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Spatial assessment of groundwater quality in the watershed draining the city of Manga, Burkina Faso, west Africa

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ABSTRACT: The groundwater in the catchment draining the town of Manga and the surrounding area, which is characteristic of crystalline basement aquifers, undergoes mineral exchange during its residence in the rocks. In addition, factors such as deforestation, human activities and their spatial distribution can influence the chemical composition of groundwater. To date, no geochemical characterisation study by spatial distribution has been carried out in the catchment area of the town of Manga. The main objective of this study was to determine the quality of groundwater and the spatial variations in its physico-chemical parameters. To achieve this, 94 water samples were collected from existing boreholes, stored in bottles, and sent to the laboratory for physicochemical analysis. The analysis results were processed and examined using univariate statistical methods for water quality, whereas kriging and inverse distance weighting (IDW) were employed to assess spatial distribution. The results indicate that the majority of samples exhibit excellent water quality, whereas some areas show elevated concentrations of specific ions, suggesting that the overall groundwater quality in the region remains largely intact. Spatial variations in pH, electrical conductivity, total dissolved solid and ionic strength were observed, with lower values in recharge areas and higher values in discharge zones of the aquifers. NO_3^- concentrations in excess of WHO standards were not found in boreholes. The highest values were mainly concentrated in the north and north-western part of the study area which are the recharge zone. Spatial analysis revealed areas with moderate spatial dependence, often associated with anthropogenic contamination sources or natural factors such as geogenic mineralization. This study provides a robust framework for understanding the spatial distribution of groundwater quality in the Manga watershed. The results obtained open a promising perspective by suggesting the use of isotopes to accurately map recharge areas and deepen the understanding of infiltration flows in regions with elevated nitrate concentrations.

Keywords: *Hydrogeochemical,groundwater quality, spatial assessment, Kriging, Inverse Distance Weighting, Manga*

INTRODUCTION

Groundwater in the catchment draining the town of Manga, like all crystalline basement aquifers, is subject to mineral exchange during its residence time in the rocks. Additionally, deforestation, human activities, and their spatial distribution can also affect the chemical composition of groundwater (Bonan, 1997; Pielke et al., 1998; Pitman et al., 2004). To effectively monitor and address these pollution sources and to develop a sustainable and integrated groundwater management plan, it is crucial to understand the present state of chemical components affecting the quality of groundwater quality (Howard, 2015; Khan et al., 2016).

Graphical methods like scatter plots and ion concentration diagrams are commonly used to evaluate the quality of groundwater from various origins. Nevertheless, these techniques do not uncover the spatial patterns that influence groundwater quality. Additionally, assessing quality parameters over extensive areas can be both costly and time-intensive, especially in economically disadvantaged countries like Burkina Faso. In order to overcome these limitations, spatial interpolation techniques, including Inverse Distance Weighting (IDW) and geostatistical methods (such as kriging and semivariogram analysis), could be used following an initial assessment with a limited number of samples. These approaches help analyze spatial dependencies and offer accurate estimates of

groundwater quality distribution (Nassri et al., 2024; Sako and Kafando, 2021). These techniques can also estimate pollutant concentrations in areas that have not been sampled, providing valuable insights into possible future changes in groundwater quality (Losser et al., 2014; Webster and Oliver, 2001; Xiao et al., 2016). While Inverse Distance Weighting (IDW) is a deterministic method based solely on mathematical functions, kriging is a geostatistical technique that combines both statistical and mathematical approaches. Kriging is considered a more effective 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 precise interpolation methods and is commonly employed in groundwater quality studies (Araghinejad and Burn, 2005; Bhuiyan et al., 2016). In Burkina Faso, most groundwater studies have concentrated on a limited number of quality parameters, such as NO_3^-, NH_4^+ (Groen et al., 1988; Millogo et al., 2024, 2020; 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 town of Manga.

Although kriging has been widely used in other geographical contexts, its application for the geochemical characterization of groundwater in Burkina Faso remains scarce. Moreover, this study represents a pioneering attempt to integrate advanced interpolation methods for detailed geochemical analysis in the Manga watershed, thereby offering new perspectives for the management and monitoring of water quality in the region.

As part of the plan to supply drinking water to the town of Manga, a number of high-flow boreholes are to be drilled. The aim of this study is firstly to understand the quality of groundwater in the region and secondly to identify spatial variations in its physico-chemical parameters. Hydrogeochemical analyses, as well as IDW and kriging methods, were used to achieve the objectives of the study. The results will help water resource managers to monitor groundwater quality in the catchment area of the town of Manga and to target areas that are less sensitive to pollution for future drilling projects.

STUDY AREA

2.1. Environmental setting

This study was conducted in the watershed that drains the city of Manga and its surrounding region, the administrative capital of the Zoundwéogo province in the Central-South part of Burkina Faso (Fig. 1).

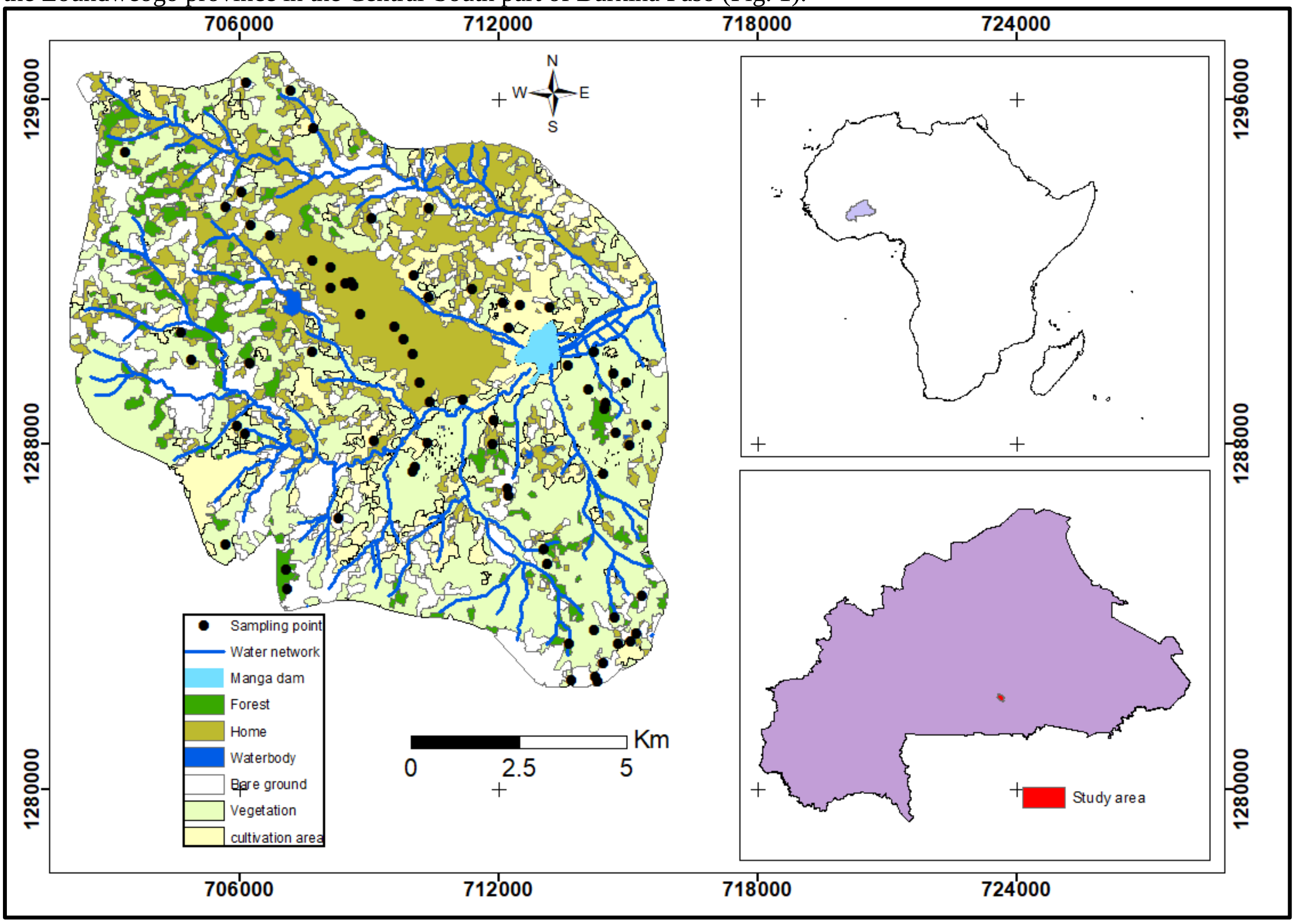


Fig. 1: Presentation of study area

Manga is situated within the Sudanian and Sahelian climatic zones, characterized by annual precipitation levels ranging from 600 to 900 mm. The region experiences a rainy season lasting 4 to 5 months, from May to October (Kagambega and Castaing, 2003), followed by a prolonged dry season of 7 to 8 months. Precipitation is erratic both spatially and temporally. The average annual rainfall is around 800 mm. Temperatures fluctuate between a minimum of 21°C and 22°C, and a maximum of 30°C to 35°C. Hydrologically, Manga lies within the Nakambé watershed, one of the country's primary hydrological basins. The predominant occupation of the municipality's population is agriculture and livestock rearing, with agricultural productivity being highly susceptible to climatic fluctuations. The city of Manga, with a population of around 205,000, relies mainly on groundwater for its drinking water supply. This dependence makes groundwater resources crucial to the well-being and public health of the local population. However, intensive agricultural activities and the use of various inputs, combined with environmental pressures, expose these resources to contamination risks, posing challenges to ensuring access to quality water for residents. These climate-related uncertainties, combined with ongoing soil degradation, loss of vegetation cover, and depletion of water resources, severely constrain agricultural output. Cultivated areas necessitate the use of fertilizers, and the majority of farmers rely on a combination of pesticides, organic fertilizers, and synthetic fertilizers to enhance crop yields. Furthermore, the increasing population density and unchecked urban expansion are rendering the soil impermeable, thereby restricting groundwater recharge. These combined pressures are expected to have a significant influence on groundwater quality in the region.

2.2. Geological and hydrogeological settings

Manga watershed is mainly situated on crystalline basement rocks, which consist of volcanic-sedimentary and plutonic formations, including granites, tonalites, and quartz diorites. Additionally, late magmatic processes are evident through the presence of dolerite dykes (Kagambega and Castaing, 2003; Sattran and Wenmenga, 2002) (Fig. 2).

These lithology formed altered and fractured aquifers (Dewandel et al., 2006). The recent model of basement aquifers, proposed by several authors (Lachassagne and Berkowitz, 2005; Ouandaogo-Yameogo et al., 2013; Taylor and Howard, 2000) distinguishes three (03) "layers" from bottom to top based on hydrogeological properties: (1) the top of the fractured basement, where fractures are tectonic in origin, generally sub-vertical, and act as major drains at depth; (2) an intermediate layer (the fractured zone). This is particularly prominent in granite formations, where it can attain thicknesses of several tens of meters. This zone is characterized by predominantly horizontal fractures. (3) The upper layer corresponds to the weathered portion of the rock, which can be further divided into two sections based on depth and the extent of weathering: the upper layer, known as the alloterites, and the lower layer, referred to as the isaloterites. The alloterites generally exhibit relatively low permeability due to their high clay content, yet they possess significant capacitive properties. These geological formations contain disseminated and vein-type sulfur minerals, which typically form gold metallotectics. The oxidation of these sulfur minerals, either through chemical weathering or exposure to air during gold extraction, can lead to the generation of acidic leachate rich in SO_4^{2-}. This leachate facilitates rock dissolution and enhances the mobility of trace elements in the environment, potentially contaminating groundwater. The discontinuous nature of aquifers and the distance from groundwater sources contribute to the drying up of traditional wells during the dry season, particularly those not located near watercourses. As a result, water supply in these areas increasingly depends on boreholes, typically equipped with manual pumps in rural regions. While these structures are theoretically less vulnerable, the pressures of population growth and increased chemical usage have led to the location of water points along fractures, which are the preferred recharge zones for the aquifers. Although these recharge zones are critical for ensuring the availability and sustainability of water resources, they also serve as conduits for anthropogenic pollutants, including nitrogen compounds, microorganisms, pesticides, chemical fertilizer runoff, and heavy metals.

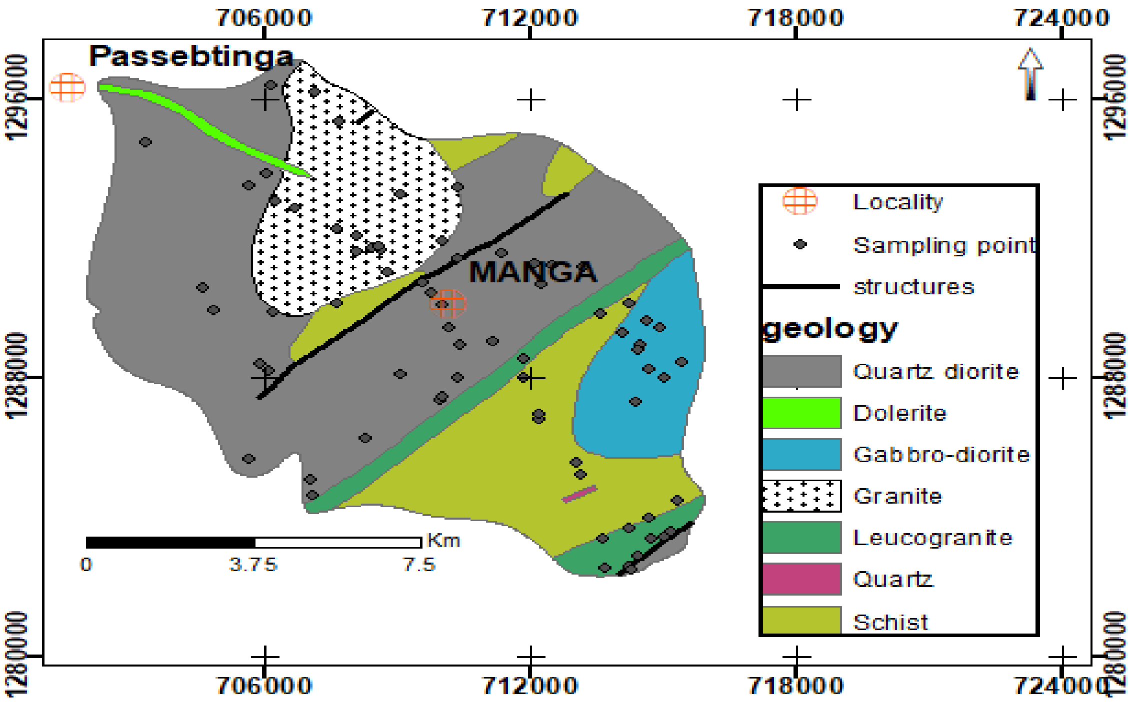


Fig. 2: Geological map

MATERIAL AND METHODS

3.1. Sample collection and analysis

For this study, we collected 94 groundwater samples from boreholes tapping fractured crystalline aquifers within the watershed draining the city of Manga. To ensure that the samples accurately reflected the groundwater, rather than water that had stagnated in the boreholes, we allowed the boreholes to be pumped for 10-15 minutes prior to sampling (Webster and Oliver, 2001). To minimize the influence of microbial activity on groundwater chemistry, each sample was filtered through a 0.2 μm filter capsule and transferred into two sets of pre-conditioned polyethylene bottles. One batch was acidified to a pH of less than 2 using ultra-pure nitric acid (HNO_3) to preserve ion stability and was subsequently used for the analysis of major cations and trace elements. The concentrations of major anions were determined in the non-acidified set of samples. Physicochemical parameters (pH, temperature, electrical conductivity, and turbidity) were measured in the field with minimal exposure to atmospheric conditions, using a calibrated meter.

The analytical accuracy was verified by calculating ionic balance error as follows (Eq. 1):

$$IBE\ (\%) = \frac{\sum Cations - \sum Anions}{\sum Cations + \sum Anions} x100$$

(1)

Generally, the IBE value should be less than ± 5%, and ideally under ± 10% (Domenico and Schwartz, 1990). In this study, all samples had IBE values below. To process the data, we used software such as Excel for statistical analysis, Diagramme fort the hydrochemical facies and ArcGIS for spatial assessment.

3.2. Spatial interpolation

Maps depicting the spatial distribution of groundwater quality parameters were created using the ordinary kriging method. If the skewness of the data is below 0.5, no transformation is necessary. However, if the skewness exceeds 0.5, data transformation must be applied prior to geostatistical analysis. The variogram analysis and the kriging interpolation were performed using the geostatistical tools integrated within ArcGIS software. For each groundwater quality parameter, the characteristics of the semi-variogram, including the partial threshold, the total threshold, the nugget and the range, were determined. The ratios between the nugget and the total threshold were used 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 chosen 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), standardized root mean square error (RMSSE) and average standard error (ASE).

RESULTS AND DISCUSSION

4.1. Hydrochemical parameters

The representation of all the waters analysed on the Piper diagram shows a bicarbonate-calcium and bicarbonate-calcium-magnesium dominance. This projection reveals a composition dominated by bicarbonate-calcium and bicarbonate-calcium-magnesium types in the cation triangle (Fig. 3). 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). Regarding the anion triangle, the low presence of NO_3^-, Cl^-, and SO_4^{2-} suggests an absence of significant contamination from anthropogenic sources, such as intensive agriculture or industry (Sako et al., 2016). The lack of dominance of these anions also indicates that the waters are not subjected to substantial inputs of mineral salts or nitrate pollution, commonly associated with fertilizers and wastewater. These results therefore suggest a relatively preserved water quality in the study area, with mineralization primarily influenced by natural interactions between 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.

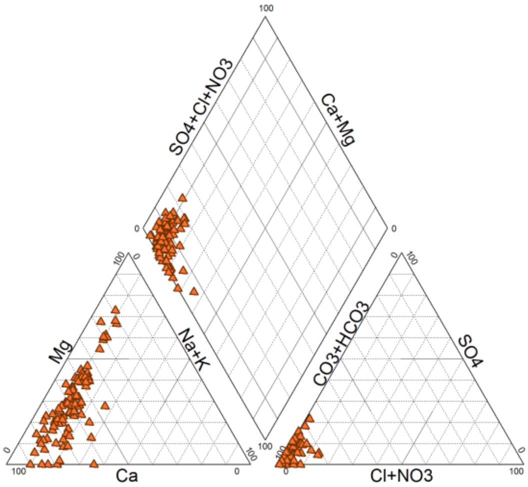


Fig. 3: Piper's Trilinear plot diagram on hydrochemical facies for the major ions of water samples

Table 1: Univariate statistical summary of physico-chemical parameters of the groundwater samples in the study area

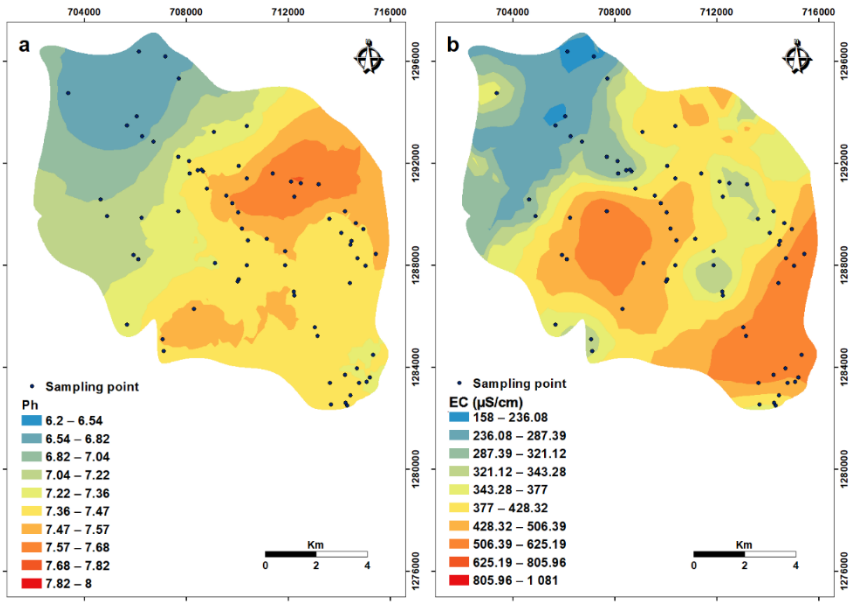
Parameter	Unit	N	Min	Max	Average	Std. D	WHO standard (2008)
pH		94	6.20	8.00	7.32	0.39	6.5-9.2
IS		94	6.20	8.00	7.32	0.39	
TDS	mg/L	94	0.00	2.10	0.04	0.22	1000
EC	µS/cm	94	109.02	745.89	296.06	115.89	400-500
TH	mg/L	94	158.00	1081.00	429.07	167.95	25
Ca^{2+}	mg/L	94	44.00	324.00	187.96	70.32	100
Mg^{2+}	mg/L	94	18.44	96.19	48.42	17.30	200
Na^{+}	mg/L	94	0.00	57.78	16.40	13.31	200
K^{+}	mg/L	94	2.30	11.96	8.00	2.24	12
HCO_3^-	mg/L	94	1.98	11.56	5.32	2.14	100
Cl^-	mg/L	94	85.40	463.60	238.49	86.42	250
SO_4^{2-}	mg/L	94	0.00	7.49	1.07	1.81	250
NO_3^-	mg/L	94	0.00	76.58	12.58	12.53	45
F^-	mg/L	94	0.00	10.94	1.27	2.61	1.5
PO_4^{3-}	mg/L	94	0.00	0.71	0.08	0.08	0.5
Fe_T	mg/L	94	0.00	1.77	0.09	0.20	0.3

Std. D: Standard deviation

4.2. Spatial distribution of hydrochemical parameters

In the north-western parts of the study zone, the lowest pH values were concentrated owing to substantial CO_2 absorption from precipitation. In contrast, pH values exhibited a slight increase in the eastern and southeastern regions (Fig. 4a), attributable to the consumption of H^+ ions as a result of extended water-rock interactions. (Hinkle and Polette, 1999). The lowest EC and TDS values are concentrated to the north-western of the study area, while the highest are to the centre and south-east (Fig. 4b,4c). The spatial distribution of electrical conductivity (EC) reflects the general trend of groundwater mineralization, ranging from 158 to 1081 µS/cm (average value of 429.07 ± 167.95 µS/cm).

Around 65% of the samples, mainly in the centre and south-eastern part of the study area, had an ionic strength value greater than 0.005. The remaining 35% (IS<0.005) spans the remainder of the area, with zones of very low values in the north and north-west (Fig. 4d). These zones (IS<0.005) are the preferred locations for groundwater recharge.



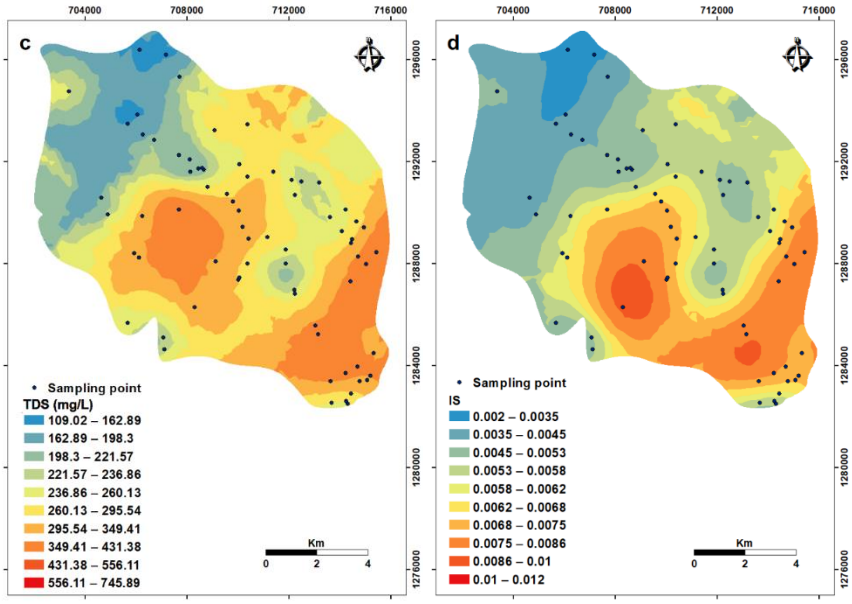
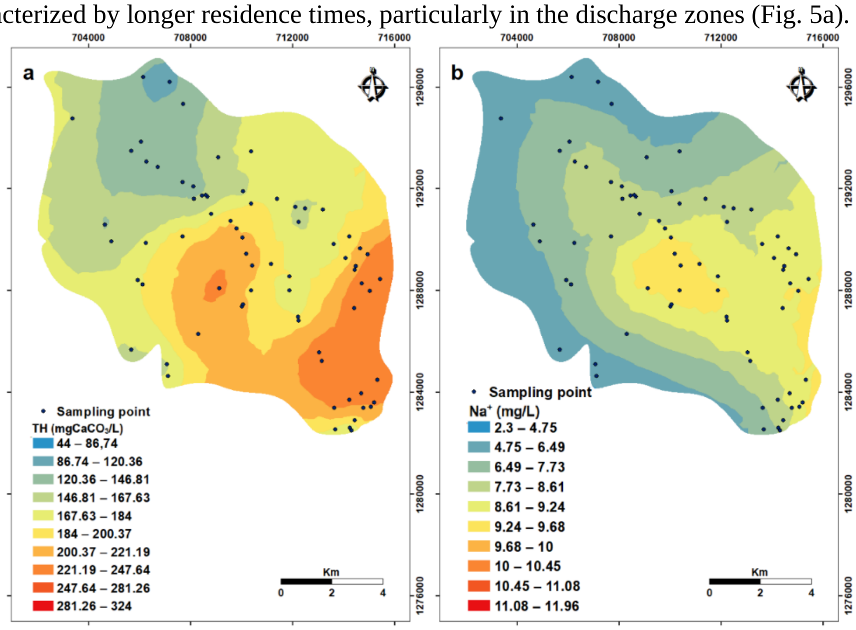


Fig. 4: Spatial distribution maps of selected physico-chemical parameters of groundwater samples from the Central-South region of Burkina Faso: **a** pH, **b** EC (µS/cm), **c** TDS and **d** Ionic strength

The results indicate that total hardness (TH) is primarily governed by Ca^{2+} and Mg^{2+} concentration, ranged from 44 to 324 mg $CaCO_3$/L with an average value of 187.96 ± 70.30 $CaCO_3$/L under WHO reference value (500 mg $CaCO_3$/L) for drinking water. However, it is noteworthy that the lowest TH values were recorded in the recharge areas, whereas the highest TH values were observed in regions characterized by longer residence times, particularly in the discharge zones (Fig. 5a).



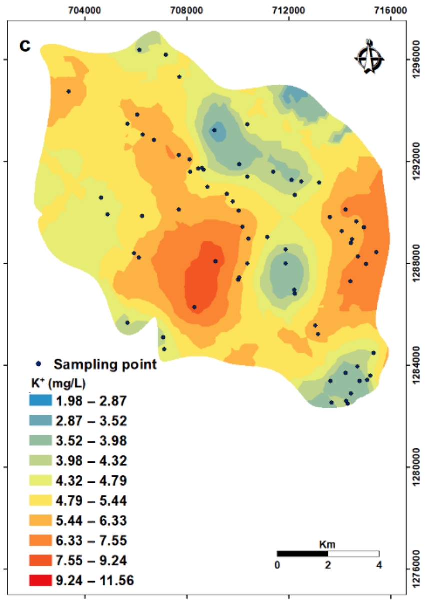


Fig. 5: a–c Spatial distribution maps of total hardness (TH), Na^+, and K^+, highlighting recharge areas with lower TH and Na^+ concentrations.

Sodium concentrations ranged from 2.30 to 11.96 mg/L (average = 8mg/L) with the higher Na^+ concentrations in the east and south-east part (Fig. 5b). K^+ concentrations in groundwater are relatively low compared with Na^+ concentrations (Wu et al., 2017), and varied from 1.98 to 11.96 mg/L (average = 5.32 ± 2.14 mg/L). In a similar manner, K^+ concentrations rose from the recharge zones towards the discharge zones (Fig. 5c).

All the samples thus exhibit SO_4^{2-} concentrations within the typical range for fresh groundwater. However, the considerable standard deviation and pronounced skewness observed suggest substantial spatial variability, possibly resulting from human activities or localized alteration of sulfide minerals, which contribute to SO_4^{2-} concentrations in the groundwater. (Fig. 6a) (Berner and Berner, 1987).

NO_3^- concentrations in excess of WHO standards were not found in boreholes. The highest values were mainly concentrated in the north and north-western part of the study area (Fig. 6b). Although the abundance of NO_3^- in groundwater is mainly linked to various anthropogenic sources (Appelo and Postma, 1993; Heaton, 1984) non-anthropogenic processes such as enrichment by evaporation, nitrogen fixation by organisms or water-rock interactions have also been recognized as potential contributors to NO_3^- concentrations in groundwater in semi-arid environments. (Aranibar et al., 2003; Heaton et al., 1983; Holloway and Dahlgren, 2002). Nitrates are regarded as the most prevalent form of groundwater contamination resulting from human activities (Ngo Billong et al., 2023; Rezaei et al., 2020) primarily due to their high solubility in water and the challenge of immobilizing them in soil (Abascal et al., 2022). Chloride concentrations varied from <1 to 7.49 mg/L. All the samples had chloride concentrations well below the WHO standard, with the highest concentrations in the north and southwest of the study area (Fig. 6c). Phosphate was identified in 85 samples (i.e., 90.42%), with concentrations ranging from <1 to 1.77 mg/L, and an average of 0.09 ± 0.20 mg/L. The high concentration was observed in the north-west of study zone (Fig. 6d). Based on the calculated WQI, 90.42%, 8.51% and 1.06% of the groundwater samples had a WQI below 25, above 25 and above 50, respectively. It is interesting to note that most groundwater samples were of excellent quality. The others of good quality were found in the north-west, central-east and south-east of the study area (Fig. 6e).

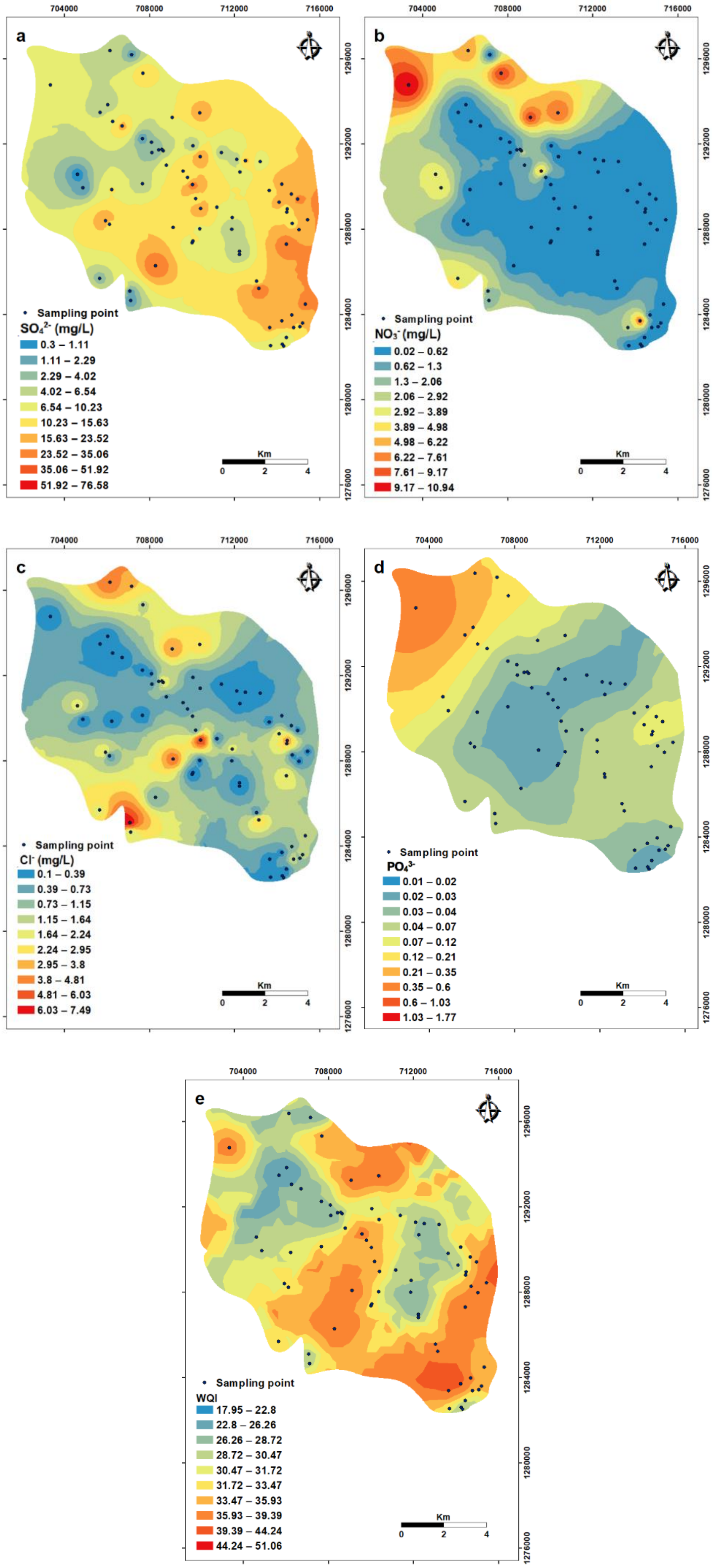


Fig. 6: Spatial distribution maps of the major anions in groundwater. **a** SO_4^{2-}, **b** NO_3^-, **c** Cl^-, **d** PO_4^{3-} and **e** WQI. Except PO_4^{3-} and WQI which are log-transformed, all the parameters were do with IDW.

In this study, the maps generated by kriging show that the values of pH, EC, TDS, and total hardness are lowest in the northern and northeastern regions of the study area. In contrast, nitrate (NO_3^-) concentrations reach higher levels in these regions, although they do not exceed the regulatory limits. This contrast may suggest a localized source of pollution specifically affecting nitrates, often associated with agricultural activities, fertilizer use, or the infiltration of wastewater (Barry, 2023). These results highlight the importance of monitoring nitrates in this area, as such concentrations may pose health risks and reveal distinct hydrological dynamics influencing the distribution of various chemical parameters.

4.3. Spatial dependence

In this study, variogram analysis was employed to evaluate the spatial distribution of groundwater quality parameters. With the exception of HCO_3^-, Na^+, WQI, IS, TH, and pH, the other parameters had a high positive asymmetry (>0.5) and were therefore log-transformed prior to variogram and kriging analysis; the variograms were then used to assess the spatial distribution of the groundwater quality parameters.

Sampling points with Cl^-, NO_3^- and SO_4^{2-} concentrations below the detection threshold were omitted from the analysis. Despite the logarithmic transformation, the calculated values for SO_4^{2-}, NO_3^-, Cl^-, and FeT displayed a significant level of skewness (i.e., skewness > 0.5). Therefore, the IDW interpolation technique was applied to create a spatial distribution map of the parameter values, as this method does not depend on spatial autocorrelation and does not presume that the values follow a normal distribution. (De Marsily, 1989; Issaks and Srivastava, 1989).

Following cross-validation analyses, spherical, exponential, and Gaussian models were selected to represent the spatial correlations of the parameters (Table 2). If the RMSE is similar to the ASE, it suggests that the prediction errors have been accurately estimated. (Nikroo et al., 2010; Sun et al., 2009).

If the RMSE is lower than the ASE, the prediction variability is overestimated. On the other hand, if the RMSE exceeds the ASE, the variability of the predictions is underestimated. The same conclusion can be drawn from the RMSSE, which should be close to unity. If the RMSSE is greater than unity, the prediction variability is underestimated. Similarly if the RMSSE is below one,, the variability is overestimated (Nas and Berktay, 2010).

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	0.55	9757.43	0.53	1.08	51.00	0.01	0.26	0.02	1.00	0.27	Moderate
EC	OK	Gaussian	0.09	22342.8	0.06	0.15	57.09	1.56	162.23	-0.03	1.01	162.39	Moderate
IS	OK	Gaussian	0.00	3091.97	0.00	0.00	52.41	0.00	0.00	0.00	1.01	0.00	Moderate
TH	OK	Exponential	0.64	7415.08	0.36	1.00	63.77	1.62	61.47	0.03	0.97	63.58	Moderate
Na^+	OK	Gaussian	2.19	12068.4	5.12	7.31	29.95	-0.01	1.54	-0.01	0.98	1.58	Moderate
HCO_3^-	OK	Gaussian	4080.0	2641.99	2910.9	6990.9	58.36	0.15	74.78	0.01	0.99	75.68	Moderate
Ca^{2+}	OK	Gaussian	0.10	1628.68	0.05	0.15	64.49	0.53	18.02	-0.02	0.96	19.65	Moderate
K^+	OK	Spherical	0.09	2680.11	0.08	0.17	50.88	0.00	2.06	-0.02	0.98	2.14	Moderate
PO_4^{3-}	OK	Spherical	0.68	6552.58	0.75	1.42	47.53	-0.01	0.19	-0.04	1.02	0.15	Moderate
F^-	OK	Gaussian	0.48	8699.12	0.26	0.74	65.20	0.00	0.08	-0.06	1.27	0.07	Moderate
WQI	OK	Spherical	27.22	1908.11	30.78	58.00	46.93	-0.19	7.68	-0.01	1.04	7.25	Moderate
TDS	OK	Exponential	0.08	4249.74	0.08	0.16	48.46	1.52	108.81	-0.01	0.98	112.80	Moderate
Fe_T	OK	Gaussian	0.00	7335.39	0.01	0.01	27.49	-0.87	26.93	-0.01	1.01	28.00	Moderate

OK: Ordinary Kriging, ME: mean error, RMSE: root mean square error, MSE: mean standardised error, RMSSE: root mean square standardised error, ASE: average standard error

Most models had ME and MSE values near 0, while RMSSE values were close to 1. Additionally, the ASE values for all parameters were similar to the RMSE values (Table 2), suggesting the overall accuracy of the model predictions.

Calcium had the smallest spatial correlation distance (i.e. range), followed by WQI, HCO_3^-, etc., while Na^+ had the highest values. The effect of nugget ranged from 27 to 65%. The F^- and Ca^{2+} showed nugget effects of 65.20% and 64.49%, respectively, reflecting weak spatial dependence, potentially pointing to an anthropogenic source for these parameters. Total iron and sodium, which have nugget effects of 27.48 and 29.95, respectively, exhibited the strongest spatial dependence, likely due to their purely geogenic origin. On the other hand, the remaining parameters (WQI, PO_4^{3-}, TDS, K^+, EC, and IS) showed moderate spatial dependence within the study area. This implies that the levels of these parameters in groundwater could be affected by both natural and human-induced factors.

CONCLUSION

The study of groundwater quality in the Manga watershed has provided valuable insights into the spatial distribution and geochemical characteristics of the region's groundwater resources. Based on hydrochemical analyses and the use of spatial interpolation techniques, such as kriging and Inverse Distance Weighting (IDW), we have identified clear spatial variations in key groundwater parameters, which included pH, EC, TH, and concentrations of major ions such as sodium, calcium, magnesium, and sulfate. These variations reflect the complex interactions between natural geological processes and anthropogenic activities, particularly agricultural practices, urban expansion, and the use of chemicals, which influence groundwater chemistry. The results indicate that the majority of groundwater samples are classified in the "excellent" quality category according to the Water Quality Index (WQI), suggesting that the overall groundwater quality in the region remains largely intact. Spatial analysis revealed areas with moderate spatial dependence, often associated with anthropogenic contamination sources or natural factors such as geogenic mineralization. This study provides a robust framework for understanding the spatial distribution of groundwater quality in the Manga watershed. The results obtained open a promising perspective by suggesting the use of isotopes to accurately map recharge areas and deepen the understanding of infiltration flows in regions with elevated nitrate concentrations. This approach would provide detailed insights into the hydrological and geochemical processes influencing groundwater quality, thereby facilitating the development of sustainable management strategies to protect the water resources in the area.

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No conflict of interest

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