GROUNDWATER QUALITY ANALYSIS IN WARM SEMI-ARID CLIMATE OF SAHEL COUNTRIES: TILLABÉRI REGION, NIGER

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Abstract: The Tillabéry Region in West Africa (Sahel Region) is affected by a severe semi-desert climate. After the rainy season, ponds and the majority of watercourses dry up. Population has to exploit superficial alluvial aquifers using traditional methods. The most important aspect in groundwater supply is its quality. Since 2004, Niger government has been developing a project to provide each village with a source of drinking water. Until now, over 500 boreholes have been made for underground water supply. Thirty-eight boreholes were selected for the groundwater quality assessment (G-WQ$_i$), each characterized by 15 different physico-chemical parameters: water temperature, pH, nitrites, nitrates, electrical conductivity, chlorides, sulphates, calcium, magnesium, potassium, fluoride, sodium, bicarbonates, dissolved iron and total manganese. The statistical analysis indicates 7 parameters that do not comply with the standards for drinking-water quality (after World Health Organization): nitrites, nitrates, electrical conductivity, carbonate hardness, sodium concentration, dissolved iron and total manganese. This concentration may have severe implications for human health and can lead to spreading of diseases. According to the G-WQ$_i$ score, 10 samples belong to the "Good water quality" class, 16 samples belong to the "Medium high water quality" class, 10 samples belong to the "Medium low water quality" class, and 2 samples correspond to the "Poor water quality" class. The results of this study can be useful for a proper managagement of water resources in the Sahel Region.

Keywords: groundwater supply, physico-chemical parameters, water quality index, semi-arid climate, Sahel Region

1. INTRODUCTION

Since the 1970s, the environment has become increasingly worrisome in the Sahel countries, due to the inadequacy and poor distribution of rainfall over time and space (Kouamé, 1999; Saley, 2003). The fight against the high prevalence of water-borne diseases, the leading causes of death and morbidity in the rural areas of developing countries - connected to the consumption of of poor physico-chemical and bacteriological quality water - is one of the objectives of the programs concerning water supply in villages (Ousmane et al., 2006). The Sahel Region of Niger's Liptako in West Africa is subject to the harshness of a semi-desert climate. It only receives rain from May till October. The value of the annual precipitation (400 mm) is considerably smaller than the estimated potential evapotranspiration of 1,500 mm to 2,000 mm (Babaye, 2012). Shortly after the rainy season, ponds and the majority of watercourses (*koris*) dry up, forcing people to resort to groundwater. The population has to exploit superficial alluvial aquifers using the traditional sump wells (Barry & Obuobie, 2012).

During the wet season, water tables recharge and water levels in wells are at their maximum. The water resources are difficult to reach, the level of water depletion needs more complex monitoring, and water quality cannot be easily observed. Groundwater usually comes in addition to readily

accessible surface waters (Hassane, 2010). In the dry season, the levels of the water tables decrease until drying up before the return of the rains. This situation forces the women, traditionally responsible for the water supply, to travel several kilometers in order to find a suitable site (Ousmane et al., 2006).

The region is characterized by a crystalline basement composed mainly of granitic and granodioritic formations, making the mobilization of groundwater resources very difficult. The poor bacteriological quality of the water, caused by the quasi-continuous presence of livestock on the periphery of these structures, adds to the problem of water availability. The consumption of this water is responsible for many diseases, such as river blindness (onchocerciasis) or dysentery, and the consequences for the health of its consumers are disastrous (Pierre, 1993).

This study conducts a descriptive, statistical analysis and mapping of 15 chemical and physico-chemical parameters based on 38 boreholes (bor.) within the Tillabéry Region, highlighting the groundwater quality index (G-WQ$_i$). This method of assessing the G-WQ$_i$ was adapted based on the surface water quality index (WQ$_i$), but related to the guidelines value for drinking-water within underground supply sources (House & Ellis, 1978; Brown et al., 1972; Bharti & Katyal, 2011; World Health Organization, 2011; Kankal et al., 2012; Kouamé et al., 2010, 2013; Gorde & Jadhav, 2013; Breabǎn et al., 2014; Mihu-Pintilie et al., 2014a;

Mihu-Pintilie et al., 2014b; Cruceanu et al., 2015; Cozma et al., 2015; Romanescu et al., 2014, 2015, 2016, 2017; Sedrati et al., 2017).

2. STUDY AREA

The Tillabéry Region is located in the middle part of the Nigerian Liptako. It is the western most part of the Republic of the Niger, situated between 0°40'0" and 1°40'0" Eand 13°42'0" and 14°30'0" N (Fig. 1). The climate is characterized by a 3 – 4 month raining season, followed by a long dry season from October to May. Niger River is the only permanent watercourse in the region, from NV-SE direction of flow.

The study area has the morphological aspect of a plain, characterized by low tabular hills, laterite plateaus and sandy plains. In general, the relief constitutes a peneplain with an average altitude of about 255 m above sea level. Vegetation is mainly distinguished in the beds of streams and notched valleys, in lateritic formations. It is a savanna type of vegetation, with sparse trees. The population is very heterogeneous, the largest ethnic group being Sonrai (60%), then Touareg (15%), Peulhs (14%), and Haussa Gourmantché and Arabs for the remaining 11%. The most important economic activities of the population in this area are agriculture, livestock and fisheries (Dupuis et al., 1991).

The Niger Liptako corresponds to the extreme eastern part of the West African craton. To the north,
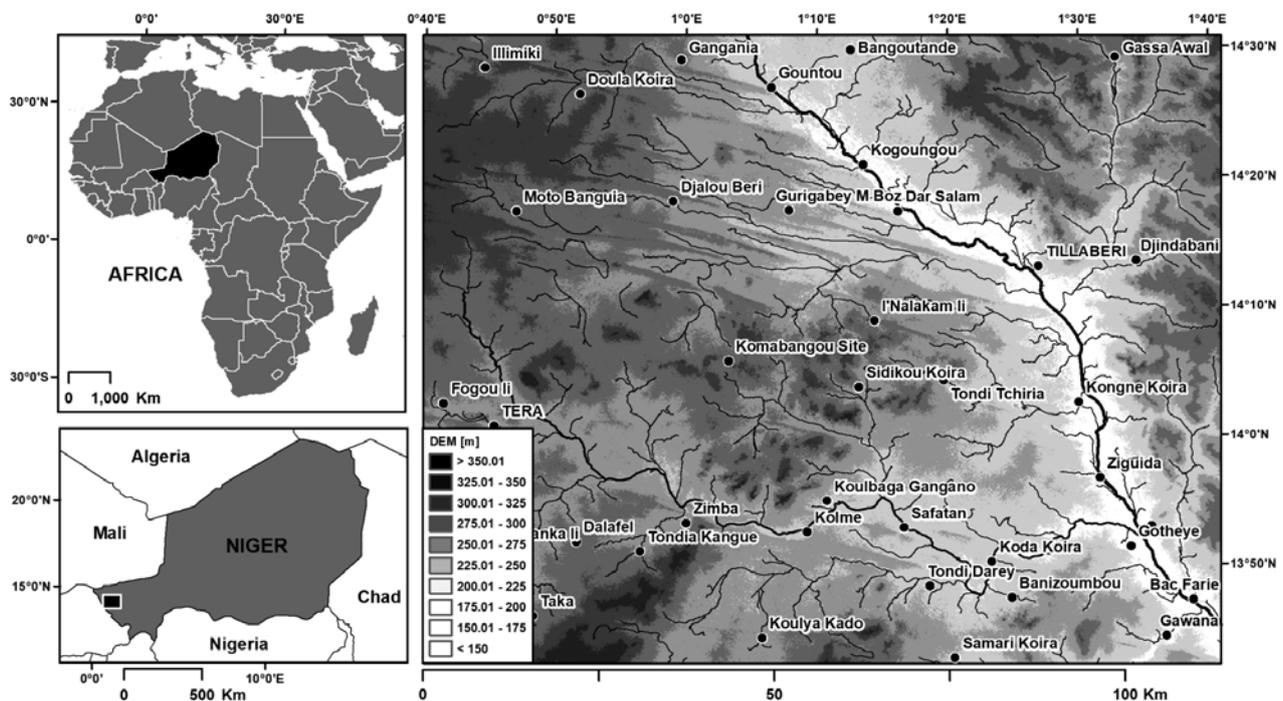

Figure 1. Geographic position of the Tillabéri Region in central Africa (Niger Country) and the distribution of human settlements

it is bounded by the Taoudenni basin and to the east by the Iullemmedens basin. The Liptako lithology belongs to the Baoulé-Mossi domain of the West African craton. The petrographic analysis of the study area reveals the presence of two geological assemblages:

1. Green rocks, in particular of the Diagorou-Darbani belt, more or less metamorphosed, separated by intrusive granitoidal Eburnian massifs. These rocks are composed of meta-sediment, metavolcano-sedimentary formations and meta-volcano-plutonic formations (Abdou et al., 1998; Soumaila & Konate, 2005). This series consists mainly of grawackes, mica schists, clay schists of quartzitoshists, tuffs and green breccias (pyroxenites, amphibolites, epidotites, chloritoshists, metabasalts, metaggabros);

2. Eburnian granitoid intrusive massifs. Granitoid massifs include granites, granodiorites and plutonic diorites (Abdou et al., 1998; Soumaila, 2000; Soumaila & Konate, 2005). These massifs contain Archean relics (Dupuis et al., 1991). The hydrogeological context corresponds to two aquifer systems, discontinuous groundwater aquifers and subsurface aquifers (Ousmane et al., 2006).

3. MATERIAL AND METHODS

The borehole data with chemical analysis used in this work were obtained from the Federal Ministry of Water Resources of Niger Republic. These data were collected in the context of the PHV/MI/AFD/project from 2004 to 2015 – Village Hydraulic Program, financed by the French Development Agency through the Ministry of Hydraulics and Sanitation operating in the area of the Tillabery basement. These chemical analyses examined the essential chemical elements influencing the quality of the water consumed by the population of the region in order to assess the health consequences on which it is based. The Program of the Village Hydraulics (PHV) is Niger government's policy that aims to provide each village with a supply point of water consumable without any danger. The parameters measured concern not only the well (depth, flow, and static level), but also the water quality. All these data have been transformed into ArcGIS format (shapefile) to facilitate the spatial analysis.

For the groundwater quality assessment (G-WQ$_i$) of the Tillabery Region we selected, from a total of 506 boreholes, 38 boreholes with groundwater chemical data. The summary of hydrogeological characteristics is: borehole depth – 3.8-80 m; flow rate – 0.2-2.6 m^3/s; static water level – 0.5-29.63 m; altitude of static water level – 188.14-279.5 m; drawdown range – 1.75-35.49 m. The lithological characteristics

were classified according to the dominant deposit: white clay (1 bor.); gray clay (1 bor.); gray sandy clay (1 bor.); glay sand (1 bor.); red clay sand (1 bor.); sandy brown clay (2 bor.); sandy clay (2 bor.); fine sand (8 bor.); fine brown sand (2 bor.); sand (1 bor.); brown sand (4 bor.); sand dune (6 bor.); sand and pebbles (1 bor.); lateritic sand (1 bor.); coarse clay sand (1 bor.); sand and gravel (1 bor.); lateritic gravel (1 bor.); lateritic crust (3 bor.) (Table 1) (Fig. 2).

The groundwater quality index (G-WQ$_i$) was determined using two evaluation methods. The first method describes the 15 physico-chemical parameters, analyzing the values of average concentrations for: water temperature [T(°C)]; pH (pH units); Nitrites [N-NO$_2^-$ (mgN/L)]; Nitrates [(N-NO$_3^-$(mgN/L)]; conductivity (µS/cm); Chlorides [Cl$^-$ (mg/L)]; Sulphates [SO$_4^{2+}$ (mg/L)]; Calcium [Ca^{2+} (mg/L)]; Magnesium [Mg^{2+} (mg/L)]; Potassium [K$^+$ (mg/L)]; Fluoride [F$^-$ (mg/L)]; Sodium [Na$^+$ (mg/L)]; Bicarbonates (mg/L); Dissolved Iron [Fe^{2+} + Fe^{3+} (mg/L)]; Total Manganese [Mn^{2+} + Mn^{7+}(mg/L)]. In order to highlight the chemical characteristics, a series of descriptive statistical parameters were determined: average, minimum, maximum, Q1–Quartile 1 (25%), Q3–Quartile 3 (75%) and Standard Deviation (Fig. 3, 4 and 5). This method is in conformity with freshwater quality standards of the Water Supply and Sanitation of Niger Republic and correlates with World Health Organization standards for drinking-water quality (Table 2).

The second evaluation method for water quality was conducted using statistical methods consisting of calculating the weight values for the 15 chemical and physico-chemical parameters. The arithmetic value of groundwater quality index (G-WQ$_i$) was obtained using the following formula (1), where Q$_i$ is calculated for each parameter analyzed using the formula (2) and W$_i$ is calculated for each parameter analyzed through the formula (3):

$$(1)\ WQ_i = \Sigma WQ_i/\Sigma W_i$$

$$(2)\ Q_i = 100[(V_i - V_o)/(S_i - V_o)]$$

$$(3)\ W_i = K/S_i$$

where: K = 1/Σ(1/S$_i$); Q$_i$- quality rating scale; W$_i$ - weight unit; V$_i$ - the estimated concentration of the parameter in water; V$_o$ - the ideal value of the parameter, V$_o$ = 0 (except for pH = 7); S$_i$ - the recommended standard value of the parameter; K = the proportionality constant (House & Ellis, 1978; Brown et al., 1972; Bharti & Katyal, 2011; Kankal et al., 2012; Gorde & Jadhav, 2013; Breabăn et al., 2014; Mihu-Pintilie et al., 2014a,b).

According to the method developed by Brown et al., (1972) and used in different studies, the water

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quality classes are based on the distribution of WQ_i values in several intervals that definied types of water quality (Breaban et al., 2014; Mihu-Pintilie et al., 2014a; Romanescu et al., 2015; 2016; 2017). The water that falls into the excellent water quality category is protected, with virtually no threat related to the standards for drinking-water quality. The good water quality range characterizes water with minimum threat levels, slightly deflecting from natural ones. Medium class quality refers to water occasionally threatened and with levels sometimes deflecting from desirable ones, while the $G-WQ_i$ score bellow to 50 the water quality is frequently threatened and the chemical parameters are often deflected from natural level (below the standards for drinking-water quality) (Brown et al., 1972).

4. RESULTS

4.1. Nutrients regime

Nitrate ($N-NO_3^-$) is found naturally in the environment and is an important plant nutrient. It is present in varying concentrations in all plants and it is a part of the nitrogen cycle. Nitrite ($N-NO_2^-$) is not usually present in significant concentrations except in a reducing environment, as nitrate is the more stable oxidation state (Breabăn et al., 2014).

Table 1. Hydrogeological characteristics for 38 boreholes in the Tillabéri Region which contain groundwater chemical data

Borehole code*	Borehole name	WGS 1984		Depth (m)	Flow rate (m³/s)	Static water level (m)	Altitude of static water level (m)	Drawdown (m)	Lithology
		X	Y						
673231	Bankara Sédentaire	0.672778	14.055556	35	1	18.53	234.47	9.3	Red clay sand
673232	Beïna	1.276389	14.279167	85	-	-	193	23.11	Brown sand
673234	Birnia Bangou	1.330000	14.072778	80	1.5	5	228	7.62	Sandy brown clay
673234	Birnia Bangou	1.327778	14.222778	44	1.5	6.75	204.25	7.62	Sandy brown clay
673236	Dambagorou (Boga)	1.490556	14.101944	35	2.6	10.86	188.14	5.2	Clay sand
673239	Darkiende	1.129722	14.080556	57	2	29.63	217.37	13.35	Sand dune
673239	Darkiende	1.179444	14.076389	51	2	30	253	13.35	Sand dune
673240	Dia Dia Peul	1.179444	14.076389	63	-	-	-	14.6	Gray clay
673250	Garbougna	1.179722	13.836389	45.58	0.8	26.9	197.1	6	Lateritic crust
673277	Hondobon Gandatche	1.564722	14.018333	69	-	-	197	35.49	Lateritic crust
673278	Hondobon Gourabon	1.574722	14.03500	40	-	-	216	12.64	Fine brown sand
673280	Kouhoum	1.583333	13.822222	60.78	-	-	192	11.03	White clay
673281	Kourwindo	1.578056	13.828333	63.78	-	-	202	3.95	Lateritic crust
673007	Tillabery	1.390000	13.84139	40	0.2	5.62	-	4.07	Lateritic sand
673010	Tillakaina	1.644167	13.93306	3.8	-	-	212	6.18	Sand
673020	Tillim	1.669167	14.45806	-	-	-	253	3.13	Gray sandy clay
673024	Tioubo Diabitira	0.760833	14.49167	6	-	0.5	279.5	5.76	Brown sand
673041	Toborack	0.759167	14.47222	10	-	-	278	15.12	Lateritic gravel
673042	Tokeyatou 1	0.759167	14.47222	6	-	-	-	10.63	Sand dune
673045	Tondi Goungo	1.149722	14.43611	12	-	-	-	7.63	Sand dune
673048	Tondi Karia	1.294167	14.44417	16	-	6	216	10.66	Sand dune
673049	Tondia	1.258056	14.49417	26	-	-	229	14.51	Sand and gravel
673055	Tondikirey	1.294444	14.31639	-	-	-	-	3.71	Sand fine brown
673057	Tongou Tonguey	0.850000	14.01389	-	-	-	237	2.36	Sand dune
673060	Tougoouak	0.850000	14.01389	-	-	-	-	6.39	Coarse clay sand
673108	Toumbinde	0.828889	13.90806	-	-	-	-	11	Sand and pebbles
673110	Touroukoukey	0.883056	13.99167	-	-	-	232	5.18	Fine sand
673125	Touroukoukwe 1	0.716667	13.92778	20	-	-	270	7.4	Fine sand
673126	Touroukoukwe 2	0.748333	13.95556	22	-	-	-	10.03	Fine sand
673146	Waire	0.775833	14.46667	-	-	-	-	3.66	Fine sand
673149	Wargantou	0.796944	14.46083	-	-	-	-	7.24	Fine sand
673151	Wargantou 1	0.750000	14.43611	-	-	-	-	1.98	Fine sand
673151	Waro	0.734444	14.42333	-	-	-	-	1.98	Fine sand
673157	Yanga	0.735833	14.41389	-	-	-	-	1.75	Sandy clay
673292	Yanga	0.674722	13.773611	57.78	4.1	25.9	222.1	5.27	Brown sand
673179	Yelewani 2	0.746944	14.33583	-	-	-	-	22.16	Fine sand
673223	Ziguida	0.875000	14.37083	-	-	-	-	28.61	Sandy clay
673226	Zoribi	0.769167	13.90528	32	-	27	-	11.16	Brown sand

* Direction of Water of the Ministry Water Supply and Sanitation of Niger Republic

Table 2. Mean values for 15 physico-chemical parameters analyzed in 38 boreholes from Tillabéri Region

Borehole code*	Water T[°C]	pH [pH units]	Nitrites $N\text{-}NO_2^-$ [mg N/L]	Nitrates $N\text{-}NO_3^-$ [mg N/L]	Conductivity [µS/cm]	Chlorides (Cl⁻) [mg/L]	Sulfates (SO_4^{2+}) [mg/L]	Calcium (Ca^{2+}) [mg/L]	Magnesium (Mg^{2+}) [mg/L]	Potassium (K^+) [mg/L]	Fluoride (F-) [mg/L]	Sodium (Na^+) [mg/L]	Bicarbonates [mg/L]	Dissolved iron $(Fe^{2+} + Fe^{3+})$ [mg/L]	Total manganese $(Mn^{2+} + Mn^{7+})$ [mg/L]
673231	26.1	-	0.02	3.52	990	4	165	83.2	39.84	4	1.23	80	268.4	0.01	-
673232	26.2	-	0.01	1.76	516	4	3	58.4	9.12	1.25	0.62	45.4	309.88	0.02	-
673234	26	-	0.02	3.08	395	4	1	26.4	21.12	4	0.41	23.5	207.4	0.03	-
673236	25.1	-	0.03	32.12	969	6	21	64	40.8	2.5	0.85	66.6	329.4	0.03	-
673239	25.6	-	0.03	6.16	2110	78	105	17.2	10.38	3.75	0.7	193	300.12	0.02	-
673239	25.6	-	0.03	6.16	2110	78	105	17.2	10.38	3.75	0.7	193	300.12	0.02	-
673240	25.9	-	0.32	20.24	1281	32	53	72	72	1.25	0.5	73	419.68	0.02	-
673250	-	-	0.01	4.4	351	21.3	3	28.4	11.17	1.8	1.25	-	197.64	0.03	-
673277	-	-	0.02	202	900	56.8	30	89.2	23.8	6	0.23	-	120	-	0.02
673278	-	-	0.15	115	694	32	2	59.2	47.3	3.5	0.16	-	297.7	0.01	-
673280	25.6	-	0.1	4.84	225	2	-	14.6	6.36	12	-	54.4	270.84	-	-
673281	25.9	-	0.03	36.52	192	10	1	8.45	4.53	1.6	0.45	18.6	58.56	-	-
673007	32.8	7.5	0.12	18.5	644	21.3	13	32	13.12	2.1	1.14	-	97.6	-	0.01
673010	32.5	7.4	0.13	49.7	744	32	14	90.4	26.49	1.2	0.38	-	179	-	0.14
673020	-	-	0.02	2.64	343	25	6	37.2	9.6	1.5	0.18	-	253.7	-	-
673024	-	-	0.01	1.76	411	18	2	44.8	7.7	2.1	0.97	-	29.3	-	-
673041	-	-	0.02	6.2	603	24.85	67	58.8	16.3	0.4	0.24	-	366	-	0.04
673042	-	-	0.07	14.1	602	24.85	290	60	28.3	0.4	-	-	395.3	-	0.09
673045	-	-	0.13	9.3	279	21.3	2	36.4	9.8	0.8	0.24	-	197.6	0.02	-
673048	-	-	0.03	2.64	608	21.3	1	60.4	25.7	1.6	0.37	-	392.7	0.01	0.01
673049	-	-	0.01	51.5	563	25	16	48.8	16.8	1.6	0.49	-	361	0.02	0.01
673055	-	-	0.4	-	303	21.3	1	31.6	11.9	1	0.82	-	146.4	0.02	0.04
673057	-	-	0.09	198.9	659	0.01	-	77.6	13.12	3.5	0.1	-	129.32	0.01	0.01
673060	-	-	0.02	9	278	21.3	2	24.4	5.1	2	0.62	-	158.6	0.05	0.01
673108	-	-	0.01	-	581	28.4	41	80	8.2	3.3	0.4	-	402.6	0.01	0.03
673110	-	-	0.06	128.5	844	28.4	51	86.8	34	1.6	0.18	-	336.7	0.04	0.04
673125	-	-	0.02	5.72	219	21.3	1	25.6	8.2	3.4	0.31	-	109.8	-	-
673126	-	-	0.17	85.8	829	42.6	33	28.4	34.5	5.6	0.43	-	256.2	0.02	-
673146	-	-	0.2	59.4	807	28.4	18	14.8	5.34	3.6	0.4	-	370.88	-	0.01
673149	-	-	6.6	65.56	374	28.4	38	32	26.9	1.7	0.74	-	117.12	0.05	0.02
673151	-	-	0.02	-	210	25	11	24	4.1	0.8	0.3	-	144	0.01	-
673157	30.1	7.4	0.01	11.9	1000	28.4	39	70	12.7	3.5	1.49	-	419.6	-	0.02
673292	-	-	0.02	55	307	21.3	1	25.2	4.1	1.2	0.29	-	109.8	1	0.09
673179	34.5	7.6	0.21	0.88	960	46.2	240	43.2	41.55	2.5	0.95	-	270.8	0.08	0.09
673223	-	-	0.02	32.7	561	35.5	65	33.2	8.9	4.7	0.55	-	200	0.04	0.01
673226	26.1	-	0.22	110	739	31.95	57	39.6	14.09	3.8	0.81	-	222.04	0.01	-

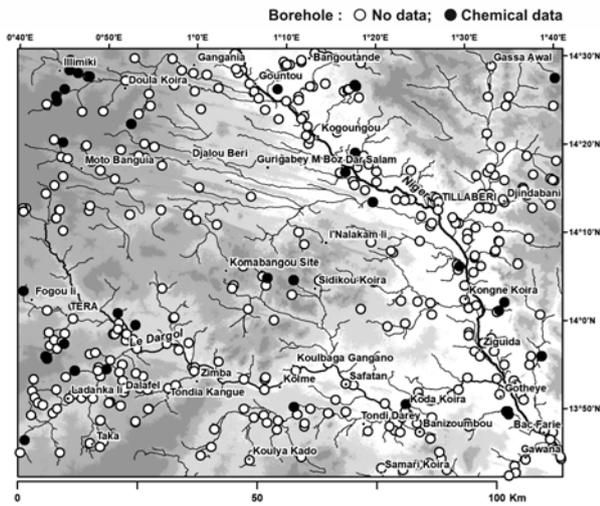* Direction of Water of the Ministry Water Supply and Sanitation of Niger Republic

Figure 2. Distribution of the boreholes in Tillabéri Region: white dots do not contain data; black dots contain groundwater chemical data

Nitrates can occur in surface waters and groundwater through agricultural activities, oxidation of human and animal excreta, and also through septic tanks. The variation of nitrate concentrations is faster in surface waters (through surface runoff of fertilizer) and slower in groundwater. However, groundwater can naturally be contaminated with nitrates through natural vegetation that overlaps these aquifers. In the case of groundwater supply, the concentrations of nitrate ($N-NO_3^-$) should not exceed a value of 50 mgN/L and nitrite ($N-NO_2^-$) a value of 3 mgN/L (World Health Organization, 2011) (Fig. 3).
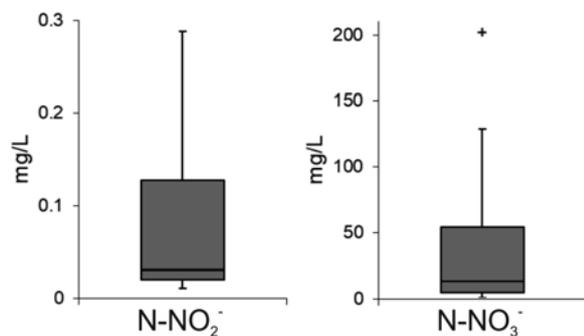
Figure 3. Nutrients concentration (nitrites and nitrates)

The distribution of the quantities of nitrites ($N-NO_2^-$) and nitrates ($N-NO_3^-$) in the study area shows a slight contamination of groundwater, but with a few exceptions (Barry & Obuobie, 2012). The concentration of nitrites ranges between 0.01 – 6.6 mgN/L, while the concentration of nitrates between 0.88 – 202 mgN/L. The concentration of nitrites which exceeds the standards for drinking-water quality corresponds to the bor.673149-Wargantou – 6.6 mgN/L.

The highest value of nitrates concentration, which exceeds the standards for drinking-water quality, corresponds to: bor.673292-Yanga – 55 mgN/L; bor.673146-Waire – 59.4 mgN/L; bor.673149-Wargantou – 65.56 mgN/L; bor.673126-Touroukoukwe 2 – 85.8 mgN/L; bor.673226-Zoribi – 110 mgN/L; bor.673278-Hondobon Gourabon – 115 mgN/L; bor.673110-Touroukoukey – 128.5 mgN/L; bor.673057-Tongou Tonguey – 198.9 mgN/L; bor.673277-Hondobon Gandatche – 202 mgN/L. The higher value of nitrates is caused by the use of nitrogen-based chemical fertilizers and the manure used for the fertilization of agricultural fields (Fig. 3).

4.2. Salinity regime

The chemical content of groundwater and its chemism are directly influenced by the geological conditions within the catchment basin. The presence of clay and sand deposits determines the accumulation of important amounts of mineral substances (Romanescu et al., 2015; 2016). The significant concentration of salts in the study area is illustrated by the value of water conductivity, which ranges between 192 – 2,110 µS/cm. The high value of conductivity (>1,000 µS/cm) corresponds to: bor.673157-Yanga – 1,001 µS/cm; bor.673240-Dia Dia Peul – 1,281 µS/cm; bor.673239-Darkiende – 2,110 µS/cm; bor.673239-Darkiende 2 – 2,110 µS/cm.

Chloride (Cl⁻) can occur in drinking water from natural and anthropogenic sources (from sewage and industrial effluents, from urban runoff of de-icing salts, and from saline intrusion). The presence of high concentrations of chloride determines the corrosion of metallic pipes from the drinking water distribution system, this corrosion depends on the alkalinity of the water (Breabăn et al., 2014; Romanescu et al., 2015). The results of this corrosion generate an increase of concentrations of metals in the drinking water supply. Concentrations of about 250 mg /L of chlorides can be identified in water tastes. In the study area, the concentration of chlorides (Cl⁻) increases from 0.01 mg/L to 78 mg/L. The average value is 25.76 mg/L. However, there is no case of chlorides (Cl⁻) concentration which exceeds the standards for drinking-water quality.

Sulphates (SO_4^{2+}) are present in groundwaters from natural sources (SO_4^{2+} are present in various minerals) and from anthropogenic sources (from the chemical industry through industrial wastes and atmospheric infiltration). However, in the groundwater, the presence of sulphates with high

concentrations is mainly due to natural sources (Romanescu et al., 2017). Sulphates can cause a series of gastrointestinal effects, if one ingests contaminated drinking water characterized by high concentrations of sulphates (SO_4^{2+} > 500 mg/L). In the groundwater samples from Tillabéry basement, the concentration of sulphates (SO_4^{2+}) ranges between 1.0 – 290 mg/L, with an average value of 41.94 mg/L. No sulphates concentration exceeds the standards for drinking-water quality (Barry & Obuobie, 2012).

The water hardness is generated by the presence of calcium (Ca^{2+}) and magnesium (Mg^{2+}) is a ordinary feature of groundwater resources (Mihu-Pintilie et al., 2014b). Human communities accept a certain degree variability inwater hardness. Concerning the concentration of calcium ions, the taste threshold for them is in the range of 100-300 mg/L, and for magnesium ions the taste threshold is lower than the calcium ions. Consumers of drinking water tolerate values above 500 mg/L concerning the water hardness (World Health Organization, 2011). The concentration of calcium (Ca^{2+}) ranges between 8.45 – 90.4 mg/L, while the concentration of magnesium (Mg^{2+}) between 4.1 – 72 mg/L. The average value for calcium (Ca^{2+}) is 44.57 mg/L, and for magnesium (Mg^{2+}) is 18.64 mg/L. The degree of hardness ranges between 12.98 – 144 mg/L (avg. 61.79 mg/L). These values do not exceed the health standards for drinking-water in Niger (Barry & Obuobie, 2012).

Potassium (K^+) has a frequent occurrence in the environment it is found in all natural waters. The presence of this cation in drinking water can occur from anthropogenic source by the use of potassium permanganate as an oxidant in the water treatment process. Some countries use potassium chloride (or mixed with sodium chloride) in the water softening process, this salt can react with calcium and magnesium ions (World Health Organization, 2011). In groundwater of Tillabéry Region, the concentration of potassium (K^+) ranges between 0.4 – 12 mg/L, with an average value of 2.73 mg/L. The lower concentration of potassium ion is a consequence of natural contamination, because in the studied area the use of potassium permanganate in water treatment has a low frequency.

Fluorides (F^-) are present in many surface waters or groundwaters, with high concentrations especially found in groundwater. The presence of fluorine is due to the existence of minerals characterized by high content of fluorine, so in such areas the groundwater can contain values above 10 mg/L. In the study area the concentration of fluorides (F^-) increases from 0.1 mg/L to 1.49 mg/L.

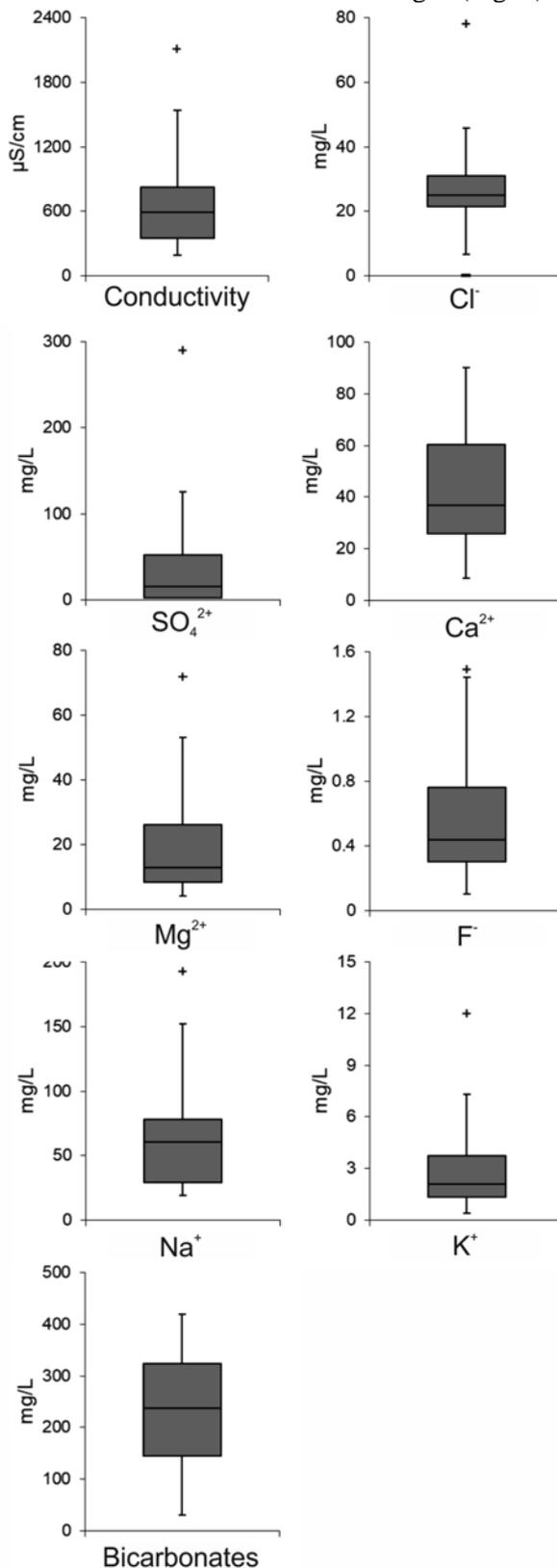The average value is 0.56 mg/L and there is no case of concentration which exceeds 10 mg/L (Fig. 4).

Figure 4. Groundwater conductivity and salinity concentrations

Sodium (Na^+) is found in drinking-water like

sodium chloride. The concentrations of sodium in drinking water are usually less than 20 mg/L, and in some countries they can greatly exceed this. The unacceptable taste of drinking water is due to the concentrations in excess of 200 mg/L (World Health Organization, 2011). The distribution of sodium (Na^+) in the groundwater of study area shows a medium contamination, but with a few exceptions because of the increase from lithology (Barry & Obuobie, 2012). The concentration ranges between 18.6 – 193 mg/L, with an average value of 77.1 mg/L. The highest value of sodium (Na^+) concentration which exceeds the standards for potable water (>20 mg/L) corresponds to: bor. 673234-Birnia Bangou – 23.5 mg/L; bor. 673234-Birnia Bangou 2 – 23.5 mg/L; bor. 673232-Beïna – 45.4 mg/L; 673280-Kouhoum – 54.4 mg/L; bor.673236-Dambagorou (Boga) – 66.6 mg/L; bor.673240-Dia Dia Peul – 73 mg/L; bor.673231-Bankara Sédentaire – 80 mg/L; bor.673239-Darkiende – 193 mg/L; bor.673239-Darkiende 2 – 193 mg/L.

Bicarbonates in combination with calcium and magnesium forms carbonate hardness (Romanescu et al., 2015). Water that has a hardness less than 60 mg/L is considered soft; 61 – 120 mg/L, moderately hard; 121 – 180 mg/L, hard; and more than 180 mg/L, very hard (Barry & Obuobie, 2012). In the study area the concentration of bicarbonates increases from 29.3 mg/L to 419.68 mg/L and the average value is 239.4 mg/L. However, 26 groundwater samples are in very hard class, 6 groundwater samples are in hard class, and the rest are in the soft and moderately hard classes (Fig. 4).

4.3. Specific toxic pollutants of natural origin

The presence of dissolved iron ($Fe^{2+} + Fe^{3+}$) is due to geological context, but it can also be an anthropic consequence (mining, water use). Anaerobic groundwater may contain ferrous iron at a concentrations up to a few milligrams per litter, this quantity does not induce the discoloration or increasing of turbidity in water when is pumped directly from a well. Stains laundry and plumbing fixtures by iron occurs at a concentration higher than 0.3 mg/L (World Health Organization, 2011).

Concentrations of dissolved iron ($Fe^{2+} + Fe^{3+}$) in Tillabéry Region vary between 0.01 mg/L and 1 mg/L (avg. 0.06 mg/L). The highest value of dissolved iron ($Fe^{2+} + Fe^{3+}$) concentration corresponds to: bor.673223-Ziguida – 0.04 mg/L; bor.673110-Touroukoukey – 0.04 mg/L; bor.673149-Wargantou – 0.05 mg/L; bor.673060-Tougoouak –

0.05 mg/L; bor. 673179-Yelewani 2 – 0.08 mg/L. However, just one borehole exceeds the standards for drinking-water: bor. 673292-Yanga – 1 mg/L (World Health Organization, 2011).

The concentrations of manganese ($Mn^{2+} + Mn^{7+}$) below 0.1 mg/L are usually acceptable to consumers. Exceeding this limit, the presence of manganese in water supplies can cause an undesirable taste and stains sanitary ware and laundry (World Health Organization, 2011). Analyzing the groundwater samples it can be observed that the concentrations of total manganese ($Mn^{2+} + Mn^{7+}$) increases from 0.01 mg/L to 0.09 mg/L and the average value is 0.03 mg/L. Only one borehole where total manganese ($Mn^{2+} + Mn^{7+}$) concentration exceeds the standards for potable water corresponds to bor.673010-Tillakaina with a value of 0.14 mg/L (Fig. 5).
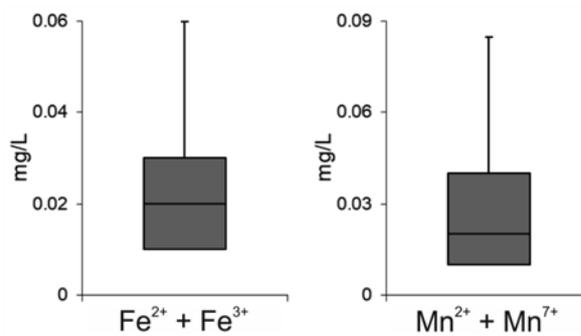

Figure 5. Dissolved iron and total manganese concentrations

5. DISCUSSIONS

5.1. Distribution of nutrient, salinity and specific toxic polluant concentrations

Nutrient analysis was performed by identifying the concentration of nitrites ($N\text{-}NO_2^-$) and nitrates ($N\text{-}NO_3^-$). Although the toxicity is relatively low, their presence in some groundwater sources can be considered as an indicator of anthropogenic pollution. An example could be the concentrations of nitrites ($N\text{-}NO_2^-$) exceeding the limit in bor.673149-Wargantou in the north-west of the study area (6.6 mgN/L) indicating a stable oxygenation environment. This sector is an arid, vegetation-free area with fine sand deposits and rock. Nevertheless, the high concentration of nitrates from this borehole is isolated in the study area.

As regards the distribution of nitrates concentration ($N\text{-}NO_3^-$) over the allowed limit, it has a much greater spread. Over 10 boreholes have been identified presenting values over 50 mg/L. These correspond to the floodplains of Niger and Dargol

rivers, where an intensive agriculture with cold season crops is practiced. The use of nitrogen-based fertilizers and manure for land fertilization and the infiltration of contaminated water into the soil represent the main cause of enrichment of drinking water sources. Moreover, the groundwater sources contaminated with nitrates ($N-NO_3^-$) also correspond to the highest population density. The most affected human settlements are: Tongou Tonguey (198.9 mgN/L) and Hondobon Gandatche (202 mgN/L) (Fig. 6).
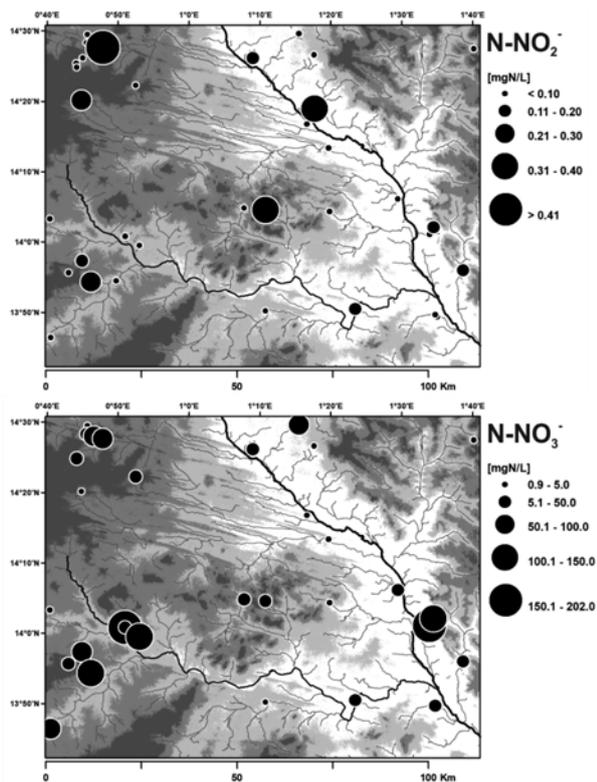

Figure 6. Distribution of groundwater nutrients concentration in Tillabéri Region

The groundwater chemistry from Tillabéry Region is directly influenced by the geological conditions and the semi-desert climate. The presence of clay, sandy-clay and sandy deposits that were accumulated across the granitic and granodiorite formations determine significant concentrations of minerals. Due to this reason, the conductivity of groundwater is frequently exceeding 1,000 µS/cm in the center of the study area, (Yanga – 1,001 µS/cm; Dia Dia Peul – 1,281 µS/cm; Darkiende – 2,110 µS/cm; Darkiende 2 – 2,110 µS/cm).

The distribution of chloride (Cl^-) and sulphates (SO_4^{2+}) is relatively uniform and does not indicate an anthropogenic contamination of drinking water sources. The maximum value of chloride concentration (Cl^-) is 78mg/L and corresponds to inhabited areas from the central-west and south-east

parts of the study area (Touroukoukwe 2 – 42.6 mg/L; Yelewani 2 – 46.2 mg/L; Hondobon Gandatche – 56.8 mg/L; Darkiende and Darkiende 2 – 78 mg/L). The maximum values of sulphates concentration (SO_4^{2+}) is 290 mg/L and corresponds to the north-west part of the area (Tokeyatou 1 – 78 mg/L). No chloride and sulphates concentrations exceed the standards for drinking-water quality.

Regarding the groundwater hardness caused by high concentrations of calcium (Ca^{2+}) and magnesium (Mg^{2+}), the values indicate a low presence of these. Higher concentrations of calcium (Ca^{2+}) and magnesium (Mg^{2+}) are found in the central sector, but any borehole do not exceeded the maximum limit (Hondobon Gandatche – Ca^{2+} 89.2 mg/L, SO_4^{2+} 23.8 mg/L; Tillakaina – Ca^{2+} 90.4 mg/L, SO_4^{2+} 26.49 mg/L). Even though, the carbonate hardness consisting of bicarbonates in combination with calcium (Ca^{2+}) and magnesium (Mg^{2+}) is very high.

In the boreholes from the central-north sector of the study area, the bicarbonate concentration in the water mass includes 26 samples in the category of very hard water. The most affected settlement by the water hardness are: Toumbinde (Bicarbonates – 402.6 mg/L, Ca^{2+} – 80 mg/L, SO_4^{2+} – 8.2 mg/L), Yanga (Bicarbonates – 419.6 mg/L, Ca^{2+} – 70 mg/L, SO_4^{2+} – 12.7 mg/L) and Dia Dia Peul (Bicarbonates – 419.68 mg/L, Ca^{2+} – 72 mg/L, SO_4^{2+} – 72 mg/L).

The distribution of potassium concentration (K^+) indicates a minimum contamination of groundwater sources in the study area. The highest value of potassium (K^+) is 12 mg/L and corresponds to the borehole from Kouhoum, located at 10 km downstream from the confluence of Niger and Dargol rivers.

The concentration of fluorides (F-) is low and shows a similar distribution to the one of potassium (K^+) and does not affect the quality of drinking water from the study area. The maximum value of fluorides (F-) is 1.49 mg/L and corresponds to the groundwater supply from Yanga locality. The only chemical indicator of water salinity which exceeds the standards for potable water is sodium (Na^+).

The ditribution of sodium concentrations (Na^+) over 20 mg/L corresponds to: Birnia Bangou (23.5 mg/L), Birnia Bangou 2 (23.5 mg/L), Beïna (45.4 mg/L), Kouhoum (54.4 mg/L), Dambagorou (Boga) (66.6 mg/L), Dia Peul (73 mg/L), Bankara Sédentaire (80 mg/L) and Darkiende (193 mg/L). In these boreholes dominate the clay, sandy and clay loam deposits, and the enrichment of groundwater sources takes place through a natural process (Fig. 7).

Distribution of specific toxic polluant was performed based on the concentration of dissolved iron ($Fe^{2+} + Fe^{3+}$) and total manganese ($Mn^{2+} + Mn^{7+}$).
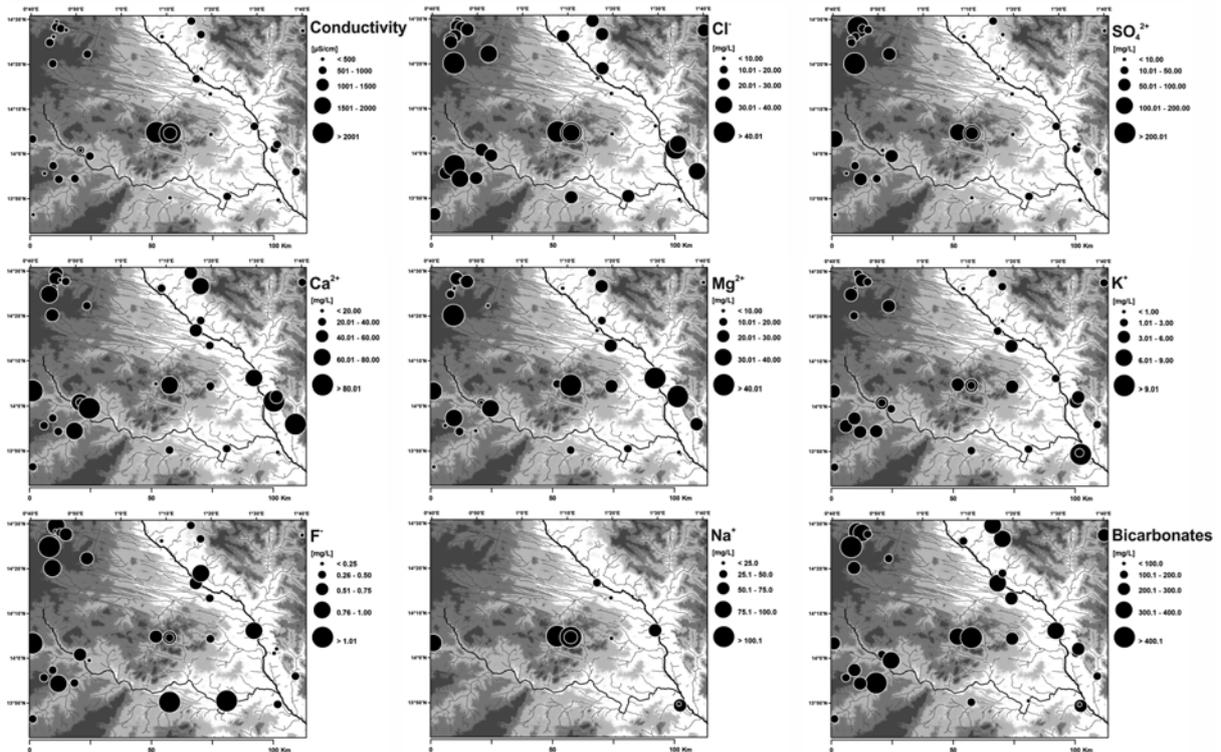
Figure 7. Distribution of groundwater conductivity and salinity concentrations in Tillabéri Region

The groundwaters contaminated with iron over the admissible limit corresponds to the south-west part of the study area and are located around the settlements: Ziguida (0.04 mg/L), Touroukoukey (0.04 mg/L), Wargantou (0.05 mg/L), Tougoouak (0.05 mg/L), Yelewani (0.08 mg/L) and Yanga (1 mg/L). The groundwater contaminated with manganese corresponds only to the borehole from Tillakaina locality (0.14 mg/L). Whithin other boreholes the concentrations of dissoved iron (Fe^{2+} + Fe^{3+}) and total manganese (Mn^{2+} + Mn^{7+}) do not exceed the health standards for drinking-water in Niger (Fig. 8).

5.2. Groundwater Quality Index (G-WQ$_i$)

In the arithmetic formula of groundwater quality index (G-WQ$_i$) 15 physico-chemical parameters were analyzed, but only 7 exceed the quality standards of the Water Supply and Sanitation of Niger Republic and World Health Organization (WHO) standards for drinking-water quality: Nitrites [N-NO$_2^-$ (mgN/L)]; Nitrates [(N-NO$_3^-$(mgN/L)]; conductivity (µS/cm); carbonate hardness (mg/L); Sodium [Na$^+$ (mg/L)]; Dissolved Iron [Fe^{2+} + Fe^{3+} (mg/L)]; Total Manganese [Mn^{2+} + Mn^{7+}(mg/L)]. Also, these parameters obtained the highest weight (W$_i$) in determining G-WQ$_i$ according to formula (F.3).

From those 38 groundwater samples analyzed, 10 boreholes are in "Good water quality" class, 16 boreholes are in "Medium high water quality" class, 10 boreholes are in "Medium low water quality" class, and 2 groundwater samples contain a "Poor water quality" (Table 3) (Fig. 9).
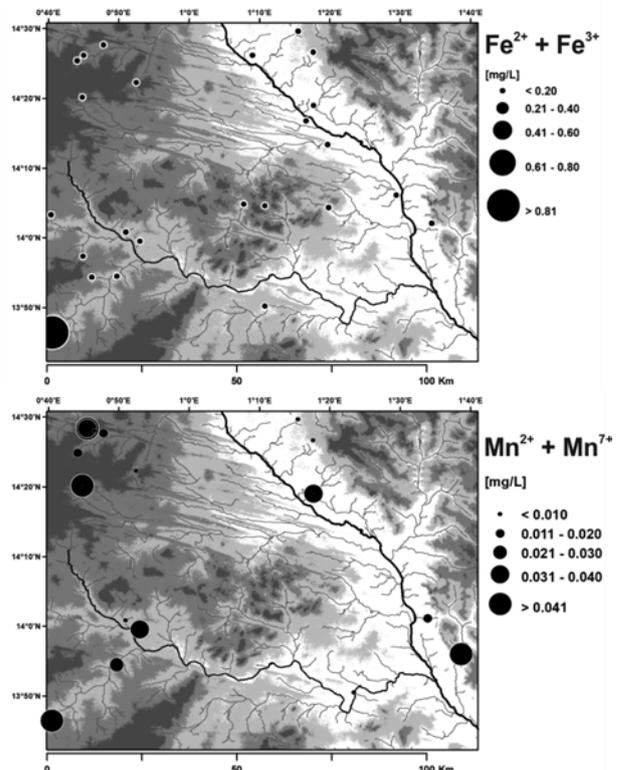

Figure 8. Distribution of dissolved iron and manganese concentrations in groundwater of Tillabéri Region

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Table 3. Physic-chemical parameters of groundwater from Tillabéri Region which exceed WHO standards for drinking-water and G-WQ$_i$ score

Borehole code*	Nitrites N-NO$_2^-$ [mg N/L]	Nitrates N-NO$_3^-$ [mg N/L]	Conductivity [µS/cm]	Carbonate hardness [mg/L]	Sodium (Na$^+$) [mg/L]	Dissolved iron (Fe^{2+} + Fe^{3+}) [mg/L]	Total manganese (Mn^{2+} + Mn^{7+}) [mg/L]	G-WQ$_i$ status
WHO standard value	3	50	± 1,000	Soft <60; Moderately hard 61-120; Hard 121-180; Very hard >180.	20	0.3	0.1	
673231				Very hard	Exceed (80)			Medium high
673232				Very hard	Exceed (45.4)			
673234			Within	Very hard	Exceed (23.5)			
673234				Very hard	Exceed (23.5)			
673236		Within		Very hard	Exceed (66.6)			
673239			Exceed (2,110)	Very hard	Exceed (193)	Whitin		Medium low
673239			Exceed (2,110)	Very hard	Exceed (193)			
673240			Exceed (1,281)	Very hard	Exceed (73)			
673250				Very hard				Good
673277		Exceed (202)		Moderately hard	Within			Medium low
673278		Exceed (115)		Very hard				
673280				Very hard	Exceed (54.4)			Good
673281				Soft				
673007				Moderately hard				
673010	Within			Hard			Exceed (0.14)	Medium low
673020				Very hard				Medium high
673024		Within		Soft		Whitin		Good
673041				Very hard				Medium high
673042				Very hard				
673045				Very hard				
673048			Within	Very hard				
673049		Exceed (51.5)		Very hard				Medium low
673055		Within		Hard				Good
673057		Exceed (198.9)		Moderately hard	Whitin			Medium low
673060		Within		Hard				Good
673108				Very hard				Medium high
673110		Exceed (128.5)		Very hard			Whitin	Medium low
673125		Within		Moderately hard				Good
673126		Exceed (85.8)		Very hard				Medium high
673146		Exceed (59.4)		Very hard				
673149	Exceed (6.6)	Exceed (65.56)		Moderately hard				Poor
673151				Moderately hard				Good
673151		Within		Moderately hard				
673157			Exceed (1,001)	Very hard				Medium high
673292	Within	Exceed (55)		Moderately hard		Exceed (1)		Poor
673179			Within	Very hard				Medium high
673223		Within		Very hard		Whitin		
673226		Exceed (110)		Very hard				Medium low

In the "Good water quality" class most samples are from Le Dargol basin (bor.673250-Garbougna; bor.673280-Kouhoum; bor.673281-Kourwindo; bor.673007-Tillabery; bor.673060-Tougoouak; bor.673125-Touroukoukwe 1) andfewer samples along the Niger River and small tributaries (bor.673024-Tioubo Diabitira; bor.673055-Tondikirey; bor.673151-Wargantou 1).

In the case of groundwater samples from "Medium high water quality" class, the spatial distribution is reversed: Niger River and small tributaries – bor.673232-Beïna; bor.673234-Birnia Bangou; bor.673234-Birnia Bangou; bor.673236-Dambagorou; bor.673020-Tillim; bor.673041-Toborack; bor.673042-Tokeyatou 1; bor.673045-Tondi Goungo; bor.673048-Tondi Karia; bor. 673146-Waire; bor.673157-Yanga; bor.673179-Yelewani 2; bor.673223-Ziguida; Le Dargol basin – bor.673231-Bankara Sédentaire; bor.673108-Toumbinde; bor.673126-Touroukoukwe 2. This phenomenon is due to anthropogenic pressure on groundwater supply sources. However, in both classes the carbonate hardness and the Sodium (Na$^+$) concentration are over WHO standard limits.
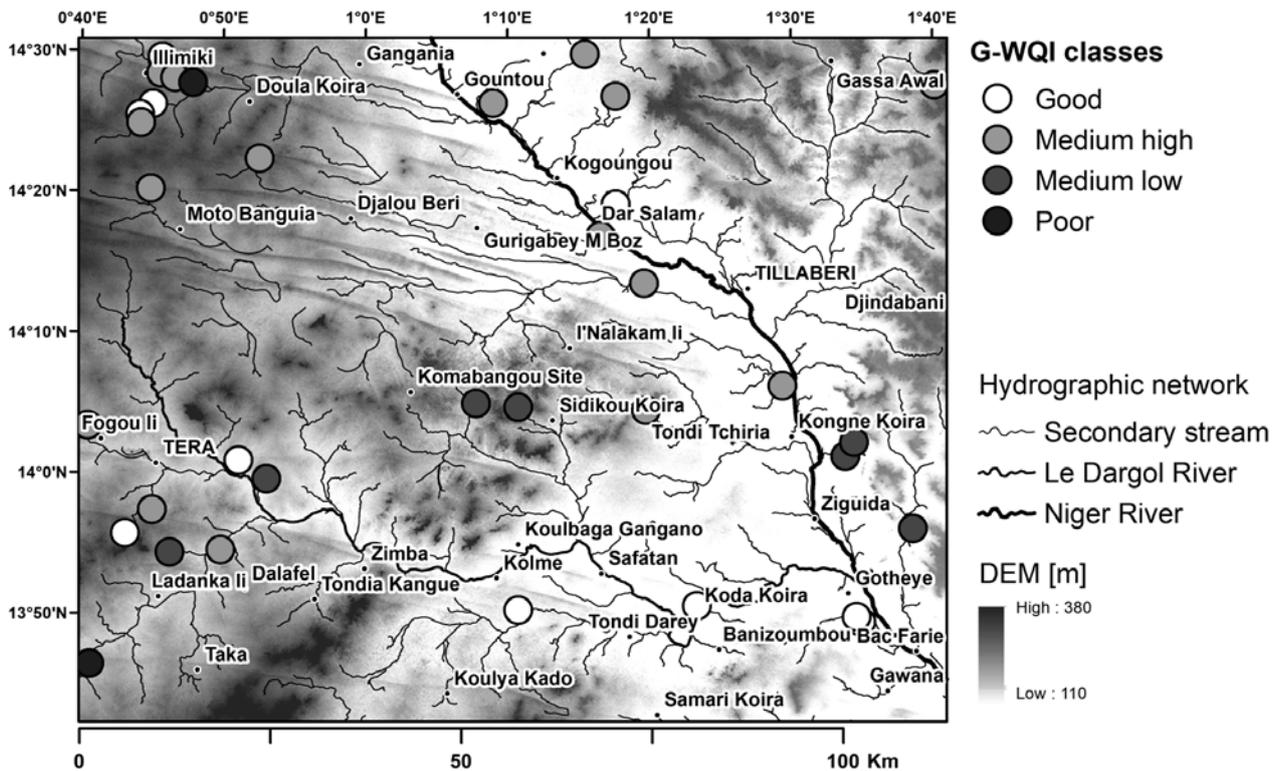
Figure 9. Spatial distributions of groundwater quality index [G-WQ$_i$] in Tillabéri Region, Niger

The "Medium low water quality" class coresponds to: bor.673049-Tondia; bor.673239-Darkiende; bor.673239-Darkiende; bor.673240-Dia Dia Peul; bor.673277-Hondobon Gandatche; bor.673278-Hondobon Gourabon; bor.673010-Tillakaina; bor.673057-Tongou Tonguey; bor.673110-Touroukoukey; bor.673226-Zoribi. These groundwater supply sites, besides having a high water hardness, also have a high contamination with nitrates (N-NO$_3^-$). The higher value of nitrates is caused by the use of nitrogen-based chemical fertilizers and manures to fertilize agricultural fields. In the case of bor.673010-Tillakaina, the concentration of total manganese (Mn^{2+} + Mn^{7+}) exceeds the WHO's standard limits.

The "Poor water quality" class is specific for two groundwater samples: bor.673149-Wargantou (northwest of the study area) and bor.673292-Yanga (southwest of the study area). Both water sources contain a very high concentration of nitrates (N-NO$_3^-$) and nitrites (N-NO$_2^-$), and also an important source of natural contamination with dissolved iron (Fe^{2+} + Fe^{3+}) (three times higher than WHO's standard limits). Even though they are relatively isolated, this source can endanger human health and the consumption of this water is responsible for many diseases (World Health Organization, 2011; Barry & Obuobie, 2012) (Fig. 9).

6. CONCLUSIONS

The Tillabéry Region is located in the middle part of the Nigerian Liptako (Sahel Region-West Africa). The annual precipitation (400 mm) is considerably less than the estimated potential evapotranspiration of 1,500 mm to 2,000 mm. Because of the permanent drought, the population has to exploit the superficial alluvial aquifers using the traditional sump wells. Within the Program of the Village Hydraulics (PHV) the Niger government's policy tried to provide each village with a source of safe drinking water. This study conducts a descriptive, statistical and concentration analysis, mapping 15 chemical and physico-chemical parameters based on 38 boreholes from PHV, highlighting the groundwater quality index (G-WQ$_i$).

The statistical analysis of physico-chemical data indicates concentrations of 7 parameters which exceed the standards for drinking-water quality according to the World Health Organization: Nitrites [N-NO$_2^-$ (mgN/L)]; Nitrates [(N-NO$_3^-$(mgN/L)]; conductivity (μS/cm); carbonate hardness (mg/L); Sodium [Na$^+$ (mg/L)]; Dissolved Iron [Fe^{2+} + Fe^{3+} (mg/L)]; Total Manganese [Mn^{2+} + Mn^{7+}(mg/L)]. From a total of the 38 groundwater sources, 11 are contaminated with nitrites and nitrates, 4 samples exceed the acceptable salinity, 9 samples contain a

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high concentration of sodium, and two samples are contaminated with manganese and dissolved iron. According to the arithmetic formula of groundwater quality index (G-WQ$_i$), 10 samples can be included in the "Good water quality" class, 16 samples - in the "Medium high water quality" class, 10 samples - in the "Medium low water quality" class, and 2 samples coresponds to the "Poor water quality" class.

Using the (G-WQ$_i$) methodology, statistical analysis and concentration mapping were performed in order to have an overview of groundwater quality of drinking-water in the Tillabery Region. The result of this method can be a useful tool for all authorities involved in water management resources from human settlements affected by drought in Sahel Region.

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