

# Hydrochemical Assessment of Water Quality and Risks related to the Use of Groundwater Resources in the Urban Area of Niamey and Nearby Rural Areas in the Regions of Dosso and Tillabery in Niger

## ABSTRACT

Groundwater continues to be useful as the main source of drinking water in semi-arid and arid regions of sub-Saharan Africa. The main goal of this work is to assess the health risks associated to the consumption of borehole water in urban and peri-urban areas of Niamey in Niger. Hydrochemical analyses were carried out from water samples of 16 boreholes using standard methods (AFNOR). The parameters measured are pH, Electric conductivity (EC),  $\text{HCO}_3^-$ ,  $\text{NO}_3^-$ ,  $\text{NO}_2^-$ ,  $\text{Cl}^-$ ,  $\text{SO}_4^{2-}$ ,  $\text{F}^-$ ,  $\text{Na}^+$ ,  $\text{K}^+$ ,  $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ ,  $\text{Fe}^{2+}$  and  $\text{Mn}^{2+}$ . 80% of the samples are very risky for the populations. About 56% of boreholes have a nitrate concentration  $< 30$  mg/L and 44% of samples have more than 50 mg/L corresponding to the limit standard set by the WHO. High nitrite contents ( $\text{NO}_2^-$ ) were determined from the same borehole water samples and contain more than 10 mg/L, and are considered unfit. Main causes are the lack of good urban waste management, and the uncontrolled use of fertilizers in the agricultural sectors. The sites containing between 2 and 3 mg/L of  $\text{Fe}^{2+}$  are located in areas of lateritic soils. About 12% of samples contain  $\text{Mn}^{2+}$  above the WHO standard (0.4 mg/L). This study of few boreholes from Niamey and its close rural areas demonstrates that nitrate, nitrite and manganese contents may cause major risks, in particular gastric, cardiovascular, carcinogenic and neurological diseases. With the growing population and urbanization, the lack of sanitation and of good management of urban waste, monitoring of groundwater quality is urgently needed to preserve human health. Regular, rapid and less costly monitoring of the pH and electrical conductivity of urban borehole waters can help to prevent the risk of poisoning by nitrate, nitrite and by heavy metals such as manganese.

*Keywords:* Groundwater, Hydrochemical, Pollution, Risks, Nitrate, Nitrite, Manganese, Health, Niamey

## 1. INTRODUCTION

Groundwater is a vital resource for both urban and rural centers in sub-Saharan Africa. The protection of this precious asset against pollution is in the public interest. The drinking water supply network provides good quality water at the best cost given the investments made. With population growth unprecedented in the world, rapid urbanization <sup>[1]</sup>, and the inadequacy of infrastructure to access drinking water networks; groundwater exploitation in the largest town Niamey and its marginal areas is very common. Dependence on borehole water is becoming increasingly considerable in urban areas <sup>[2, 3]</sup> The growing demand for

drinking water and irrigated agriculture has led to the expansion of drilling sites without prior studies on the potential risks of micro-elements to human and environmental health risks. This potential risk mainly affects the most disadvantaged populations living in the old districts and slums of Niamey city without public sanitation<sup>[4]</sup>. Despite the existence of an environmental code in Niger that regulates the exploitation and use of groundwater, in many private uses, this code is not followed by the population because of the cost of analyses in appropriate laboratories. The groundwater can be naturally contaminated by hydrochemical alterations of rocks rich in toxic elements and compounds or even more by pollutants from anthropogenic activities. Many studies have pointed out that the storages and poor waste management in the urban and peri-urban areas of Niamey are major sources of groundwater contamination. This contamination can be caused by the infiltration of sanitary water or rainwater draining various pollutants into aquifers and that are harmful to the health of the population<sup>[5; 6,7, 8]</sup>. Physicochemical parameters related to the natural structure of water include temperature, pH, conductivity, major ions: bicarbonate, chloride, sulphate, calcium, magnesium, sodium, potassium, and others,<sup>[9; 10]</sup>. Undesirable elements mainly include nitrogenous compounds (ammonium, nitrite, nitrate), fluorides, iron, manganese and other heavy metals, etc. In addition to these, there are microorganisms of bacteriological and fungal strains with very harmful consequences for the well-being of children<sup>[9]</sup>. Recent studies have been conducted to better understand the aquifers of the Niamey region and the impacts of pollution and their relationship with the surface waters of the Niger River<sup>[11;12 13;14]</sup>.

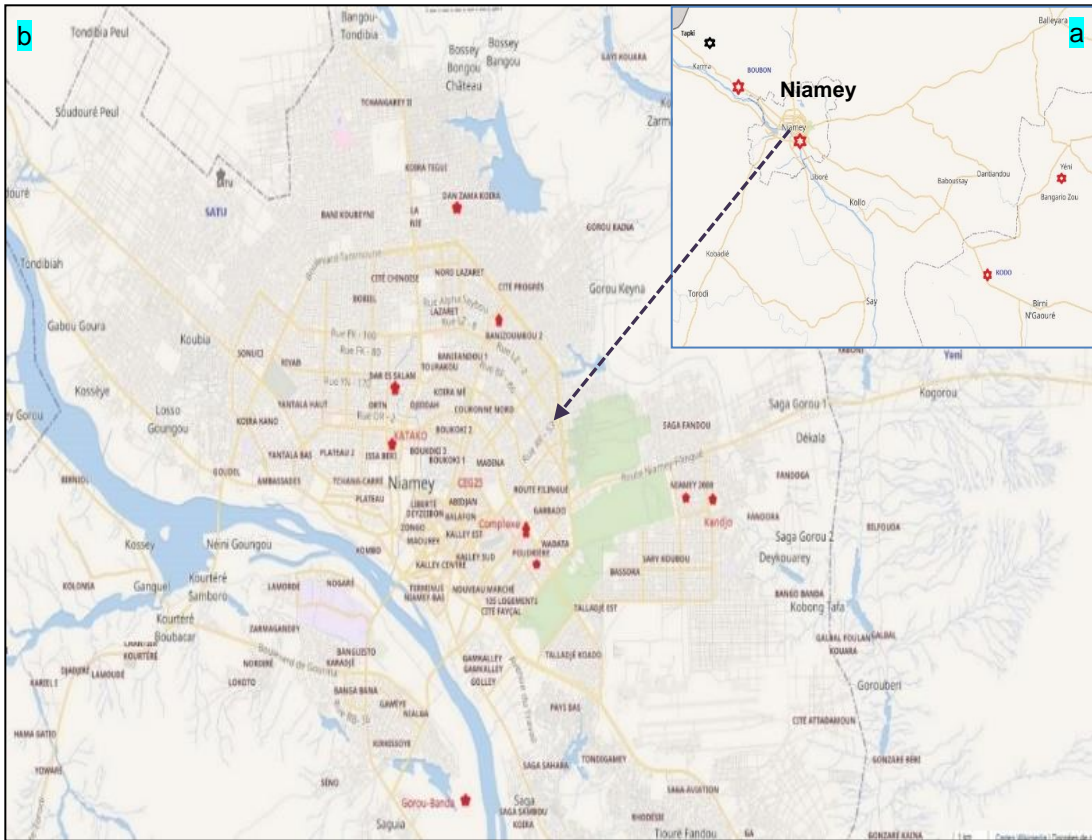
The aim of this study is to determine the Hydrochemical properties in order to assess the health risks related to the water of 16 boreholes from selected districts of the city of Niamey and peri-urban areas in the regions of Tillabery and Dosso.

## 2. METHODOLOGY

### 2.1. Study area

The studies areas are located in the city of Niamey and its nearby rural municipalities located in the regions of Dosso and Tillabery (Fig. 1a). The choice of rural peripheral areas is to allow an assessment of the effects of population pressure and urbanization on groundwater resources in Niamey. The geographical coordinates of selected sites are represented in the Table. 1. The urban area of Niamey (capital of Niger) in West Africa, is located between latitudes 13°28" N and 13°35" N and longitudes 2°03" E and 2°10" E (Fig. 1b). It is the largest agglomeration with an estimated population of 1,496,260 in 2024 and with an annual growth of about 59,030 inhabitants, i.e. a rate of 4.11%/year<sup>[15]</sup> United Nations<sup>1</sup>. According to the same source; between 1950 and 2024, the population of Niamey and its surroundings has grown exponentially (Fig. 2). The hydrogeological situation of the Niamey region is characterized by three main distinct aquifers<sup>[14;16;17]</sup>. According to the later source, these are the Basement aquifer, the Continental Terminal (CT) aquifer and the alluvial aquifer. The Basement Aquifer is discontinuous and located in the Precambrian basement known as "MetaLiptako"<sup>[16;18]</sup>. The lithology is composed of plutonic rocks (granites, granulite) and metamorphic rocks (heifers, quartzites, green schists) with different levels of alterations<sup>[19;20]</sup>. The basement aquifer is the deepest of the three aquifers considered<sup>[18;19]</sup>. We also note the Continental Terminal (CT) aquifer, which is on the contrary continuous and is located in porous sandstones of the Mesozoic and Cenozoic nature of the Continental Terminal<sup>[18 19]</sup>. Its lithology is composed of sedimentary sandstones from the Upper Cretaceous to the present day and forms the vast regional basin of the lullemeden<sup>[21]</sup>. The latter is located east and northeast of Niamey. The CT consists of several layers, i.e. several aquifers. However, Niamey is located at the extreme southwestern edge of the lullemeden basin where the continental terminal outcrops. The third, which consists of the alluvial aquifer is continuous<sup>[14;18]</sup>. It is rather made up of the

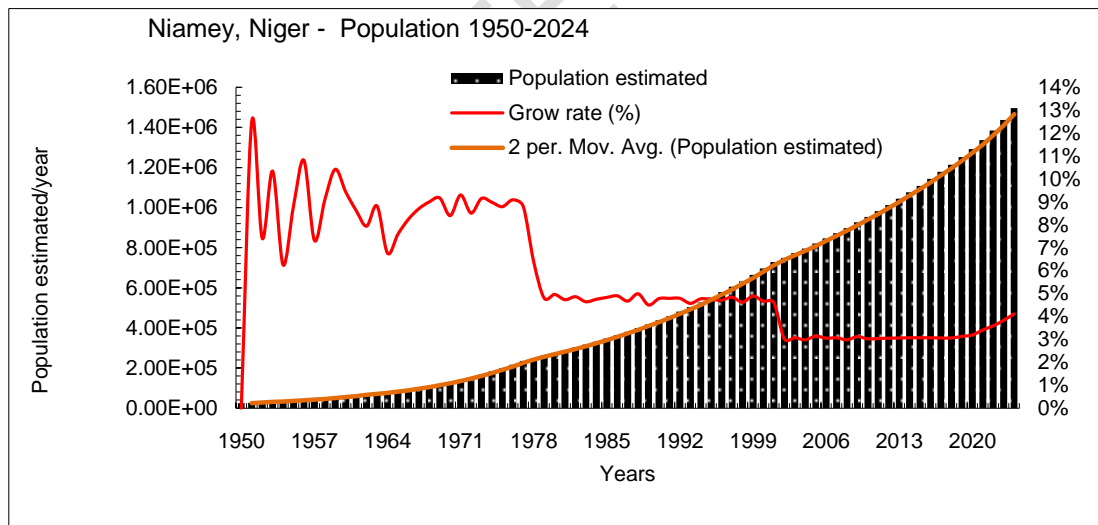
alluvium of the Niger River of a Quaternary age. Its lithology is composed of sand that is not very coherent. This porous aquifer is limited to the alluvial plain and the Niger River valley. Another very restricted alluvial aquifer is located along a wadi to the north-east of Niamey. These alluvial aquifers are the shallowest of the three aquifers considered.



**Figure 1:** Map of the urban area of Niamey and its suburban rural areas

**Table 1:** The table of the regions, urban or rural sites and their geographical coordinates of selected borehole water sampled

Regions	Urbain/Rural	Sites/Districts	Latitude North	Longitude East
Niamey	Urbain-District	Kandjo/Niamey_2000	13°30'49"	2°06'35"
		CEG 25_Wadata	13° 32' 33"	2° 04' 31"
		Tchini Koura/Airport	13°13'60"	2°25'60"
		Banizombou	13°34'0"	2°9'0"
		Poudrière	13° 30' 50"	2° 9' 7"
		SATOU	13.5717°	2.0486°
		Dan Zama Koura	13° 34' 33"	2° 7' 32"
		Dar Salam	13°30'0"	1°24'0"
		Complexe_Wadata	13° 30' 50"	2° 8' 51"
		Niamey 2000	13.5243°	2.1826°
		Katako/Boukotchi	13° 30' 43"	2° 06' 28"
		Rural	Gorou Banda	13°26'23"
Dosso	Rural	Kodo	13°13'60"	2°42'0"
		Yeni	13°25'53"	2°59'36"
Tillabery	Rural	Tapki	14° 21' 07"	3° 19' 22"
		Boubon	13°36'0"	1°55'60"



**Figure 2:** Graph of both populations estimated yearly and the growing rate from 1950 to 2024. Data sources [\[22\]](#)

## 2.2. Data

The materials studied consist of a set of 16 borehole water samples collected from different districts in the urban community of Niamey as well as sites in nearby rural areas in the

regions of Tillabery (Boubon and Tapki) and Dosso (Yeni and Kodo). These sites emplacements and geocoordinates are indicated in the [figure 1](#); [the table 1](#). Water samples were taken from the 250 ml sterilized vials which are labelled and then placed in ice boxes before being sent to the laboratory for analysis.

### 2.3. Methods

The physicochemical analyses are respectively the determinations of pH, electrical conductivities (EC) and turbidities of the samples. In the laboratory, major anions ( $\text{HCO}_3^-$ ,  $\text{Cl}^-$ ,  $\text{F}^-$ ,  $\text{NO}_2^-$ ,  $\text{NO}_3^-$ ,  $\text{SO}_4^{2-}$ ) and cations ( $\text{Na}^+$ ,  $\text{K}^+$ ,  $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ ) as well as heavy metals ( $\text{Fe}^{2+}$ ,  $\text{Mn}^{2+}$ ) were measured. These analyses were performed with an AAS spectrophotometer DR 3800 at Quality-Control Lab (QCL) Niamey-Niger. The pH and water turbidity were recorded with a nephelometer. An electric conductometer was used to measure EC in the same laboratory. A simple statistic method was applied here to analyze data obtained. In order to evaluate the impact of Hydrochemical parameters on human health, we compared these results the standard limits given by the World Health Organization (WHO).

## 3. RESULTS AND DISCUSSION

### 3.1. Results

The overall results of the Hydrochemical analyses obtained in the laboratory are presented in Table 2 below. The table also shows the standards set by the World Health Organization (WHO).

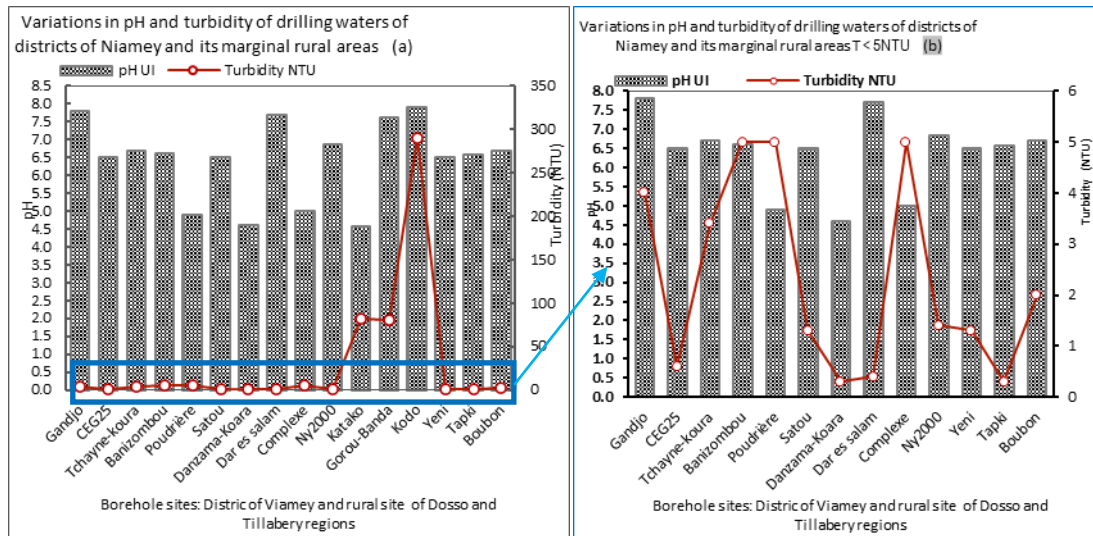
#### 3-1.1. pH and Turbidity

The results of pH and turbidity measurements are shown in Figure 3. The recorded pH values for the water samples show that 25% of the values are very acidic (4 to 5). All borehole sites are located in the districts of Niamey: Poudrière, Dan Zama Koara, Complexe and Katako. About 50% are slightly acidic or almost neutral pH (6.5 to 6.95) and 25% are neutral or weakly basic pH (7.6 to 7.94).

Turbidity is an indicator of the content of organic and/or mineral particles suspended in the water. In general, these materials are very small particles such as debris of lithospheric origin, plant residues or micro-organisms. The turbidity results of the sampled borehole water are presented in [Table 2](#) and figure 3. About 81% (being 13) of the samples have a turbidity index below 5 NTU ([Fig 3b](#)). The 19% are represented by samples from the Katako (Niamey), Gorou-Banda (Niamey) and Kodo (Dosso) rural areas with 81, 82 and 292 NTU respectively. These high index values indicate that the water contained are unfit to consummation. Combining the figure 3a and 3b it appears clearly that there is no dependency between pH and turbidity of borehole waters. This is due to the fact that the water turbidity is defined by suspended particle matters while the pH is determined by soluble matters (anions and cations).

**Table 2:** Physical and chemical parameters of water samples collected from 16 boreholes in the urban community of Niamey Niger and its

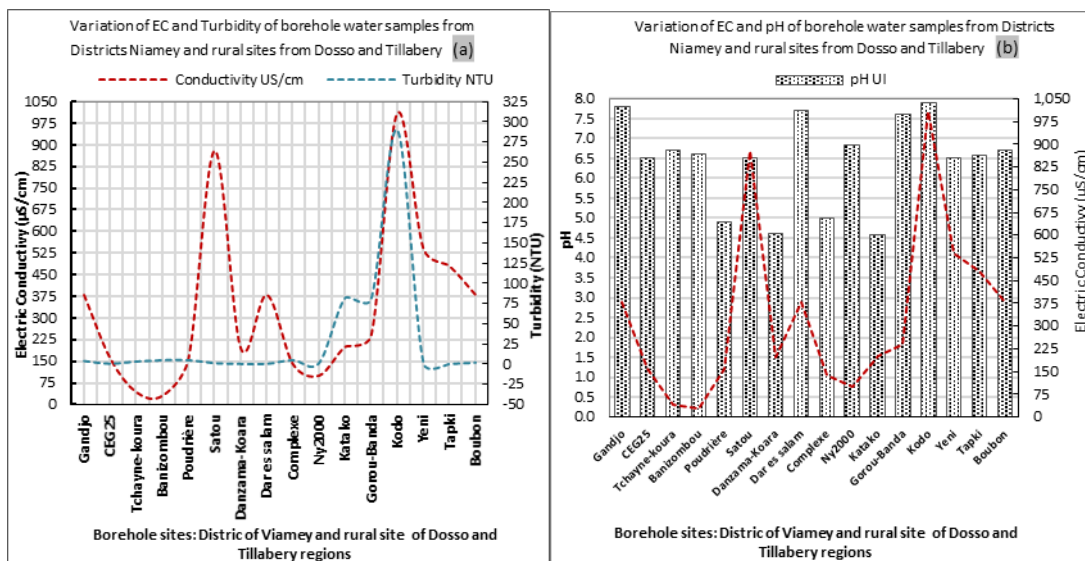
Hydrochemical Properties	Units	Urban area of Niamey - Districts											Dosso-rural		Tillabery-rural		WHO Values	Guide
		Gan djo	CE G25	Tchi ni-Kou ra	Bani-Zom bou	Pou dr ière	Sat ou	Danzama-Koara	Dar-es Sala am	Comp lexe	Niam ey-2000	Kat ako	Gor ou-Ban da	Ko do	Yen i	Tapki		
pH	UI	7,8	6,5	6,7	6,6	4,9	6,5	4,6	7,7	5,00	6,85	4,59	7,62	7,9	6,50	6,57	6,70	6.5 and 9.5
Electric Conductivity (EC)	µS/cm	380	160	42,6	30	160	880	196	380	140	100	200	240	1010	540	480	380	1,600 µS/cm
Turbidity	NTU	4	0,6	3,4	5	5	1,3	0,3	0,4	5	1,4	82	81	290	1,3	0,3	2	Not mentioned (WHO) 5 NTU
HCO <sub>3</sub> <sup>-</sup>	mg/L	92	12	8	30	30	380	3,7	150	63	28	30	31	30	152	3,7	150	NA
Cl <sup>-</sup>	mg/L	13	6,5	0,1	8	0,1	35	19	8	7	4	20	46	0,1	23	19	8	PN, but a taste can be noted from 250 mg/l
SO <sub>4</sub> <sup>-2</sup>	mg/L	19	4	0	1	4	8	6	7	3	0.08	1	9	4	18	6	7	500 mg/l
F <sup>-</sup>	mg/L	0,3	0	0	0	0	0,31	0,19	0,19	0	0	0	0,12	0,12	0,56	0,19	0	1.5 mg/L
NO <sub>3</sub> <sup>-</sup>	mg/L	60	1,5	56	8,8	95	29	150	0,34	70	0	100	30	180	29	8	4,34	<ul style="list-style-type: none"> <li>50 to 3mg/L (short-term exposure –</li> </ul>
NO <sub>2</sub> <sup>-</sup>	mg/L	23,5	0,002	14,1	0,008	49,1	0,01	50	0,001	20,5	0,001	50	9,5	36	0,01	0,08	0,022	<ul style="list-style-type: none"> <li>0.2 mg/l long-term</li> </ul>
Na <sup>+</sup>	mg/L	12	6,3	4	3,5	4	26	12	10	2,5	7	60,5	30	4	26	12	11	<ul style="list-style-type: none"> <li>0.5 mg/L</li> </ul>
K <sup>+</sup>	mg/L	4	1,4	6	1	1,4	3,8	0,023	1,4	1,4	0	4,00	9,5	1,4	3,8	0,023	1,7	No NES guideline: < 20 mg/l
Ca <sup>2+</sup>	mg/L	22	1,6	6,8	7,5	8	72	13	18	7	11,5	72	5,4	8	72	13	24	
Mg <sup>2+</sup>	mg/L	8,2	1,2	2,5	3,5	2,5	31	1,2	16	3,4	3,9	38	2,9	2,5	7	1,2	3,6	
Fe <sup>(2+)</sup>	mg/L	0,063	0,012	0,2	0,053	0,06	0,067	0,12	0,01	0,039	0,031	0,053	0,7	0,06	31	2,12	0,4	No. Value
Mn <sup>2+</sup>	mg/L	0,2	0,02	0,3	0,3	0,5	0,3	0,12	0,1	0,04	0,1	0,3	0,8	0,5	0,3	0,12	0,1	0.4 mg/L



**Figure 3:** (a) Variation in pH and turbidity of borehole water from the different sampling sites in Niamey and surrounding rural areas (b) Sites with Turbidity < 5 NTU. The figure shows no relationship between the pH and the Turbidity of boreholes waters.

### 3.1.2. Electric Conductivity

Electrical conductivity measures the ability of water to conduct an electric current. The higher the concentration of dissolved charged chemicals (known as salts) in the water, the greater the electrical current that can be conducted. Naturally charged ions capable of influencing the electrical conductivity of water include sodium ( $\text{Na}^+$ ), potassium ( $\text{K}^+$ ), calcium ( $\text{Ca}^{2+}$ ), magnesium ( $\text{Mg}^{2+}$ ), chloride ( $\text{Cl}^-$ ), sulphate ( $\text{SO}_4^{2-}$ ) and nitrate ( $\text{NO}_3^-$ ). Assay results from all 16 boreholes water samples are shown in Table 1. Data of EC are compared with the turbidity and pH as shown by the figure 4. About 88 % of borehole water samples are characterized with EC comprised between 30  $\mu\text{S}/\text{cm}$  and 500  $\mu\text{S}/\text{cm}$ . These values comply with the standard defined by the WHO, which is estimated to be a maximum of 1,600  $\mu\text{S}/\text{cm}$  (Table 2). Those with EC ranged between 500 and 1010  $\mu\text{S}/\text{cm}$  are located in the new district of Satou (880  $\mu\text{S}/\text{cm}$ ), the rural zones of Kodo (1010  $\mu\text{S}/\text{cm}$  and Yeni (540  $\mu\text{S}/\text{cm}$ ) in the region of Dosso. All samples (Poudrière, Dan Zama-Koara, Complexe and Katako) with high acidities (< 5) have EC varying between 140 and 200  $\mu\text{S}/\text{cm}$  (Fig. 4b). The borehole sample from the district of Satou is characterized by low turbidity (5 NTU) and high EC (880  $\mu\text{S}/\text{cm}$ ) while the sample from Kode has the highest turbidity index (292 NTU) and EC (1010  $\mu\text{S}/\text{cm}$ ). In the case of sample from the district of Katako, although the index of turbidity is high, the EC remain relatively low. These observations show that the physicochemical properties of boreholes are different therefore, the sources of aquifers and contaminations (natural or anthropogenic) are also different.



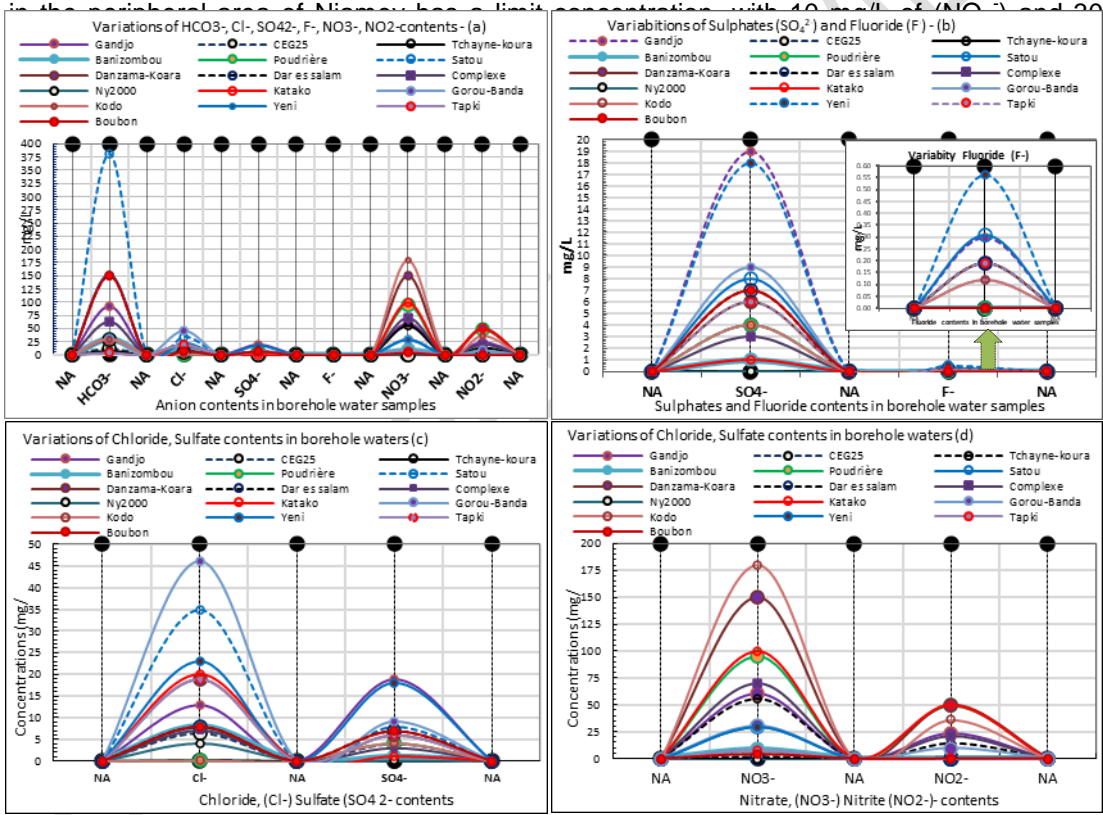
**Figure 4:** Variabilities of the electric conductivity (EC) of borehole water samples from different district in the urban areas of Niamey and its surroundings rural areas in the regions of Tillabery and Dosso. (a): figure 4a shows a comparison between EC and the turbidity and clear show the differences in water particulate matter contents (b): the figure allows to compare the EC and pH of samples. It indicated a relative low EC value for borehole water samples characterized with high acidifies.

### 3.1.3. Variations of Anions ( $\text{HCO}_3^-$ , $\text{Cl}^-$ , $\text{SO}_4^{2-}$ , $\text{F}^-$ , $\text{NO}_3^-$ and $\text{NO}_2^-$ ) contents in borehole waters

Data of major anions determined are shown in Table 2 and represented by the figure 5. The bicarbonate ( $\text{HCO}_3^-$ ), nitrates ( $\text{NO}_3^-$ ), nitrites ( $\text{NO}_2^-$ ) and chlorides ( $\text{Cl}^-$ ) are dominantly contained in most of samples (Fig. 5a). In contrast, sulphates ( $\text{SO}_4^{2-}$ ) and fluorides ( $\text{F}^-$ ) are relatively low contained (Fig. 5a and 5b). For bicarbonate ( $\text{HCO}_3^-$ ), about 63% of samples have a concentration between 3 mg/L and 50 mg/L, 25% contain between 50 and 200 mg/L and only 2% have a concentration of 380 mg/L. The highest concentrations were determined from the sites in the districts of Satou (380 mg/L), Dar Es Salaam (150 mg/L), the rural zones of Boubon (150 mg/L) and Yeni (152 mg). The districts of Gandjo and Complexe sites indicate concentrations of 92 mg/L and 63 mg/L respectively.

Chlorites ( $\text{Cl}^-$ ) contents range from 0.1 mg/L to 46 mg/L (Table 2). In the urban area of Niamey, the highest levels were found at Gorou-Banda (46mg/L), Satou (35 mg/L), Katako (20 mg/L), Dan Zama Koara (19mg/L) and Gandjo (13 mg/L). In rural areas, the highest concentrations were found at Yeni (23 mg/L) and Tapki (19 mg/L). the lowest concentration (0.1 mg/L) was obtained in Tchini-Koura, Poudrière and Kodo. For the other sites, these concentrations range from 4 mg/L to 8 mg/L (Table 2). Approximately 88% of the samples contain less than 10 mg/L sulphate, 25% with less than 1 mg/L. Concentrations of 19 mg/L and 18 mg/L were determined from the Gandjo and Yeni sites respectively (Fig. 5b-c). All these concentrations are largely below the WHO limit standard (500mg/L). Fluoride ( $\text{F}^-$ ) contents are very low and ranges in between 0 mg/L and 0.56 mg/L (Table 2; Fig. 5a-b). About 50% of samples contain less than 0.1 mg/L. The borehole sites of Gandjo and Satou (Niamey) are characterized with concentrations of 0.31 mg/L. The highest concentration (0.56 mg/L) was determined in the rural area of Yeni (Fig. 5b). Fluoride contents of borehole waters are below the WHO limit (1.5 mg/L), therefore do not pose a health risk to populations. According to Table 2; nitrate ( $\text{NO}_3^-$ ) concentrations ranged from 0mg/L to 180

mg/L. Approximately 56% of samples (9) have less than 30 mg/L and 44% (7) have a content greater than 50 mg/L. Drilling sites in the Poudrière District (95 mg/L), Dan Zama-Koura (150 mg/L), Katako (100 mg/L) and Kodo (180 mg/L) have nitrate concentrations 2 to 3 times higher than the WHO limit (50 mg/L) (Fig. 5d). It should be noted that the sites in the Katako and Kodo neighborhoods are centers of intense commercial activity. The localities of Gandjo (60 mg/L), Tchini-Koura (56mg/L) and Complexe (70mg/L) are either old districts or old villages, recently integrated into the urban area of Niamey. The nitrite (NO<sub>2</sub>-) concentrations in the drilling water samples range from 0.001 mg/L to 50 mg/L. It can be noted that these same 7 sites with higher nitrate concentrations also have nitrite levels above the WHO limit standard (10 mg/L NO<sub>2</sub>-) (Table 2; Fig. 5d). Very high concentrations of NO<sub>2</sub>- (50 mg/L) corresponding to 5 times the WHO limit standard were determined from sites in the district of Poudrière, Dan Zama-Koara and Katako (Table 2). Borehole waters in the Gandjo, Tchini-Koura, Complexe (Niamey) and Kodo (Dosso region) districts are characterized by concentrations ranging from 14 mg/L to 36 mg/L and are above the standard. Sites in CEG\_25, Banizombou, Satou, Niamey\_2000, Dar es Salaam, Tapki and Boubon districts are characterized by very low nitrite levels (Fig. 5d). The Gorou-Banda site,



**Figure 5:** Variabilities of anions contents of borehole water samples from different district of the urban areas of Niamey and its surroundings rural areas located in the regions of Dosso and Tillabery. (Figure 5a shows a clear predominance of bicarbonates, nitrates, nitrites and chlorites. Figure 5b highlights water contents of low concentrated sulfates and fluorides<sup>-</sup> anions. Figure 5c highlights the chlorites compared to sulfates. Nitrates and nitrites contents are represented by figure 5d and shows the relative dominancy of anion nitrates in most of samples.)

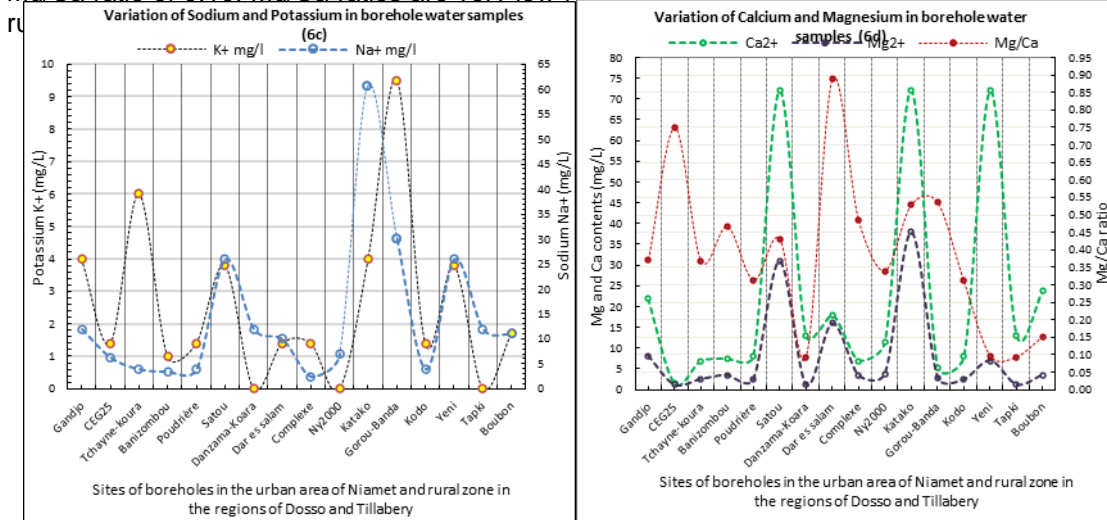
### 3.1.4. Variations of major cations ( $\text{Na}^+$ , $\text{K}^+$ , $\text{Ca}^{2+}$ and $\text{Mg}^{2+}$ ) contents in borehole waters

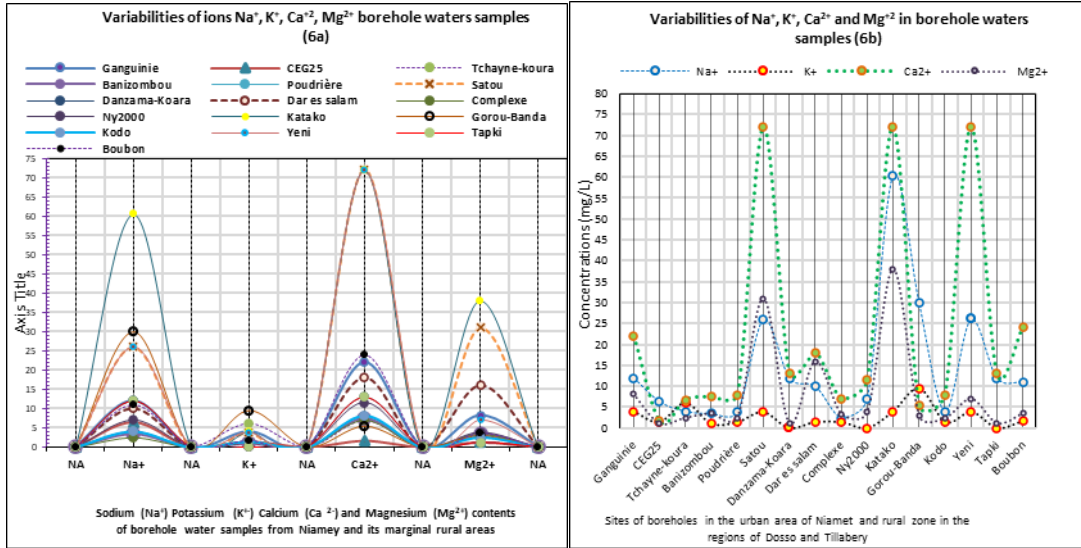
#### a. Sodium ( $\text{Na}^+$ ) and Potassium ( $\text{K}^+$ )

Sodium is widely contained in borehole water at varying concentrations depending on the site (Fig. 6a-b). About 44% of the samples have a low concentration comprised between 3.5 and 9.9 mg/L. 50% of the samples have between 10 and 30 mg/L and only 6% (1) are defined with 60.5 mg/L. Katako, Satou and Gorou-Banda sites in Niamey concentrate 60.5 mg/L, 26 mg/L and 30 mg/L respectively, while the majority of the city's drilling waters have levels below 8 mg/L except for Gandjo (12 mg/L), Danzama Koara (12 mg/L) and Dar es Salam (10 mg/L). Dosso region, highest concentration is 26 mg/L at Yeni. The Kodo site in the same region has a concentration of 4 mg/L. For the Tillabery sites, these concentrations are 12 mg/L and 11 mg/L respectively for the Tapki and Boubon wells. These values are however low to affect the taste (200-300 mg/L) of these waters. Potassium concentrations are generally low in all samples analyzed, ranging from 0 to 9.5 mg/L. Approximately 63% have less than 2 mg/L, 31% of the samples contain between 3.5 and 6 mg/L and 6% with 9.5 mg/L. The latter value was determined from the site of Gorou-Banda. As sodium, these values are very low to affect water quality. By comparing  $\text{Na}^+$  and  $\text{K}^+$  contents, only a few sites show very significant deviations where potassium is more contained than sodium in waters (Fig. 6b).

#### b. Calcium ( $\text{Ca}^{2+}$ ) and Magnesium ( $\text{Mg}^{2+}$ )

Calcium and magnesium are essential Hydrochemical constituent's characteristic of groundwater. The results of the borehole water analyses indicate highly variable concentrations of both cations depending on the site (Table 2, Fig. 6a, 6d). A predominance of  $\text{Ca}^{2+}$  in comparison with  $\text{Mg}^{2+}$  is observed in all samples (Fig. 6d). The majority of samples (81%) are characterized by contents ranging from 1.6 to 24 mg/L. The highest contents (72 mg/L) were determined in the urban area of Niamey at districts of Satou, Katako and the rural area of Yeni (Fig 6d).  $\text{Mg}^{2+}$  contents range from 1.2 mg/L to 38 mg/L. The highest levels are determined from the same borehole water samples of Satou (31 mg/L) and Katako (38 mg/L) in Niamey. The ratios  $\text{Mg}/\text{Ca}$  are 0.43 and 0.53 respectively for the sites of Satou and Katako. However, we observe that the site in Yeni contains relatively low  $\text{Mg}^{2+}$  (7 mg/L) with  $\text{Mg}/\text{Ca}$  ratio of 0.10. **Mg/Ca ratios are very low ( $< 0.2$ ) for borehole water samples from most**



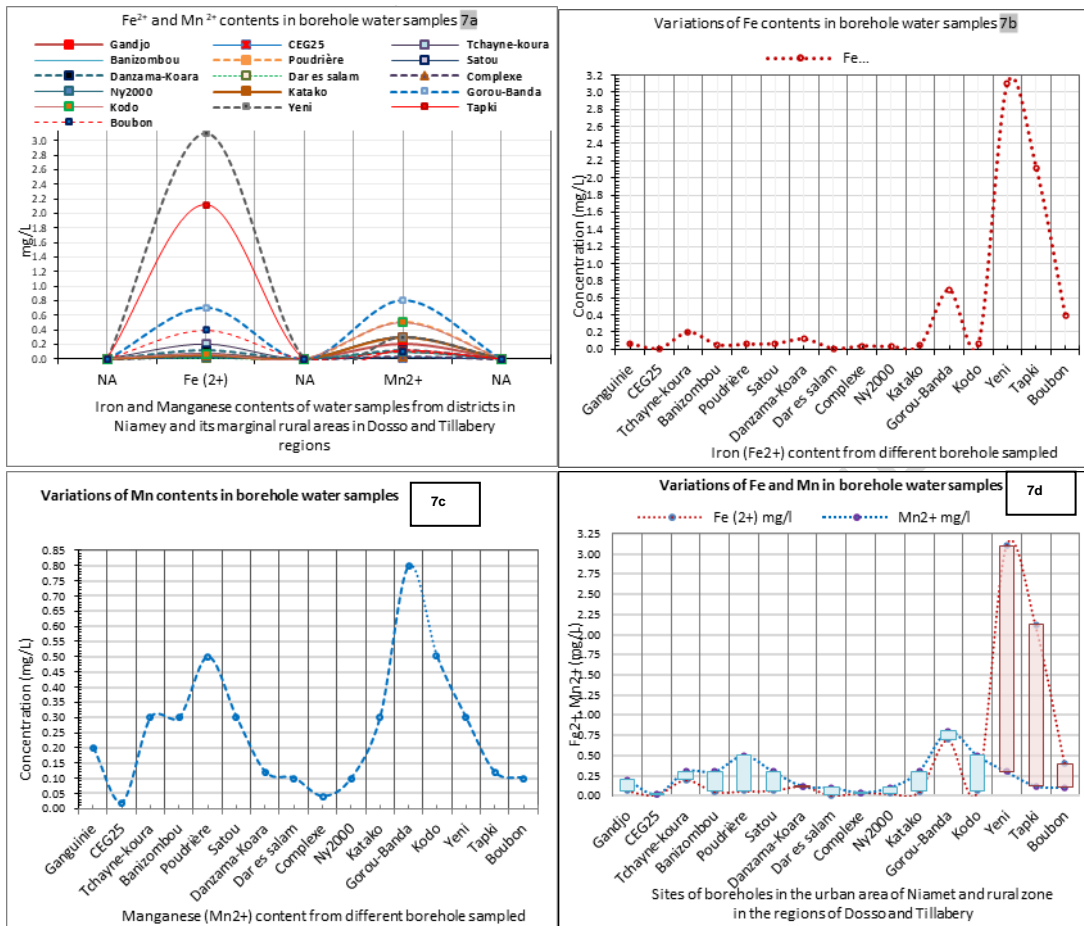


**Figure 6:** Variations of Sodium, Potassium, Calcium and Potassium contents in borehole water samples from the urban area of Niamey and its marginal rural areas located in Tillabery and Dosso regions (Fig. 6a). [Fig. 6a highlights the water contents of cations. Fig. 6c shows variations of Na and K of borehole waters. Fig 6d shows the variations in Ca, Mg contents and (Mg/Ca) ratios indicating differences of the elemental sources]

### 3.3.3. Variations iron ( $Fe^{2+}$ ) and manganese ( $Mn^{2+}$ ) contents in borehole waters

This study is limited to iron ( $Fe^{2+}$ ) and manganese ( $Mn^{2+}$ ), as usually determined for groundwater quality assessment, although other heavy and hazardous metals impacting human health may interfere. L'analyse élémentaire par absorption atomique a permis d'obtenir les résultats dressés dans le tableau 2. Figure 7a shows that iron can be contained in water in much higher quantities than manganese. However, for lower Fe contents, manganese contents are higher than iron (Fig. 7d).  $Mn^{2+}$  contents is higher in all borehole water samples located in the districts of Niamey. In the rural areas only the sample from Kodo (Dosso) has Mn content higher than Fe. The question is whether there is contamination of groundwater by human activities or is it a process of pedogenesis?

The statistical analyses indicate that, about 75% of the samples have iron concentrations ranged between 0.06 mg/L and 0.3 mg/L. Approximately 12.5% have concentrations varying between 0.3 and 1 mg/L and 12.5% have Fe-contents ranging from 2mg/L to 3mg/L. The Gorou-Banda site, on the outskirts of Niamey and Boubon (Tillabery) contain slightly high Fe concentrations of 0.7 mg/L and 0.4 mg/L respectively (Fig. 7b) to affect water color. The highest Fe-contents are determined from samples collected in the rural area of Yeni (Dosso region) and Tapki (Tillabery region) with 3.1 mg/L and 2.2 mg/L respectively. A more plausible explanation for such high concentrations may be the that, sites are located on lateritic plateaus, whose subsoils are made up of ferruginous rocks.  $Mn^{2+}$  concentrations vary between 0.1 mg/L and 0.8 mg/L depending on the sites. In the urban area of Niamey, the districts of Poudrière and the peripheral site of Gorou Banda are characterized by contents of 0.5 mg/L to 0.8 mg/L respectively. From the rural areas of Kodo (Dosso) a concentration of 0.5 mg/L is obtained. The comparative figure 7d, shows that 5 of the



**Figure 7:** Fe<sup>2+</sup> and Mn<sup>2+</sup> from borehole water samples collected in the urban Niamey and its marginal suburban areas in the regions of Dosso and Tillabery Niger. (Fig. 7a shows Fe and Mn variations with high Fe contents in few rural samples. The figure 7b highlight Fe<sup>2+</sup> contents from site located on lateritic basements. Fig. 7c show the relatively high Mn<sup>2+</sup> contents in groundwater. Figure 7d shows differences in Mn and Fe contents in the urban and rural groundwaters. The figure shows a predominance of Mn in all districts of Niamey and exceptionally the rural Kodo. Fe-content is more contained in borehole waters of Yeni, Tapki and Boubon.)

### 3.2. DISCUSSIONS

Environmental degradation, related to the poor management of solid waste, sanitaires in rural areas, followed by agricultural practices with abusive uses of chemical fertilizers and pesticides in the rural zones, have contributed significantly to negatively impacted the hydrochemical and biological quality of surface- and groundwaters. One of the consequences among many others is the increase in turbidity and chemical constituents dangerous to living organisms. Turbidity is the quantity of particulate matter suspended in water and is caused by organic and inorganic substances, such as: clay, sludge sediments,

fine-grained organic and inorganic materials, a mixture of soluble organic colors, and micro-organisms e.g. [23;24;25;26]

a. *The pH of borehole waters:*

The pH is an important indicator of water quality. The result of analyses (Table 2, Fig. 3) indicates that 25% of samples have pH neutral or slightly basic (7.6 to 7.94). About 50% have pH slightly acidic and comprised between 6.5 and 6.95. In sum, 75% are in range of the recommendation of drinking water pH stated by [27] that is in between 6.5 and 9.5. Very acidic borehole water samples are determined from the districts of Poudrière (4.9), Dan Zama Koara (4.6), Complexe (5) and Katako (4.59). These sites of old districts located in the urban area of Niamey and characterized by high density of settlements. These districts are also places of intense urban activities and transport traffic. According to [28;29;30], acidic water can occur naturally, coming from highly dissolved oxygen levels induced by rainfall or tree roots and soil microbes that produce acids and emit carbon dioxide. Furthermore, [31;32] suggested that the natural pH of groundwater not affected by human activities should be at least 4.5. The acidic samples (pH 4.5 and 5) have the highest nitrate and nitrite contents (Fig. 5a, 5d). Groundwater contamination can mainly come from the poor management of solid organic waste and latrines directly in contact with sandy soils typical of this region facilitating the infiltration of water pollutants [33;34;35]. Previous studies have shown that the pH of groundwater can be influenced by the environment (rural, urban, agricultural) in which drilling is located [7;8;33;35]. Acidic groundwater may promote the mobility of elements such as Al, Mn and other toxic metals and make the waters unfit for drinking [36; 37]. In addition, recent studies have proven that acidic groundwaters are linked to the presence of heavy metals such as: Pb, As, Cu, Ni, Cd, Cr and Zn. The use of acidic groundwaters for agriculture can also lead to serious poisoning through the products [6;14;37]. The study of [6] leads in the area of Gountou Jena indicated that vegetable such as lettuce and tomatoes can adsorb heavy metals released into groundwater used for cultivation. Our results are in agreement with the presence of high levels of metal ( $Mn^{2+}$ ) contents in samples from Poudrière, and Katako (Table 2, Fig. 7c and 7d). The most significant risks are environmental. In fact, it has been also suggested that acidification of groundwaters may affect plants, vegetation and infrastructure [36;37]. Acidification of groundwater may impact the geochemical equilibrium in soils and aquifers [36,38,39,40]. According to [41], acidic waters are not a priori forbidden for human consumption, but this acidity gives them a greater corrosive property than cement or pipe metals. However, studies lead by [42,43] reported that an exposure to heavy metals in groundwaters can be dangerous to human health. The consumption of acidic water, as is the case here for borehole waters of Poudrière, Dan Zama Koara, Complexe and Katako, may induce to gastric disorders according to [44]. Therefore, the trade and consumption waters (in sachets or bottles) from these acidic borehole sites expose the populations of the agglomeration to a high risk of poisoning. The acidification of groundwater by infiltration of organic and inorganic pollutants must call for better management of solid and liquid waste in urban environments. By controlling the pH of water from drilling, we can avoid consuming water that is harmful to health.

b. *Groundwater turbidities and risk implications*

Turbidity is the quantity of particulate matter suspended in water and is caused by organic and inorganic substances, such as: clay, sludge sediments, fine-grained organic and inorganic materials, a mixture of soluble organic colors, and micro-organisms e.g. [27, 45,46]. In this study, the highest turbidity index was determined from samples the sites of Katoko (Niamey), Gorou-Banda (suburban) and Kodo (Dosso region) with values varying from 82, 81, to 290 NTU, respectively (Fig.3a, 3b). These values are well above the standard limit (5 NTU) fixed by the [18]. Except the latter sites, all boreholes analyzed, the turbidity of the water varies between 0.3 and 5 NTU (Fig. 3b) and is well within the WHO standard. According to

[47], turbidity itself does not always represent a direct risk to public health. However, it can be due to the presence of minerals, organic matters, pathogenic microorganisms (bacteria, fungi, etc.) thereby, an effective indicator of dangerous events. In the same way, [18] suggests that studies are emerging to demonstrate an increasing risk of gastro-intestinal infections that correlates with high turbidity and turbidity events in distribution. The borehole waters (> 5NTU) in this study may contain high rates suspended matters and makes them unsafe for consumption. The types of illnesses commonly associated with the consumption of turbid water are mainly gastrointestinal infections caused by bacteria such as E. Coli and viruses that cause severe diarrhea, infections and vomiting [5; 18].

#### c. Electric conductivity (EC)

According to [18], there is a clear structuring of EC and depth to the water-table in the area of study. The deepest wells (15–30 m) have relatively low EC (36–340  $\mu\text{S cm}^{-1}$ ), whereas shallow wells (5–15 m) show high and variable EC values (36–1617  $\mu\text{S cm}^{-1}$ ). The majority of samples analyzed has an EC value comprised between in 30 and 480  $\mu\text{S/cm}$  (Table 2, Fig 4). According to [17, 47] low EC values (45 to 46  $\mu\text{S/cm}$ ) are characteristics of deep groundwater and are less affected by the surface runoff. The two representative sites are Tchini Koura and Banizombou and the area are only recently inhabited. The boreholes containing shallow water table have an EC value comprised in between (36–1617  $\mu\text{S cm}^{-1}$ ). Since the water table is shallow, it can be easily contaminated by infiltration of anthropogenic pollutants from sanitary waters, latrines but also runoff from urban waste storage (waste solid or liquid organic matters) areas e.g. [7;8]. According to [7;14;48;49], pollution resulting from human activities due to the storage of urban waste and agricultural fertilizers in rural areas is an important factor that induces fluctuations in the electrical conductivity of groundwater. The EC-values, ranged in between 100 to less than 500  $\mu\text{S/cm}$  indicate that, these waters are weakly mineralization [14;18]. The mineralize waters have an EC ranged in between 500 to more than 1010  $\mu\text{S/cm}$  (Fig. 4a). EC and pH are not correlated in all cases. However, on observe que acidic waters exhibit low EC-values. It is therefore a factor in predicting and reducing the risk of intoxication. The analysis of variation between EC and turbidity shows that there is a relativity between the samples from the Katako, Gorou-Banda and Kodo boreholes. The Gorou Banda site is very sparsely populated compared to the Katako and Kodo sites which represent areas of strong anthropogenic activity, so it is likely that the lithological conditions play a significant role in the determination of the EC. Geology, soil type, and geochemistry are the main natural factors that control the electrical conductivity of groundwater [50]. In addition, rainwater runoff and its infiltration into the water table can carry chemicals along its paths and influence electrical conductivity. As water passes through the calcareous layers, it dissolves magnesium calcium carbonate, which increases electrical conductivity [51]. The residence time of water in rocks and soils has an impact on electrical conductivity e.g. [52;53].

#### d. Bicarbonate ( $\text{HCO}_3^-$ )

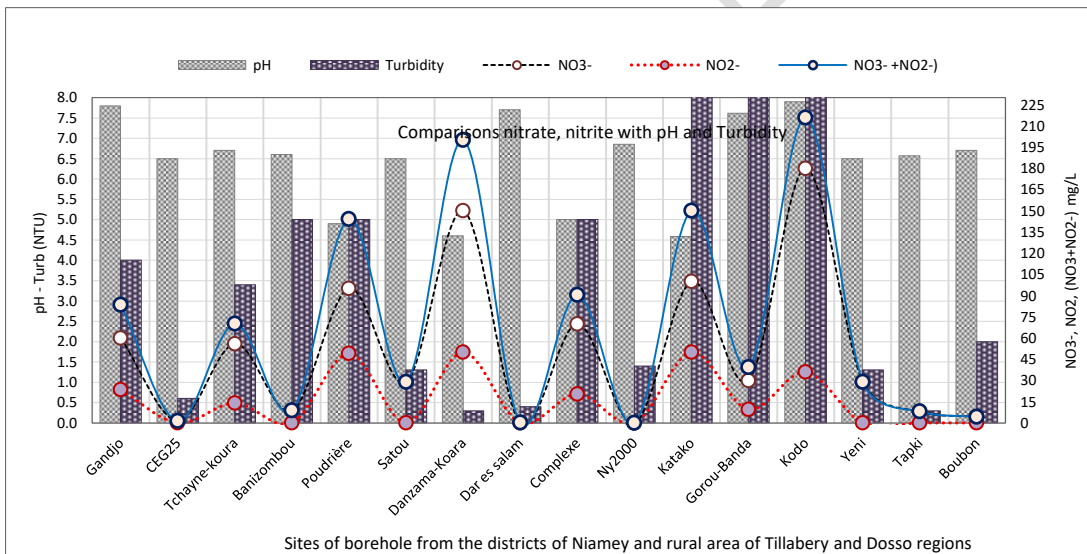
The alkalinity of water is a crucial factor in maintaining the stability of its pH. It is mainly influenced by the presence of the conjugate bases of inorganic carbon ( $\text{HCO}_3^-$  and  $\text{CO}_3^{2-}$ ) and organic acids (-COOH), as well as orthophosphate ( $\text{H}_2\text{PO}_4^-$ ,  $\text{HPO}_4^{2-}$  and  $\text{PO}_4^{3-}$ ), ammonia, silicate, as well as  $\text{OH}^-$  ions [54]. Figure 5 (a and b) shows the predominance of  $\text{HCO}_3^-$  contents. Bicarbonates contribute to the buffering capacity of the water against changes in pH levels [55; 56]. Bicarbonate ( $\text{HCO}_3^-$ ) contributes to reduce large pH swings that can compromise water quality [54]. The samples analyzed indicate relatively high concentrations of  $\text{HCO}_3^-$  for the sites in the Satou district (380 mg/L), Dar Es Salaam (150 mg/L), and the rural areas of Boubon (150 mg/L) and Yeni (152 mg). These values are indicative of the presence of carbonate rock (e.g. calcite, dolomite), carbonate salts (e.g.

halite, gypsum). According to <sup>[54]</sup> the CO<sub>2</sub> stored after infiltration under the action of rainwater facilitated by permeable soil layers. There is no limit value defined by the WHO.

e. Nitrate (NO<sub>3</sub><sup>-</sup>) and Nitrite (NO<sub>2</sub><sup>-</sup>):

An excessive nitrate in drinking groundwater has been reported to cause various health complications, including abortions, blue baby syndrome, increased risk of methemoglobinemia and gastric cancer, damage to stomach lining, mouth ulceration, and reproductive damage <sup>[57; 58]</sup>. The <sup>[59]</sup> sets a limit value of 50 mg/l for nitrate and 3g/L for short term exposures. In long term exposure the limit value is only 0.2 mg/L. An excessive exposure to nitrates or nitrites can also lead to acute acquired methemoglobinemia, also known as blue disease, a blood abnormality that causes the blood to lose its ability to carry oxygen to the tissues (anoxia). This is particularly dangerous in infants under 4 months of age e.g. <sup>[60]</sup>. This disease can mainly affect pregnant women <sup>[58]</sup>. In this study, the nitrate (NO<sub>3</sub><sup>-</sup>) contents of seven (7) boreholes indicates high nitrate values than 50 mg/l (Table 2; Fig. 5a; 5d). The borehole located in the districts of Poudrière, Dan Zama-Koura, Katako and the boreholes in the rural commune of Kodo (Dosso region) have concentrations almost 2 to 3 times higher than the limit standard set by the WHO (50mg/L). It should be noted that the sites of the Katako and Kodo districts have the same particularity of being centers of intense commercial activities. Based on the studies made by <sup>[7;8;18]</sup>, it can be suggested that the high contents of nitrate and nitrite in urban areas are the result of the contamination by the sewages, septic tanks and latrine uses that are still at a rudimentary stage for domiciles situated in old districts. In rural areas, where there are virtually no septic tanks, the use of latrines or in the nature is common. This is compounded by weeding and poor agricultural practices through the intensification of mineral fertilizers <sup>[16;17;61]</sup>. The sites in the new districts of Gandjo and Tchini-Koura on the outskirts of the city of Niamey are located in the same area and indicate values slightly above the norm. According to <sup>[49]</sup>, the consumption of water from these 5 boreholes has very negative impacts on human health in the short term. Water from boreholes located in the districts of Niamey (CEG\_25, Banizombou, Cité Satou, Gorou-Banda) and those in rural areas; Tapki and Boubon (Tillabery region) show acceptable values (1.5 mg/L to 30 mg/L) in accordance with the WHO standard. However, these waters can have long-term negative effects <sup>[37]</sup>. Extremely low values of nitrate are observed from sites in the districts of Dar es Salaam (0.34 mg/L) and Niamey 2000 (0 mg/L) districts. The nitrite (NO<sub>2</sub><sup>-</sup>) levels of these same borehole water samples vary between 0.001 mg/L and 50 mg/L. It can be seen that the 7 sites with concentrations above the WHO limit standard (10 mg/L) also correspond to the same boreholes with levels above 50 mg/L in NO<sub>3</sub><sup>-</sup> (Fig. 5a and 5b). The highest concentrations of nitrite (Fig. 5a) corresponding to 5 times the WHO limit standard, were determined from the sites in the Poudrière, Dan Zama Koara, and Katako districts. The boreholes in the districts of Ganguinie, Tchini-Koura, Complexe and Kodo (Dosso region) have concentrations ranging from 14 mg/L to 36 mg/L and do not comply with the standard. The sites in the CEG\_25, Banizombou, Satou, Niamey\_2000, Dar es Salaam, Tapki and Boubon districts are characterized by very low nitrite levels. The Gorou-Banda site in a suburban area has a limit concentration of 10 mg/L (NO<sub>2</sub><sup>-</sup>) and 30 mg/L of NO<sub>3</sub><sup>-</sup>, so it is within the defined limit standard. According to the <sup>[61]</sup>, nitrate and nitrite are more common in groundwater than in surface water, and are two of the most frequently detected groundwater contaminants. The nitrate content of groundwater and surface water is normally low <sup>[62]</sup>. The natural nitrate concentrations in aquifers dependent on the soil and rocks geochemistry <sup>[52;62]</sup>. Soil bacteria can contribute by reducing various forms of nitrogen into nitrate, which is a desirable process, as most of the nitrogen used by plants is absorbed as nitrate <sup>[60;63]</sup>. Nitrates are very leachable and infiltrate very easily in to groundwater <sup>[64;65]</sup> leading to their pollution. Nitrates are also formed by the oxidation of organic waste by the action of nitrogen-binding bacteria <sup>[66]</sup>. According to <sup>[67]</sup>, the largest source of nitrogenous compounds is human and animal wastes, industrial and agricultural activities. For example, long-term storage and poor management of urban waste can be a major source of nitrate

pollution. The highest levels of nitrate and nitrite contamination are found in shallow aquifers that are easily polluted by wastewater from latrines in urban centers and in cultivation sites by fertilizer application, particularly in rice fields and other crop sites of economic interest [16; 17; 18; 19; 20]. In addition, detectable levels of nitrite in the water indicate bacterial contamination e.g. [17]. Based on this last observation, we can suggest that our samples may contain bacteria. The present study is in agreement with the study made by [16;17; 19]. The authors shown that most of aquifers in Niamey and its surroundings are polluted by nitrates. This pollution is the result of unregulated urbanization with the construction of artisanal latrines and deforestation in suburban areas. It has been shown that in rural areas near Niamey, deforestation to meet the city's needs for wood is the source of high nitrate levels in aquifers [17; 19]. In view of these results, the populations living in the Niamey agglomeration and its surrounding rural areas are exposed to serious dangers due to the pollution of the aquifers consumed. A comparison with pH and the turbidity shows that the nitrate-nitrite contents in borehole water samples do not depend on the turbidity (Fig. 8). However, we found that nitrate and nitrite contents are higher while the pH of water is acidic except in the case sample from Kodo characterized with high turbid index (292). Therefore, nitrate-nitrite rich water could be easily detected simply by determining the pH at low cost.



**Figure 8.** Comparative analyses of nitrate-nitrite contents in borehole water from the urban area of Niamey and its marginal rural areas located in the regions of Dosso and Tillabery.

The figure show that nitrate and nitrite contents are higher in very acidic water independently to their turbidities. An exception is made the borehole water samples from Kodo in Dosso region with a turbid index of 292 NTU

#### f. Chlorites

According to the <sup>[18]</sup>, chloride salt concentration above 250 mg/L can produce a distinct (salty) taste in drinking water. In addition, an increase in chloride concentrations can indicate pollution from wastewater sources <sup>[60]</sup>. The variations of chloride contents in borehole water samples of this study are shown in [table 2](#) and [figure 5a-c](#). The concentrations obtained vary depending on the site, between a minimum of 0.1 mg/L (for Tchi-Koura) and a maximum of 46 mg/L (for Gorou-Banda). All sites have values less than 250 mg/L, indicating that none of these boreholes have a salty taste and do not constitute a major risk to human health. It has been noted that hypertension associated with sodium chloride (Na-Cl) consumption appears to be related to sodium ions (Na+) and not to chloride ions <sup>[68]</sup>. Chlorides are naturally contained in borehole water or from pollution induced by the poor management of industrial or domestic waste <sup>[18]</sup>. High chloride salt contents in groundwater can affect the suitability of water for human consumption both because of the effects of the salts on the taste of water which directly or indirectly affect human health <sup>[69;18]</sup>. Contamination with chloride salts can also reduce the suitability of soil and irrigation water for agricultural use <sup>[69]</sup>.

#### g. The sulphate (SO<sub>4</sub><sup>2-</sup>) contents

The <sup>[43]</sup> in sanitary standard for drinking water quality limit the sulfate concentration less than 250 mg/L. Sulphate ions (SO<sub>4</sub><sup>2-</sup>) are very little contained in the boreholes water samples from the in Niamey and nearby rural sites ([Table 2](#); [Fig. 5b-c](#)). These results are in accordance with <sup>[16]</sup> suggesting that sulphate is found in small amounts in groundwater. Our data shows that, SO<sub>4</sub><sup>2-</sup> contents vary from a minimum of about 0 mg/L to a maximum of 19 mg/L ([Fig.5c](#)). The lowest values were determined in water samples from the urban area of Niamey, while those from sites in suburban areas are relatively higher. Sulphate contents in the water from investigated boreholes does not present a risk for the population.

#### h. Fluorides (F<sup>-</sup>).

Fluoride is one of the major pollutants in groundwater and one of the prime concerns of the world population due to its toxicity, which results in adverse health impacts <sup>[70;71;72;73]</sup>. According to the <sup>[43]</sup>, the permissible limit for fluoride concentration in groundwater is < 1.5 mg/L. An increasing amount of fluoride ions in drinking water can cause kidney, liver, endocrine glands, neuron system dental fluorosis, skeletal fluorosis, arthritis, bone damage, osteoporosis, damage the heart, muscular, fatigue, joint-related problems, and chronicle issues e.g. <sup>[74; 75]</sup>. The borehole waters analyze here indicate contents below 1.0 mg/L ([Figure 5b](#), [Table 2](#)). High concentration (> 1.5 mg/L) of fluoride in groundwater is reported in many countries of the World e.g. <sup>[16;70; 72;73;76]</sup>. The majority of countries impacted are in Africa, Asia, and Europe <sup>[70]</sup>. It is estimated that more than 200 million people in the world are affected by fluoride related groundwater issues and health problems. In this study, the highest F<sup>-</sup> content (0.56 mg/L) is determined from the rural commune of Yeni located in the Dosso region ([Fig. 5b](#)). In the urban area of Niamey, the highest concentrations are determined from the boreholes of the district of Satou (0.31 mg/L), Gandjo (0.30 mg/L), Dar-es-Salaam (0.19 mg/L) and Danzama Koara (0.19 mg/L). <sup>[16]</sup> found the same F<sup>-</sup> contents similar contents in the urban zone of Niamey that ranges in between 0.2 to 0.3 mg/L. However, F<sup>-</sup> contents (0.4 to 1.2 mg/L) above the values those obtained in this study have been determined in the peri-urban zone of Niamey by. L'auteur <sup>[16]</sup>, trouve également les teneurs en F<sup>-</sup> les plus élevées (0,5 à 1,6 mg/L) dans la zone rurale du sud-ouest de Niamey, principalement dans la zone rurale de Kollo située dans la région de Tillabery. We suggest that F<sup>-</sup> in the groundwater from the urban area may not result from human activities, since the high populated areas exhibit very low contents. High F<sup>-</sup> content in groundwater could be a result of pedogenic processes. In fact, fluoride in groundwater results from weathering and

subsequent leaching of minerals rich in fluoride from rocks and soil, such as fluorite ( $\text{CaF}_2$ ), cryolite ( $\text{Na}_3\text{AlF}_6$ ), fluocerite ( $\text{CeF}_3$ ), yttrifluorite ( $\text{Ca, Y (F, O)}_2$ ), villianmite ( $\text{NaF}$ ), sellaite ( $\text{MgF}_2$ ), fluorapatite ( $\text{Ca}_5(\text{PO}_4)_3\text{F}$ ), etc., as well as volcanoes [77,78,79,74,80; 81]. In Niger, [13] reported fluoride contents ranged in between 0.1 to 11 mg/L in groundwaters from the Continental Intercalary (CI) of the Irhazer Basin in the northern part of Niger. In the CH aquifer, high fluoride contents 2.0 to 4.3 mg/L exceeding the guideline value were measured in boreholes of drinking water in the region of Maradi [82, 83].

i. Sodium ( $\text{Na}^+$ ) and Potassium ( $\text{K}^+$ )

The WHO, (2011) recommended level should be less than 200 mg/L. The consequence of consumption beyond this limit (200mg/L) is high blood pressure, which leads to the risk of cardiovascular disease, gastric, cancer, obesity, osteoporosis, Meniere's disease and kidney disease. Sodium is widely contained in borehole water analyzed at varying concentrations depending on the site (Fig. 6a and 6b). Higher contents are in the sites of Katako (60.5 mg/L), Satou (26 mg/L) and Gorou-Banda (30 mg/L) of the urban Niamey. Outside the urban commune, the drilling site located in the rural commune of Yeni (Dosso region) contains a relatively higher level of  $\text{Na}^+$  (26 mg/L). These localities represent areas of high human densities and of important commercial activities (Katoko and Yeni). [16] obtained higher values ranging from 131 mg/L and 197 mg/L in the urban area of Niamey and in suburban area of Kollo (25 km west of Niamey) with concentrations ranging from 70 to 92 mg/L. According to [16], variations can be attributed to human activities and the use of agricultural fertilizers in rural areas. However, the Na-contents in the borehole drinking waters do not represent a major risk to the populations. Currently, there is no evidence that potassium levels in drinking-water, even water treated with potassium permanganate, are likely to pose any risk for the health of consumers [84]. Potassium ions ( $\text{K}^+$ ) in the borehole waters, are poorly contained in the majority of the samples (Fig. 6a and 6b). The highest level (9.5 mg/L) was determined from the site of Gorou Banda (Fig. 6b).  $\text{K}^+$ -content are higher than Na in borehole waters These values are of the same order as those determined from a recent study [16] from borehole water samples collected in the urban Niamey and the Kollo region. This last study identified a site in the rural area of Kollo (Abara Gongou 2.2087 13.3826) located about 20 km from Niamey containing 17.8 mg/L of  $\text{K}^+$ . The WHO [85] recommends increasing dietary potassium intake to lower blood pressure and decrease the risk of cardiovascular disease, stroke and coronary heart disease in adults (strong recommendation). The WHO suggests that potassium intake should be at least 3510 mg/day in adults with reserves WHO [83].

j. Calcium ( $\text{Ca}^{2+}$ ) and Magnesium ( $\text{Mg}^{2+}$ )

$\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$  cations are essential Hydrochemical constituent's characteristic of groundwater [86]. The calcium levels recommended by the WHO vary between 1000mg/day (children from 10 years old) and 1300mg/day for adults. However, it is limited to a maximum ranging in between 10 – 15mg/L [43].

The results of the borehole water analyses indicate highly variable concentrations of both cations depending on the site (Fig. 6a, 6d). A predominance of  $\text{Ca}^{2+}$  was observed in all samples. For  $\text{Ca}^{2+}$ , the highest content (72 mg/L) were determined at the site of the Satou district, Katako and Dar es Salaam (18 mg/L) in the urban area of Niamey. In nearby rural areas, the highest content (72 mg/L) was obtained in. A similar study determined varying concentrations between 94.2 mg/L and 371 mg/L at sites in Niamey [16]. The concentration of  $\text{Mg}^{2+}$  remains relatively higher in these same three sites of urban Niamey. The predominance of  $\text{Ca-HCO}_3^-$  and  $\text{Ca (Mg)-HCO}_3$  elements indicates that these groundwaters are shallow [87]. These are critically components of drinking water, satisfying the human system's need for essential minerals that also protect it from disease. Adequate calcium and

magnesium intakes in water reduce the risk of certain cardiovascular diseases, diabetes, rectal cancer, neurological disorders [88; 89; 90; 91;92;93].

#### k. Iron ( $\text{Fe}^{2+}$ ) and Manganese ( $\text{Mn}^{2+}$ ) contents

The iron ( $\text{Fe}^{2+}$ ) and the manganese ( $\text{Mn}^{2+}$ ) ions are metals that occur in soils and rocks [94]. When the lithospheric materials undergo a process of alteration in an aquifer environment,  $\text{Fe}^{+2}$  and  $\text{Mn}^{+2}$  ions are released into the water. In groundwater, iron usually occurs in the oxidation state – reduced soluble divalent ferrous iron ( $\text{Fe}^{2+}$ ) [94]. When groundwater comes into contact with oxygen in the atmosphere, iron is oxidized in the ferric state ( $\text{Fe}^{3+}$ ) and precipitated as iron ore [94]. The conditions of subsoil reduction have a significant influence on the high iron content of groundwater. Other unnatural sources include industrial effluents, acid mine drainage, wastewater and leachate from landfills and that contribute locally to iron and manganese in groundwater [94]. About 75% of the borehole samples from this study have iron concentrations ranged between 0.06 mg/L and 0.3 mg/L (Fig 7a, 7b). Approximately 12.5% have concentrations varying between 0.3 and 1 mg/L and 12.5% have Fe-contents ranging from 2mg/L to 3mg/L (Fig. 7b). The Gorou-Banda site, on the outskirts of Niamey and Boubon (Tillabery) contain slightly high Fe concentrations of 0.7 mg/L and 0.4 mg/L respectively (Fig. 7b) to affect water color. These results are in same order than those reported in previous studies [16;17;18;83]. The highest Fe-contents are determined from samples collected in the rural area of Yeni (Dosso region) and Tapki (Tillabery region) with 3.1 mg/L and 2.2 mg/L respectively (Fig. 7b). A more plausible explanation for such high concentrations may be the that, sites are located on lateritic plateaus, whose subsoils are made up of ferruginous rocks. No health guideline values are proposed for  $\text{Fe}^{+2}$ . However, excessive ingestion and overaccumulation of Fe can cause hemorrhage, metabolic acidosis, cardiac depression, and tissue damage [95]. The potential adverse effects of drinking water containing more than 2 mg/l of iron are mainly gastrointestinal; The most common constipation, nausea, diarrhea and vomiting may also occur. Groundwater with high manganese content remains a problem worldwide [96]. According to the [43], the maximum permissible levels in drinking water must not exceed 0.4 mg/L for Mn. Adverse health effects of excess  $\text{Mn}^{2+}$  include chronic intoxication, pulmonary embolism, nerve damage, bronchitis, impotence, and parkinsonism [97;18; 96]. No health guideline values are proposed for iron.  $\text{Mn}^{2+}$  contents in borehole water studied vary in between 0.1 mg/L and 0.8 mg/L. In the urban area of Niamey, the districts of Poudrière and the peripheral site of Gorou Banda are characterized by contents of 0.5 mg/L to 0.8 mg/L respectively. Therefore, Mn contents are above the standard set value recommended by the [43]. From the rural areas of Kodo (Dosso) a concentration of 0.5 mg/L is obtained. The comparative figure 7d, shows that 5 of the boreholes contain water with  $\text{Mn}^{2+}$  concentrations of 0.3 mg/L close to the value recommended by the [43]. With the exception of sites located in the district of CEG 25 the complex in the urban area of Niamey,  $\text{Mn}^{2+}$  concentrations are above the WHO recommended standard (0.4 mg/L) (Fig. 7c). Our results are in line with data from [16]. The presence of high concentrations of iron (Fe) and manganese (Mn) in groundwater is very common in areas with a tropical climate [98]. According to [39], the urban Niamey is characterized by an unconfined aquifer composed of clayey to silty sandstones locally interbedded with discontinuous eoliths and clay lenses and covered with laterites. This unconfined terminal continental aquifer (CT) thins near the Niger River valley with greater hydraulic gradients [14]. Therefore, it can be expected that  $\text{Fe}^{+2}$  and  $\text{Mn}^{+2}$  ions were released into the acquirer from the weathering of lithospheric materials that undergo a process of alteration as it was stated by several authors [98; 94]. Except for the wells located in rural areas of Yeni, Tapki and Boubon, Mn-contents are above the Fe content specifically in all districts of Niamey. The question that rises is whether Mn in groundwater is affected by anthropogenic activities or only from a lithospheric process?

#### 4. CONCLUSION

Hydrochemical analyses were carried out on 16 borehole water samples from 16 sites, 12 of which are located in the urban area of Niamey, 2 sites in the rural communes of the Dosso region (Kodo and Yeni) and finally 2 others located in the Tillabery region in the rural communes of Boubon and Tapki. The results reveal the presence of very acidic water with pH (< 5) and that the majority of low mineralized waters (EC < 500  $\mu$ S/cm). Only few samples Satou (880  $\mu$ S/cm), Yeni (540  $\mu$ S/cm) and Kodo (1010  $\mu$ S/cm) in the Dosso region. There is also borehole water with high turbidity (> 5NTU) in Niamey and in rural areas. For the anions contained, the concentrations of chlorine, fluorine and sulphates are low for most samples. However, the high concentrations of nitrate ( $\text{NO}_3^-$  > 50mg/L) and nitrite ( $\text{NO}_2^-$  >10mg/L) were determined from more than half of boreholes and constitute serious risks to the health of the population. The study shows that water samples from boreholes locate in former settlements and market centers (traditional public markets) are the most impacted by the contaminations. Therefore, sources of nitrate and nitrite in urban groundwater could result from rainwater infiltration, Sewers, septic tank and toilet uses still at the rudimentary stage in old districts. To this, we could add the lack of good sanitation of urban waste deposits located near the boreholes. In rural areas, poor agricultural practices such as excessive fertilizer applications and the use of rudimentary latrines could contribute to groundwater contamination. Contamination of groundwater with metallic elements such as iron and manganese could be associated with geogenic processes. An important factor in detecting water with high nitrate or nitrite concentration is the determination of its acidity which must have a pH < 5. This is true except for very cloudy water (Kodo case). Thus, a rapid and less expensive pH measurement allows to know whether a very low or not turbid water contains nitrates and nitrites in high concentrations that is unfit for the consumption. The analysis of heavy metals reveals concentrations that are much too high for  $\text{Fe}^{2+}$  (2 to 3.1 mg/L) and  $\text{Mn}^{2+}$  (9.5 mg/L), which are well above the standards set by the WHO. The sites of the high contents are lateritic zones where the alternation of ferruginous rocks is very marked. Finally, the consequences of the consumption of uncontrolled borehole water are gastric, cardiovascular, carcinogenic and neurological diseases, among others. There is an urgent need to assess the quality of groundwater before it is used for consumption. Sanitation of urban and rural areas through better management of solid and sanitary waste is necessary in order to minimize the contamination of groundwater and even surface water for the well-being of the population.

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