International Journal of Environment and Climate Change

Volume 15, Issue 1, Page 178-202, 2025; Article no.IJECC.129437
ISSN: 2581-8627
(Past name: British Journal of Environment & Climate Change, Past ISSN: 2231–4784)

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

MOUNKAILA Mohamed [a*], MAHAMADOU Zeinabou [b], ABASS SALEY Abdoulatif [c], RABILOU SOULEY Moussa [b], INOUSSA Maarouhi Maman [d] and SOUMANA Salifou [a]

[a] *Department of Nuclear Physics and Chemistry of Institute of Radio Isotope, University Abdou Moumouni, BP, 10727, Niamey, Niger.*
[b] *Materials-Water-Environment Laboratory, University Abdou Moumouni, BP, 10662, Niamey, Niger.*
[c] *Ecole des Mines, de l'Industrie et de la Géologie (EMIG), BP 732, Niamey, Niger.*
[d] *Department of Biology, University Abdou Moumouni BP, 10662, Niamey, Niger.*

Authors' contributions

This work was carried out in collaboration among all authors. Author MM and MZ wrote the original draft, did the methodology, did formal analysis, conceptualized and resources. Author AAS did formal analysis, did data curation and reviewed. Author RSM reviewed. Authors IMM and SS supervised the study. All authors read and approved the final manuscript.

Article Information

DOI: https://doi.org/10.9734/ijecc/2025/v15i14684

Open Peer Review History:
This journal follows the Advanced Open Peer Review policy. Identity of the Reviewers, Editor(s) and additional Reviewers, peer review comments, different versions of the manuscript, comments of the editors, etc. are available here: https://www.sdiarticle5.com/review-history/129437

Original Research Article

Received: 10/11/2024
Accepted: 13/01/2025
Published: 17/01/2025

**Corresponding author: E-mail: mohamedmounkailam@gmail.com;*

***Cite as:** Mohamed, MOUNKAILA, MAHAMADOU Zeinabou, ABASS SALEY Abdoulatif, RABILOU SOULEY Moussa, INOUSSA Maarouhi Maman, and SOUMANA Salifou. 2025. "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". International Journal of Environment and Climate Change 15 (1):178-202. https://doi.org/10.9734/ijecc/2025/v15i14684.*

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 parameter measured are pH, Electric conductivity (EC), HCO_3^-, NO_3^-, NO_2^-, Cl^-, SO_4^{2-}, F^-, Na^+, K^+, Ca^{2+}, Mg^{2+}, Fe^{2+} and 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 the limit standard set by the WHO. High nitrite contents (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 wastes managements, and the uncontrolled use fertilizers in the agricultural sectors. The sites containing between 2 and 3 mg/L of Fe^{2+} are located in areas of lateritic soils. About 12% of samples contain 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 need 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 (United Nation World Population Prospects, 2019), 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 (Nazoumou et al., 2016; Cobbing, 2020) 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 (Sy et al., 2011). 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 (Chippaux et al., 2012; Tankari Dan-Badjo et al., 2012; da Silva Peixoto et al., 2020; Nemčić-Jurec et al., 2022). Physicochemical parameters related to the natural structure of water include temperature, pH, conductivity, major ions: bicarbonate, chloride, sulphate, calcium, magnesium, sodium, potassium, and others, (Rice et al.; 2012; Turunen et al., 2024). 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 (Chippaux et al., 2012). 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 (Olofsson, 1994; IAEA, 2017; Andrews et al, 1994; Hassane, 2010).

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 grographical 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 (United Nations, 2024). 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 (Hassane, 2010; Wannous et al., 2024; BGR, 2012). 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" (Wannous et al., 2024; Hassane et al., 2016). The lithology is composed of plutonic rocks (granites, granulite) and metamorphic rocks (heifers, quartzites, green schists) with different levels of alterations (Heckman, 2023; Ousmane et al., 2007). The basement aquifer is the deepest of the three aquifers considered [18;19]. 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 [18 19]. Its lithology is composed of sedimentary sandstones from the Upper Cretaceous to the present day and forms the vast regional basin of the Iullemmeden (Abdou et al., 2019) 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 Iullemmeden basin where the continental terminal outcrops. The third, which consists of the alluvial aquifer is continuous (Hassane, 2010; Hassane et al., 2016). 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.

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"	2°7'47"
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"

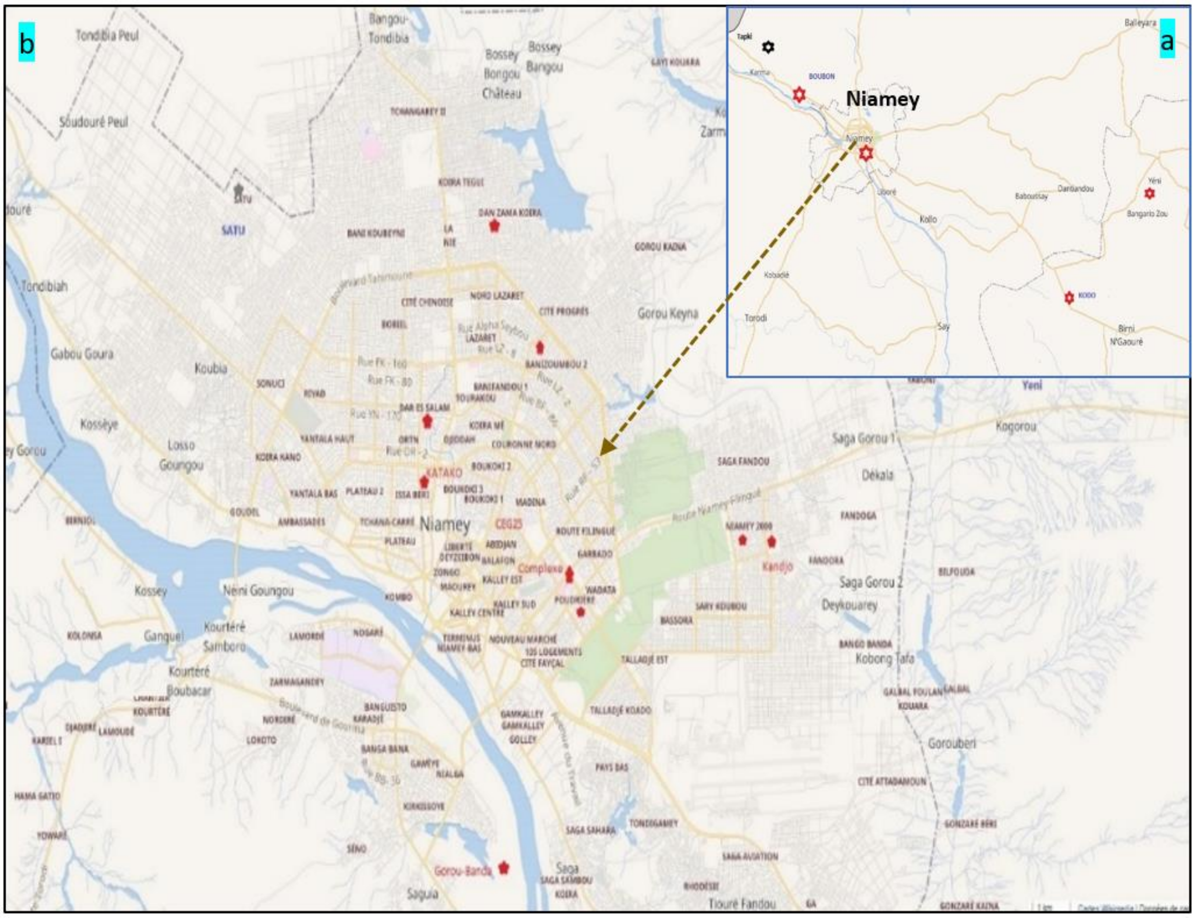

Fig. 1. Map of the urban area of Niamey and its suburban rural areas

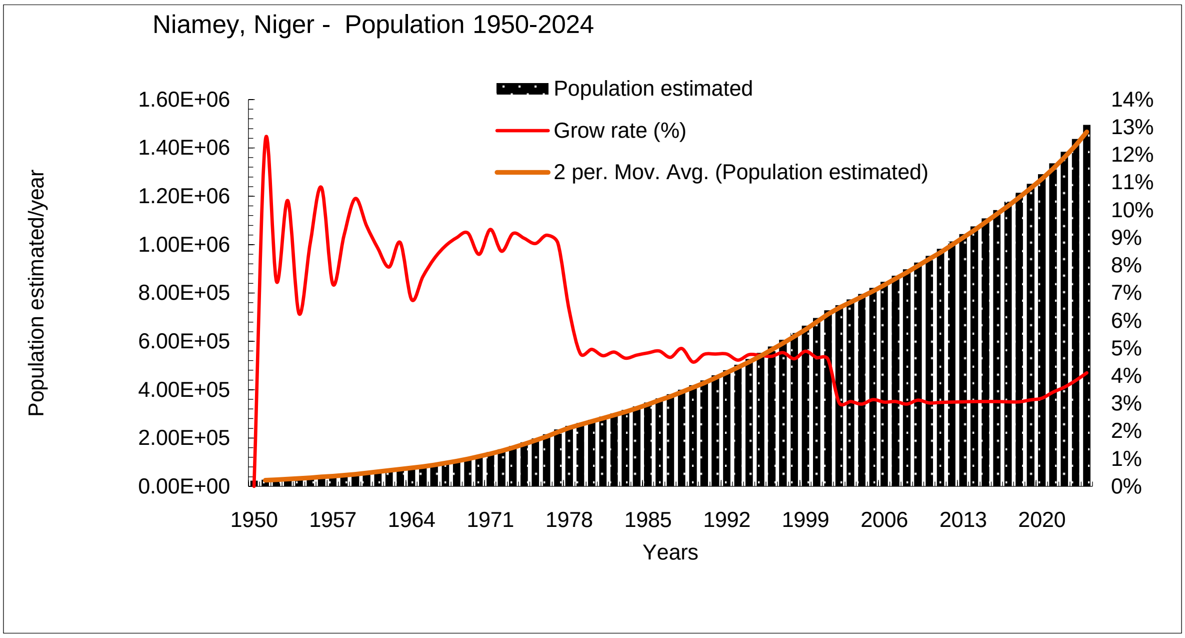

Fig. 2. Graph of both populations estimated yearly and the growing rate from 1950 to 2024. Data sources (United Nations, 2024)

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 Fig. 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 (HCO_3^-, Cl^-, F^-, NO_2^-, NO_3^-, SO_4^{2-}) and cations (Na^+, K^+, Ca^{2+}, Mg^{2+}) as well as heavy metals (Fe^{2+}, 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 2 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 Fig. 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 Fig. 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 Fig. 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).

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 (Na^+), potassium (K^+), calcium (Ca^{2+}), magnesium (Mg^{2+}), chloride (Cl^-), sulphate (SO_4^{2-}) and nitrate (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 Fig. 4. About 88 % of borehole water samples are characterized with EC comprised between 30 µS/cm and 500 µS/cm. These values comply with the standard defined by the WHO, which is estimated to be a maximum of 1,600 µS/cm (Table 2). Those with EC ranged between 500 and 1010 µS/cm are located in the new district of Satou (880 µS/cm), the rural zones of Kodo (1010 µS/cm and Yeni (540 µS/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 µS/cm (Fig. 4b). The borehole sample from the district of Satou is characterized by low turbidity (5 NTU) and high EC (880 µS/cm) while the sample from Kode has the highest turbidity index (292 NTU) and EC (1010 µS/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.

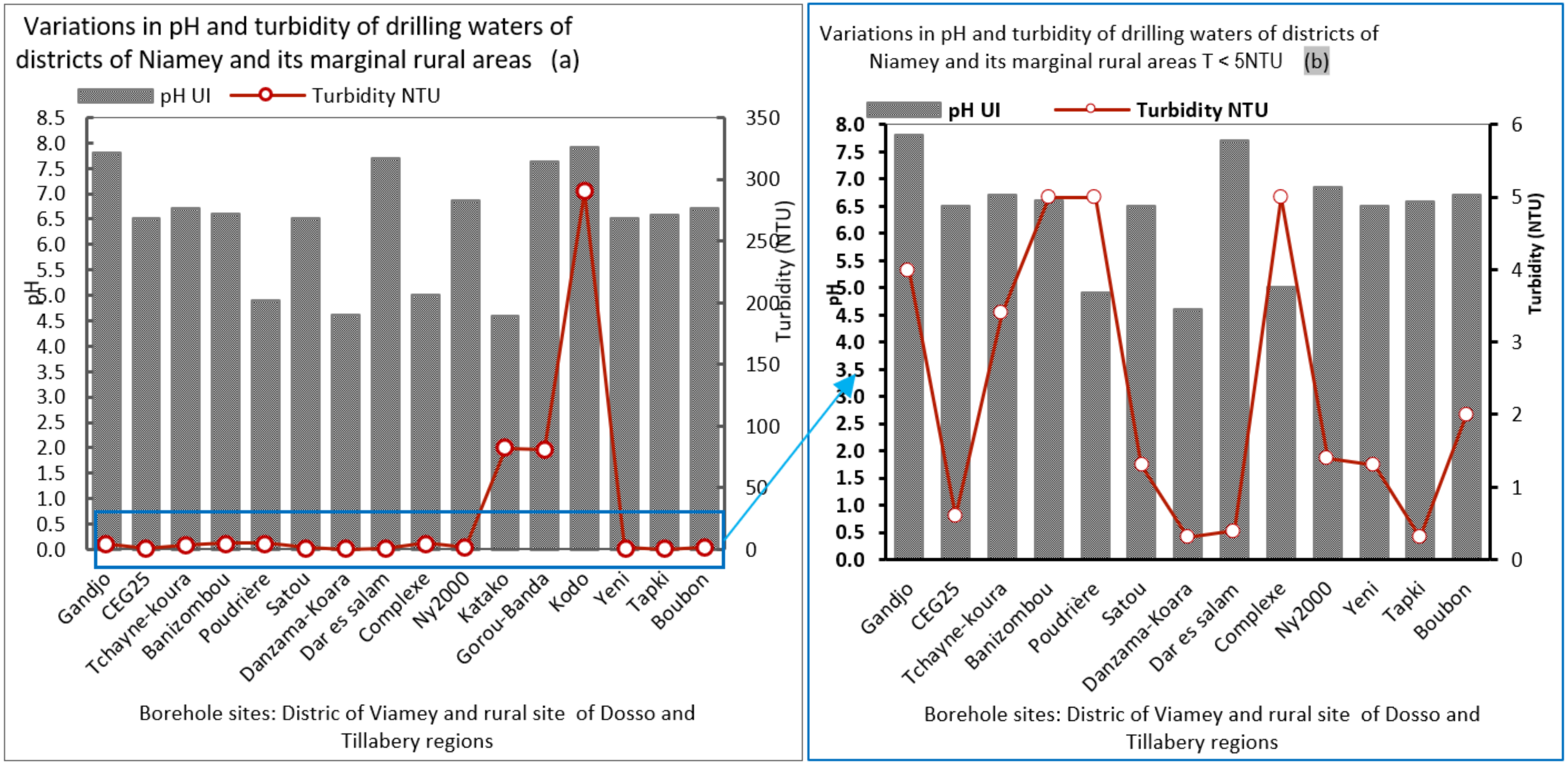

Fig. 3(a). Variation in pH and turbidity of borehole water from the different sampling sites in Niamey and surrounding rural areas (b) Sites with Turbidity < 5 NTU. The figure shows no relationship between the pH and the Turbidity of boreholes waters

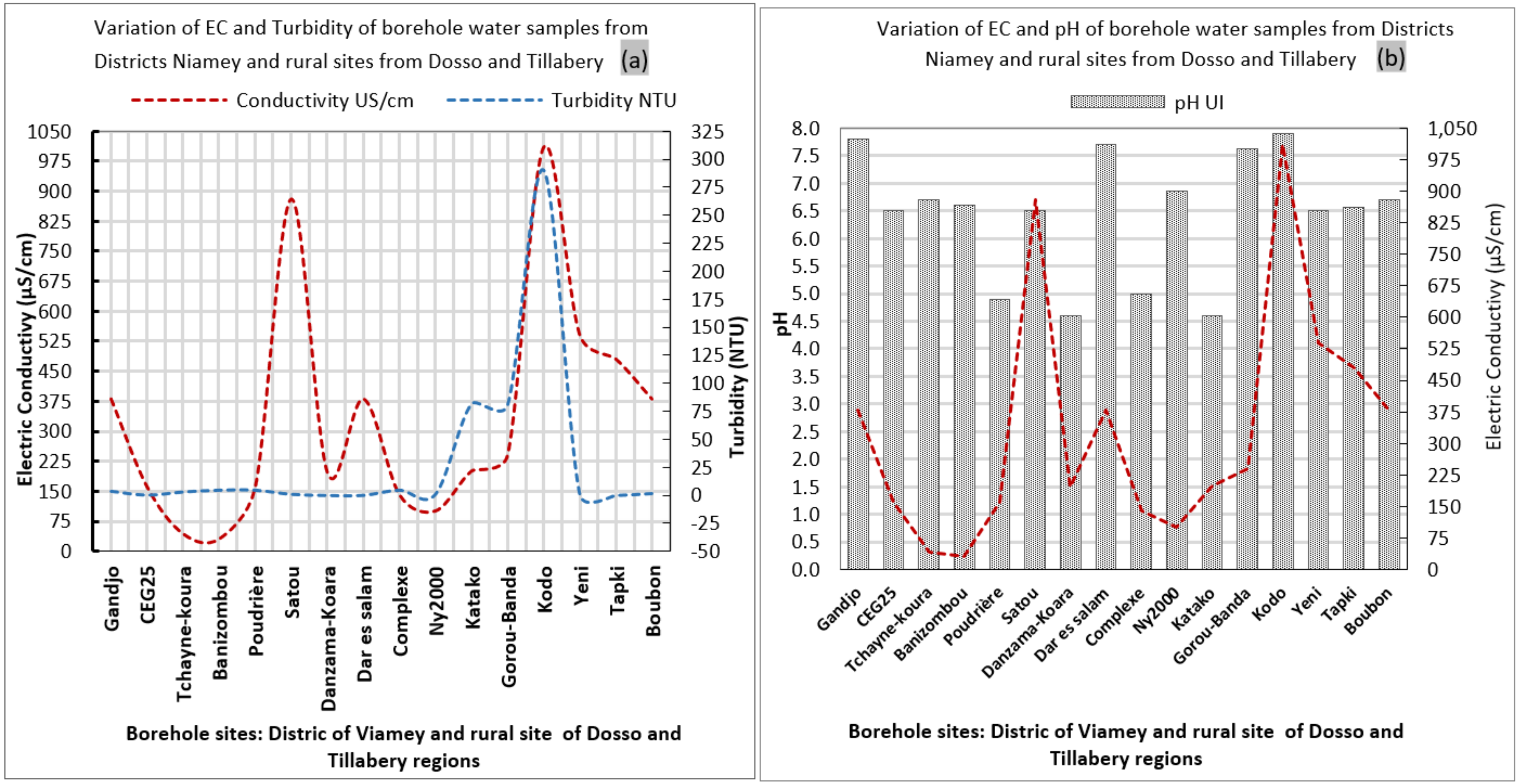

Fig. 4. Variabilities of the electric conductivity (EC) of borehole water samples from different district in the urban areas of Niamey and its surroundings rural areas in the regions of Tillabery and Dosso. (a): Fig. 4a shows a comparison between EC and the turbidity and clear show the differences in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

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 Guide Values**
		Gandjo	***CEG25***	***Tchini-Koura***	***Bani-Zombou***	***Poudrière***	***Satou***	***Danzama-Koara***	***Dar-es Salaam***	***Complexe***	***Niamey-2000***	***Katako***	***Gorou-Banda***	***Kodo***	***Yeni***	***Tapki***	***Boubon***	
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_3^-	mg/L	92	12	8	30	30	380	3,7	150	63	28	30	31	30	152	3,7	150	NA
Cl^-	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_4^{-2}	mg/L	19	4	0	1	4	8	6	7	3	0.08	1	9	4	18	6	7	500 mg/l
F^-	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_3^-	mg/L	60	1,5	56	8,8	95	29	150	0,34	70	0	100	30	180	29	8	4,34	• 50 to 3mg/L (short-term exposure –
NO_2^-	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	• 0.2 mg/l long-term • 0.5 mg/L
Na^+	mg/L	12	6,3	4	3,5	4	26	12	10	2,5	7	60,5	30	4	26	12	11	No NES guideline: < 20 mg/l
K^+	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	
Ca^{2+}	mg/L	22	1,6	6,8	7,5	8	72	13	18	7	11,5	72	5,4	8	72	13	24	
Mg^{2+}	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	
$Fe^{(2+)}$	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^{2+}	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

3.1.3 Variations of Anions (HCO_3^-, Cl^-, SO_4^{2-}, F^-, NO_3^- and NO_2^-) contents in borehole waters

Data of major anions determined are shown in Table 2 and represented by the Fig. 5. The bicarbonate (HCO_3^-), nitrates (NO_3^-), nitrites (NO_2^-) and chlorides (Cl^-) are dominantly contained in most of samples (Fig. 5a). In contrast, sulphates (SO_4^{2-}) and fluorides (F^-) are relatively low contained (Fig. 5a and 5b). For bicarbonate (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 (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 (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 (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 (NO2-) 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_2^-) (Table 2; Fig. 5d). Very high concentrations of NO_2^- (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, in the peripheral area of Niamey has a limit concentration, with 10 mg/L of (NO_2^-) and 30 mg/L of NO_3^-.

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

a. Sodium (Na^+) and Potassium (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 Na+ and K+ contents, only a few sites show very significant deviations where potassium is more contained than sodium in waters (Fig. 6b).

b. Calcium (Ca^{2+}) and magnesium (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 Ca^{2+} in comparison with 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). 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 Mg/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 Mg^{2+} (7 mg/L) with Mg/Ca ratio of 0.10. Mg/Ca ratios are very low (< 0.2) for borehole water samples from most rural sites. This can be a result of geogenic processes or anthropogenic activities.

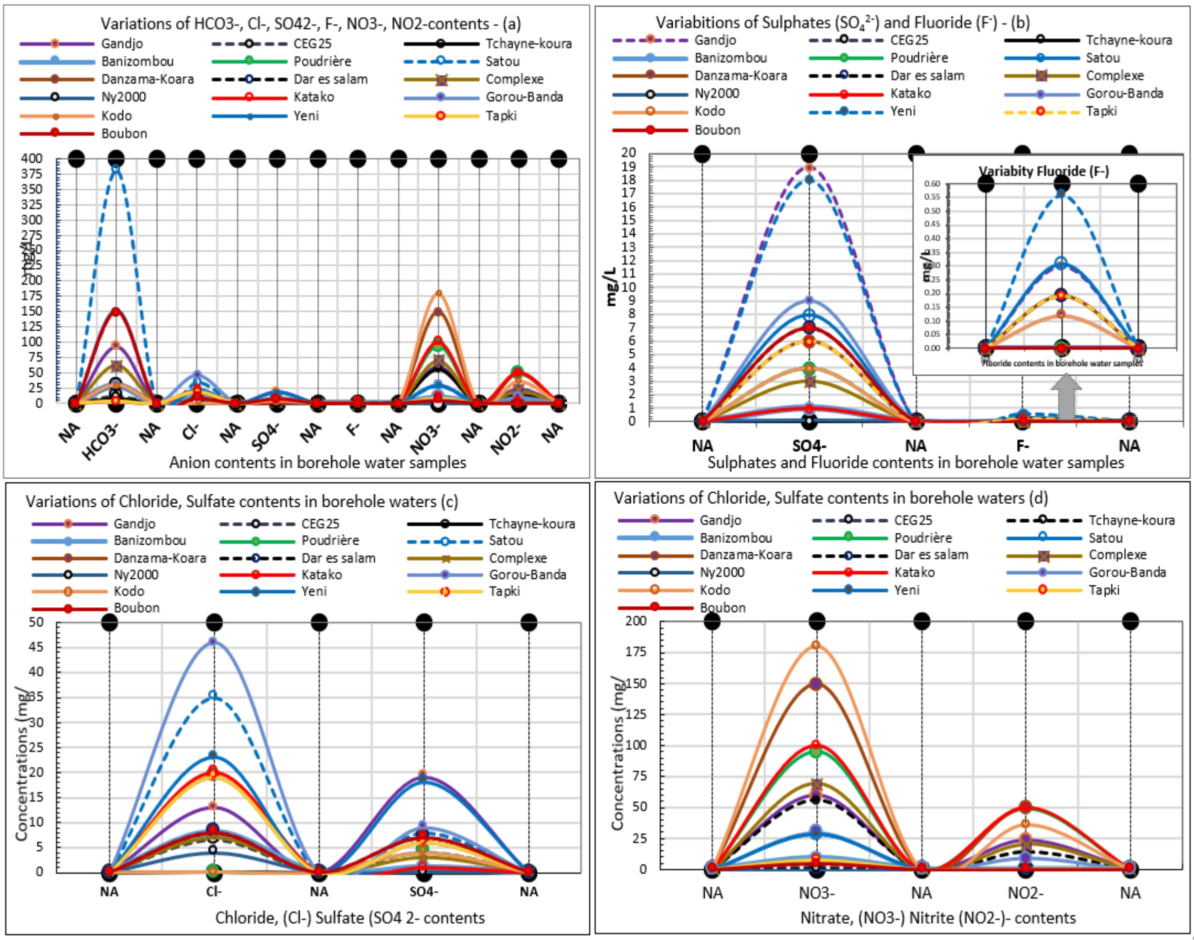

Fig. 5. Variabilities of anions contents of borehole water samples from different district of the urban areas of Niamey and its surroundings rural areas located in the regions of Dosso and Tillabery. (Fig. 5a shows a clear predominance of bicarbonates, nitrates, nitrites and chlorites. Fig. 5b highlights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

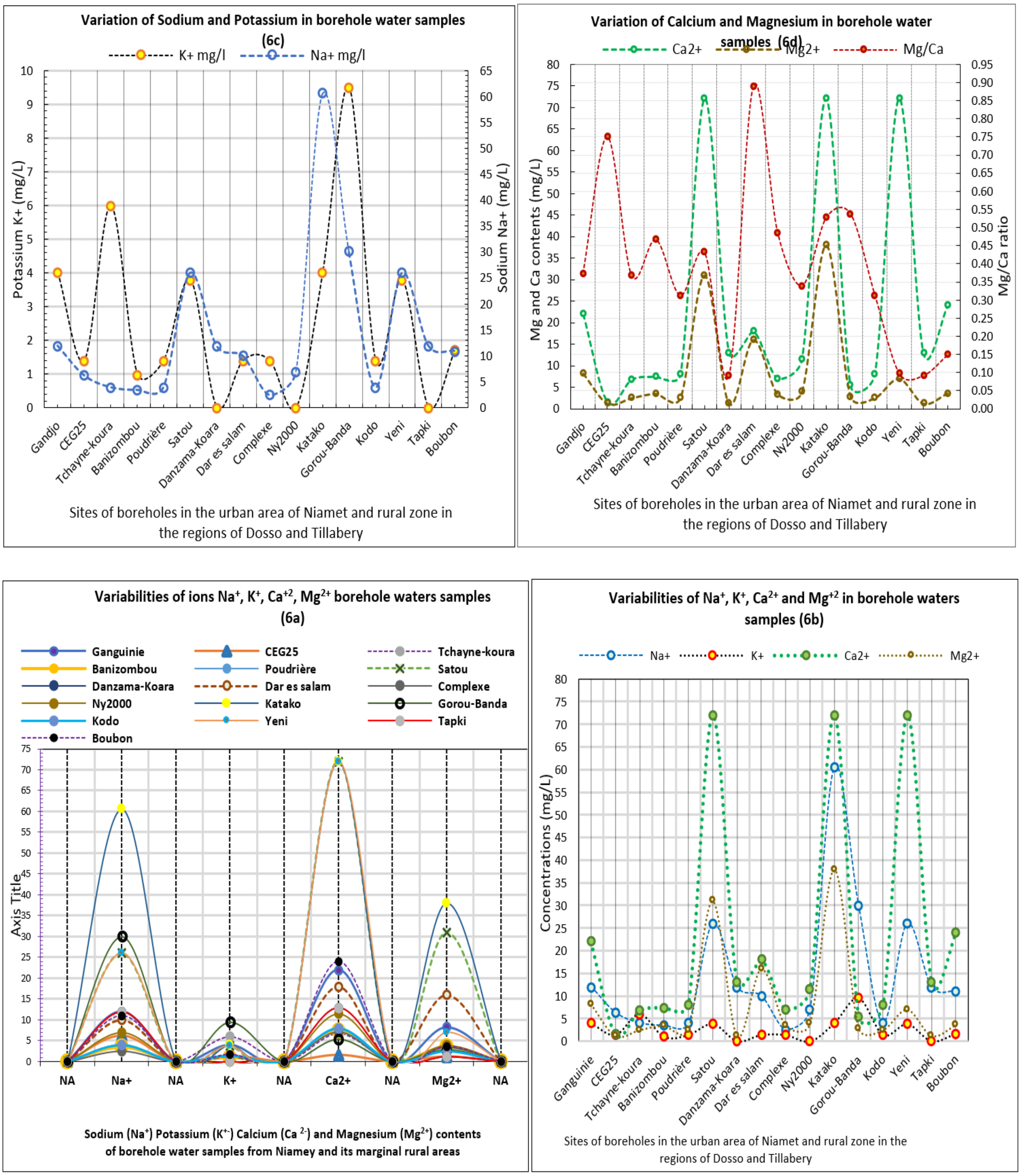

Fig. 6. Variations of Natrium, Potassium, Calcium and Potassium contents in borehole water samples from the urban area of Niamey and its marginal rural areas located in Tillabery and Dosso regions (Fig. 6a). [Fig. 6a highlights the water contents of cations. Fig. 6c shows variations of Na and K of borehole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

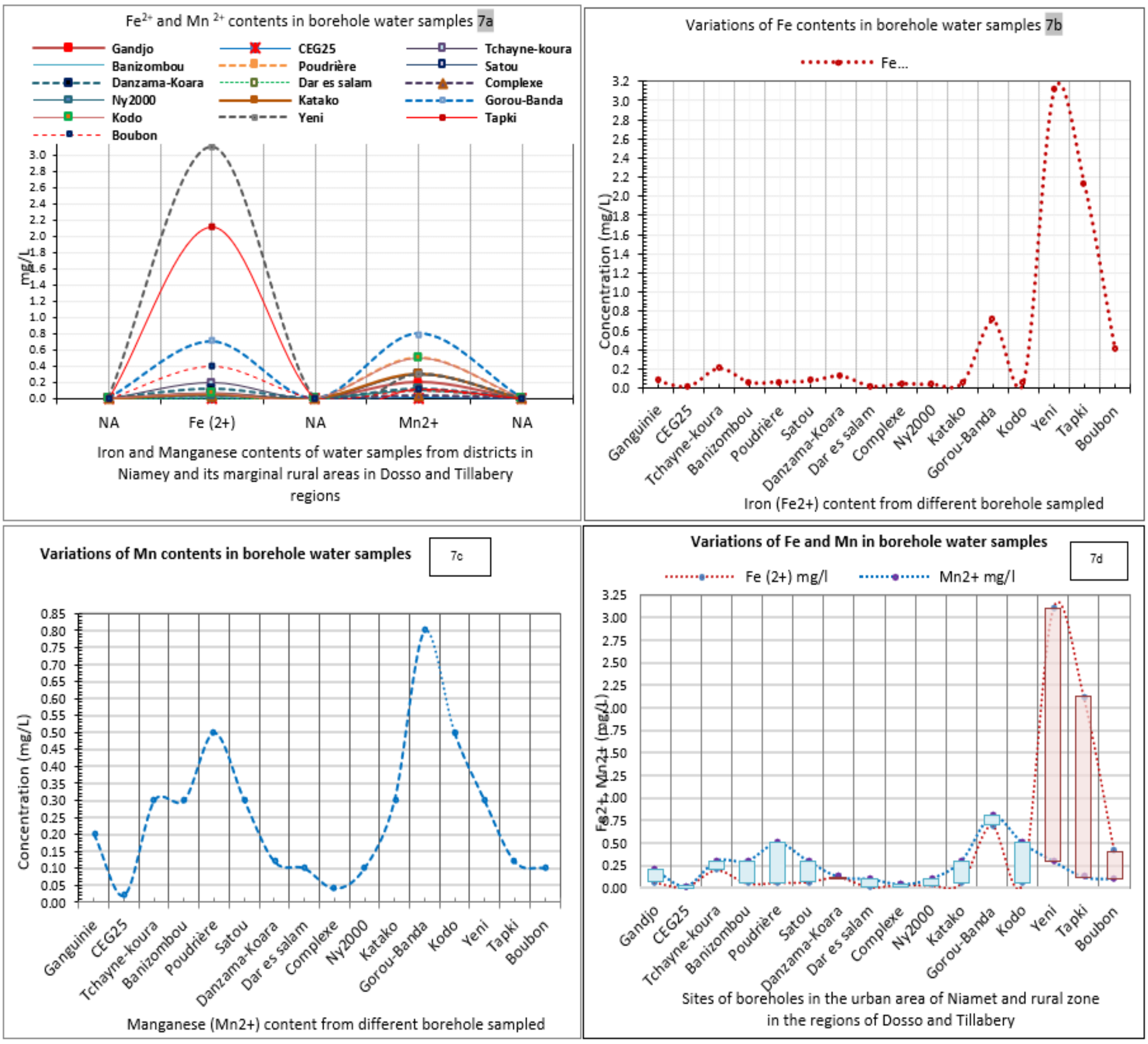

Fig. 7: Fe^{2+} and Mn^{2+} from borehole water samples collected in the urban Niamey and its marginal suburban areas in the regions of Dosso and Tillabery Niger. (Fig. 7a shows Fe and Mn variations with high Fe contents in few rural samples. The Fig. 7b highlight Fe^{2+} contents from site located on lateritic basements. Fig. 7c show the relatively high Mn^{2+} contents in groundwater. Fig. 7d shows differences in Mn and Fe contents in the urban and rural groundwaters. The Fig. 7d 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.)

3.1.5 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 Table 2. Fig. 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 Fig. 7d, shows that 5 of the boreholes contain water with Mn^{2+} concentrations of 0.3 mg/L the which is close to the value recommended by the WHO (0.4 mg/L).

3.2 Discussion

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 (Knutsson, 1994; Chislock et al., 2013; Lelykesehatan, 2011; Gauthier et al., 2001).

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 WHO (2008) 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 (Appelo et al., 1999; Prakash et al. 2022; Soundala et al., 2022), 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, (Kjøller et al., 2004; Fest et al., 2007) 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 nitrate 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 facilizing the infiltration of water pollutants (Zhou et al., 2015; Boukari et al., 2006; Scanlon et al., 2005). Previous studies have shown that the pH of groundwater can be influenced by the environment (rural, urban, agricultural) in which drilling is located (da Silva Peixoto et al., 2020; Nemčić-Jurec et al., 2022; Boukari et al., 2006). Acidic groundwater may promote the mobility of elements such as Al, Mn and other toxic metals and make the waters unfit for dinking (Rawat, et al., 2019; Fest et al., 2005). 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 (Tankari Dan-Badjo et al., 2012; Hassane, 2010; Fest et al., 2005). The study of Tankari Dan-Badjo et al. (2012) 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 (Rawat, et al., 2019; Fest et al., 2005) Acidification of groundwater may impact the geochemical equilibrium in soils and aquifers (Rawat, et al., 2019; Appleyard and Cook, 2008; Takem et al., 2015; Rodier, 2009). According to Jaishankar et al. (2014), 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 (Nagajyoti et al., 2010; Bricha et al., 2007) 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 WHO, (2011). 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. (WHO, 2008; Baraldi, 2015; Pantaleo et al., 2018). 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 WHO (2011). 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 Kurwadkar et al. (2020), 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, WHO (2011) 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 (Chippaux et al., 2002; Hassane et al., 2016).

c. Electric conductivity (EC)

According to Hassane et al. (2016), there is a clear structuring of EC and depth to the water-Table 1 in the area of study. The deepest wells (15–30 m) have relatively low EC (36−340 μS cm−1), whereas shallow wells (5–15 m) show high and variable EC values (36−1617 μS cm−1). The majority of samples analyzed has an EC value comprised between in 30 and 480 μS/cm (Table 2. Fig. 4). According to (BGR, 2012; Kurwadkar et al., 2020) low EC values (45 to 46 μS/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 1 have an EC value comprised in between (36−1617 μS cm−1). Since the water Table 1 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 (da Silva Peixoto et al., 2020; Nemčić-Jurec et al., 2022). According to Hassane et al. (2016), da Silva Peixoto et al., 2020, Pantaleo et al., 2018, Kurwadkar et al., 2020, 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 μS/cm indicate that, these waters are weakly mineralization (Hassane et al., 2016). The mineralize waters have an EC ranged in between 500 to more than 1010 μS/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 (Butler and Cogley, 1998). In addition, rainwater runoff and its infiltration into the water Table 1 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 (Kjøller et al., 2004). The residence time of water in rocks and soils has an impact on electrical conductivity (Singh et al., 2013; Devaraj et al.; 2022).

d. Bicarbonate (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 (HCO_3^- and CO_2^{2-}) and organic acids (-COOH), as well as orthophosphate ($H_2PO_4^-$, HPO_4^{2-} and PO_4^{3-}), ammonia, silicate, as well as OH^- ions (Edzwald and Tobiason 2011). Fig. 5 (a and b) shows the predominance of HCO_3^-contents. Bicarbonates contribute to the buffering capacity of the water against changes in pH levels (Schock, 1990; Paladino et al.; 2018). Bicarbonate (HCO_3^-) contributes to reduce large pH swings that can compromise water quality (Edzwald and Tobiason, 2011). The samples analyzed indicate relatively high concentrations of 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 Edzwald and Tobiason (2011) the CO_2 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_3^-) and Nitrite (NO_2^-)

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 (Wu e al, 2019; WHO, 2006). The WHO (2017) 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 (Burnol et al., 2006). This disease can mainly affect pregnant women (WHO, 2006). In this study, the nitrate (NO_3^-) 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 (da Silva Peixoto et al., 2020; Nemčić-Jurec et al., 2022; Hassane et al., 2016), 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 (Wannous et al., 2024; BGR, 2012; Copeland et al., 2006). 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 [49], 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 (Fest et al., 2005). 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_2^-) 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 $NO3^-$ (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_2^-) and 30 mg/L of NO_3^-, so it is within the defined limit standard. According to Copeland et al. (2006), the 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 (Lasagna et al., 2015). The natural nitrate concentrations in aquifers dependent on the soil and rocks geochemistry (Singh et al., 2013; Lasagna et al., 2015). 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 (Burnol et al., 2006; Baran et al., 2007). Nitrates are very leachable and infiltrate very easily in to groundwater (Einsiedl et al., 2007; Ward et al., 2004) leading to their pollution. Nitrates are also formed by the oxidation of organic waste by the action of nitrogen-binding bacteria (Kirmeyer et al., 2004). According to Annie Locas et al. (2008), 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 (Wannous et al., 2024; BG, 2012; Hassan et al., 2016; Ousmane et al., 2007). 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 (Wannous et al., 2024; BG, 2012; Heckman, 2023). 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 (BG, 2012; Heckman, 2023). 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.

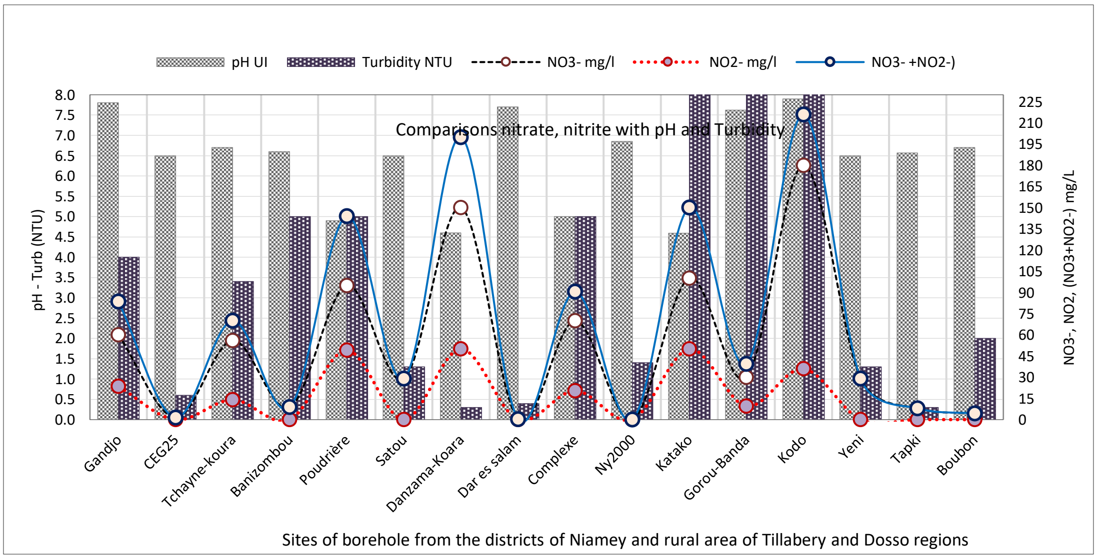

Fig. 8. Comparative analyses of nitrate-nitrite contents in borehole water from the urban area of Niamey and its marginal rural areas located in the regions of Dosso and Tillabery

Fig. 8 shows 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 WHO (2011), 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 (Burnol et al., 2006). The variations of chloride contents in borehole water samples of this study are shown in Table 2 and Fig. 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 (Favreau et al., 2009). Chlorides are naturally contained in borehole water or from pollution induced by the poor management of industrial or domestic waste (Hassan et al., 2016). 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 (Singh et al., 2004; Hassan et al., 2016). Contamination with chloride salts can also reduce the suitability of soil and irrigation water for agricultural use (Singh et al., 2004).

g. The sulphate (SO_4^{2-}) contents

The WHO (2011) in sanitary standard for drinking water quality limit the sulfate concentration less than 250 mg/L. Sulphate ions (SO_4^{2-}) 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 (Wannous et al., 2024) suggesting that sulphate is found in small amounts in groundwater. Our data shows that, SO_4^{2-} 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^-).

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 (Shaji et al., 2024; Solanki et al., 2022; Podgorski e al., 2022; Craig et al., 2015). According to the WHO (2011), 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 (Chandrajith et al., 2012; Mapoma and Xie, 2014). The borehole waters analyze here indicate contents below 1.0 mg/L (Fig. 5b, Table 2). High concentration (> 1.5 mg/L) of fluoride in groundwater is reported in many countries of the World (Wannous et al., 2024; Solanki et al., 2022; Podgorski e al., 2022; Craig et al., 2015; Onipe et al., 2020). The majority of countries impacted are in Africa, Asia, and Europe (Solanki et al., 2022). 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^- 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). Wannous et al. (2024) found the same F^- contents similar contents in the urban zone of Niamey that ranges in between 0.2 to 0.3 mg/L. However, F^- 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. The author (Wannous et al., 2024) also finds the highest F- levels (0.5 to 1.6 mg/L) in the rural area of southwest Niamey, mainly in the rural area of Kollo located in the region of Tillabery. We suggest that F^- in the groundwater from the urban area may not result from human activities, since the high populated areas exhibit very low contents. High F^- 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 (CaF_2), cryolite (Na_3AlF_6), fluocerite (CeF_3), yttrofluorite (Ca, Y) $(F, O)_2$, villianmite (NaF), sellaite (MgF_2), fluorapatite ($Ca_5(PO_4)_3F$), etc., as well as volcanoes (Mahamadou et al., 2022;

Brindha et al., 2011; Malago et al., 2017; Chandrajith et al., 2012; Schlesinger et al., 2020; Battaleb-Looie et al 2012a; Battaleb-Looie et al., 2012b). In Niger, Andrews et al. (1994) 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 (Gourouza et al., 2019; Ousmane et al., 2023).

i. Sodium (Na^+) and Potassium (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 Na^+ (26 mg/L). These localities represent areas of high human densities and of important commercial activities (Katoko and Yeni). Wannous et al. (2024) 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 Wannous et al. (2024), 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 WHO (2009). Potassium ions (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). 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 K^+. The WHO (2005) 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 (2009).

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

Ca^{2+} and Mg^{2+} cations are essential Hydrochemical constituent's characteristic of groundwater (Shuaibu et al., 2024). 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 (WHO, 2011). The results of the borehole water analyses indicate highly variable concentrations of both cations depending on the site (Fig. 6a, 6d). A predominance of Ca^{2+} was observed in all samples. For 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 Mg^{2+} remains relatively higher in these same three sites of urban Niamey. The predominance of Ca-HCO^{-3} and Ca (Mg)-HCO_3 elements indicates that these groundwaters are shallow Razowska-Jaworek (2014). 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 (Jacqmin et al., 1994; Yasui and Yoshida 1997; Melles and Kiss 1992; Rasic-Milutinovic et al., 2012; Helte et al., 2022).

k. Iron (Fe^{2+}) and Manganese (Mn^{2+}) contents

The iron (Fe^{2+}) and the manganese (Mn^{2+}) ions are metals that occur in soils and rocks Röllin et al. (2018). When the lithospheric materials undergo a process of alteration in an aquifer environment, Fe^{+2} and Mn^{+2} ions are released into the water. In groundwater, iron usually occurs in the oxidation state – reduced soluble divalent ferrous iron (Fe^{2+}) (Röllin et al., 2018). When groundwater comes into contact with oxygen in the atmosphere, iron is oxidized in the ferric state (Fe^{3+}) and precipitated as iron ore

(Röllin et al., 2018). 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 (Röllin et al., 2018). 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 (Wannous et al., 2024; BGR, 2012; Hassan et al., 2016; Ousmane et al., 2023). 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 Fe^{+2}. However, excessive ingestion and overaccumulation of Fe can cause hemorrhage, metabolic acidosis, cardiac depression, and tissue damage (SAWQG, 1996). 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 (Anne et al., 2021). 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 Mn^{2+} include chronic intoxication, pulmonary embolism, nerve damage, bronchitis, impotence, and parkinsonism (Grazuleviciene et al., 2009; Hassan et al., 2016; Anne et al., 2021). No health guideline values are proposed for iron. 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 WHO (2011). From the rural areas of Kodo (Dosso) a concentration of 0.5 mg/L is obtained. The comparative Fig. 7d, shows that 5 of the boreholes contain water with Mn^{2+} concentrations of 0.3 mg/L close to the value recommended by the WHO (2011). With the exception of sites located in the district of CEG 25 the complex in the urban area of Niamey, Mn^{2+} concentrations are above the WHO recommended standard (0.4 mg/L) (Fig. 7c). Our results are in line with data from Wannous et al. (2024). The presence of high concentrations of iron (Fe) and manganese (Mn) in groundwater is very common in areas with a tropical climate (Nwankwo et al., 2020). According to Hassan et al. (2016), Wannous et al. (2024), 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 excepted that Fe^{+2} and 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 (Röllin et al., 2018; Nwankwo et al., 2020). 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 µS/cm). Only few samples Satou (880 µS/cm), Yeni (540 µS/cm) and Kodo (1010 µS/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 (NO_3^- > 50mg/L) and nitrite (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 consummation.

The analysis of heavy metals reveals concentrations that are much too high for Fe^{2+} (2 to 3.1 mg/L) and 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.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of this manuscript.

ACKNOWLEDGEMENTS

The authors warmly thank all the members of the team at the Quality-Control Lab (QCL) Niamey-Niger for having facilitated all analyses.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

REFERENCES

Abdou Babaye, M. S., Orban, P., Ousmane, B., Favreau, G., Brouyère, S., & Dassargues, A. (2019). Characterization of recharge mechanisms in a Precambrian basement aquifer in semi-arid south-west Niger. *Hydrogeology Journal*.

Andrews J.N., Fontes J.-C., Aranyossy J.-F., Dodo, A., Edmunds, W. M. Joseph, A. and Travi Y. (1994). The evolution of alkaline groundwaters in the continental intercalary aquifer of the Irhazer Plain, Niger. Water Resources Research, 30, 45-61.

Anne, K.; Hannu, K.; Tarja, H.; Birgitta, B.; Sirpa, H. (2021). Variation in Groundwater Manganese in Finland. Environ. Geochem. Health 2021, 43, 1193–1211.

Annie Locas A. Locas, Christine Barthe C. Barthe, Aaron B. Margolin A. B. Margolin, and Pierre Payment P. Payment. (2008). Groundwater microbiological quality in Canadian drinking water municipal wells. *Canadian Journal of Microbiology*. 54(6): 472-478.

Appelo, C. A. J., Drijver, B., Hekkenberg, R., & De Jonge, M. (1999). Modeling in situ iron removal from ground water. *Groundwater*, *37*(6), 811-817.

Appleyard S, Cook T (2008). Reassessing the management of groundwater use from sandy aquifers: acidification and base cation depletion exacerbated by drought and groundwater withdrawal on the Gnangara Mound, Western Australia. Hydrogeology Journal 17(3), 579-588

Baraldi, R. (2015). *Portrait statistique de la santé mentale des Québécois: Résultats de l'Enguête sur la santé dans les collectivités canadiennes Santé mentale 2012*. desLibris.

Baran N., Mouvet C., Négrel P. (2007). Hydrodynamic and geochemical constraints on pesticide concentrations in the groundwater of an agricultural catchment (Bréville's, France). Environmental Pollution, 148: 729-738

Battaleb-Looie S, Moore F, Jacks G, Ketabdari MR. (2012b). Geological sources of fluoride and acceptable intake of fluoride in an endemic fluorosis area, southern Iran. Environ Geochem Health 34:641–650.

Battaleb-Looie S, Moore F, Jafari H, Jacks G, Ozsvath D. (2012a). Hydrogeochemical evolution of groundwaters with excess fluoride concentrations from Dashtestan, South of Iran. Circa Earth Sci 67:1173–1182.

BGR, (2012). Projet AGES Appui à l'Autorité du Bassin du Fleuve Niger pour la Gestion des Eaux Souterraines Campagne de mesure des eaux souterraines dans la région de Niamey, Niger 4ème trimestre 2012 03 – 07 / 12 / 2012

Boukari, M., A. Alassane, F. Azonsi, F.A.L. Dovonou, A. Tossa & D. Zogo. (2006). Groundwater pollution from urban development in Cotonou City, Benin. Book Groundwater Pollution in Africa. 1st Edition 2006, CRC Press. Book ISBN. 9780429224416.

Bricha, Saâdia, Khadija Ounine, Saïd Oulkheir, Nourredine El Haloui, and Benaissa Attarassi. (2007). "Study of the Physico-Chemical and Bacteriological Quality of the M'nasra Groundwater, Morocco." *Afrique Science* 3 (3): 391–404)

Brindha, K. and Elango, L. (2011) Fluoride in Groundwater: Causes, Implications and Mitigation Measures. In: Monroy, S.D. (Ed.), Fluoride Properties, Applications and Environmental Management, 111-136.

Burnol, A., Blanc, P., Xu, T., Spycher, N., & Gaucher, E. C. (2006). Uncertainty in the reactive transport model response to an alkaline perturbation in a clay formation.

Butler J. N., and Cogley, D. R. (1998). Ionic Equilibrium: Solubility and pH calculation. John Wiley. Sons. Inc, Toronto, 170.

Chandrajith, R., Padmasiri, J. P., Dissanayake, C. B., & Prematilaka, K. M. (2012). Spatial distribution of fluoride in groundwater of Sri Lanka.

Chippaux J.P., Houssier S., Gross P., Bouvier C. et Brissaud F. (2002), Etude de la pollution de l'eau souterraine de la ville de Niamey, Niger, Bulletin de la Société de Pathologie Exotique ; 95(2) : 119-123.

Chislock, M. F., Doster, E., Zitomer, R. A., & Wilson, A. E. (2013). Eutrophication: causes, consequences, and controls in aquatic ecosystems. *Nature Education Knowledge*, *4*(4), 10.

Cobbing, J. (2020). As águas subterrâneas eo discurso da escassez na África Subsaariana. *Hydrogeology Journal*, *28*, 1143-1154.

Copeland KA, Harris EN, Wang NY, Cheng TL. (2006). Compliance with American Academy of Pediatrics and American Public Health Association illness exclusion guidelines for child care centers in Maryland: who follows them and when? Pediatrics. 118(5)-1369-80.

Craig, L., Lutz, A., Berry, K.A., Yang, W., (2015). Recommendations for fluoride limits in drinking water based on estimated daily fluoride intake in the Upper East Region, Ghana. Sci. Total Environ. 532, 127–137

da Silva Peixoto F, Cavalcante IN, Gomes DF (2020). Influence of land use and sanitation issues on water quality of an urban aquifer. Water Resour Manage 34:653–674.

Devaraj, S., Jenifa Latha, C., Geetha Priya, M., Jesudhas, C.J., Yarrakula, K. (2022). Hydrological Modelling for Ungauged Basins: An Overview of the Past, Present, and Future Directions. In: Panneerselvam, B., Pande, C.B., Muniraj, K., Balasubramanian, A., Ravichandran, N. (eds) Climate Change Impact on Groundwater Resources. Springer, Cham.

Edzwald J.K and Tobiason J.E. (2011). Chemical principles, source water composition, and watershed protection (Chapter 3). In: Edzwald JK (ed.) Water Quality & Treatment: A Handbook on Drinking Water (6th edn). AWWA and McGraw-Hill, New York.

Einsiedl, F., Hertkorn, N., Wolf, M., Frommberger, M., Schmitt-Kopplin, P., & Koch, B. P. (2007). Rapid biotic molecular transformation of fulvic acids in a karst aquifer. *Geochimica et Cosmochimica Acta*, 71(22), 5474–5482.

Favreau G, Cappelaere B, Massuel S, Leblanc M, Boucher M, Boulain N, Leduc C. (2009). Land clearing, climate variability, and water resources increase in semiarid southwest Niger: a review. Water Resour Res 45(7):1–18.

Fest E.P.M.J, Temminghoff E.J.M, Griffioen J, Van Riemsdijk W.H. (2005) Proton buffering and metal leaching in sandy soils. Environ Sci Technol 39:7901–790822

Fest, E. P., Temminghoff, E. J., Griffioen, J., Van Der Grift, B., & Van Riemsdijk, W. H. (2007). Groundwater chemistry of Al under Dutch sandy soils: effects of land use and depth. *Applied Geochemistry*, *22*(7), 1427-1438.

Gauthier, V, Barbeau B, Milettes R, Block J-C and Prevost M (2001). Suspended particles in the drinking water of two distribution systems. Water Sci. Technol. Water Supply 1 237-245

Gourouza Marou, Zeinabou Mahamadou, Mabinty Bayo-Bangoura, Karifa Bayo, and

Anne Boos, (2019). Adsorption of fluorides on dromedary bones charred and enabled with HC, Asian Journal of Science and Technology, 09, (03), 9487-9491.

Grazuleviciene, R., Danileviciute, A., Nadisauskiene, R., & Vencloviene, J. (2009). Maternal Smoking, GSTM1 and GSTT1 Polymorphism and Susceptibility to Adverse Pregnancy Outcomes. *International Journal of Environmental Research and Public Health*, *6*(3), 1282-1297.

Hassane, A.; Leduc, C.; Favreau, G.; Bekins, B.; Margueron, T. (2016). Impacts of a large Sahelian city on groundwater hydrodynamics and quality: Example of Niamey (Niger). Hydrogeol. J. 2016, 24, 407–423.

Hassane, A.B. (2010). Shallow and Deep Aquifers and Urban Pollution in Africa: Case of the Urban Community of Niamey, Niger. Ph.D. Thesis, Department of Earth Science, Hydrogeology, Abdou Moumouni University, Niamey, Niger, (In French).

Heckman, N.N, M. (2023). AGES Support for Groundwater Management in the Niger Basin. BMZ-No.: 2019.2342.4 BGR-No.: 05-2411. DOI: 10.25928/AGES-BN-Geol.

Helte E, Säve-Söderbergh M, Larsson SC, Åkesson A. (2022). Calcium and magnesium in drinking water and risk of myocardial infarction and stroke-a population-based cohort study. Am J Clin Nutr. Oct 6;116(4):1091-1100.

International Atomic Energy Agency IAEA, report RAF/7/011. (2017). Integrated and Sustainable Management of Shared Aquifer Systems and Basins of the Sahel Region. Iullemmeden Aquifer System. Reproduced by the IAEA Vienna, Austria, 2017.

Jacqmin, H., Commenges, D., Letenneur, L., Barberger-Gateau, P., & Dartigues, J. F. (1994). Components of drinking water and risk of cognitive impairment in the elderly. *American journal of epidemiology*, *139*(1), 48-57.

Jaishankar M, Mathew BB, Shah MS, Gowda KRS. (2014). Biosorption of Few Heavy Metal Ions Using Agricultural Wastes. Journal of Environment Pollution and Human Health 2(1): 1–6

Kirmeyer, G.J., Le Chevallier, M., Baribeau, H., Martel, K., Thompson, G., Radder, L., Klement, W. and Flores, A. (2004). Optimizing chloramine treatment. 2nd edition. American Water Works Research Foundation and American Water Works Association, Denver, Colorado (AwwaRF Report 90993)

Kjøller C, Postma D, Larsen F (2004). Groundwater acidification and the mobilization of trace metals in a sandy aquifer. Environmental Science & Technology 38, 2829-2835

Knutsson, G. (1994). Acidification Effects on Groundwater—Prognosis of the Risks for Future. IAHS Publication No. 222.

Kurwadkar, S.; Kanel, S.R.; Nakarmi, A. (2020). Groundwater pollution: Occurrence, detection, and remediation of organic and inorganic pollutants. *Water Environ. Res.*2020, *92*, 659–1668.

Lapworth, D.J.; Nkhuwa, D.W.C.; Okotto-Okotto, J.; Pedley, S.; Stuart, M.E.; Tijani, M.N.; Wrigh, J. (2017). Urban groundwater quality in sub-Saharan Africa: Current status and implications for water security and public health. *Hydrogeol. J.* 2017, *25*, 1093–1116.

Lasagna, M., Franchino, E., & De Luca, D. A. (2015). Areal and vertical distribution of nitrate concentration in Piedmont plain aquifers (North-western Italy). In *Engineering Geology for Society and Territory-Volume 3: River Basins, Reservoir Sedimentation and Water Resources* (pp. 389-392). Springer International Publishing.

Lelykesehatan, (2011). Turbidity of Water. WordPress.Com, 2011

Mahamadou, Z., Moussa, R. S., Mounkaila, M., & Gourouza, M. (2022). Use of calcined camel bones for water fluoridation of five boreholes in the Maradi region, Niger. *World Journal of Advanced Research and Reviews*, *16*(3), 350-363.

Malago, J., Makoba, E., & Muzuka, A. N. (2017). Fluoride levels in surface and groundwater in Africa: a review. *American Journal of Water Science and Engineering*, *3*(1), 1-17.

Mapoma, H. W., & Xie, X. (2014). Basement and alluvial aquifers of Malawi: an overview of groundwater quality and policies. *African Journal of Environmental Science and Technology*, *8*(3), 190-202.

Melles, Z., & Kiss, S. A. (1992). Influence of the magnesium content of drinking water and of magnesium therapy on the occurrence of preeclampsia. *Magnesium Research*, *5*(4), 277-279.

Nagajyoti, P.C., Lee, K.D. & Sreekanth, T.V.M. (2010). Heavy metals, occurrence and toxicity for plants: a review. *Environ Chem.* 8, 199–216.

Nazoumou Y, Favreau G, Adamou M. M, & I. Maïnassara. (2016). Small-scale groundwater irrigation, a sustainable solution against poverty and food crises in Niger Cahiers Agricultures 25(1), 15003. https://doi.org/10.1051/cagri/2016005

Nemčić-Jurec, J., Ruk, D., Oreščanin, V., Kovač, I., Ujević Bošnjak, M., & Kinsela, A. S. (2022). Groundwater contamination in public water supply wells: risk assessment, evaluation of trends and impact of rainfall on groundwater quality. *Applied Water Science*, *12*(7), 172.

Nwankwo, C. B., Hoque, M. A., Islam, M. A., & Dewan, A. (2020). Groundwater constituents and trace elements in the basement aquifers of Africa and sedimentary aquifers of Asia: medical hydrogeology of drinking water minerals and toxicants. *Earth Systems and Environment*, *4*, 369-384.

Olofsson, B. (1994). Flow of groundwater from soil to crystalline rock. *Applied Hydrogeology*, *2*, 71-83.

Onipe, T., Edokpayi, J. N., & Odiyo, J. O. (2020). A review on the potential sources and health implications of fluoride in groundwater of Sub-Saharan Africa. *Journal of Environmental Science and Health, Part A*, *55*(9), 1078-1093.

Ousmane, B. I., Nazoumou, Y., Favreau, G., Babaye, M. S. A., Mahaman, R. A., Boucher, M., & Taylor, R. G. (2023). Changes in aquifer properties along a seasonal river channel of the Niger Basin: Identifying groundwater recharge pathways in a dryland environment. *Journal of African Earth Sciences*, *197*, 104742.

Ousmane, B.; Daddyga, A.; Soumaila, A.; Margueron, T.; Boubakar, A.; Garba, Z.; Ousmane, S. (2007). Origine de Ia pollution des nappes superficielles et profondes au niveau de Ia communauté urbaine de Niamey (Niger). *Afr. Geosci. Rev.14*, 375–398.

Paladino O., Seyedsalehi M., Massabo M. (2018). Probabilistic risk assessment of nitrate groundwater contamination from greenhouses in Albenga plain (Liguria, Italy) using lysimeters

Pantaleo, P.A.; Komakech, H.C.; Mtei, K.M.; Njau, K.N. (2018). Contamination of groundwater sources in emerging African towns: The case of Babati town, Tanzania. *Water Pract. Technol.*2018,*13*, 980–990.

Podgorski, J., & Berg, M. (2022). Global analysis and prediction of fluoride in groundwater. *Nature Communications*, *13*(1), 4232.

Prakash J, Agrawal SB, Agrawal M. (2022). Global Trends of Acidity in Rainfall and Its Impact on Plants and Soil. J Soil Sci Plant Nutr. 2023;23(1):398-419. doi: 10.1007/s42729-022-01051-z. Epub 2022 Nov 17. PMID: 36415481; PMCID: PMC9672585.

Rasic-Milutinovic, Z., Perunicic-Pekovic, G., Jovanovic, D., Gluvic, Z., & Cankovic-Kadijevic, M. (2012). Association of blood pressure and metabolic syndrome components with magnesium levels in drinking water in some Serbian municipalities. *Journal of water and health*, *10*(1), 161-169. Sengupta P. (2013). Potential health impacts of hard water. Int J Prev Med. Aug ;4(8):866-75. PMID: 24049611; PMCID: PMC3775162.

Rawat, K. S., Jeyakumar, L., Singh, S. K., and Tripathi, V. K. (2019). Appraisal of groundwater with special reference to nitrate using statistical index approach. Groundwater for Sustainable Development. 8, 49–58.

Razowska-Jaworek, L. (2014). *Calcium and Magnesium in Groundwater*. CRC Press.

Rice, E. W., Bridgewater, L., & American Public Health Association (Eds.). (2012). *Standard methods for the examination of water and wastewater* (Vol. 10). Washington, DC: American public health association.

Rodier J. (2009). The analysis of the water, Edit. Dunod, Paris, p. 1293- 1487/p.196

Röllin, Halina B. Claudina Nogueira, Bukola Olutola, Kalavati Channa and Jon Ø. Odland, (2018). Prenatal Exposure to Aluminum and Status of Selected Essential Trace Elements in Rural South African Women at Delivery. Int. J. Environ. Res. Public Health 2018, 15, 1494;

SAWQG, (1996). South African water quality guidelines, vol 1. Domestic use (2nd edn). Department of Water Affairs and Forestry, Pretoria.

Scanlon, B. R., Reedy, R. C., Stonestrom, D. A., Prudic, D. E., & Dennehy, K. F. (2005). Impact of land use and land cover change on groundwater recharge and quality in the southwestern US. *Global Change Biology*, *11*(10), 1577-1593.

Schlesinger, W. H., Klein, E. M., & Vengosh, A. (2020). Global biogeochemical cycle of fluorine. *Global Biogeochemical Cycles*, *34*(12), e2020GB006722.

Schock, M. R. (1990). Internal corrosion and deposition control. *MCGRAW-HILL, INC., (USA). 1194*,

Sci. Total Environ. 634:427–438.

Shaji, E., Sarath, K. V., Santosh, M., Krishnaprasad, P. K., Arya, B. K., & Babu, M. S. (2024). Fluoride contamination in groundwater: A global review of the status, processes, challenges, and remedial measures. *Geoscience Frontiers*,*15*(2), 101734

Shuaibu, A., Kalin, R. M., Phoenix, V., Banda, L. C., & Lawal, I. M. (2024). Hydrogeochemistry and water quality index for groundwater sustainability in the Komadugu-Yobe Basin, Sahel Region. *Water*, *16*(4), 601.

Singh, K. P., Mohan, D., Sinha, S., & Dalwani, R. (2004). Impact assessment of treated/untreated wastewater toxicants discharged by sewage treatment plants on health, agricultural, and environmental quality in the wastewater disposal area. *Chemosphere, 55*, 227–255.

Singh, S. K., Srivastava, P. K., Pandey, A. C., & Gautam, S. K. (2013). Integrated assessment of groundwater influenced by a confluence river system: Concurrence with remote sensing and geochemical modelling. *Water resources management, 27*(12), 4291–4313.

Solanki, Y. S., Agarwal, M., Gupta, A. B., Gupta, S., & Shukla, P. (2022). Fluoride occurrences, health problems, detection, and remediation methods for drinking water: A comprehensive review. *Science of the Total Environment*, *807*, 150601.

Soundala, P.; Saraphirom, P. (2022). Impact of Climate Change on Groundwater Recharge and Salinity Distribution in the Vientiane Basin, Lao PDR. J. Water Clim. Chang. 2022, 13, 3812–3829.

Sy, I., Koita, M., Traoré, D., Keita, M., Lo, B., Tanne, M., & Cissé, G. (2011). Vulnérabilité sanitaire et environnementale dans les quartiers défavorisés de Nouakchott (Mauritanie): Analyse des conditions d'émergence et de développement des maladies en milieu urbain sahélien. Revue en sciences de l'Environnement, 11, 1-17.

Takem, G. E., Kuitcha, D., Ako, A. A., Mafany, G. T., Takounjou-Fouepe, A., Ndjama, J., ... & Ayonghe, S. N. (2015). Acidification of shallow groundwater in the unconfined sandy aquifer of the city of Douala, Cameroon, Western Africa: implications for groundwater quality and use. *Environmental Earth Sciences*, *74*, 6831-6846.

Tankari Dan-Badjo A., Yadji G., Nomaou D. L., Moussa Tawaye O. (2012). Risk of Exposure of the Population OF Niamey (Niger) to Heavy Metals through the Consumption of Market Garden Products. Bio. Resources Review. Vol 2 N.

Turunen, K., Lukkarinen, V., & Korkka-Niemi, K. (2024). Chemical and isotopic evidence to clarify the salinity of the bedrock groundwater at Finnish mining site. *Journal of Hydrology: Regional Studies*, *51*, 101665.

United Nation. World Population Prospects (2019). https://population.un.org/wpp/.

United Nations, Department of Economic and Social Affairs, Population Division (2024). World Population Prospects 2024, Data Sources. UN DESA/POP/2024/DC/NO. 11. www.un.org/development/ desa/pdf.

United Nations, Department of Economic and Social Affairs, Population Division (2024). World Population Prospects 2024, UN DESA/POP/2024/DC/NO. 11.

Wannous, M., Osenbrück, K., Tanimoun, B., & Koeniger, P. (2024). Hydrochemical Characterisation of the Basement Aquifer with a Focus on the Origin of Nitrate in the Highly Urbanised Niamey Region, SW of Niger. *Water*, *16*(21), 3016.

Ward MH, Cantor KP, Cerhan J, Lynch CF, Hartge P. (2004). Drinking water nitrate and cancer: results from recent studies in the Midwestern United States [Abstract]. Epidemiology 15: S214.

Weiss, P. T., LeFevre, G., & Gulliver, J. S. (2008). Contamination of soil and groundwater due to stormwater infiltration practices, a literature review.

WHO (2008). Novaluron in drinking-water: Use for vector control in drinking water sources and containers. Background document for preparation of WHO Guidelines for drinking-water quality. Geneva, World Health Organization (WHO/HSE/AMR/08.03/11).

WHO, (2009). Calcium and magnesium in drinking-water: public health significance In: F. Kozisek (Eds.) Health and Regulatory aspects of calcium and magnesium in drinking water In: L. Razowska- Jaworek (Ed) Calcium and magnesium in drinking water; occurrence and significance for human health. International Association of Hydrogeologist selected papers. CRC Press, pp 135 – 145

WHO, (2011). Guidelines for drinking water quality. 4th Edition. A publication of the World Health Organization (WHO), Gutenburg, pp 468-475.

WHO, (2017). Report on one health, technical and ministerial meeting to address zoonotic diseases and related public health threats. Dakar. https://www.afro.who.int/sites/default/files/2017-pdf,

WHO. (2006). The world health report 2006: working together for health. ISBN 924 156317 6 https://iris.who.int/bitstream/handle/10665/43432/9241563176

WHO. Implementation of the International Health Regulations, (2005). report of the Review Committee on the Functioning of the International Health Regulations (2005) in Relation to Pandemic (H1N1) 2009. Doc. A64/10. May 5, 2011.

Wu J., Lu J., Wen X.H., Zhang Z.H., Lin Y.C. (2019). Severe Nitrate Pollution and Health Risks of Coastal Aquifer Simultaneously Influenced by Saltwater Intrusion and Intensive Anthropogenic Activities. Arch. Environ. Contam. Toxicol. 77:79–87.

Yasui, M., Ota, K., & Yoshida, M. (1997). Effects of low calcium and magnesium dietary intake on the central nervous system tissues of rats and calcium-magnesium related disorders in the amyotrophic lateral sclerosis focus in the Kii Peninsula of Japan. *Magnesium research*, *10*(1), 39-50.

Zhou, X., Shen, Y., Zhang, H., Song, C., Li, J., & Liu, Y. (2015). Hydrochemistry of the natural low pH groundwater in the coastal aquifers near Beihai, China. *Journal of Ocean University of China*, *14*, 475-483.

Peer-review history:
The peer review history for this paper can be accessed here:
https://www.sdiarticle5.com/review-history/129437