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RESEARCH ARTICLE

SPATIAL ASSESSMENT OF THE PHYSICOCHEMICAL PARAMETERS OF GROUNDWATER IN THE WATERSHED DRAINING THE COMMUNE OF TOÉCÉ, BURKINA FASO, WEST AFRICA

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ABSTRACT

This study focuses on assessing the quality of basement aquifers in the catchment area of the Toécé commune, located in the south-central region of Burkina Faso. It highlights the complex challenges of managing water quality, which is influenced by both geo-geogenic and anthropogenic factors. To analyse this spatial variability, geostatistical tools such as ordinary kriging and the inverse distance weighting (IDW) method were used to map the distribution of physico-chemical parameters based on 249 water samples taken from boreholes. These methods were used to identify areas sensitive to pollution, in particular those affected by high nitrate concentrations. The results show that groundwater quality is highly variable in the region, ranging from areas with good quality water to polluted areas. The study also recommends the use of isotopes for more precise mapping of recharge areas and a better understanding of infiltration flows, particularly in areas with high nitrate concentrations. This approach could provide crucial information for the implementation of sustainable management strategies and the protection of groundwater resources in this region and at national level.

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INTRODUCTION

Groundwater quality is a key factor in the management of water resources, particularly in regions where water supply is largely dependent on aquifers, as is the case in Burkina Faso. However, in addition to mineralisation linked to water-rock interaction, deforestation, human activities and their spatial distribution can also affect groundwater chemistry (Bonan, 1997; Pielke *et al.*, 1998; Pitman *et al.*, 2004). To ensure effective management of pollution sources and to develop a sustainable and integrated plan for the management of groundwater resources, it is crucial to have a good understanding of the current status of the chemical constituents that affect groundwater quality (Howard, 2015; Khan *et al.*, 2016). In areas such as the catchment draining the commune of Toécé and its surrounding area in the south-central region, which is underlain by crystalline basement aquifers, monitoring and assessing water quality is crucial to ensuring access to safe drinking water and preventing health risks. However, this task presents significant challenges, not least the difficulty of measuring water quality parameters over vast areas and the costs associated with such monitoring, particularly in developing countries.

To overcome these obstacles, spatial interpolation techniques such as kriging and inverse distance weighting (IDW) are proving to be effective tools for estimating the distribution of groundwater quality from a limited number of samples. These methods can also estimate pollutant concentrations in unsampled areas, providing valuable information on possible changes in groundwater quality (Losser *et al.*, 2014; Webster and Oliver, 2001; Xiao *et al.*, 2016). They can be used to map the physico-chemical parameters of water, taking into account spatial dependence, and to identify areas that are sensitive to pollution or variations in quality that require special management (Sako and Kafando, 2021). Whereas kriging is a sophisticated geostatistical technique that integrates both mathematical and statistical approaches to provide more accurate estimates, IDW is based on deterministic principles that use mathematical functions. Kriging is considered a more efficient linear unbiased estimator because it incorporates spatial correlation and dependence into its predictions (Büttner *et al.*, 1998; Clark, 1979; Isaaks and Srivastava, 1989). Kriging is often considered one of the most accurate interpolation methods and is commonly used in groundwater quality studies (Araghinejad and Burn, 2005; Bhuiyan *et al.*, 2016).

In Burkina Faso, most groundwater studies have focused on a limited number of quality parameters, such as NO_3^-, $NH4^+$(Groen *et al*., 1988; Millogo *et al*., 2020, 2024; Ouandaogo-Yameogo *et al*., 2013; Sako *et al*., 2016). To our knowledge, no geochemical characterisation study using spatial distribution has been carried out in the catchment area draining the commune of Toécé and its surrounding area. The aim of this study is to gain an understanding of the physico-chemical quality of groundwater and to use geostatistical methods (kriging and IDW) to analyse the spatial variations in its parameters in the catchment area draining the commune of Toécé and the surrounding area. By applying advanced geostatistical tools, this research aims to provide essential information for the sustainable management of groundwater in the region, helping to put in place appropriate strategies for preserving this vital resource for local populations.

DESCRIPTIONOF STUDY SITE

Environmental setting: The study area, which is the watershed draining the commune of Toécé and the surrounding area, is located in the centre-south region of Burkina Faso. (Figure 1). The climate is of the Sudanian-Sahelian type, characterized by distinct alternating dry and rainy seasons. Average temperatures ranged from 25 to 40 °C. The hottest months are October, March, and April, while August and December are the coldest. Rainfall is unevenly distributed both temporally and spatially, with an annual average of approximately 800 mm. Isohyets are moving further south as a result of increasingly low rainfall (DGMB, 2010). The hydrographic network in the area is dense, and the region lies within the boundaries of two distinct watersheds. The land is primarily used for agriculture, including subsistence rainfed crops, orchards, and market gardening. Patches of vegetation are scattered throughout the farmland. The availability of water, though often temporary, supports irrigation, particularly at the onset of the dry season. Livestock farming is also practiced on the more expansive lands. These activities collectively exert pressure on water resources and may influence their quality. The farmland is dotted with vegetation in places. The presence of water, albeit temporary, encourages irrigation, especially at the start of the dry season. Livestock farming is also practised on the extensible land. All these activities increase the pressure on water resources and can have an impact on their quality.

Geological and hydrogeological settings: The study area is underlain by a crystalline foundation composed mainly of granitoids, which make up the majority of the surface outcrops (Figure 2). The granitoids are oriented in a NE-SW direction, aligning with the schistosity of the surrounding greenstone belts. Two distinct generations of granitoids are present in the area. The first generation, known as the early granitoids, is characterized by a low degree of weathering and is extensively fractured. The second generation is more recent and less fractured, with a thin weathered layer. Late magmatic activity is evidenced by the intrusion of dolerites, which appear as NNE-SSW oriented dykes, discontinuous over several tens of kilometres. These dykes are primarily found in the southern and southwestern portions of the study area (Kagambega, 2005; Kagambega and Castaing, 2003). Advanced lateritization affects all the terrains. The porosity of laterites, coupled with lithostructural discontinuities predominantly oriented NE-SW, provides preferential pathways for the infiltration of meteoric waters. These features may also facilitate the movement of accidental or diffuse pollution within the area. Alluvium composed of gravel, sand, and clay is found in rivers or along riverbanks, sometimes extending over considerable distances.

MATERIAL AND METHODS

Sample collection and analysis: For this investigation, a total of 249 groundwater samples were obtained from boreholes tapping into fractured crystalline aquifers within the watershed that drains the city of Manga. To ensure that the samples represented the groundwater itself, rather than water that had stagnated in the boreholes, the wells were pumped during 10 to 15 minutes prior to sampling, in accordance with the procedure recommended by (Webster and Oliver, 2001). To minimize potential interference from microbial activity on the groundwater chemistry, each sample was filtered through a 0.2 µm filter capsule and then transferred into two sets of pre-conditioned polyethylene bottles. One set was acidified to a pH of less than 2 with ultra-pure nitric acid (HNO_3) to maintain ion stability, and these samples were designated for analysis of major cations and trace elements. The concentrations of major anions were measured in the non-acidified samples. Key physicochemical parameters, including pH, temperature, electrical conductivity (EC), and turbidity, were determined in situ with minimal exposure to atmospheric conditions, using a calibrated field meter. Analytical accuracy was verified by calculating the ionic balance error, as described in Equation 1.

$$\text{IBE } (\%) = \frac{\sum Cations - \sum Anions}{\sum Cations + \sum Anions} x 100 \quad (1)$$

In general, the value of IBE should be less than ± 5%, and certainly less than ± 10% (Domenico and Schwartz, 1990). In this study, all samples had IBE values lower than 10%. To better understand the chemistry of water samples, diagram software was employed to characterize the hydrochemical facies.

Spatial interpolation: Spatial distribution maps of groundwater quality parameters were generated through the ordinary kriging method. If the skewness of the data was less than 0.5, no transformation was necessary. However, for data with skewness greater than 0.5, a transformation was applied prior to conducting the geostatistical analysis. Variogram analysis and kriging interpolation were performed using the geostatistical tools available within the ArcGIS software. For each groundwater quality parameter, the characteristics of the semi-variogram were analyzed, including the partial sill, the total sill, the nugget effect, and the range. The ratio of the nugget to the total sill was calculated to assess the spatial dependence of the parameters. A nugget/threshold ratio of less than 24% indicates strong spatial dependence, suggesting that the parameter is mainly influenced by internal or natural factors. A ratio of between 25% and 75% indicates moderate dependency, with natural and anthropogenic factors playing a role. Finally, a ratio greater than 75% means that the parameter is weakly correlated spatially and could come mainly from external sources (Mehrjardi *et al*., 2008). The optimal model was selected based on the results of cross-validation tests. The predictive performance of the fitted models was assessed using several indicators: mean error (ME), root mean square error (RMSE), standardised root mean square error (RMSSE) and average standard error (ASE).

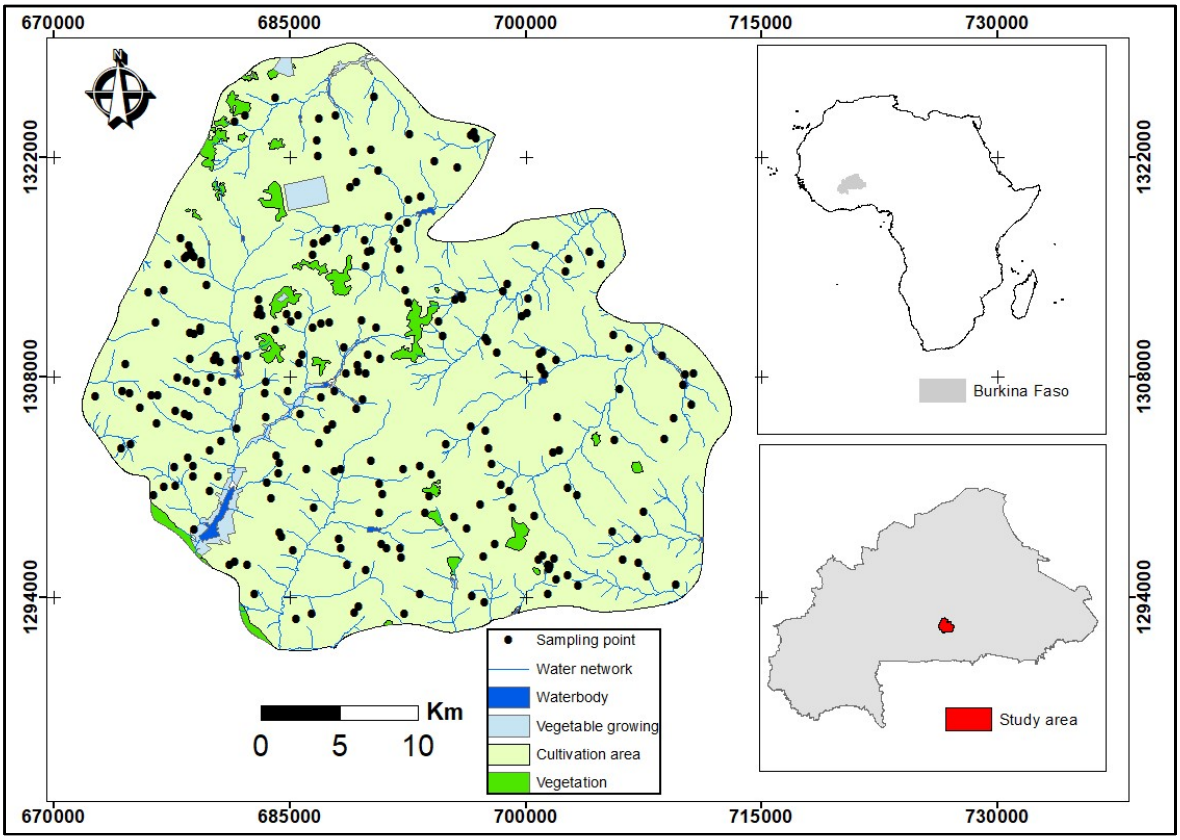

Figure 1. Geographical location of the groundwater sampling sites and land occupation map showing major regional watercourses in study areas

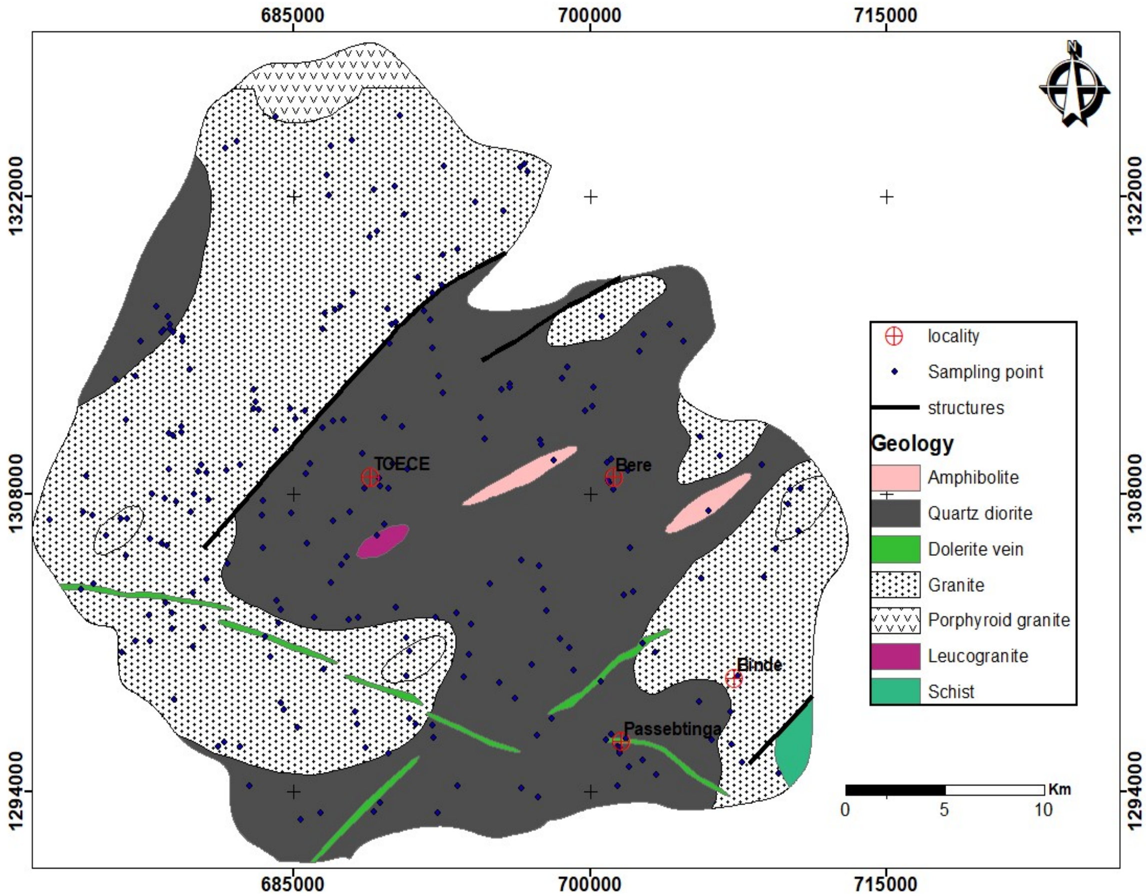

Figure 2. Simplified geological map of the study area

RESULTS AND DISCUSSION

Hydrochemical parameters: The analysis of all water samples represented on the Piper diagram reveals a predominance of bicarbonate-calcium and bicarbonate-calcium-magnesium water types. This projection reveals a composition dominated by bicarbonate-calcium and bicarbonate-calcium-magnesium types in the cation triangle (Figure 3).

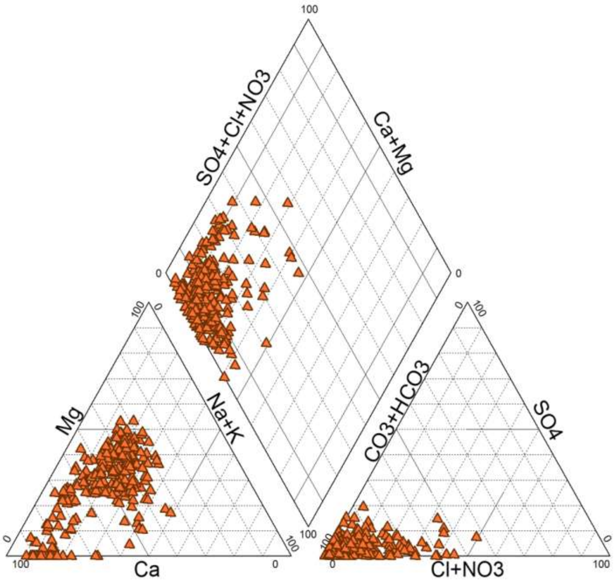

Figure 3. Piper's Trilinear plot diagram on hydrochemical facies for the major ions of water samples

This profile is characteristic of groundwater influenced by carbonaceous rocks and/or natural ion exchange with the soil (Millogo *et al*., 2024; Ouandaogo-Yameogo *et al*., 2013). Only five groundwater samples (around 2%) had NO_3^- levels above WHO standards. Concerning the anion triangle, there was a low presence of NO_3^-, Cl^-, and SO_4^{2-} suggesting low contamination by anthropogenic sources, such as intensive agriculture or industry (Sako *et al*., 2016). The lack of dominance of these anions in the majority of waters also indicates that the waters are poorly subjected to substantial inputs of mineral salts or nitrate pollution, commonly associated with fertilisers and wastewater. These results therefore suggest that the water quality in the study area is relatively well preserved, with mineralisation mainly influenced by natural interactions between the water and the geological substrate. Table 1 below shows the variation in values for each physico-chemical parameter in the groundwater samples analysed in the study area.

The pH of the sampled groundwater ranged from 4.5 to 7.9, with a mean value of 6.43 ± 0.52, indicating that the groundwater is predominantly neutral in nature. The lowest pH values were concentrated in the north-western and south-western parts of the study area due to substantial CO_2 gain from rainwater, whereas pH increased slightly in the east and south-east part of the area (Figure 4a) due to H^+consumption following prolonged water-rock interactions (Hinkle and Polette, 1999). The lowest EC and TDS values are concentrated to the west and south of the study area, while the highest are to the east (Figure 4b,4c). The spatial distribution of EC provides a general trend of the groundwater mineralisation, and it ranged from 130 to 907 µS/cm with an average of 255.02 ± 107.31 µS/cm.

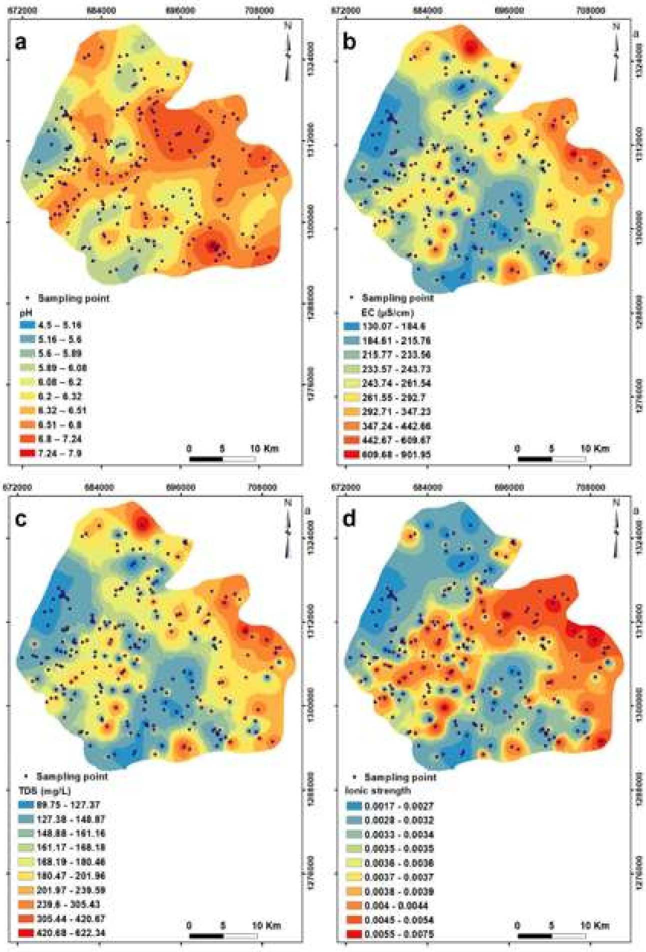

Figure 4. Spatial distribution maps of selected physico-chemical parameters of the groundwater sampled in central south region of Burkina Faso: a pH, b EC (µS/cm), c TDS and d ionic strength. All the parameters, except pH, were do with IDW

Groundwater with low ionic strength (i.e., <0.005) suggest a high rate of freshwater influx into the aquifer, typically corresponding to recharge areas. Conversely, groundwater with high ionic strength indicate reduced freshwater inflow, and these regions are generally regarded as discharge areas. (Hem, 1961). Only 10% of the samples, mainly in the eastern part of the study area, had an ionic value greater than 0.005. The remaining 90% (IS<0.005) cover the rest of the area, with zones of very low values in the north, north-west and south (Figure 4d). These zones (IS<0.005) are the preferred locations for groundwater recharge. However, it can be noticed that the lowest TH values were observed in the recharge area, whereas, the higher TH values were found in area with long residence time/discharge area (Figure 5a). Sodium concentrations ranged from 3.05 to 23.73 mg/L (average=8.16mg/L) with the higher Na^+ concentrations in the western part (Figure5b). Due to its limited mobility during chemical processes, K^+ concentrations in groundwater are generally lower than Na^+ concentrations (Wu *et al*., 2017), ranging from <1 to approximately 8.14 mg/L (average = 4.25 ± 1.08 mg/L). Similarly, K^+ concentrations exhibited an increasing trend from recharge areas towards discharge areas (Figure 5c). However, the high standard deviation and high skewness observed reflect extensive spatial variation and possible anthropogenic or localised weathering contributions of sulphide minerals to SO_4^{2-} concentrations in groundwater (Figure 6a) (Berner and Berner, 1987).

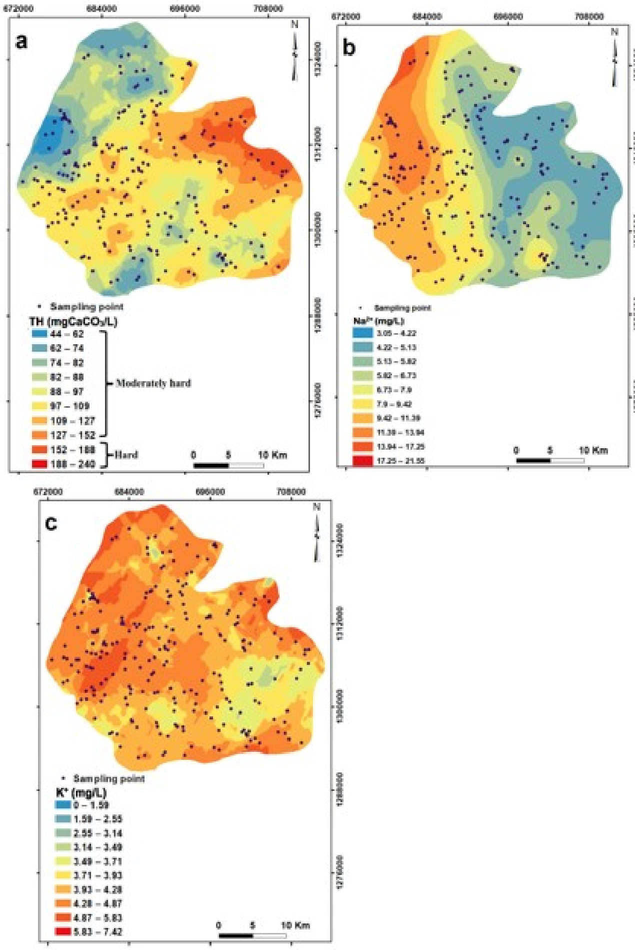

Figure 5. a–c Spatial distribution maps of total hardness (TH), Na^+ and K^+ with recharge areas showing lower TH and Na^+,

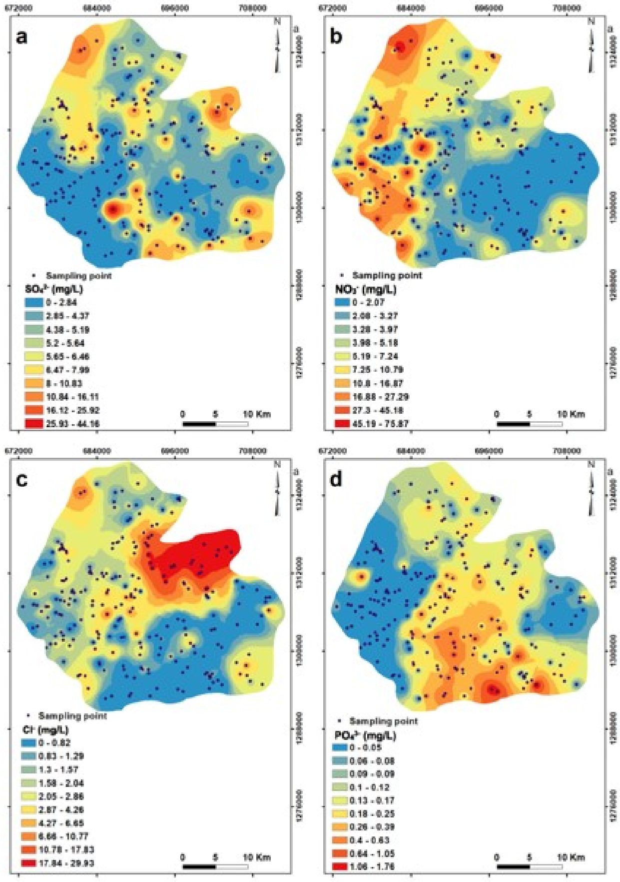

Figure 6. Spatial distribution maps of groundwater major anions after log-transformation: a SO_4^{2-}, b NO_3^-, c Cl^- and d PO_4^{3-}

NO_3^- concentrations in excess of WHO standards were found in 16% of boreholes, mainly concentrated in the eastern part of the study area. The high concentration was found in the south of study area (Figure 6b). Cl^- concentrations varied from <1 to 29.94 mg/L. All the samples had chloride concentrations well below the WHO standard, with the highest concentrations in the north-east of the study area (Figure 6c). Phosphate concentrations ranged from <1 to 1.77 mg/L with an average =0.15 ± 0.23 mg/L. The high concentration was found in the south of study area (Figure 6d). Fluoride concentrations in groundwater samples ranged from <0.04 to 2.08 mg/L, with an average of 0.37 ± 0.36 mg/L. The highest values of fluoride were found in southern west of the study area (figure 7a). Total iron concentrations ranged from <1 to 23.3 mg/L, with an average of 1.07 ± 2.06 mg/L. Iron concentrations are variable throughout the study area and do not appear to be related to lithology (Figure 7b). The calculated Water Quality Index (WQI) ranged from 16 to 146.33, with an average of 35.37 ± 22.29. Based on these results, the groundwater quality varied from "excellent" (WQI = 1–25) to "unfit for consumption" (WQI > 150). Interestingly, groundwater samples of average, poor and inadequate quality were mainly found in areas with high pH values and high concentrations of SO_4 (Figure 7c).

Spatial dependence: Variogram analysis was used in this study to assess the spatial distribution of groundwater quality parameters. With the exception of Mg^{2+}, K^+ and pH, the other parameters had a high positive asymmetry (>0.5) and were therefore log-transformed prior to variogram and kriging analysis; sampling points with Cl^-, NO_3^- and

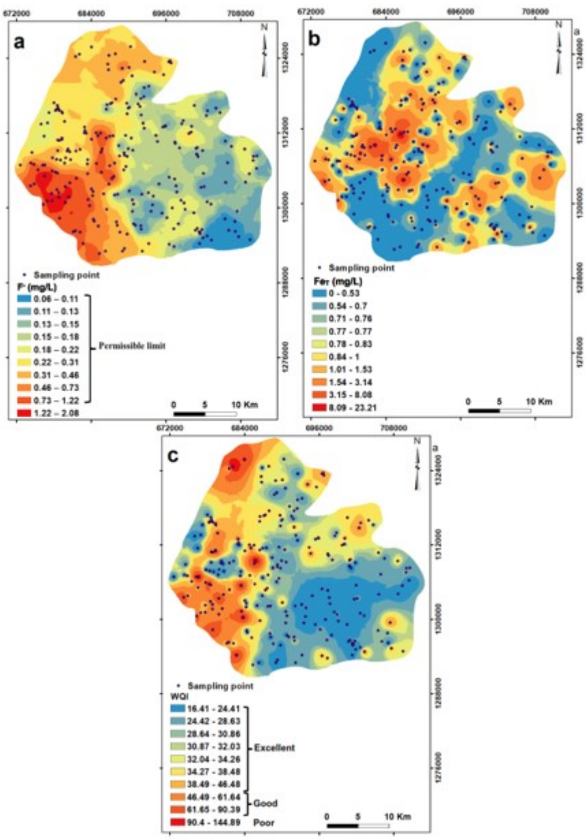

Figure 7. a–c Spatial distribution maps of a F^-, bFe_T, cgroundwater quality index (WQI)

Table 1. Univariate statistical summary of physico-chemical Parameters of the groundwater samples

Parameter	Unit	N	Min	Max	Mean	Median	Std. D	WHO standard (2008)
pH		249	4.50	7.90	6.43	6.40	0.52	6.5-9.2
IS		249	0.00	0.01	0.00	0.00	0.00	
TDS	mg/L	249	89.70	625.83	175.96	160.77	74.04	1000
EC	µS/cm	249	130.00	907.00	255.02	233.00	107.31	400-500
TH	mg/L	249	40.00	400.00	104.38	96.00	45.01	25
Ca^{2+}	mg/L	249	9.62	138.87	28.67	22.44	16.44	100
Mg^{2+}	mg/L	249	0.00	26.21	8.37	8.72	5.70	200
Na^{+}	mg/L	249	3.05	23.73	8.16	7.03	3.59	200
K^{+}	mg/L	249	0.00	8.14	4.28	4.16	1.08	12
HCO_3^-	mg/L	249	65.88	610.00	142.33	134.20	58.71	100
Cl^-	mg/L	249	0.00	29.94	3.65	1.50	6.28	250
SO_4^{2-}	mg/L	249	0.00	44.25	4.53	3.28	5.13	250
NO_3^-	mg/L	249	0.00	76.66	6.71	1.40	13.31	45
F^-	mg/L	249	0.04	2.08	0.37	0.22	0.36	1.5
PO_4^{3-}	mg/L	249	0.00	1.77	0.15	0.07	0.23	0.5
Fe_T	mg/L	249	0.00	23.44	1.07	0.48	2.06	0.3
Mn	µg/L	249	0.00	0.41	0.01	0.00	0.04	400
WQI	mg/L	249	16.22	133.61	34.68	28.68	20.05	

Std. D: Standard deviation

Table 2. Indices of best- fit semivariogram models and cross-validation coefficients of the groundwater physico-chemical parameters

Variable	Method	Fitted model	Nugget	Range	Partial sill	Sill	(Nugget/ Sill)x100	ME	RMSE	MSE	RMSSE	ASE	Spatial dependence
pH	OK	Spherical	0.10	6982.63	0.16	0.25	38.26	0.00	0.38	0.00	0.97	0.40	Moderate
TH	OK	Exponential	0.04	3162.74	0.04	0.08	48.67	-0.62	30.50	-0.04	1.05	29.41	Moderate
Na^{+}	OK	Spherical	0.03	47.052	0.29	0.32	9.37	-0.009	1.98	0.01	0.97	1.92	Strong
HCO_3^-	OK	Exponential	0.00	581.76	0.06	0.06	0.00	-1.17	38.99	-0.06	1.08	36.22	Strong
Mg^{2+}	OK	Gaussian	18.93	16668.96	15.34	34.27	55.24	-0.02	4.79	0.00	1.05	4.55	Moderate
Ca^{2+}	OK	Exponential	0.13	8013.10	0.13	0.26	48.86	0.95	8.89	0.05	0.72	14.75	Moderate
K^{+}	OK	Gaussian	1.09	479.85	0.18	1.27	85.53	0.02	1.06	0.01	0.88	1.20	Weak
Cl^-	OK	Gaussian	0.62	17535.62	1.14	1.75	35.15	-0.18	3.41	0.00	1.10	5.77	Moderate
F^-	OK	Gaussian	0.11	2971.44	0.23	0.34	33.58	0.01	0.19	-0.01	0.99	0.26	Moderate

OK: Ordinary Kriging, IDW: Inverse Distance Weighting, ME: mean error, RMSE: root mean square error, MSE: mean standardised error, RMSSE: root mean square

PO_4^{3-} concentrations below detection limits were excluded from the analysis. Despite the log transformation, the calculated WQI, IS, TDS, EC, SO_4^{2-} , PO_4^{3-} , NO_3^- and Fe_T values showed a high level of skewness (i.e. skewness > 0.5). Consequently, the IDW interpolation method was used to produce a spatial distribution map of the parameters values, as this method does not require spatial autocorrelation and does not assume that the values are normally distributed (De Marsily, 1989; Issaks and Srivastava, 1989). After cross-validation analyses, spherical, exponential and Gaussian models were selected to model the spatial correlations of the parameters (table 2). If the RMSE is close to the ASE, the prediction errors are assumed to be correctly estimated (Nikroo *et al*., 2010; Sun *et al*., 2009). If the RMSE is lower than the ASE, the variability of predictions is overestimated. Conversely, if the RMSE is greater than the ASE, the variability of the predictions is underestimated. The same can be deduced from the RMSSE, which must be close to unity. If the RMSSE is greater than unity, the variability of the prediction is underestimated. Similarly, if the RMSSE is less than one, the variability is overestimated (Nas and Berktay, 2010). Most models had ME and MSE values close to 0, while RMSSE values were close to 1. In addition, the ASE values for all parameters were similar to the RMSE values (table 2), indicating the overall predictive accuracy of the models. Potassium had the smallest spatial correlation distance (i.e. range), followed by, HCO_3^-, etc., while K^+ had the highest values. The nugget effect varied from 0 to 85%. The K^+ displayed, with nugget effects of 85.53%, had a low spatial dependence, perhaps indicating an anthropogenic origin for these parameters. Iron is not linked to anthropogenic pollution because of its low correlation (0.0064) with nitrate. This therefore implies an increase in iron content linked to the interaction between the borehole water and the dewatering equipment (i.e. the pump). Many of the hand pumps used to operate boreholes are not made of stainless steel. This shows that, despite the resources invested to obtain quality water for consumption, the operating equipment can make it unfit for human consumption. Sodium, HCO_3^-, with nugget effects of 20.56 and 0, respectively, showed strong spatial dependence attributable to their solely geogenic origin. In contrast, the other parameters (pH, TH, Mg^{2+}, Ca^{2+}, Cl^- and F^-) were moderately dependent in the study area. In other words, the abundance of these parameters in groundwater could be influenced by both geogenic and anthropogenic factors.

CONCLUSION

This study highlights the complexity of groundwater chemistry in the Toécé catchment and the need for integrated management approaches that take account of geogenic and anthropogenic influences on water quality. The parameters measured, such as pH, electrical conductivity, nitrate, sulphate and iron concentrations, vary according to local geology and human practices, particularly farming. Geostatistical tools have been used to map these disparities and highlight the most vulnerable areas. The water quality index (WQI) showed varied results, with some areas having good quality water, while others were degraded by pollution.

Following on from the results obtained, we propose the use of isotopes to accurately map recharge areas and further our understanding of infiltration flows, particularly in areas with high nitrate concentrations. This method would provide detailed information on the hydrological and geochemical processes affecting groundwater quality, making it easier to put in place sustainable management strategies aimed at preserving the region's water resources in particular and the country as a whole in general.

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