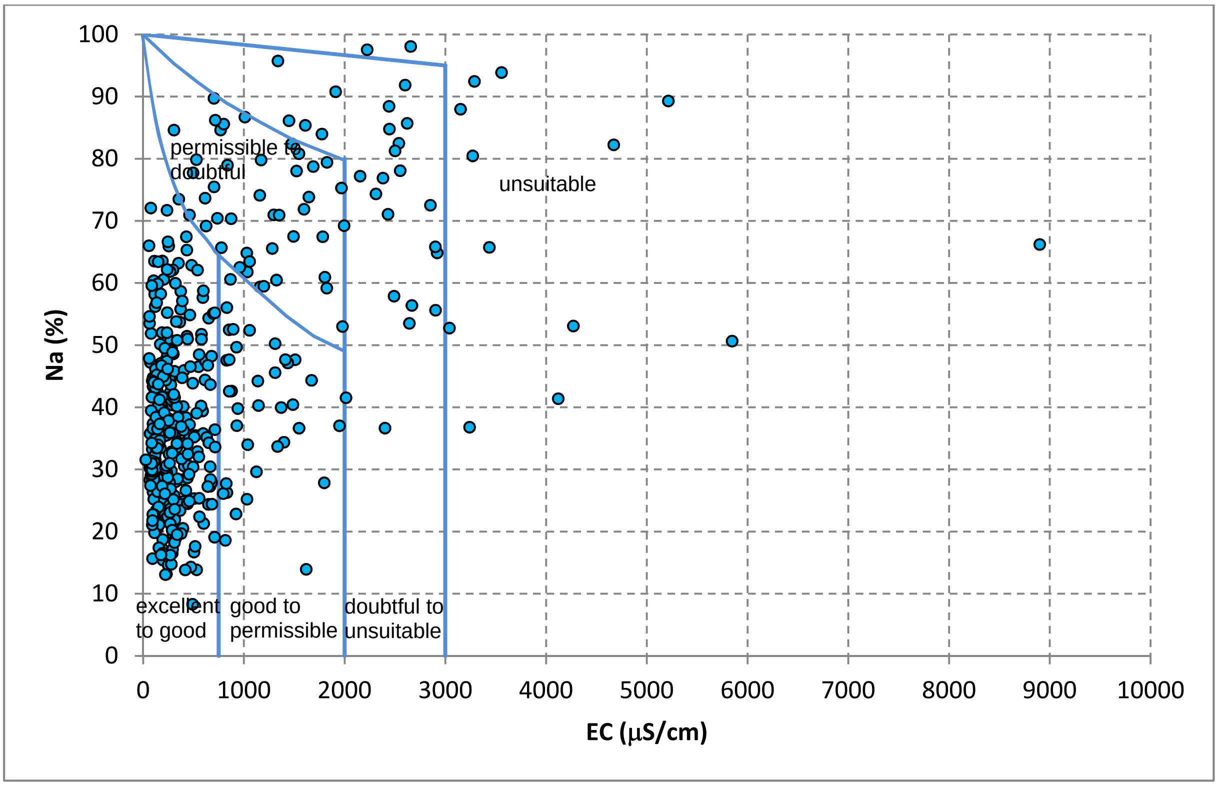

Figure 17. Wilcox plot to define whether the water is suitable for irrigation.

The *SAR (Sodium Adsorption Ratio)* evaluates the sodium hazard in relation to calcium and magnesium concentrations (Figure 18) and is calculated as follows:

$$SAR = \frac{Na^{+}}{\sqrt{\frac{Ca^{2+} + Mg^{2+}}{2}}}$$

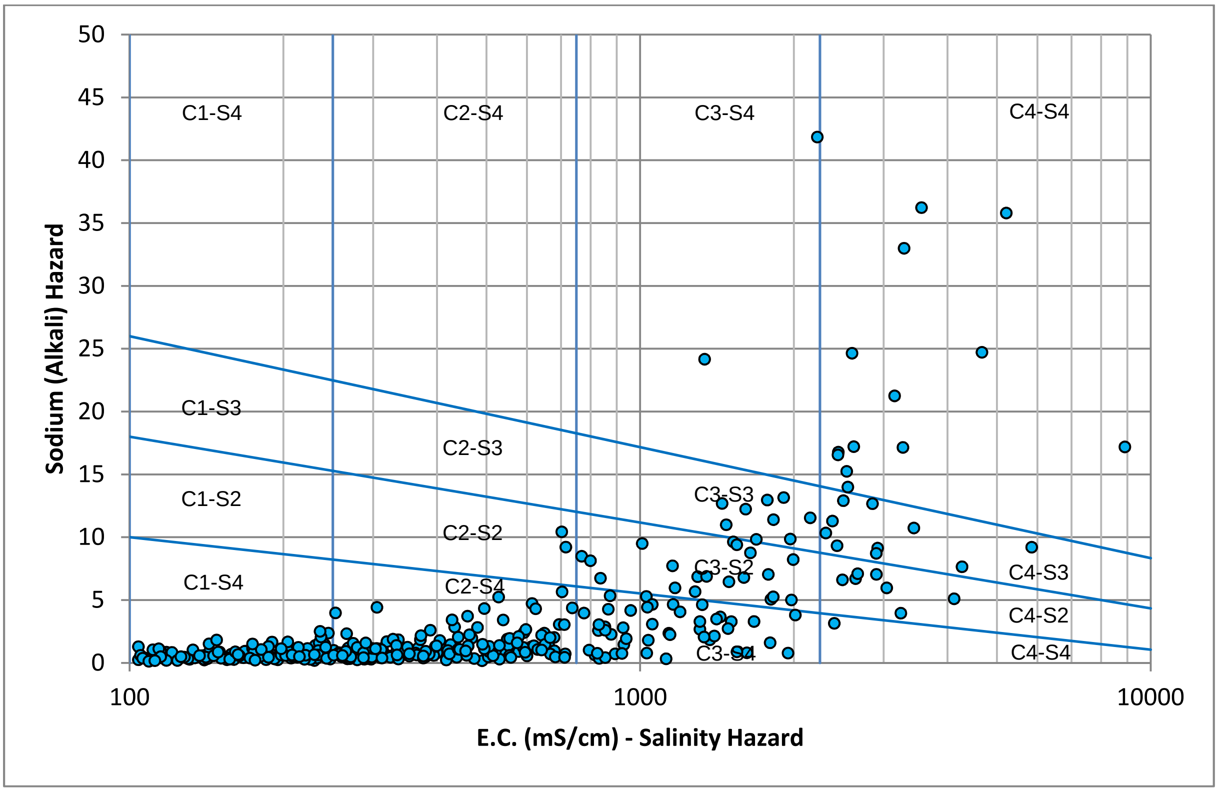

Figure 18. SAR-Diagram for estimation of water suitability for irrigation.

Magnesium hazard (MH): it is calculated as:

$$\mathrm{MH} = \frac{\mathrm{Mg}^{2+}}{\mathrm{Ca}^{2+} + \mathrm{Mg}^{2+}} * 100$$

MH > 50 is considered harmful and unsuitable for irrigation use.

A map of suitability of groundwater for irrigation was produced taking into consideration all three parameters (Figure 19). The blue dots in the map indicate water points where the water is suitable for irrigation for the three indices considered. The light red dots correspond to water points where the water is classified as unsuitable by one of the methods. The red dots show the water points classified as unsuitable by at least two of the methods. Finally, the dark red dots are those water points where the three methods classified the water as unsuitable for irrigation. Groundwater is unsuitable for irrigation to the east and west of the Bahr el Ghazal, to the south of the Lake, and in the vicinities of the Lake Fitri.

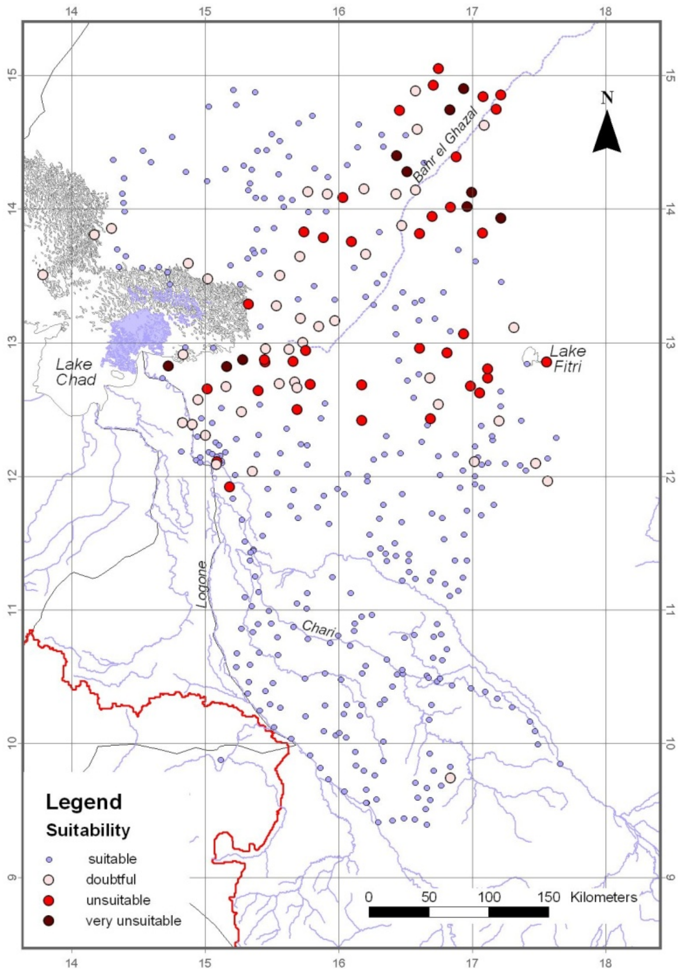

Figure 19. Map of suitability of groundwater for irrigation. It shows that groundwater to the east and west of the Bahr el Ghazal, to the south of the Lake Chad and in the vicinities of the Lake Fitri should not be used for irrigation, mainly because of high salinity and sodium content.

Another problem in irrigation water is the presence of boron. Boron concentration must not be higher than 1 mg/l for boron accumulation in leaves not to reach toxic levels. Concentrations of boron in samples analyzed are always below this limit.

Chloride is also a hazard when present in irrigation water because it can be directly adsorbed into the leaves during sprinkler irrigation (Morris & Devitt, 1991). Chloride plant toxicity is defined as:

- Cl < 150 mg/l — non toxic
- 150 mg/l < Cl < 350 mg/l — moderate toxicity
- Cl > 350 mg/l — severe toxicity

However, groundwater in the region in general does not present high concentrations of chloride (Figure 20). Only 6 samples (or 1%) have more than 350 mg/l of chloride and 12 (or 3%) present values between 150 mg/l and 350 mg/l. All of them coincide with water points already unsuitable, due to sodium content.

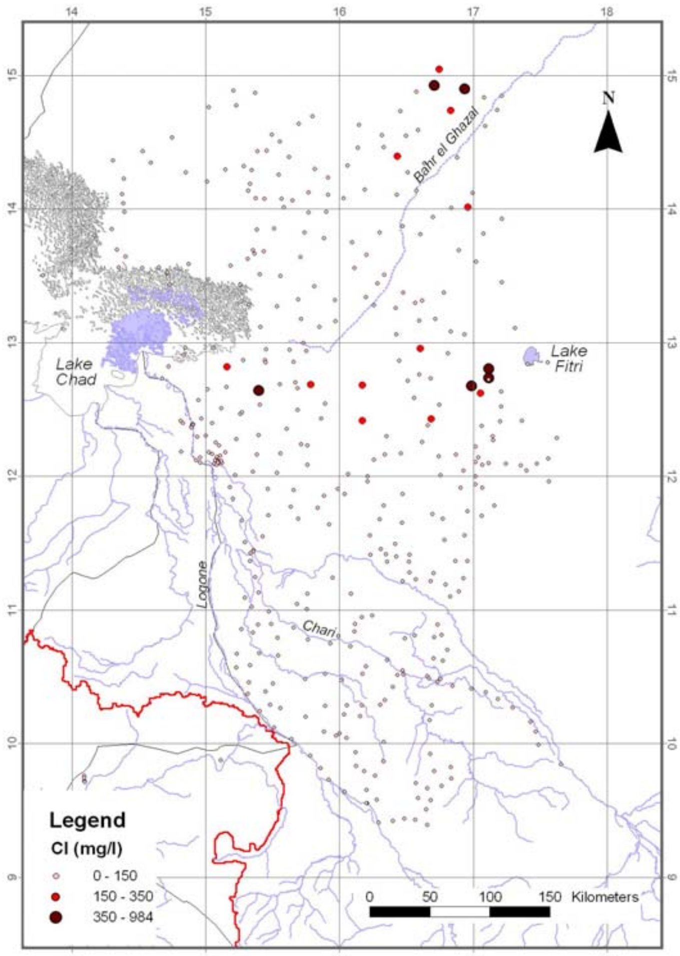

Figure 20. Spatial distribution of chloride concentrations. A total of 6 samples surpass the 350 mg/l meaning that this water cannot be used for irrigation due to high plant toxicity. Twelve samples present concentrations between 150 mg/l and 350 mg/l and should not be used for long-period irrigation, due to moderate toxicity. All the other samples present low chloride concentrations.

2.8. 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. However, naturally induced high concentrations of nitrate have been reported from arid and semi-arid regions in Africa, probably due to mineralisation of soil organic matter accumulated during wet periods and destroyed during dry epochs.

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 baby disease", due to lack of oxygen in blood. For this reason, the upper limit accepted by the WHO norms (and also EU norms and EPA norms 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.

A total of 59 samples (or 13%) present levels of nitrate above the 50 mg/l allowed by the norms (Figure 21). The sources of nitrate are different depending on the human activities of the region. To the north of 12° latitude north, pollution is due to livestock watering directly from the borehole leading to accumulation of animal faeces at the wellhead. In the south, agriculture is the main activity, especially cultivation of rice. The high pollution here might be an effect of the excessive use of nitrogenised fertilizers (see chapter 2.2).

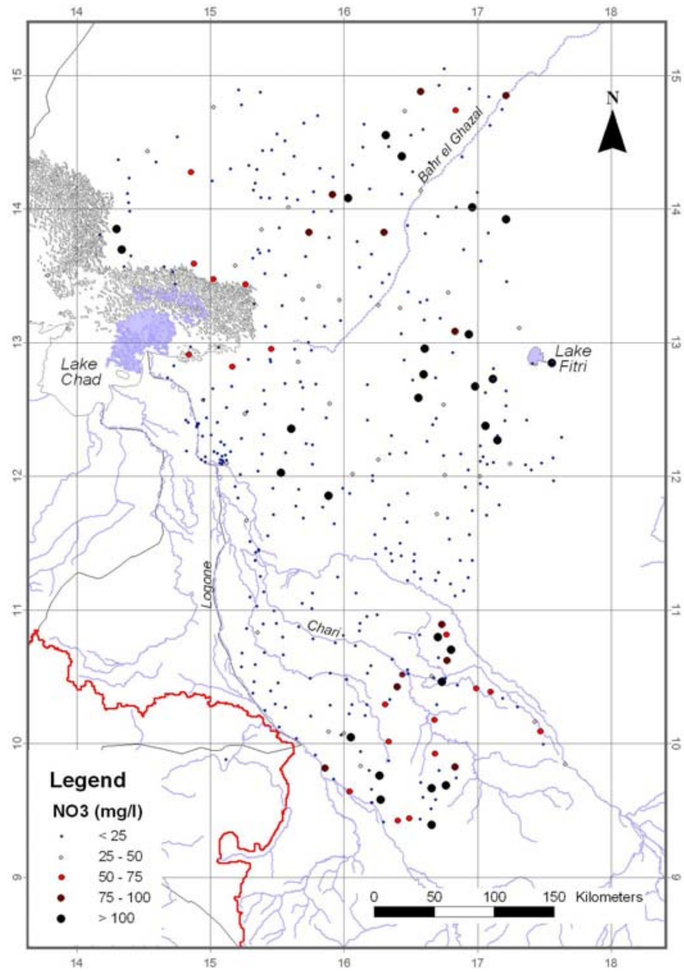

Figure 21. Spatial distribution of nitrate concentrations. A total of 59 samples (or 13%) show concentrations above the limit of 50 mg/l given by the WHO. Pollution has different sources. To the north of 12° latitude north pollution is thought to be the result of animal faeces from livestock watering directly from the borehole. In the south, pollution is due to agricultural use as the result of excessive application of nitrogenised fertilizers.

The presence of nitrate indicates the urgent need for borehole and groundwater protection in the region. Hand dug wells should be abandoned in benefit of drilled, well constructed and protected boreholes. If this technique is not possible, then a better management of hand dug wells is recommended.

2.9. Sulfate

The presence of sulfate in drinking water at concentration higher than 250 mg/l can be detected by a bitter taste and very high concentrations above 1,000 mg/l have laxative effect to unaccustomed users. However, sulfate in water does not cause serious health implications and WHO has not set any limitation for this anion although a concentration of 500 mg/l is considered as the upper recommendable limit.

The map of Figure 22 shows the presence of elevated sulfate in the study area, especially to the east and west of the Bahr el Ghazal, to the SE of the Lake Chad and in the vicinities of the Lake Fitri. As already shown, all these regions are also characterized by elevated concentrations of chloride and sodium as a result of a very low hydraulic conductivity of the aquifer that leads to very low flow velocity or very high residence time of groundwater in the aquifer.

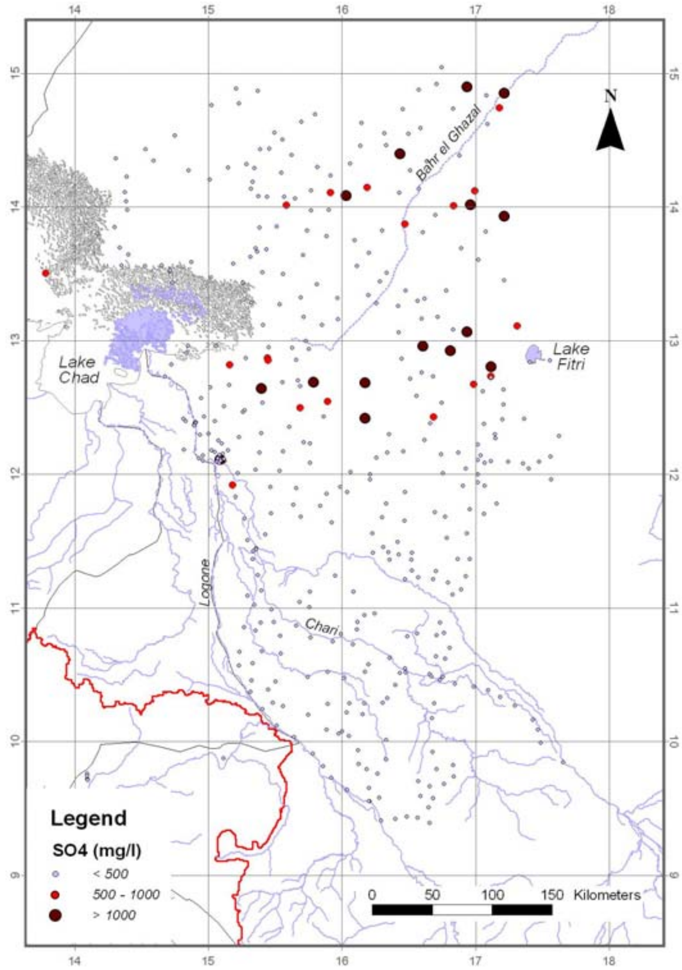

Figure 22. Spatial distribution of sulfate. Sulfate in concentrations above 1,000 mg/l is present in 14 samples, and 18 samples have concentrations between 500 mg/l and 1,000 mg/l. All these samples are located to the east and west of the Bahr el Ghazal, to the SE of the Lake Chad and in the vicinities of the Lake Fitri.

Concentrations between 500 mg/l and 1,000 mg/l are present in 18 samples (or 4%), and 14 samples (or 3%) show concentrations higher than 1,000 mg/l.

3. Summary and Conclusions

The results of 441 chemical analyses of groundwater (mainly from the Quaternary aquifer) and surface water from the Chadian part of the Lake Chad Basin can be summarized as follows:

- Most of the pH values comply with the WHO recommendations, except in 7 samples (1.6%) where water is slightly acidic (pH < 6.5). Rather alkaline water was found in 12 samples (2.7%) with pH values higher than 8.5. However, only at Royono the acidity could be of concern (pH = 4).
- Water in general is of low TDS with 90% of the samples showing TDS concentration of less than 1,500 mg/l. However, high TDS figures appear to east and west of the Bahr el Ghazal, to the SE of the Lake Chad, and in the proximities of the Lake Fitri. They are mainly the result of elevated concentrations of sodium and sulfate.
- Groundwater shows fluoride contents above the upper WHO limit of 1.5 mg/l in 12 samples (3%), especially along the Bahr el Ghazal, to the south of the Lake Chad, and in the vicinity of Lake Fitri. Elevated fluoride concentrations between 0.5 mg/l and 1.5 mg/l are present all along the Logone River, as well as along the Chari River to the north of parallel 11° north.
- The highest sodium concentrations are present along the Bahr el Ghazal and to the SE of the Lake Chad as well as in the proximities of the Lake Fitri. All other samples have

concentrations below 50 mg/l. In general, sodium appears in excess compared to chloride indicating either anion exchange or the absence of NaCl salts in the region.

- A total of 59 samples (13%) present levels of nitrate above the limit of 50 mg/l allowed by the WHO. The high nitrate concentrations are due to pollution related to human activities in the region like livestock breeding and agriculture.
- Groundwater is locally characterized by the presence of elevated sulfate, especially to the east and west of the Bahr el Ghazal, to the SE of the Lake Chad and in the vicinities of the Lake Fitri.

It can be concluded that groundwater in the area is generally suitable for human consumption. However, problem regions where water is inappropriate appear scattered, as concluded below:

- Nitrate pollution is punctual and due to livestock watering directly from the borehole to the north of 12° latitude north. In the south of the study area, the high nitrate pollution is regional and is caused by an excessive application of nitrogenised fertilizers in the rice production.
- The areas east and west of the Bahr el Ghazal, to the SE of the Lake Chad and in the proximities of the Lake Fitri are characterized by very high concentrations of chloride, sodium, and sulfate. This is due to the fact that the aquifer in these regions shows a very low hydraulic conductivity that leads to very low flow velocity and very high residence time of groundwater in the aquifer.
- High salt concentration to the east and west of the Bahr el Ghazal, to the SE of the Lake Chad and in the proximities of the Lake Fitri suggests that these areas as unsuitable for irrigation with groundwater.
- The high fluoride concentrations have different genesis as follows:
  - The zones to the south of the Lake and along the Bahr el Ghazal are characterized by neutral to slightly alkaline groundwater (pH above 7) and enhanced concentrations of bicarbonate, potassium, and sodium as well as magnesium and lithium. Thus, the presence of mica could be the cause for the high fluoride content in this region.
  - Post-tectonic granite intrusions are encountered at Moyto, in the Mayo-Kebbi region, and in the proximities of the Lake Fitri. Here, groundwater flow through weathered granite would lead to high fluoride concentrations.
  - The Logone River is known to be flowing along a structural feature (fault zone). Thus, upwelling groundwater from the basement into the shallow aquifer is probably the cause of high fluoride in this area.

4. Recommendations

It is highly recommended that groundwater protection measures be implemented to safeguard the resource against pollution caused by human activities (see nitrate and chloride concentrations in the Chari Logone region in chapter 2.2 and nitrate concentration in chapter 2.8).

In regions with high nitrate concentrations, hand dug wells should be abandoned in benefit of drilled, well constructed and protected boreholes. If this technique is not possible, then a better management of hand dug wells is recommended

Further, due to high salt concentration, groundwater should not be used for irrigation purposes to the east and west of the Bahr el Ghazal, to the south of the Lake Chad and in the proximities of the Lake Fitri.

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