Asian Journal of Physical and Chemical Sciences

7(2): 1-15, 2019; Article no.AJOPACS.49000
ISSN: 2456-7779

Application of GIS in the Assessment of Groundwater Quality in the Yenagoa Watershed of the Niger Delta Region of Nigeria

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Authors' contributions

This work was carried out in collaboration among all authors. Author OKK designed the study, performed the statistical analysis, wrote the protocol and wrote the first draft of the manuscript. Authors FEE and DEE managed the analyses of the study. Author DEE managed the literature searches. All authors read and approved the final manuscript.

Article Information

DOI: 10.9734/AJOPACS/2019/v7i230093
Editor(s):
(1) Dr. Ogunwande Isiaka Ajani, Associate Professor, Department of Chemistry, Faculty of Science, Lagos State University, Nigeria.
Reviewers:
(1) Yongchun Zhu, Shenyang Normal University, China.
(2) Farhaoui Mohamed, Morocco.
Complete Peer review History: http://www.sdiarticle3.com/review-history/49000

Original Research Article

Received 05 May 2019
Accepted 10 July 2019
Published 14 September 2019

ABSTRACT

The spatial variations in groundwater quality in parts of the Yenagoa watershed (YWS) in the Niger Delta Region of Nigeria has been investigated using Geographic Information System (GIS). An understanding of the factors responsible for groundwater vulnerability could facilitate the use of geographic information system in the control and management of groundwater quality. This study is due to the fact that the spatial distribution maps of groundwater quality in the YWS obtained by GIS modeling are not documented. The quality of groundwater accounts for the environmental and human health status of the residents in the YWS. Therefore, twenty (20) water samples obtained from shallow boreholes were analyzed for physicochemical properties. The physicochemical parameters such as pH, conductivity, total dissolved solids, sulphate, nitrate, sodium, chloride, magnesium, total hardness and iron contents were measured using standard laboratory procedure.

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Except for the iron content, the results obtained from the physicochemical analyses were within limits of the World Health Organization Standards for drinking water. These results were transformed into spatial distribution maps using GIS modeling and interpretation. The Index Overlay method and Inverse Distance weighted method form component parts of the GIS modeling used in the generation of the spatial distribution maps for each physicochemical parameter. These modeled results were related to the World Health Organization (WHO) Standard for drinking water. The maps generated from GIS modeling indicated zones that were suitable for groundwater extraction as opposed to zones unsuitable for groundwater extraction. In conclusion, 55% of the boreholes in the Yenagoa watershed were affected by high iron content.

Keywords: Groundwater; geographic information system; inverse distance weighted; physico-chemical parameters; Yenagoa watershed; Niger delta region.

1. INTRODUCTION

Water is an important resource which is very important to life. Water occupies 70% of the earth and constitutes 70% body weight of all living organisms. About 97% of water found on earth is salty and only 3% is present as fresh water, from which about 0.6 % constitutes groundwater [1]. The groundwater is highly valued because of self-filtration, purification and some properties not possessed by surface water [2]. The Geographic Information System (GIS) and Statistical approaches are regarded as ground-breaking methods in the assessment of groundwater quality [3]. Therefore, GIS is a working tool for data management, data analysis, spatial data display, and non-spatial data analysis.

Geographic Information Systems (GIS) are tools that are very efficient in the storage management, and display of spatial data generated for the management of water resources (V et al., 2018). The use of GIS in groundwater resource management is on the increase. In an attempt to emphasize the relevance of GIS in the management of groundwater resources, applications aligned toinverse overlay method using inverse weighted technique has been provided in this study [4].

These attributes when linked together are used in several fields for decision making (Stafford, 1991; Yeung, 2003). The use of GIS technology has significantly increased the assessment of environmental concerns, natural resources, and groundwater. In groundwater research, GIS is mostly used for managing site inventory date, suitability analyses, estimation of groundwater vulnerability in term of contamination, leaching and modeling solute transport, groundwater flow mapping, and modeling and linking of groundwater quality index assessment models. The latter is used with spatial data to create modeling for decision-making systems [5,6,7].

In this paper, GIS modeling has been used in the characterization of the quality of groundwater in the YWS [8,9]. This was based on the physicochemical analysis of the groundwater. The parameters of interest such as pH, conductivity, total dissolved solids, sulphate, nitrate, sodium, chloride, magnesium, total hardness, and iron contents are useful in the understanding of groundwater quality [10]. For instance, groundwater with high or low pH outside the limits of the World Health Organization is deleterious to human health [11].

Again, groundwater with high total dissolved solids makes the water cloudy and these solids become sources of the bacterial substrate [12]. The knowledge of the concentration of the sulphate in groundwater is an important parameter in groundwater quality assessment [13]. An excessive amount of sulphate has severe consequences for human health [14]. Industrial effluents, fertilizers, and sewage systems generate nitrates to form pollutants. Nitrate present in a groundwater sample signals different sources of pollution. These pollution sources include fertilizers used in subsistent agriculture in rural areas. In urban areas, the sources are from water derived from sewage [15].

The presence of even a trace of nitrate indicates sewage contamination. The concentration of chloride varies in natural waters which is related to mineral content in water. It is a common knowledge that seawater contains extremely very high amounts of chloride and coastal aquifers which suffer from seawater intrusion will show the abnormal concentration of chloride. Pollution from industrial effluents can be a source of elevated chloride concentration in the industrial areas [16].

The element iron is an essential supplement in human nutrition. Within the study area, the groundwater is essentially rich in total iron due to the natural presence of pyrite. The oxidation of pyrite found in the groundwater leads to the corrosion of steel pipes. The [11] state the stipulated limit of iron as 0.3 mg/L. Therefore, in this study, a combination of physicochemical parameters of groundwater and GIS application in the modeling of the results has provided a framework for the delineation of potable and non-potable water in the Yenagoa watershed.

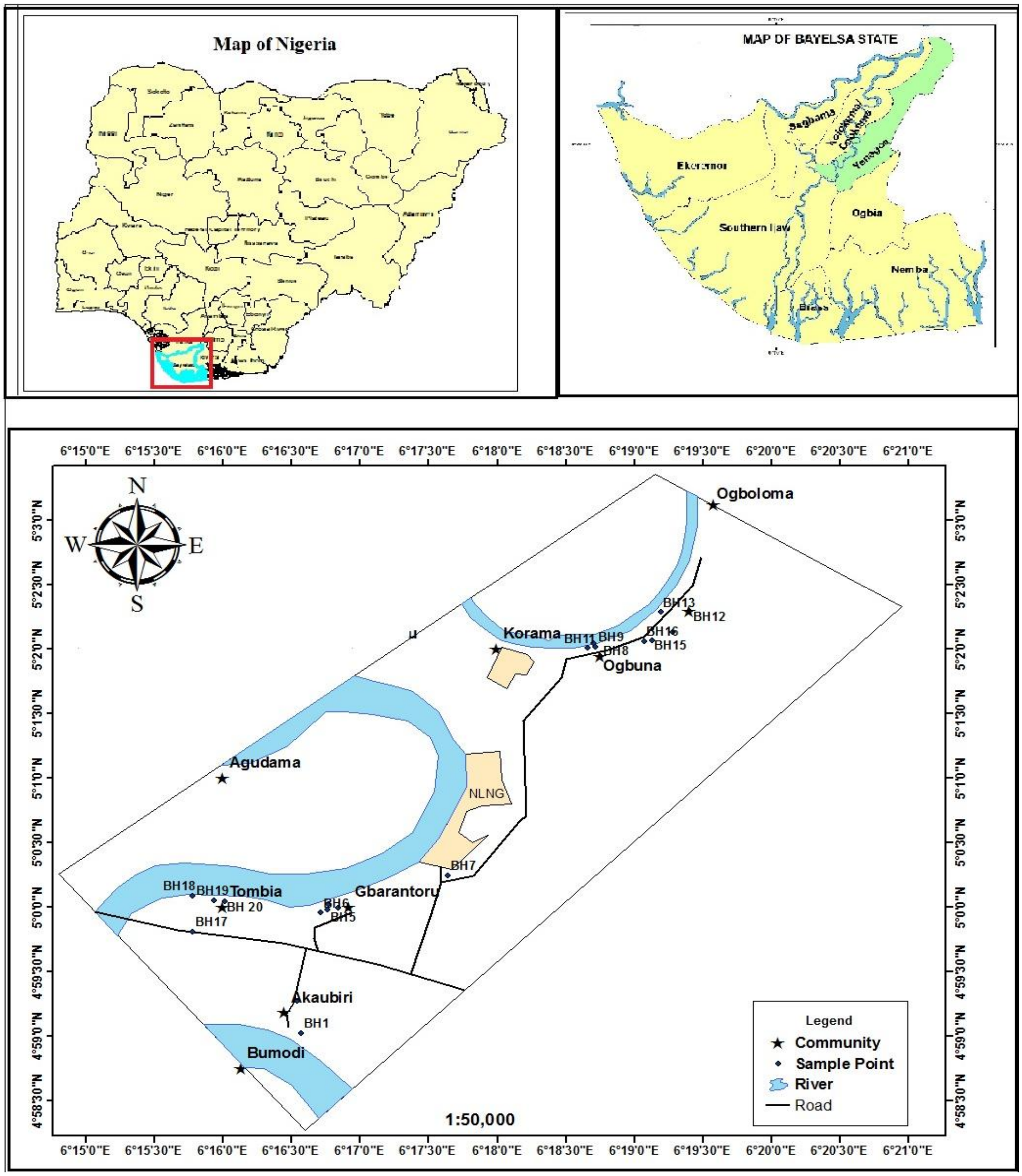


Fig. 1. Study area map showing Borehole location

1.1 Physiography and Geology of the Area

The area selected for this study is situated in the central Niger Delta sedimentary basin of Southern Nigeria (Fig. 1). The area lies within Latitude 503'30"N - 4068'30"N and Longitude 6°15'0"E - 6°21'0"E. The area has a good road network that links to component parts of the study area. The topography of the area is low-lying with a maximum of 40m elevation. The study area which falls within the South-Western flank of the Niger Delta Region of Nigeria has been geologically described by Reyment [17].

The Niger Delta Basin was formed by a failed rift (Aulacogen) junction at the pulling apart of the South American plate from the African plate. The rifting in the basin was initiated during the late period of the Jurassic and terminated in the period of the mid-Cretaceous. Several faults occur which are more of thrust faults. The delta covers a land area in excess of 105,000 km^2 (Reijers, 2011).

These structures are facies of the pro-delta Akata Formation, facies of the Agbada Formation which constitute a paralic delta front. The Benin Formation constitute a continental delta top facies. The Akata Formation is the basal lithostratigraphic unit found in the Niger Delta Region, ranging from Paleocene to Holocene age [17,18].

Its marine pro-delta mega facies are composed of thick shales, turbidite sands, and small amounts of silt and clay. The Akata formation is made up of high pressure, low density, deep marine deposits consisting of plant relics near the contact with overlying Agbada formation. The planktonic foraminifer may account for over 50 percent of the rich microfauna and benthonic assemblage [19].

This assemblage indicates a shallow marine shelf depositional environment [20]. The streak of sand and silt have been deposited at the high energy delta advanced into the sea. The approximate range of thickness is from 0-6000 meters. The formation crops out subsea at the outer delta area and is not visible at the shore [18,21].

2. METHODOLOGY

2.1 Data Collection and Analysis

The primary data was recalled from fieldwork. This primary data included groundwater taken from existing boreholes for physicochemical analysis. A total of twenty (20) samples of the groundwater were taken (Fig. 1) using polypropylene plastic bottles. These water samples were taken after a one-minute pre-pumping activity.

This action was taken to homogenize the water sample and minimize the impacts of rust contained in the pipes. The pH, Electrical Conductivity (EC) and Total Dissolved Solids (TDS) were determined on site using portable pH, and Electrical Conductivity electrodes (Oakton), Total Dissolved Solid meter (HANNA) respectively.

For the analysis of metals contained in the water, the samples of water were acidified using nitric acid (50 % v/w) of pH<2. The samples of water were kept in ice cool condition and carried to the laboratory for further chemical analysis. The major elements namely Mg^{2+}, Ca^{2+}, Na^{+}, and K^{+}) were analysed using an Atomic Absorption Spectrometer (AAS) (Thermo Fisher Scientific M series), and the major anions namely Cl^{-}, SO_4, NO_3^{-}were analyzed using ion chromatograph (Dionex). The bicarbonate (HCO_3) was determined by titrimetric method [22].

The geographical locations of the boreholes in the study area were determined by using a handheld global positioning system (GPS) instrument GARMIN GPS-60 receiver. The obtained data were in a non-spatial database form. Herein, they were arranged in excel system and related to the spatial data option provided in ArcMap. Both spatial and non-spatial data set were integrated to generate thematic maps of the groundwater.

For spatial interpolation, inverse distance weighted approach in GIS was used to delineate the distribution of natural and subsurface anthropogenic groundwater contaminants. An indiscriminate method of statistical sampling was used to study the spatial spread of the groundwater quality parameters [23]. Consequently, the map of the Yenagoa watershed was gridded using cells of 250m x 250m to ensure that samples collected are evenly spread in the study area.

Subsequently, the results from the chemical laboratory analysis were inputted into an excel spreadsheet and imported into a GIS environment to produce a spatial distribution map for each of the water quality parameters. These maps were compared with standards. The outcome of the GIS modeling applied for the spatial study are provided (Fig. 2). The processes for the spatial study are provided in the workflow diagram (Fig. 2).

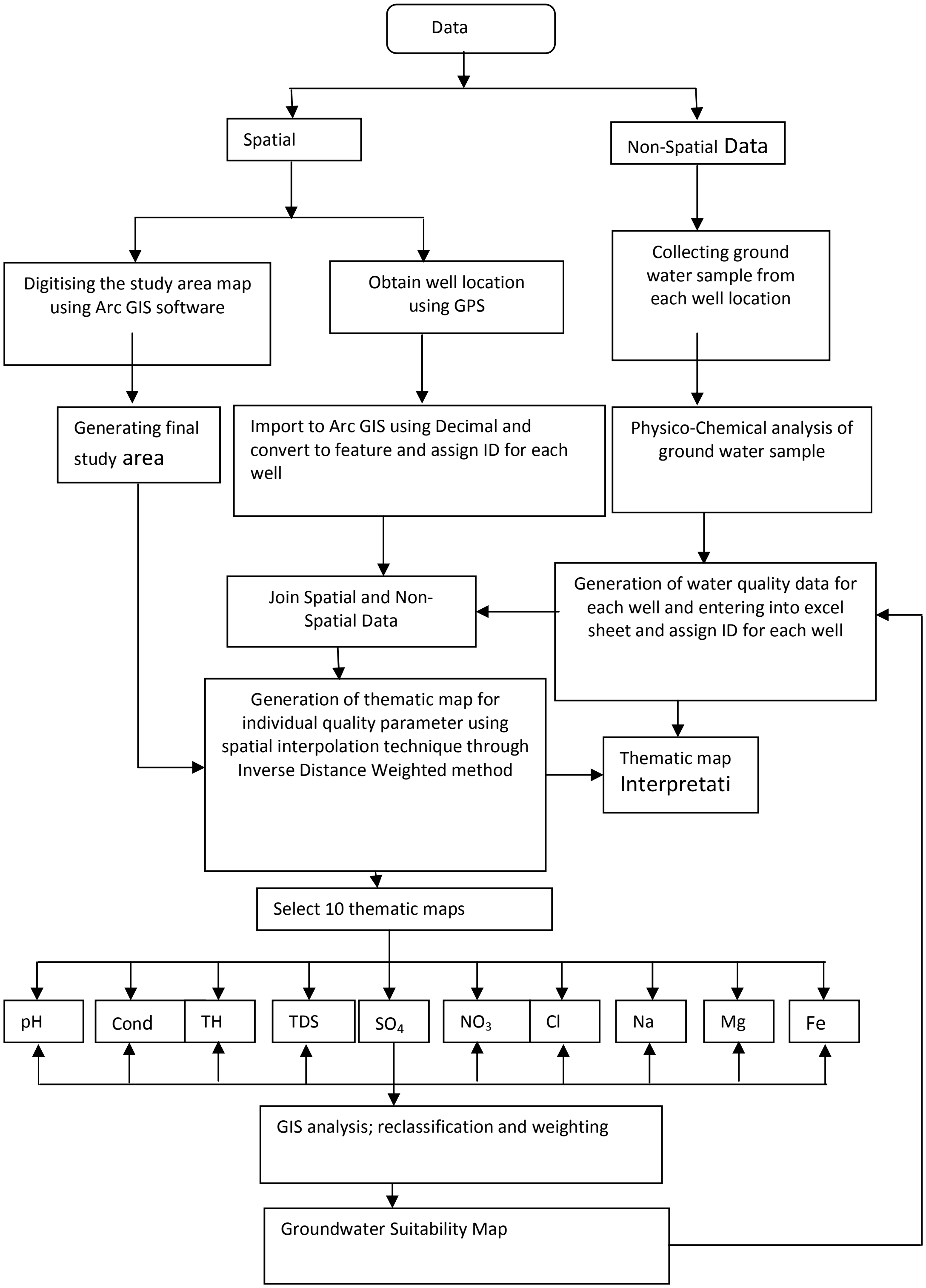


Fig. 2. Workflow diagram of the study

2.2 GIS Analysis using Index Overlay Method

The GIS application was used to analyze all data layers through the process called "Overlay". The spatial technique consists of the application of Index Overlay for the superposition of one layer upon another using a thematic scheme, thus producing a new layer. In this study, the map classes generated on each added map were designated to different value scores and the maps were provided with different weightages [24].

The weighted overlay method tool is the most used novel approach for overlay analysis. This method is used to detect and solve multi-criteria problems as site suitability models and selection. In this study, the input layers considered for the analysis of groundwater suitability were the pH, Total Hardness (TH), Total Dissolved Solids (TDS), Sodium (Na^+), Nitrate (NO_3^-), Chloride (Cl^-), Conductivity, Sulphate (SO_4^{2-}), Magnesium (Mg^{2+}), and Iron (Fe^{2+}) contents.

The score reading for all parameter classes for each map was assigned along with the map weightages entered as attribute data.

3. RESULTS AND DISCUSSION

3.1 Physicochemical Properties of Groundwater

The pH, conductivity, total dissolved solids, sulphate, nitrate, and sodium contents of the groundwater in the YWS were within limits recommended by WHO. The sulphate content in the samples ranged from 2.32 mg/L to 4.84 mg/L.

There is a strong suggestion of the reduction of sulphate thus promoting corrosion of sewers. The nitrate concentration from the analysis ranged between 0.12 mg/L and 0.33 mg/L. Thus, this range is within the safe limits provided by WHO. For potable water, the concentration of nitrates should be less than 50 mg/L [11]. The sodium concentration in the area ranged from 3.75 mg/L to 18.68 mg/L.

Herein, the sodium concentration is within the safe limits provided by the WHO (i.e. below 200 mg/L). There is minimal or no intrusion of saline water in the study area. In another form, there is minimal or no ingress of domestic and industrial wastewater into the groundwater.

The chloride content in the area ranged from 11 mg/L to 62 mg/L. Again, this range is within the limits recommended by WHO. In addition, low sodium and chloride contents are good indications of low rock salt in the study area. The total iron content in the groundwater ranges from 0.13 mg/L to 0.39 mg/L. This upper value is above the safe limits recommended by WHO. Thus, the use of this groundwater without iron treatment is deleterious to health.

3.2 GIS Analysis using Index Overlay Method

The GIS application using the Index Overlay method provided a set of map classes occurring on each input. These maps have been assigned to different value scores and the maps have been provided with different weights. This method has detected and solved multi-criteria problems in the selection of suitable sites for groundwater mapping in the study area. Water suitability means area that are good for drinking.

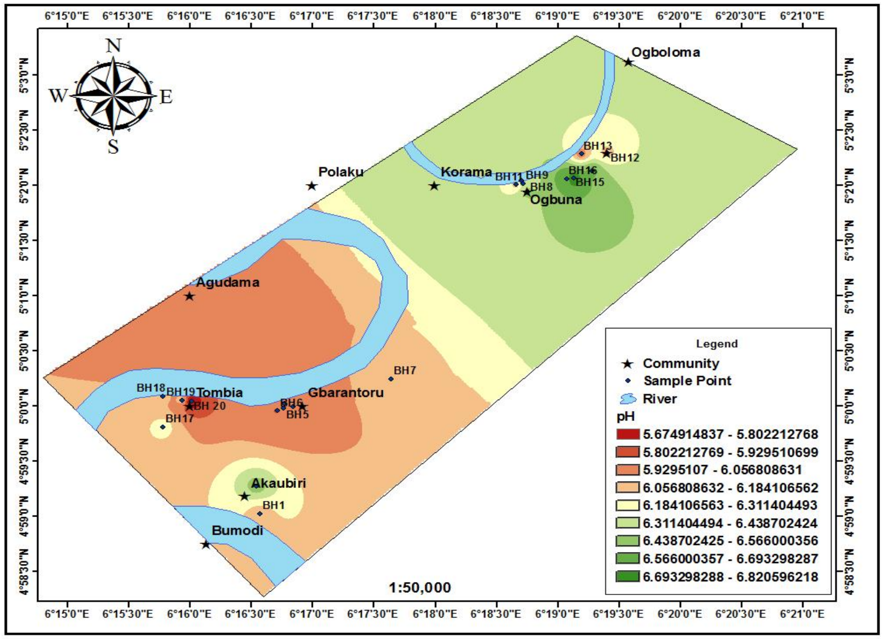
The physicochemical parameters of pH, Total Hardness (TH), Total Dissolved Solids TDS), Sodium (Na^+), Nitrate (NO_3^-), Chloride (Cl^-), Conductivity, Sulphate (SO_4^{2-}), Magnesium (Mg^{2+}), and Iron (Fe^{2+}) contents have greatly supported the outcome of the groundwater mapping. This is due to the fact that the score reading for all parameter classes for each map was assigned along with the map weightings entered as attribute data.

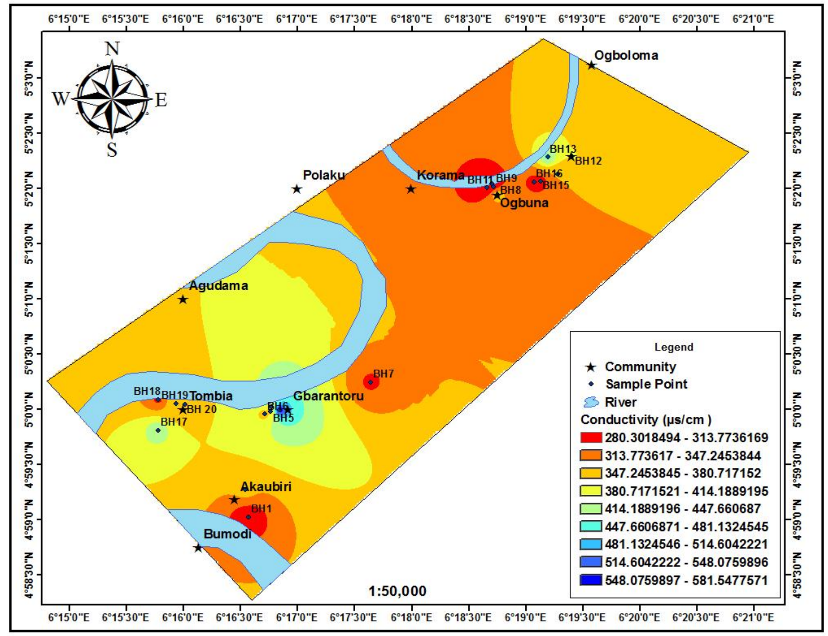
The spatial maps based on weightage and class are provided:

M1= Weightage*[class (pH)]
M2= Weightage*[class (Conductivity)]
M3 = Weightage*[class (TDS)]
M4 = Weightage *[class (TH)]
M5 = Weightage *[class (Na^+)]
M6 = Weightage * [class (Mg^{2+})]
M7 =Weightage * [class (NO_3-)]
M8 =Weightage* [class (Cl^-)]
M9 = Weightage *[class (SO_4^{2-})]
M10= Weightage*[class (Fe^{2+})]

Table 1. Showing physicochemical parameter of groundwater

Latitude	longitude	Sample code	Community	pH	Conductivity S/m	TDS ppm	No_3 ppm	Cl ppm	SO_4 ppm	TH	Mg ppm	Na ppm	Fe ppm
4.983667	6.276111	BH1	Akaibiri	6.14	285	142	0.218	14	2.48	17	2.87	5.48	0.31
4.987861	6.275722	BH2	Akaibiri	6.59	355	178	0.231	20	3.5	34	3.54	7.6	0.364
5.000389	6.279556	BH3	Gbarantoru	6.01	420	210	0.31	20	4	52	4.2	6.5	0.136
4.999861	6.280667	BH4	Gbarantoru	5.97	583	292	0.318	34	4.8	48	5.68	9.45	0.142
4.999656	6.279361	BH5	Gbarantoru	5.96	363	182	0.22	20	3.85	36	2.53	6.84	0.36
4.999222	6.2785	BH6	Gbarantoru	5.92	364	182	0.23	30	3.64	30	4.86	8.35	0.132
5.004056	6.294028	BH7	Gbarantoru	6.15	310	155	0.197	12	3	26	2.25	5.42	0.38
5.032306	6.312556	BH8	Ogbuna	6.49	379	189	0.271	13	4.3	43	2.84	5.46	0.348
5.033528	6.311917	BH9	Ogbuna	6.35	304	152	0.176	14	2.34	27	3	4.96	0.186
5.034	6.311778	BH10	Ogbuna	6.52	279	140	0.185	11	2.97	30	2.56	3.75	0.36
5.033361	6.311056	BH11	Ogbuna	6.08	285	143	0.121	12	2.58	21	2.58	4.34	0.272
5.038194	6.323444	BH12	Okolobiri	6.15	382	191	0.278	62	4.84	43	10.72	18.68	0.188
5.038	6.319889	BH13	Okolobiri	5.99	457	274	0.328	16	4.75	44	3.52	7.48	0.174
5.035417	6.321361	BH14	Okolobiri	6.6	348	174	0.281	12	3.84	41	2.84	4.72	0.328
5.034306	6.318833	BH15	Okolobiri	6.83	298	199	0.217	12	3.76	35	1.78	5.46	0.146
5.03425	6.31789	BH16	Okolobiri	6.62	306	153	0.227	13	4	35	2.1	4.8	0.346
4.996806	6.262944	BH17	Tombia	6.24	436	218	0.29	14	3.46	45	3	5.75	0.33
5.001417	6.263	BH18	Tombia	6.08	307	154	0.214	21	3.2	22	4.34	6.58	0.39
5.000861	6.265528	BH19	Tombia	6.1	376	188	0.245	32	4	19	5.63	9.36	0.136
5.000639	6.266833	BH 20	Tombia	5.67	357	178	0.235	33	3.85	10	5.82	9.65	0.382
		Min		5.67	279	140	0.121	11	2.34	10	1.78	3.75	0.132
		Max		6.83	583	292	0.328	62	4.84	52	10.72	18.68	0.39
		Mean		6.223	359.7	184.7	0.2396	20.75	3.658	32.9	3.833	7.0315	0.2705
		WHO (2011)		6.8 -8.5	1000	500	50	250	100	100	10	200	0.3


N
S
W
E
Ogboloma
Polaku
Korama
Ogbuna
BH13
BH12
BH11
BH9
BH8
BH16
BH15
Agudama
BH7
BH18
BH19
Tombia
BH 20
BH17
BH6
BH5
Gbarantoru
Akaubiri
BH1
Bumodi
1:50,000
Legend
Community
Sample Point
River
pH
5.674914837 - 5.802212768
5.802212769 - 5.929510699
5.9295107 - 6.056808631
6.056808632 - 6.184106562
6.184106563 - 6.311404493
6.311404494 - 6.438702424
6.438702425 - 6.566000356
6.566000357 - 6.693298287
6.693298288 - 6.820596218


N
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Agudama
BH7
BH18
BH19
Tombia
BH 20
BH17
Gbarantoru
BH5
Akaubiri
BH1
Bumodi
1:50,000
Legend
Community
Sample Point
River
Conductivity (µs/cm)
280.3018494 - 313.7736169
313.773617 - 347.2453844
347.2453845 - 380.717152
380.7171521 - 414.1889195
414.1889196 - 447.660687
447.6606871 - 481.1324545
481.1324546 - 514.6042221
514.6042222 - 548.0759896
548.0759897 - 581.5477571

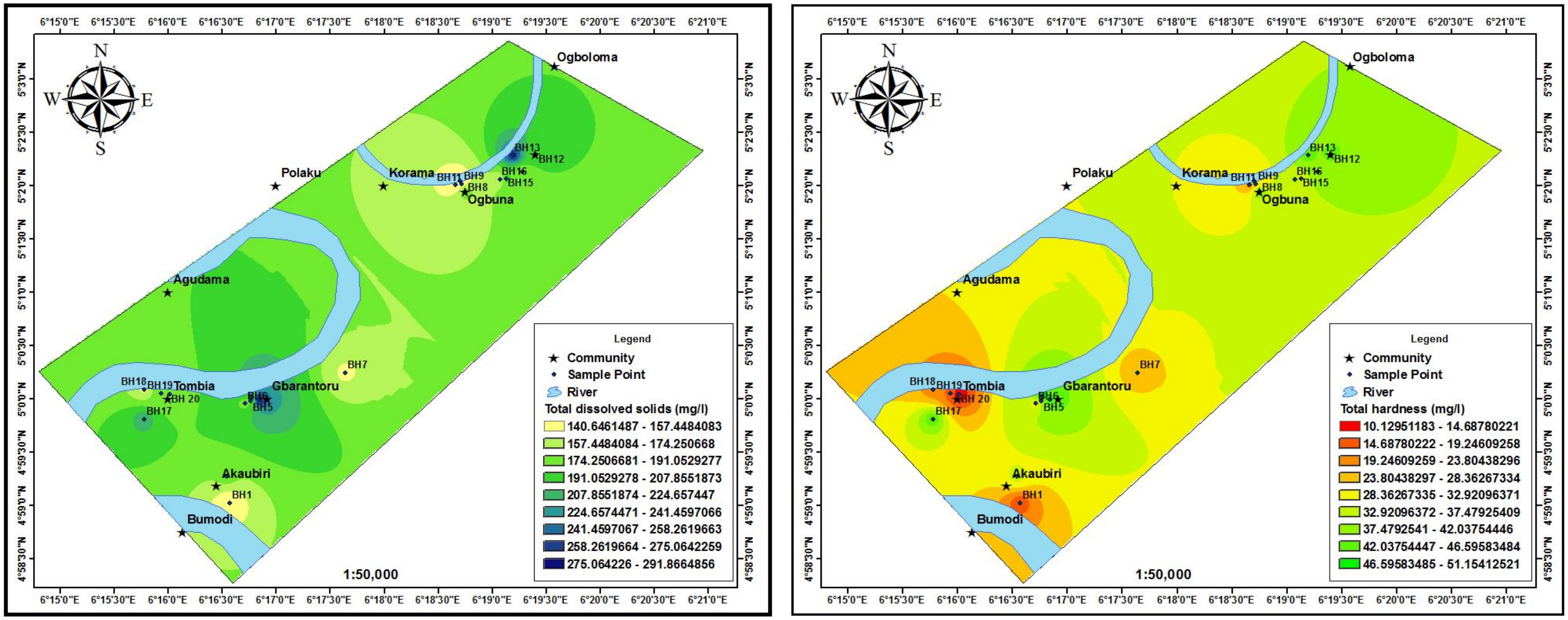
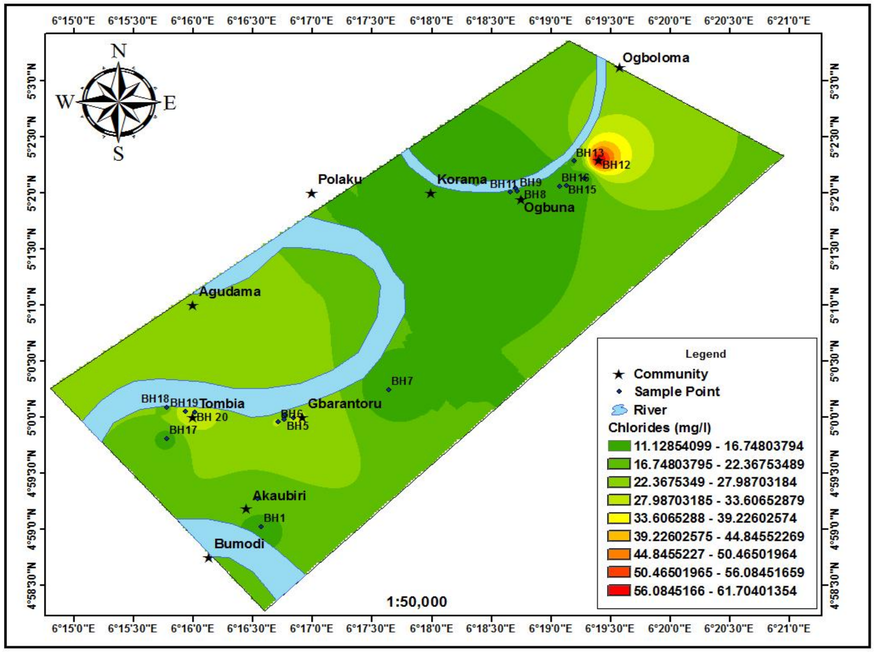
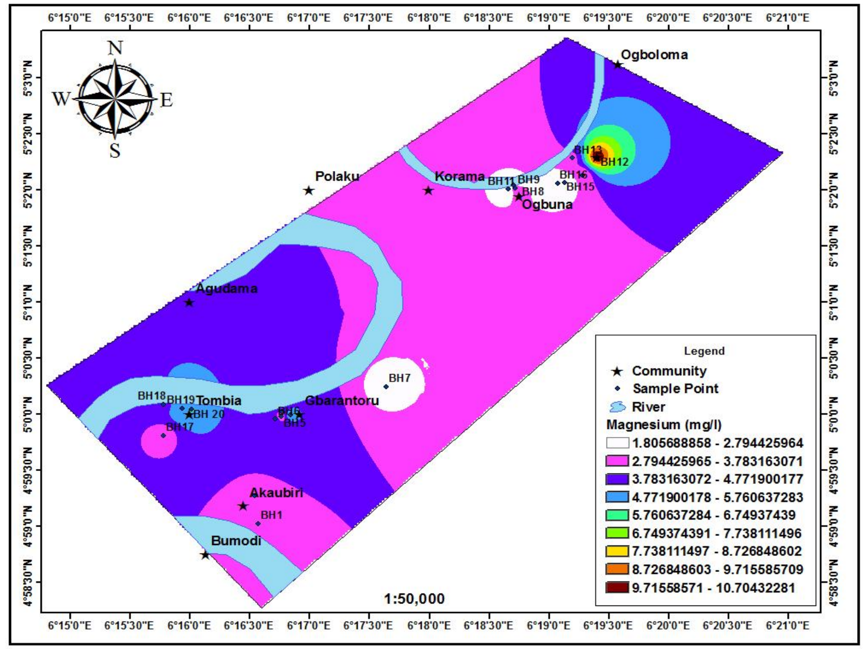


Fig. 3a. Spatial distribution of groundwater


Ogboloma
Polaku
Korama
Ogbuna
Agudama
Tombia
Gbarantoru
Akaubiri
Bumodi
BH1
BH5
BH6
BH7
BH8
BH9
BH11
BH12
BH13
BH15
BH16
BH17
BH18
BH19
BH 20
Legend
Community
Sample Point
River
Chlorides (mg/l)
11.12854099 - 16.74803794
16.74803795 - 22.36753489
22.3675349 - 27.98703184
27.98703185 - 33.60652879
33.6065288 - 39.22602574
39.22602575 - 44.84552269
44.8455227 - 50.46501964
50.46501965 - 56.08451659
56.0845166 - 61.70401354
1:50,000


Ogboloma
Polaku
Korama
Ogbuna
Agudama
Tombia
Gbarantoru
Akaubiri
Bumodi
BH1
BH5
BH7
BH8
BH9
BH11
BH12
BH13
BH15
BH16
BH17
BH18
BH19
BH 20
Legend
Community
Sample Point
River
Magnesium (mg/l)
1.805688858 - 2.794425964
2.794425965 - 3.783163071
3.783163072 - 4.771900177
4.771900178 - 5.760637283
5.760637284 - 6.74937439
6.749374391 - 7.738111496
7.738111497 - 8.726848602
8.726848603 - 9.715585709
9.71558571 - 10.70432281
1:50,000

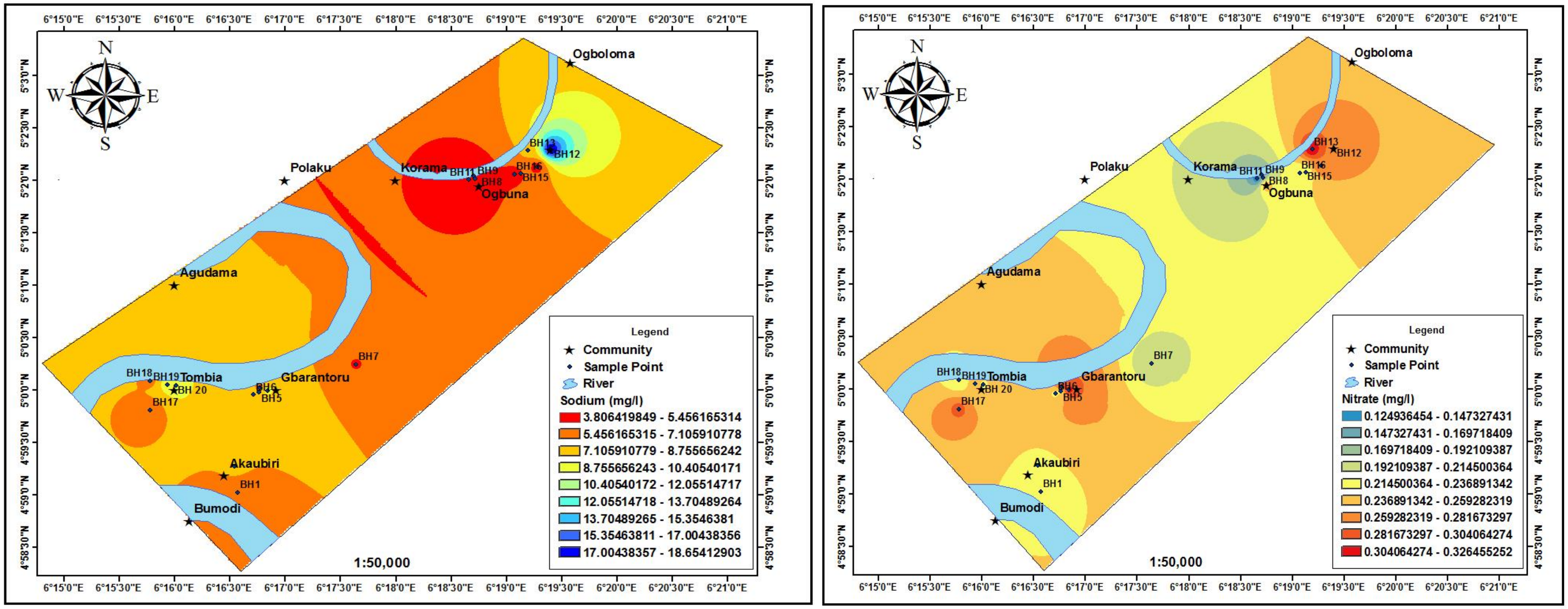


Fig. 3b. Spatial distribution of groundwater

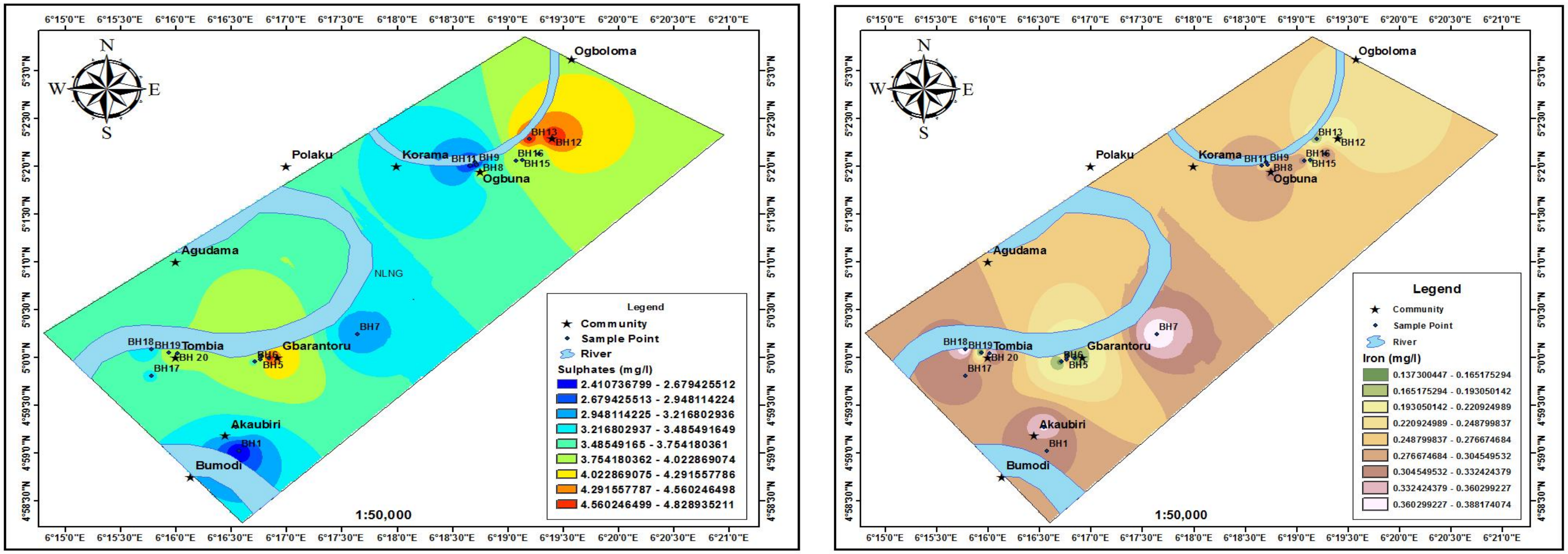


Fig. 3c. Spatial distribution of groundwater

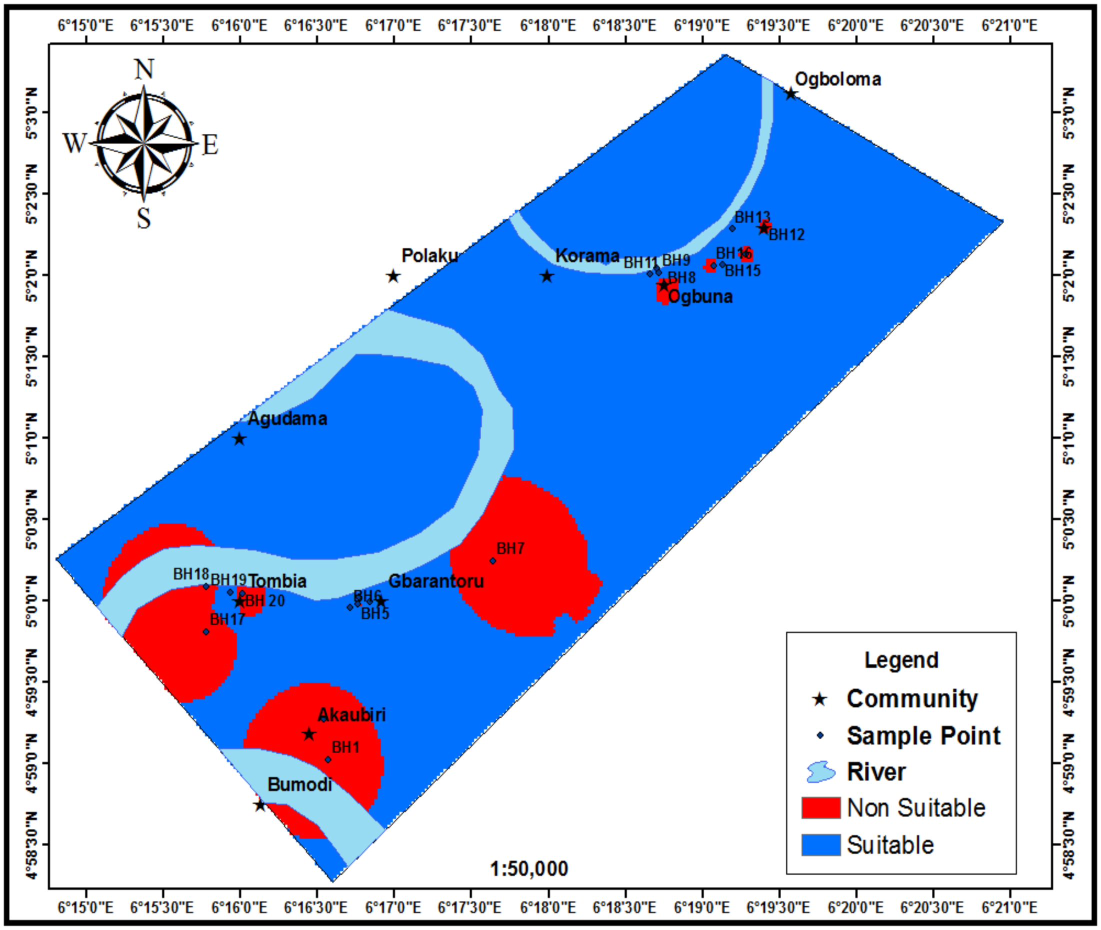


Fig. 4. Ground water quality suitability map

4. CONCLUSION

This study has successfully investigated the use of GIS indexing overlay method to characterize areas suitable for potable groundwater extraction in the Yenagoa watershed of the Niger Delta Region of Nigeria. The physicochemical analysis of the groundwater provided a framework for the required parameters for the spatial analysis. The spatial analysis and interpretations of groundwater quality modeling were successfully demonstrated using GIS and statistical methods and also compared with WHO standard for drinking.

These were the powerful tools used in the evaluation, description of spatial analysis, and mapping of groundwater characteristics models [25]. The estimated water quality indices demonstrate that the groundwater in the YWS possesses suitable zones for groundwater extraction and unsuitable zones that should be avoided. These areas have been delineated by producing different spatial extent maps (Fig. 3a, 3b, and 3c).

Herein, the study offers the required information for the Local, Regional, and International Organizations to pursue the sustainable control and management of groundwater resources. The spatial distribution results of groundwater quality in the Yenagoa watershed indicated the presence of high iron content in some areas. As provided in Figure 4, 45% of the boreholes analyzed provides non-potable groundwater. Therefore, this study provides information on groundwater quality and the potential water crisis that may exist in the YWS.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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