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Research Article

Spatial Distribution Analysis of Groundwater Quality Parameters in the East Region of Burkina Faso Using GIS Techniques

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Abstract

Groundwater quality assessment is critical for achieving Sustainable Development Goal 6 (SDG-6), which aims to ensure the availability and sustainable management of water and sanitation for all. In Burkina Faso, groundwater is a vital natural resource supporting socio-economic development, particularly in arid and semi-arid regions where water scarcity and quality are significant challenges. Climatic conditions in the country made of a long, hot and dry season followed by a short rainy period, result in considerable variability in water availability. Rapid population growth exacerbates these challenges by increasing water demand in both urban and rural areas; therefore, putting additional pressure on the already limited water resources. Moreover, the expansion of mining and agricultural activities further stresses these resources with contaminations from use of hazardous substances and over-extraction. The use of fertilizers and pesticides contributes to pollution, posing serious risks to human health and local ecosystems. Given the strategic importance of groundwater for Burkina Faso development amidst these growing challenges, a comprehensive understanding of groundwater quality is essential. This study focuses on the Eastern Region of Burkina Faso and aims to analyze the spatial distribution of physicochemical parameters related to groundwater quality in order to support sustainable water resource management and public health initiatives. Water samples from 42 sites were collected and analyzed for parameters such as pH, electrical conductivity (EC), total dissolved solids (TDS), and concentrations of calcium, magnesium, sodium, potassium, chloride, sulfate, bicarbonate, and nitrate. The data were processed using the Inverse Distance Weighted (IDW) interpolation method in ArcGIS 10.8 to produce spatial maps of these parameters. A Water Quality Index (WQI) was calculated to classify groundwater quality as "Excellent" ($WQI < 50$), "Good" ($50 \leq WQI \leq 100$), or "Poor" ($WQI > 100$). The results revealed significant spatial variability in groundwater quality with concentrations sometimes exceeding WHO-standards. Specifically, 38.10% of the analyzed samples exceeded the standard for nitrates while 28.57% of the samples show turbidity above recommended thresholds. TDS levels vary considerably, reaching maximum values of 1,336 mg/L and electrical conductivity values reached 1,336 µS/cm. These results demonstrate marked heterogeneity in water quality parameters across the region. The generated maps could serve as valuable tool for decision-makers to enable identification of areas requiring particular attention for groundwater quality management.

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Keywords

Physico-chemical Parameters, Water Quality Index, GIS, Statistical Analysis, East-Region, Burkina Faso

1. Introduction

Groundwater is widely used for domestic, industrial, and agricultural activities worldwide. It stands out as one of the most precious natural resources, crucial for mankind's socio-economic development [33]. Given its pivotal role in supporting African continent's development for achieving United Nations sixth Sustainable Development Goal (SDG 6), groundwater is subject to numerous pressures. The degradation of groundwater resources is a key problem in Africa [41], with overexploitation and contamination identified as primary threats [20]. Recently, groundwater quality has become a major concern in Africa, with issues such as nitrate (NO_3) and arsenic highlighted [25, 28]. The sustainability of groundwater quality and quantity is crucial for drinking, domestic and irrigation purposes. As emphasized by some authors [37], the importance of water quality assessment for drinking water security, ecological integrity and sustainability is crucial. Regular monitoring of groundwater quality is necessary, coupled with public awareness campaigns. Water quality standards have been established for various water uses by different agencies [39] and serving as guidelines to determine water suitability.

In Burkina Faso, the hydraulic connectivity between groundwater resources and surface water makes them vulnerable to various forms of pollution; a critical situation exacerbated by 80% of the territory made of crystalline basements rocks with limited water potential. Monitoring the quality of these water resources is vital for the country's water management and sustainable development, particularly in the Eastern Region of Burkina Faso; the study area. This bad situation of the national water quality monitoring system is indeed stressed by scientists [10] to show that for twenty-two (22) stations installed within the Gourma Water Agency (AEG) basin out of the 80 national monitoring stations, recorded data series were discontinuous with very little utility. According to AEG website (https://eaugourma.bf/), many water quality problems are currently encountered in the region and often linked to anthropogenic activities like:

i. illegal use of chemical fertilizers and other crop treatment products (in vegetable and cotton cultivation);
ii. artisanal gold mining, and
iii. use of prohibited products in fishing.

Spatial distribution mapping of groundwater quality using GIS is an effective approach for preventing groundwater pollution. Indeed, GIS is widely recognized as a crucial tool for analysing spatial and temporal variations of groundwater quality [4, 18]. Scientists commonly use different GIS interpolations methods to map groundwater quality, with IDW interpolation being widely used for investigating the spatial distribution of physicochemical parameters [2, 32]. IDW is an algorithm used to spatially interpolate data or estimate measurement values, calculating weights inversely from the observation location to the point's estimated site [7].

In this study, GIS-based groundwater quality assessment is deemed crucial for sustainable socio-economic development, understanding vulnerability, and obtaining reliable information on current water quality status in the study area. The study provides an overview of groundwater conditions related to various water quality parameters, including temperature (T), pH, turbidity, TDS, electrical conductivity (EC), calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^+), potassium (K^+), bicarbonate (HCO_3^-), chloride (Cl^-), sulphate (SO_4^{2-}) and nitrate (NO_3^-). Additionally, Water Quality Index map (WQI) was derived to categorize groundwater quality in the study area. The results from the spatial distribution maps of the water quality parameters serve as crucial guidelines for the region, enabling the assessment of potential threats with insurance for water safety to drinking purposes.

2. The Study Area

2.1. General Information

In this study, we focus on Burkina Faso, a landlocked country of 274, 200 km^2 in West Africa. The country features diverse climatic zones with annual rainfall gradient ranging from 1200 mm in the South to less than 600 mm in the North [26]. Altitude values predominantly fall between 250 m and 350 m, with a maximum reaching around 750 m; resulting in a relatively flat relief [5].

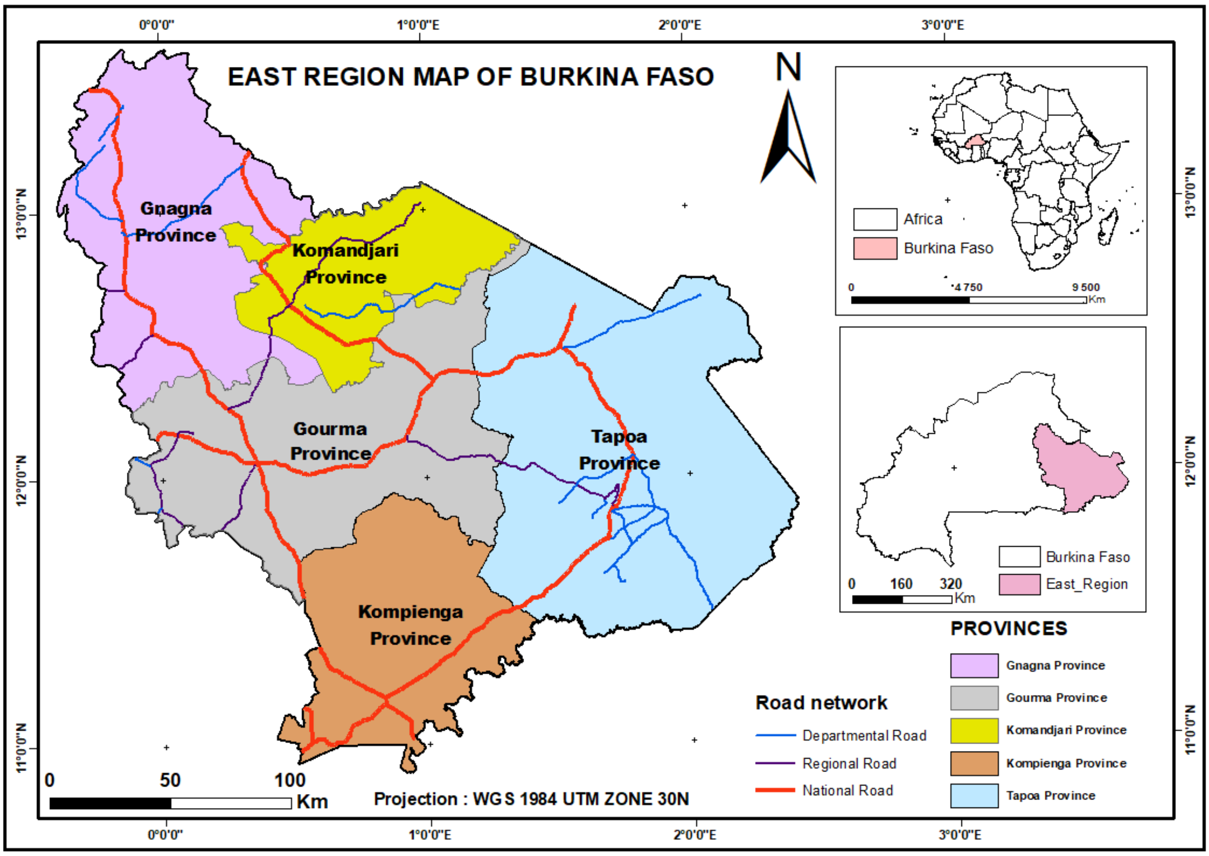


Figure 1. *Location of the study area in Burkina Faso.*

The specific area of interest in this study is the East Region, that is one of Burkina Faso 13 administrative regions established on July 2, 2001 (Figure 1). The capital city of this region is Fada N' Gourma. As of 2019, the living population of the region was 1,941,505 inhabitants with 51% being females. This population represents 9.47% of the whole country's population. The East Region is rich in terms of lands and natural resources, supporting both agriculture and pastoralism. It hosts extensive cross-border natural reserves and serves as a corridor for transhumant routes from northern Benin to western Niger, facilitating pastoralists access to livestock export market in the regional capital of Fada N'Gourma.

2.2. Geological and Hydrogeological Setting

Located on the southwest of the West African craton, Burkina Faso is essentially made of crystalline formations in more than 80% of its area. The geological history of the country is principally marked by 5 periods from the Precambrian to the Quaternary [19] bearing different formations. 80% of the country is underlain by geological formations composed of Paleoproterozoic granitoids of the Baoulé-Mossi domain [8] covered by Neoproterozoic sedimentary rocks in the west, north, and southeast and Cenozoic Continental Terminal rocks in the northwest and extreme east [31]. In this study, by operating under the assumption that the lithological map accurately represents the geological features and through the analysis of the "Groundwater Resources in the ECOWAS region", as developed recently [6], six lithological classes were identified within the study area. These classes include claystone; granite, gneiss and schist; sandstone; sandstone and clay; sandstone and claystone; and schist and quartzite (Figure 2a). Hydrogeology of Burkina Faso is closely linked to the geological structures and rainfall occurrence. Dominant aquifer flow type is a crucial parameter characterizing hydraulic properties of an aquifer and plays a significant role in successful groundwater prospection [6]. Therefore, building on the recent findings [14] regarding rock consolidation types (partly consolidated; consolidated, (meta-) sedimentary; and consolidated, metamorphic rocks), the aquifer types in the East region are categorized into two groups: (i) fractured and (ii) intergranular/fractured (Figure 2b). In Burkina Faso, the use of groundwater in a basement environment represents a major asset for rural populations, due to the questionable quality of surface water.

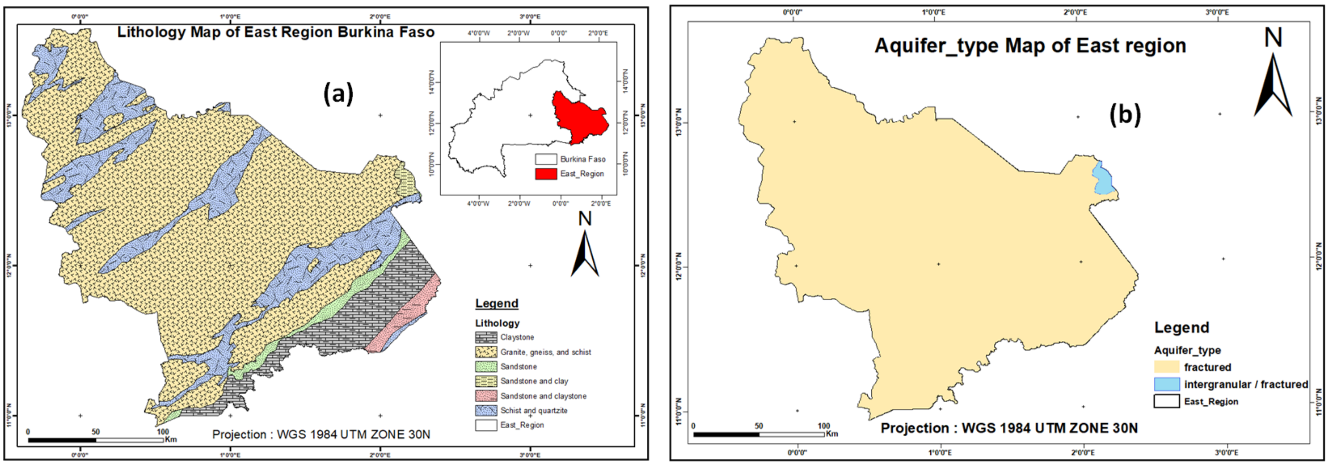


Figure 2. *(a) The geology map and (b) Aquifer flow type of the study area.*

3. Materials and Methods

3.1. Land Use/Land Cover Pattern in East Region

The groundwater quality in the settlement area is affected by anthropogenic activities like agriculture systems and seepage from un-sewered sanitation systems such as soakpits and septic tanks. For example, Land Use/Land Cover (LULC) is a parameter that represents a potential anthropogenic factor specially related to nitrate (NO_3^-) contamination in groundwater. Using ESA World Cover 10m, v200 10 database [42] within the Google Earth Engine platform, LULC information was derived for the East Region at a spatial resolution of 10 m. Distinct categories of LULC include bare/sparse vegetation, built-up, cropland, grassland, herbaceous wetland, permanent water bodies, shrubland and tree cover.

Water sources identified in the East Region are subject to multiple uses depending on accessibility, water quality and flow. Based on these criteria, the main observed uses include among others, drinking water supply (50%), small-scale agriculture (30%), livestock watering (100%), and other domestic uses. A same water source can be used for multiple purposes.

3.2. Data Availability

Water quality data for this study were selected from 42 sampling locations based on groundwater quality information reported by Burkina Faso water resources office (DGRE) for year 2020.

Table 1. *Database for spatial analysis of water quality.*

Sample N°	NO_3^- (mg/l)	Ca^{2+} (mg/l)	Mg^{2+} (mg/l)	Na^+ (mg/l)	K^+ (mg/l)	HCO^3 (mg/l)	Cl^- (mg/l)	SO_4^{2-} (mg/l)	EC (S/m)	TDS (mg/l)	T (℃)	pH	Turbidity (NTU)
S1	105.6	50.36	16.67	23.7	21.7	225.7	4.14	4.0	554	554	32	6.09	1.56
S2	51.48	17.04	20.33	6.00	1.00	124.44	1.7	2.0	207	208	31.3	6.04	0.46
S3	64.24	48,0	28.14	23.5	1.9	291.58	2.61	7.0	495	495	29.8	6.62	0
S4	107.8	53.16	27.68	14.4	1.00	197.8	3.24	2.0	527	527	31.6	6.92	0
S5	127.6	49.88	30.61	18.0	2.2	245.7	3.57	10.0	561	561	32.4	6.51	0.03
S6	73.48	88.32	51.74	35.3	3.2	488.6	3.55	10	850	850	32.1	7.03	0.53
S7	62.92	31.6	14.25	27.6	1.5	160.3	2.23	2.00	385	385	31.8	6.68	2.58
S8	93.28	51,0	21.90	6.0	0.8	205.5	2.6	5	494	494	33.7	6.93	0
S9	74.8	57.76	32.35	5.8	1	274.13	3.75	11	593	593	33.3	7.09	0.1
S10	51.04	55.16	31.14	22.9	3.00	318.42	2.25	2	542	542	31.4	7.02	0.87
S11	183.04	104.52	67.64	37.8	5.00	503.6	1.54	18	1173	1173	31.7	6.92	0.86
S12	59.84	34,0	21.61	20.9	1.2	189.1	2	4	398	398	31.1	6.61	1.13

Sample N°	NO_3^- (mg/l)	Ca^{2+} (mg/l)	Mg^{2+} (mg/l)	Na^+ (mg/l)	K^+ (mg/l)	HCO^3 (mg/l)	Cl^- (mg/l)	SO_4^{2-} (mg/l)	EC (S/m)	TDS (mg/l)	T (℃)	pH	Turbidity (NTU)
S13	71.55	52,0	32.06	80.2	1	469.1	12.4	2	623	623	30.6	7.42	1.77
S14	68.64	55.2	33.08	19.5	0.6	338.92	1.7	6	572	572	31.2	7.07	2.58
S15	115.72	84.56	48.86	26.8	2.3	404.67	5.31	19	415	415	32	6.75	0.7
S16	3.96	31.96	6.41	6.7	1.2	139.08	0.77	5	190	190	29.6	7.73	60.6
S17	47.52	39.72	20.76	18.5	2.1	206.7	1.81	2	410	410	31.8	6.84	5.02
S18	8.8	25.96	24.34	11.1	0.9	209	0.68	2	301	301	33	6.83	1.55
S19	3.96	34.04	32.35	12	1.5	276.82	0.65	2	355	355	30.5	7.32	0.34
S20	1.32	38.2	23.38	3.8	0.8	265.96	1.5	2	338	338	33.8	7.3	0.74
S21	1.76	28.56	14.18	5.0	0.9	164.21	0.84	2	260	260	32.7	7	1.18
S22	0.44	45.92	24.37	54.9	1.3	419.9	0.73	22	721	721	32.4	7.32	1.85
S23	11.44	14.04	13.09	1.8	0.6	106.3	0.58	4	37.5	37.5	30.2	5.84	39.75
S24	15.4	15.32	24.05	2.1	1.3	148.23	0.76	3	92.2	92	27.2	5.91	101.8
S25	1.32	33.44	16.09	3.2	0.5	195.81	0.35	2	164.6	164.6	32.7	6.04	106.1
S26	0.88	50.8	12.83	5.1	0.9	235.46	0.58	2	342	342	33.01	6.66	2.04
S27	10.12	75.48	31.58	3.7	1.2	377.47	0.81	2	429	429	32.1	7.27	0.8
S28	9.68	26.36	12.61	3,00	2.4	152.5	0.49	2.0	207	207	29.4	6.96	14.96
S29	3.96	36.24	9.53	1.8	3.4	175.92	0.41	2.0	282	282	29.1	7	41.54
S30	10.56	29.28	9.46	9.4	1.2	164.7	1.02	2.0	228	228	32.1	6.56	4.22
S31	3.52	32.48	30.03	36.1	1.3	352.9	1,00	5.0	449	449	32.2	6.7	2.96
S32	2.64	20.64	38.38	13.8	1.5	275.72	0.79	3.0	376	376	32.9	7.05	2.87
S33	7.92	23.6	13.36	9.8	2.2	164.7	0.88	2.0	264	264	32.5	6.64	3.1
S34	6.6	54.6	45.04	29	3	404.9	0.73	2.00	561	561	31	6.94	4.17
S35	3.96	24.56	14.18	2.2	1.2	161.28	0.83	2.00	169	169	28.4	6.45	7.83
S36	10.56	50.32	35.48	7.6	0.7	347.33	1.58	3	520	520	31.6	7.03	2.16
S37	71.55	52,0	32.06	80.2	1	469.1	12.4	2	623	623	30.6	7.42	1.77
S38	10.56	12.8	17.74	4.2	0.7	141.40	0.55	2	158	158	31.9	6.13	2.2
S39	0.44	10.8	5.88	0.6	2.4	82.23	0.6	2	63.4	63	23.1	7.81	26.5
S40	7.04	28.16	17.13	7.1	0.9	194.71	0.53	2	224	224	27.8	6.36	6.36
S41	3.96	17.64	10.53	1.0	2.3	118.34	0.51	2	64.1	64	28.7	7.15	14.33
S42	0.44	125.72	75.48	18.1	70.8	859.2	0.85	2	1336	1336	30.7	6.9	85.12

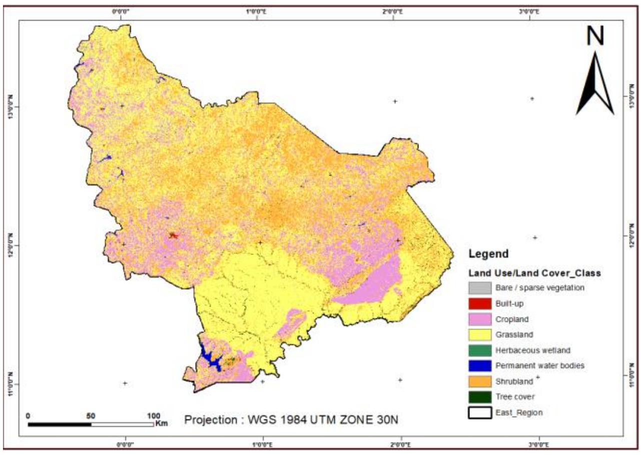


Figure 3. Land use map in East Region.

3.3. Geo-statistical Analysis

3.3.1. GIS Interpolations Analysis

A spatial distribution study is a crucial tool for understanding the spatial variation of groundwater hydro-chemical parameters. In this particular study, the spatial distribution map of groundwater quality parameters was created using ArcGIS 10.8^{TM} with the spatial statistical analysis module and the IDW interpolation technique. The IDW interpolation method employs a model that calculates undefined values based on nearby points rather than distant ones. According to [11], every observation is projected in an IDW interpolation as well as a weighted average of the neighbouring sample points. This interpolation technique was used by several investigators in their study (inverse distance weighted) techniques [36, 38, 23]. This approach is known for its precision, and the results can be easily interpreted compared to other interpolation methods [18, 3]. Additionally, this type of interpolation fits to real-world parameters. Spatial distribution maps of water quality parameters and the Water Quality Index (WQI) were generated.

3.3.2. Statistical Analyses

The statistical correlation analysis has proven to be a highly suitable technique for identifying correlations among numerous physicochemical determinants, representing a significant advancement in surface water and groundwater quality management [24]. The correlation study is valuable for uncovering predictable relationships that can be practically exploited, enabling the measurement of the strength and statistical significance of the relations between two or more water quality parameters [17]. In this study, the interrelationship of the sampled water quality determinants was examined using a correlation matrix. In this method, a normalization of the determinants was conducted to mitigate the scaling effect, considering the different measuring scales of the representative samples. The approach involves a computer-based normalization procedure, where selected variables are divided by their maximum values. As highlighted by scientists [22], the use of statistical analysis contributes to a better understanding of the interactions and variations among physicochemical determinants.

3.3.3. Water Quality Index Evaluation

The Water Quality Index (WQI) is a valuable tool used to evaluate succinctly the overall water quality status. Developed by a researcher [15], WQI assigns a single numerical value that encapsulates the overall water quality at a specific location and time, considering various water quality parameters. The IDW interpolation method was used in this study to generate a spatial distribution map of WQI values. This method was chosen because it does not rely on spatial autocorrelation and does not assume that the values follow a normal distribution [12, 16].

The calculation of WQI value for each sample was carried out using established guideline values [40]. This index value serves as a comprehensive indicator, condensing multiple water quality parameters into a single metric to facilitate a more accessible and meaningful assessment of water quality at a given site and timeframe.

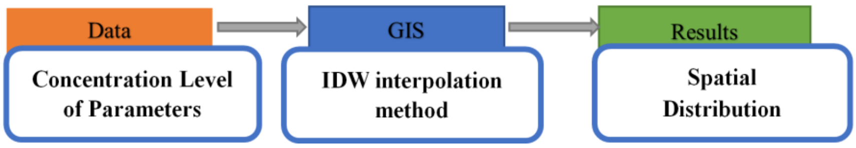


Figure 4. Methodology flowchart used in the study.

Table 2. Weight of physico-chemical parameters.

Parameter	WHO (2011) Standard (Si)	Weightages factor (wi)	Relative weight (Wi)
pH	7,5	4	0.129
Total Dissolved Solids (TDS)	500	4	0.129

Parameter	WHO (2011) Standard (Si)	Weightages factor (wi)	Relative weight (Wi)
Calcium (Ca^{2+})	75	2	0.0645
Magnesium (Mg^{2+})	30	2	0.0645
Sodium (Na^{+})	200	2	0.0645
Potassium (K^{+})	12	2	0.0645
Bicarbonate (HCO^{3-})	500	3	0.0967
Chloride (Cl^{-})	250	3	0.0967
Sulphate (SO_4^{2-})	200	4	0.129
Nitrates (NO_3^{-})	50	5	0.1612
Total	-	31	0.9996

The following steps are used to determine WQI.

Water quality parameters are assigned a weight (wi) according to their relative importance in the overall water quality for drinking purposes. Weights are assigned based on the previous studies by the researchers. The maximum weight of 5 has been assigned to the parameter NO_3, due to its major importance in water quality assessment. Similarly weight 4 has been assigned to pH, TDS and SO_4, weight 3 assigned to HCO_3 and Cl, weight 2 to Ca, Mg, Na and K.

Relative weight (Wi) is computed from the equation (1),

$$Wi = {}^{wi}/_{\sum wi} \quad (1)$$

A quality rating scale (qi) for each parameter is calculated using equation (2) below

$$qi = (Ci/Si) \times 100 \quad (2)$$

Ci is the concentration of each parameter in the water sample in mg/L.

Si is the prescribed standard value of each chemical parameter [40].

Sub Index SIi is to be determined for each chemical parameter using equation (3).

$$SIi = Wi \times qi \quad (3)$$

WQI is then determined with equation (4)

$$WQI = \sum SIi \quad (4)$$

The computed WQI values range from 20,4454325 to 139,575742 and therefore, can be categorized into three types of “Excellent, Good, and Poor water quality” (Table 3).

Table 3. *Classification of water quality.*

WQI value	Water quality type
< 50	Excellent
50 - 100	Good
100 - 200	Poor

4. Results and Discussion

4.1. Characteristics of Groundwater Hydrochemistry of the Study Area

The findings on the groundwater hydrochemistry samples are shown in Table 1. The statistical analysis of the groundwater quality parameters has been laid down in Table 4. Also, this Table includes the number of samples that exceed the limits parameter-wise, along with their respective values.

Table 4. *Results of water samples analysis in laboratory compared to WHO standards.*

Parameter	No	WHO standards (2011)	Concentration observed				No of samples out of WHO standards	Percentage (%) of samples exceed WHO standards
			Minimum	Mean	Maximum	SD		
pH (-)	42	6.5 - 8.5	5.84	6.83	7.81	0.46	8	19.04

Parameter	No	WHO standards (2011)	Concentration observed				No of samples out of WHO standards	Percentage (%) of samples exceed WHO standards
			Minimum	Mean	Maximum	SD		
EC (µS/cm)	42	1000	37.5	417.95	1336	268.24	2	4.76
TDS (mg/L)	42	1000	37.5	417.95	1336	268.25	2	4.76
Sodium (mg/L)	42	200	0.6	17.15	80.2	18.81	-	0.00
Potassium (mg/L)	42	12	0.5	3.70	70.8	11.08	-	-
Bicarbonate (mg/L)	42	250	82.22	267.80	859.2	147.55	-	-
Chloride (mg/L)	42	250	0.35	2.04	12.4	2.62	-	0.00
Nitrate (mg/L)	42	50	0.44	37.41	183.04	44.78	16	38.10
Sulphate (mg/L)	42	250	2	4.50	22	4.87	-	0.00
Calcium (mg/L)	42	200	10.8	43.12	125.72	24.52	4	9.52
Magnesium (mg/L)	42	50	5.88	25.92	75.47	15.13	3	7.14
Temperature (℃)	42	-	23.1	31.11	33.08	2.00	-	-
Turbidity (NTU)	42	5	0	13.21	106.1	26.99	12	28.57

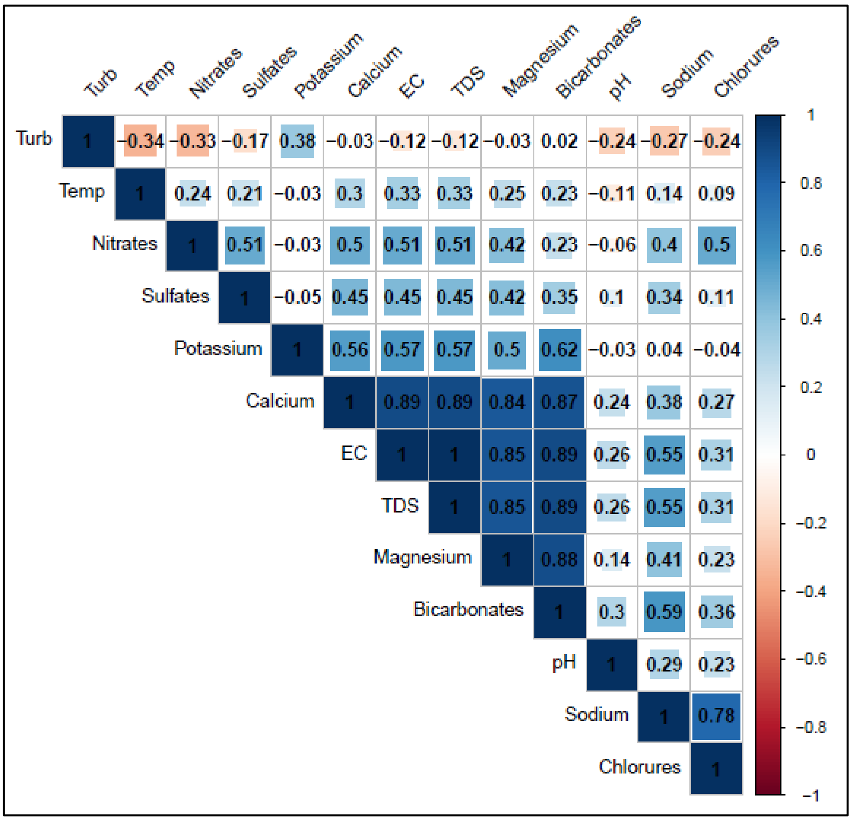


Figure 5*. Correlation matrix of water quality parameters.*

The relationship between the sampled water quality determinants was analysed using correlation matrix to derive correlation metrics. The results from the correlation are illustrated in Figure 5, representing the correlation matrix of water determinants at a significant level of p=0.05.

Sodium (Na^{+}) and Chloride (Cl^{-}): 0.78. A strong correlation between sodium and chloride is often indicative of salt water contamination or seawater intrusion. It can also indicate contamination by domestic or industrial wastewater.

Calcium (Ca^{2+}) and Bicarbonate (HCO_3^{-}): 0.87. This correlation is typical of groundwater circulating in limestone areas. It indicates carbonate rocks dissolution such as limestone ($CaCO_3$), which releases calcium and bicarbonates into the water.

Sulphate (SO_4^{2-}) and Calcium (Ca^{2+}): 0.45. A correlation between these two ions can indicate the dissolution of minerals such as gypsum ($CaSO_4$-$2H_2O$) in water. This dissolution increases sulphate and calcium concentration.

Nitrate (NO_3^-) and Chloride (Cl^-): 0.5. A correlation between nitrate and chloride can indicate pollution from domestic wastewater, agriculture (fertilisers) or landfill leachate. These sources can introduce both nitrates and chlorides into groundwater.

Magnesium (Mg^{2+}) and Sulphate (SO_4^{2-}): 0.42. The correlation between magnesium and sulphate can also be associated with the dissolution of evaporitic minerals such as epsomite ($MgSO_4$-$7H_2O$) or the alteration of volcanic rocks.

Calcium (Ca^{2+}) and Magnesium ($Mg^{2+)}$: 0.84. These two cations are often correlated in groundwater, as they often come from the same geological sources (dissolution of carbonate or silicate rocks). A strong correlation may indicate a cation exchange process or the alteration of rocks containing calcium and magnesium.

4.2. Spatial Analysis of Groundwater Quality

The results of the spatial mapping of water quality parameters are presented in Figure 6, and the following sections contribute to the discussion of the derived results from the considered parameters in the study.

Temperature: Naturally, water bodies show temperature changes daily and seasonally due to different activities that can contribute to changes in surface water temperature. This parameter measures range from 23.1 to 33.1 ℃.

pH of water is an important indicator for assessing the quality and pollution of any aquifer system as it is closely related to other chemical constituents of water. It is also the indicator of acidic or alkaline condition of water status. WHO recommended a maximum permissible limit of pH between 6.5 and 8.5. For this study, pH ranges from 5.84 to 7.81.

Electrical conductivity (EC) measures the ability of any substance or solution to conduct electricity through water. EC is directly proportional to the dissolved material in water sample. Pure water like distilled water is not a good electricity conductor but rather a good insulator. An increase in ion concentration enhances water electrical conductivity. In general, the number of dissolved solids in water determines its electrical conductivity. In the samples collected, EC ranges from 37.83 μS/cm to 1335.13 μS/cm.

Turbidity (Tur): Water turbidity, which reflects transparency, is an important criterion for assessing water quality. Turbidity values range from 0.01 to 104.58 NTU.

Total dissolved solids (TDS) are one of the most important characteristics of groundwater, which determines the quality of water for drinking and domestic purposes. This water quality parameter is essential for classifying groundwater and checking its suitability for various uses [9]. Water can dissolve a wide range of inorganic and organic minerals or salts such as potassium, calcium, sodium, bicarbonates, chlorides, magnesium, sulphates, etc. These minerals produced an un-wanted taste and diluted colour in the appearance of water. TDS is an important parameter for water use. Water with high TDS value indicates a highly mineralized water, which, when being dissolved solids, can cause health issues such as constipation [37]. In the study, TDS ranges from 37.5 to 1336 mg/L.

DO: Dissolved Oxygen is vital for aquatic life. The decomposing organic matter, dissolved gases, industrial and mineral wastes, and agricultural runoff result into lower DO levels [35, 1]. Concentration levels of DO below 5.0 mg/L adversely affect aquatic life [34].

Calcium and Magnesium are among the most common constituents in natural water and their salts are important contributors to water hardness. They are very essential minerals to human well-beings. Calcium ranges from 10.81 mg/L to 125.62 mg/L and Magnesium, from 5.88 mg/L to 75.43 mg/L in the study area.

Sodium: Sodium is a silver white metallic element found in low quantity in water. A proper quantity of sodium in human body prevents many fatal diseases like kidney damage, hypertension, headache, etc... Sodium exists in most groundwater. Many rocks and soils contain sodium compounds, which easily dissolve to liberate sodium in groundwater. Sodium in the study area ranges from 0.6 to 80.2 mg/L.

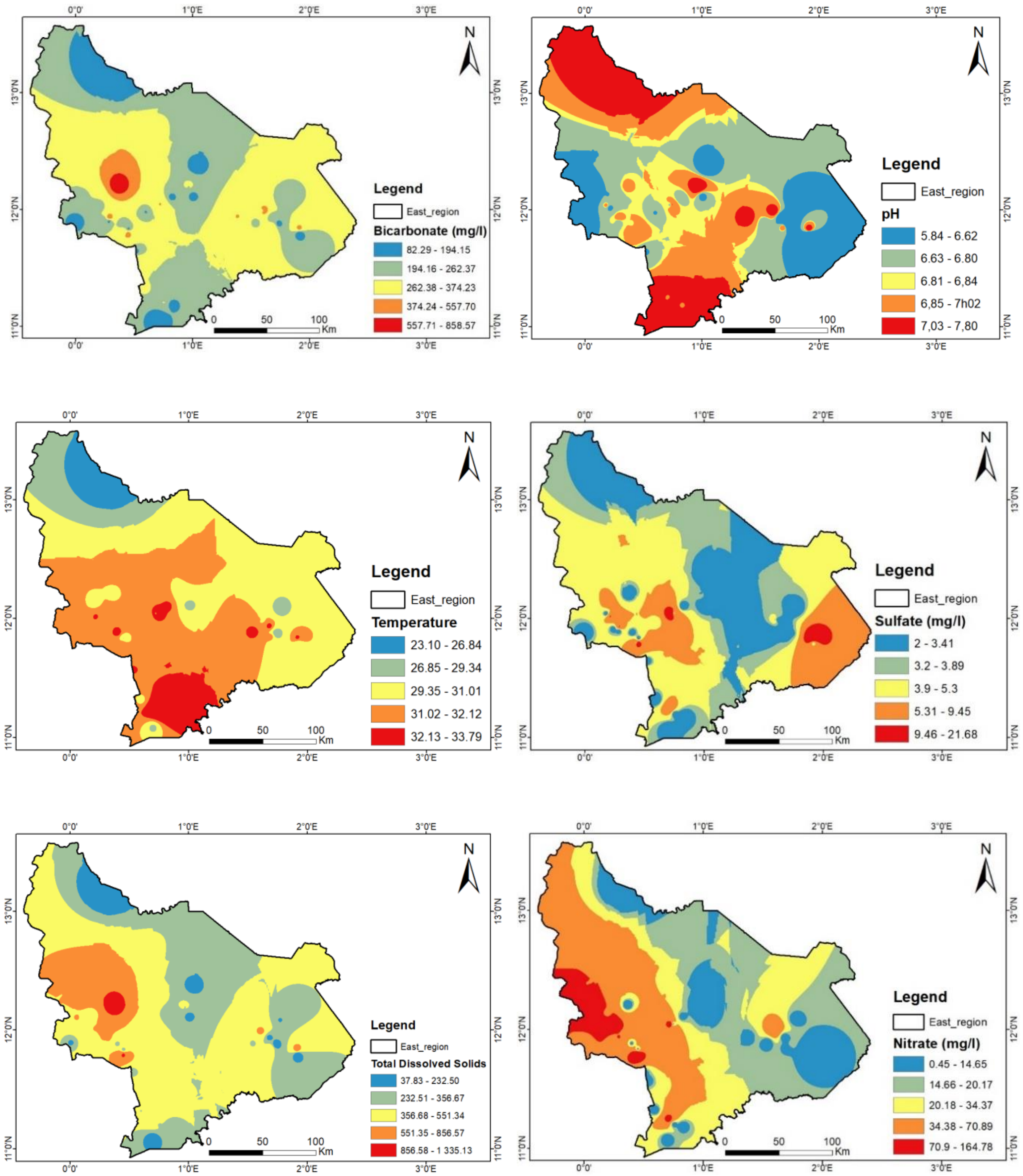
Potassium: Potassium is silver white alkali that is highly reactive with water. Potassium is necessary for living organisms functioning hence found in all human and animal tissues, particularly in plants cells. It is vital for human body functions like heart protection, regulation of blood pressure, protein dissolution, muscle contraction, nerve stimulus, etc. Potassium is rarely deficient but may cause depression, muscles weaknesses, heart rhythm disorder, etc. Potassium in groundwater is generally lesser due to its low mobility. Potassium values range from 0.50 mg/L to 70.72 mg/L.

Sulphate is one of the major anions in natural waters and often provided by industrial and household discharges as a contaminant from tanneries, textiles, etc. In this study, sulphate concentration in groundwater ranges between 2 to 22 mg/l, which is well within acceptable limit of 200 mg/L [40].

Chlorides are widely distributed in nature as salts of sodium (NaCl), potassium (KCl), and calcium. Higher levels of chlorine in groundwater can pose hazards to human health [27, 30]. Chloride concentration in the study groundwater samples ranges from 0.41 mg/L to 10.62 mg/L; well below the permissible limit of 250 mg/L.

Bicarbonate is produced by the reaction of carbon dioxide with water on carbonate rocks viz. limestone and dolomite. Carbon dioxide in soils, reacts with the rock-forming minerals to form bicarbonate, which induce alkaline environment in groundwater. The study area depicts bicarbonate values of 82.29 mg/L to 858.57 mg/L; values higher than the threshold of 600 mg/L.

Nitrate is a naturally occurring ion and a significant component in the nitrogen cycle. Nitrate sources include the nitrogen cycle, industrial waste, and nitrogenous fertilizers, among others. In other words, nitrate presence in groundwater results from human activities such as agriculture, industry, domestic effluents and emissions from combustion engines. Natural nitrate levels in groundwater are generally very low, typically less than 10 mg/L of NO_3. Nitrates concentration serves as an indication of micronutrients presence in water bodies and their ability to support plant growth. Nitrate is also one of the most important parameters causing water quality issues, particularly the blue baby syndrome in infants. Nitrate ions in groundwater are undesirable as they can lead to Methaemoglobinaemia in infants of less than 6 months of age [13]. In the study area, nitrate concentration exceeds permissible limits of WHO standards (50 mg/L) ranging from 0.44 to 183.04 mg/L. High nitrate levels in potable water increase chances of gastric ulcer/cancer and pose other health hazards to infants and pregnant women [29]. Additionally, there is a risk of birth malformations and hypertension [21]. This information underscores the importance of monitoring and managing nitrate concentration in groundwater to ensure water quality and safeguard public health.



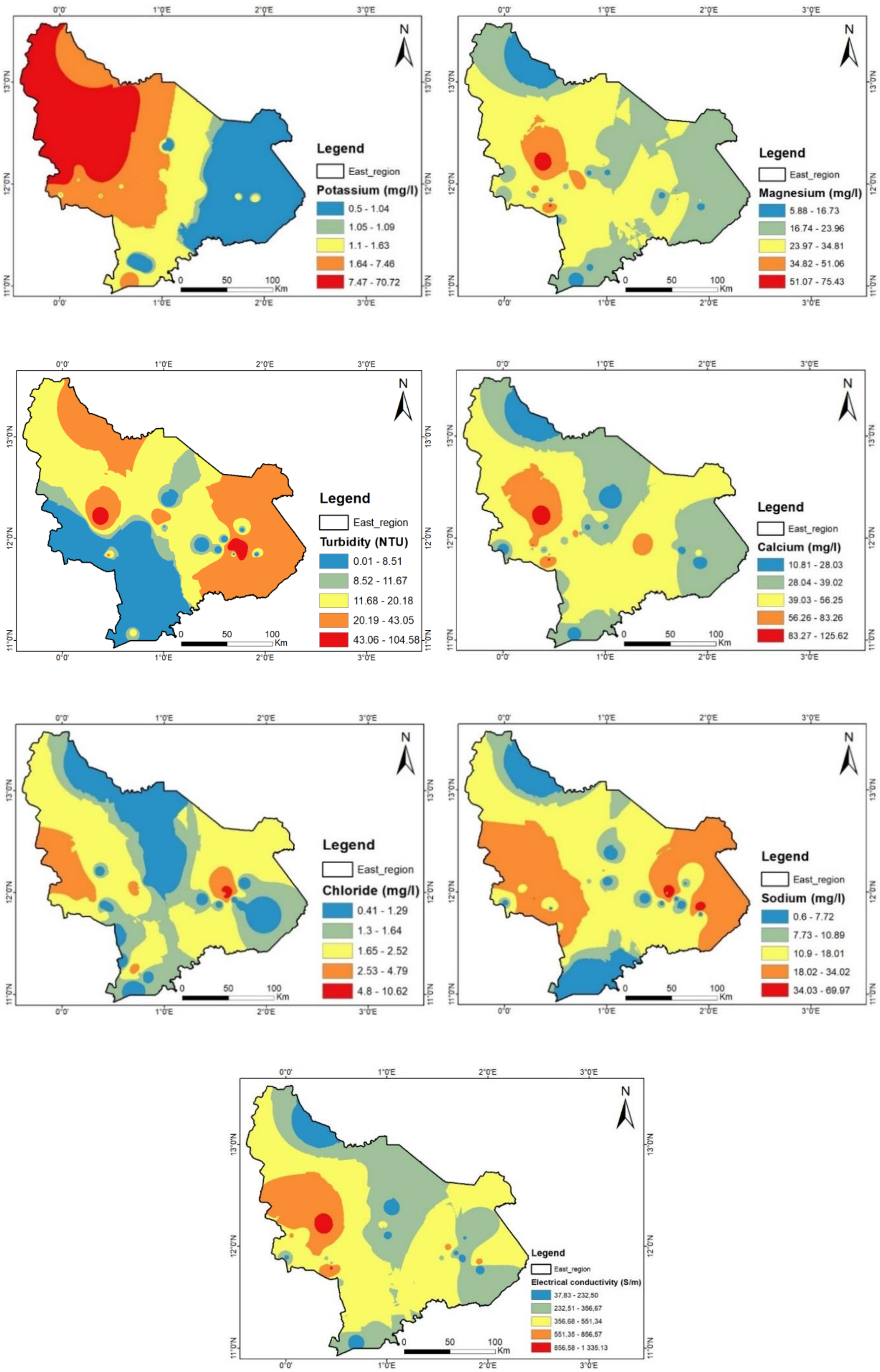


Figure 6. *Spatial distribution map of seven parameters of water quality in East Region.*

4.3. Mapping Water Quality Index

WQI map in Figure 7 indicates that the major portion has excellent groundwater quality (0 - 50), while some areas exhibit good water quality (50 -100), and others show poor water quality (> 100). The map illustrates that the quality of groundwater in the East Region ranges from excellent to poor categories, particularly for its suitability to human consumption. Notably, there is a poor groundwater quality in the Gourma province. Fada N'Gourma, the capital city of the province, encompasses highly populated areas, industries and urbanized zones that contribute polluting the environment.

GIS spatial distribution maps offer comprehensive visual representation that facilitate better understanding of the current groundwater quality situation in the East Region for a more informed conclusion. The findings emphasize the need for treating groundwater in the Fada N'Gourma province before consumption. In addition, the study results underline the necessity to develop and implement suitable water management practices in order to protect the region groundwater resources.

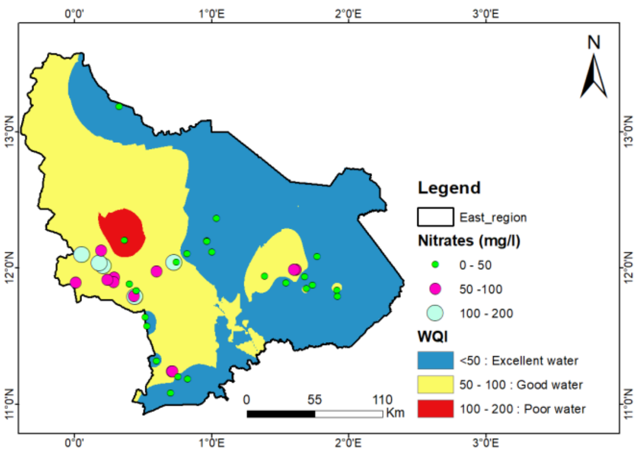


Figure 7. Spatial distribution of WQI in the East Region of Burkina Faso.

5. Conclusion

Groundwater is a vital environmental resource and its quality degradation poses significant societal and environmental risks. This study assessed groundwater quality in the East Region of Burkina Faso using WQI and GIS techniques. The findings indicate that the lower part of the transitional zone exhibits acidic conditions, while the early part of the region shows increased conductivity, TDS, EC, nitrate, DO, and turbidity. This trend suggests a depletion of water quality as one moves towards the lower part of the region.

The study underscores the necessity of regular, comprehensive groundwater analyses to monitor pollution levels and types. Raising public awareness is crucial to maintaining the highest possible standards of groundwater quality. The high WQI values observed in many samples suggest that the water is unsuitable for direct consumption and requires sustainable treatment through appropriate physical and chemical processes.

Other substantial points to raise or recommend from the study results are the following:

1. Spatial Distribution Mapping: WQI and GIS techniques effectively illustrated variations in groundwater quality across the East Region, proving their utility in spatial analysis.
2. Water Quality Implications: Identifying areas with poor water quality is essential for addressing environmental and societal concerns.
3. Utility for Water Resources Management: The generated maps provide critical information for water resource managers to support planning and management of groundwater quality.
4. Future Planning and Decision-Making: The insights gained can guide sustainable water use in the East Region.
5. Community and Environmental Impact: The study highlights the broader significance of groundwater quality on local communities and the environment.
6. Recommendations: Mitigation strategies should be developed based on the findings to improve groundwater quality in poor water quality areas.
7. Effectiveness of GIS and WQI: These tools have proven powerful for groundwater mapping and quality assessment while offering detailed spatial analyses that are easy to interpret.
8. Diverse Applications: The methodologies are successfully applied across various geographical settings, from urban to agricultural and industrial areas.
9. Valuable Insights for Management: GIS and WQI integration provides critical insights into groundwater potential, contamination hotspots, and areas needing immediate attention.
10. Identification of Vulnerability: The study highlights the impact of land use practices on groundwater quality, emphasizing the need for targeted interventions.
11. Advanced Techniques: Incorporating advanced technologies like machine learning, enhances predictive capabilities, leading to more accurate and timely forecasts.
12. Integrated Approaches: Future research should focus on combining GIS, WQI, remote sensing, and machine learning for a holistic understanding of groundwater systems, considering climate change and socio-economic factors.
13. Recommendations for Policy and Practice: The findings call for stricter regulations, sustainable land use practices, and continuous groundwater monitoring to protect and well-manage groundwater resources effectively.
14. Collaboration and Capacity Building: Collaborative

efforts between researchers, policymakers, and communities, along with training initiatives, are essential for the effective application of advanced groundwater management technologies.

15. Sustainability and Resilience: The goal is to ensure the sustainable and resilient use of groundwater resources through informed decision-making and the adoption of innovative management strategies.

Abbreviations

AEG	Agence de l'Eau du Gourma/Gourma Water Agency
ANTEA	French Firm Group Name on Engineering and Counselling
BGR	Bundesanstalt für Geowissenschaften und Rohstoffe - German Federal Institute for Geosciences and Natural Resources
BGS	British Geological Survey
BRGM	Bureau de Recherches Géologiques et Minières/Geological and Mining Research Office
DGRE	Direction Générale des Ressources en Eau/ General Directorate for Water Resources
DO	Dissolved Oxygen
℃	Degree Celsius
EAWAG	Eidgenössische Anstalt für Wasserversorgung, Abwasserreinigung und Gewässerschutz - Swiss Federal Institute of Aquatic Science and Technology
EC	Electrical Conductivity
ECOWAS/CEDEAO	Economic Community Of West African States/Communauté Economique Des Etats de l'Afrique de l'Ouest
ESA	European Space Agency
GIS	Geographic Information System
IDW	Inverse Distance Weighted
IGRAC	International Groundwater Resources Assessment Centre
LULC	Land Use Land Change
MEF	Ministère de l'Environnement et des Forêts
mg/L - mg/l	Milligrams Per Liter
NTU	Nephelometric Turbidity Unit
PANA	Programme d'Action National d'Adaptation aux Changements Climatiques
pH	Potential of Hydrogen
SDG-6	Sixth Sustainable Development Goal
TDS	Total Dissolved Solids
µS/cm	Micro Siemens Per Centimeter
UNESCO	United Nations Education, Science and Cultural Organization
USGS:	United States Geological Survey
WHO	World Health Organization
WQI	Water Quality Index

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Issoufou Ouedraogo: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Resources, Software, Visualization, Writing – original draft, Writing – review & editing

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Wennegouda Jean Pierre Sandwidi: Supervision, Validation, Writing – review & editing

Rodrigue Fotie Lele: Formal Analysis, Software, Visualization, Writing – review & editing

Conflicts of Interest

The authors declare no conflicts of interest.

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