



Geostatistical Modelling of Groundwater Quality at Rumuola Community, Port Harcourt, Nigeria

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Authors' contributions

This work was carried out in collaboration between both authors. Author VEA designed the study, wrote the protocol for the sample collection, data analysis and did the computer analysis. Author FAA did the fieldwork for the study, the computer analysis and wrote the first draft of the manuscript. Author VEA reviewed the draft and made contributions to it. Both authors read and approved the final manuscript.

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ABSTRACT

The groundwater quality of Rumuola community of Rivers State, Nigeria was investigated. This study was done to determine the pollution potential of a solid waste open dump in a borrow pit in the community. The leachate pollution index was calculated for the borrow pit at the centre of the community using weighted additive leachate pollution index. The result showed that the LPI value was 5.31 and has low pollution potential. It was discovered that the groundwater in the entire community was acidic with pH levels ranging from 3.6 to 4.2, which is below NSDWQ's permissible range of 6.5-8.5. Nickel and arsenic also showed concentrations that were above permissible limits with nickel values averaging 0.033 mg/l which is slightly above the limit of 0.02 mg/l. Arsenic had concentrations that ranged from 0.16 to 1.57 mg/l which is above permissible limits of 0.01 mg/l. WQI was determined using weighted arithmetic water quality index analysis. As a result of the high concentrations of arsenic, the WQI values were very high with values ranging from 144 to 1367 and this shows that the water in the study area is unsuitable for drinking. In modelling the water quality

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index of Rumuola community, geostatistical methods were applied. Ordinary kriging, Empirical Bayesian kriging (EBK), inverse distance weighting (IDW) and cokriging interpolations methods were used to produce surface maps showing the distribution of variables using ARCGIS software. The best interpolators were: EBK for pH, TDS, Sulphate and nitrate; Ordinary kriging for Nickel and Hardness; IDW for Iron and arsenic; Cokriging for WQI.

Keywords: Water quality index; geostatistics; kriging; groundwater pollution; groundwater modeling; geostatistical modeling.

1. INTRODUCTION

Groundwater is important to the entire world's population, in semi-arid and arid regions there is even more focus given to it because of the insufficiency of surface water [1]. In Nigeria, more than 57 million people do not have access to clean water as a result of ground water pollution [2,3]. There are many pollutants of groundwater but those of uttermost concern are naturally occurring arsenic, fluoride and nitrate [4]. It is imperative that groundwater is assessed systematically and monitored continually applying proven scientific methods to determine its quality to ensure that it can be used for domestic purposes, and that no adverse effects are experienced due to its use [5]. Groundwater problems exist because there is inadequate infrastructure to treat and distribute water to the populace [6]. Effluents from industrial sources are a big problem especially in developing cities like Port Harcourt with a high presence of industries [7]. Groundwater can also be polluted by leachate from landfills practices [8] the magnitude of which depends on the quantity and composition of the leachate from the landfill which usually contains heavy metals [9,10] and the groundwater level [11,12]. People living in warmer climates like Nigeria are at higher risk of exposure and associated problems because of the need to take more water [9,13,14]. Groundwater quality across regions is spatially related and geostatistical methods of evaluating spatial relationships are relevant to predict the variables at areas where sampling may be impossible. Geostatistics does not only look at the incidence of a variable but also at the location, the Spatial association between values and the effect geographical factors have on the distribution of variables at a location [15].

According to Hassan [4], the techniques of geostatistics are used to: forecast values at locations not sampled, evaluate the uncertainty affiliated with the forecasted values and model the spatial patterns of the parameter being considered. There are different interpolation methods that can be applied in groundwater

modelling for example: Ordinary kriging, Empirical Bayesian kriging, cokriging and inverse distance weighting.

Kriging which is linear interpolation method, presupposes a statistical model and has standard errors that measure the level of uncertainty of the values that have been forecasted [16,17,18]. Classical kriging assumes that the variogram estimated initially is the correct variogram of the studied data but, this assumption is not always true in practice and this is why EBK was introduced [16]. Empirical Bayesian Kriging (EBK) is different from classical kriging because it considers the error introduced by the semivariogram model. EBK does not use just one semivariogram as kriging does but applies many semivariograms [16]. Cokriging is a kriging method that estimates samples that were thought of as poorly collected with the aid of a sample that was collected more appropriately. For cokriging to be applied there has to be some very high correlation (positive or negative) between the two samples. Inverse Distance Weighting is a deterministic method for interpolating spatial data. In this method, weights are given to points to be measured, and the amount of weight given to that point is dependent on the distance of that point to another unknown point. If the power of these weights is increased, the effect of points that are farther away will be undermined and keeping the power low will mean that the weights will be distributed more uniformly between points close by. If the points have the same distance between them, then the weights, in turn, are the same [19].

To decide which model best fits or predicts most accurately, cross-validation is done and the mean prediction error should be closer to zero, a lower root mean square prediction error (RMSE) and the root mean square standardized error should be closer to 1. However, If RMSE is less than 1 then the prediction is underestimated and if greater than 1 then the prediction is overestimated [4].

In this study, the leachate from an open dump in the study area was evaluated to determine its

constituents and to ascertain its pollution potential. The water quality index from surrounding boreholes was calculated using weighted arithmetic water quality index method and finally geostatistical interpolation methods were applied with the aid of ARCGIS to create surface maps showing distribution of contaminants across the region.

2. MATERIALS AND METHODS

This study was conducted in Rumuola community in Obio-Akpor local government area in Rivers state, Nigeria. Rivers state is found in the coastal plain of the eastern Niger Delta [20]. Temperature ranges from 21.2-23.2°C to 28.7-33.4°C. Annual rainfall is 4,700 mm/year [20]. This area was extensively studied and it was understood that, the borrow pit at Rumuola community was born as a result of sand mining done many years ago to aid the construction of major roads in the state [21]. The Rumuola borrow pit lies longitudes E 007° 00' 01.0" to E 007° 03' 09.7" and latitudes N 04° 50' 08.5" to N 04° 50' 14.2". Although the region has evolved and houses have emerged, the enormous borrow pit still remains. A large pond has been formed covering an area of 135,000m² with a depth of 7.68m, the water table lies at 7.49 m and this shows that the pit has cuts into the water-table [21].

The groundwater quality was determined using weighted arithmetic water quality index and the groundwater parameters were modelled using geostatistical methods. The leachate pollution index was calculated using weighted additive leachate pollution index and the leachate values were compared to effluent standards. In Calculating WQI, the Weighted Arithmetic Water Quality Index (WAWQI) Method was used, and it is outlined as follows:

Step 1: Collect data of the water quality parameters that will be used to determine the WQI.

Step 2: Calculate k using Equation 1

$$k = \left(\frac{1}{\sum_{i=1}^n \frac{1}{S_i}} \right) \quad (1)$$

Where

k = Proportionality constant
 S_i = Standard permissible limit for the nth parameter

Step 3: Calculate the quality rating for the nth parameter q_n.

$$q_n = 100 \left(\frac{v_n - v_{io}}{s_i - v_{io}} \right) \quad (2)$$

Where:

V_n = Estimated concentration of the nth parameter of the given sampling location.
 V_{io} = Ideal value of the nth parameter in pure water [22].
 S_i = Standard permissible limit of the nth parameter.

Step 4: Calculate the unit weight of the nth parameters using Equation 3

$$W_n = \left(\frac{k}{s_i} \right) \quad (3)$$

Step 5: Calculate the Water Quality Index using Equation 4

$$WQI = \left(\frac{\sum w_n q_n}{\sum w_n} \right) \quad (4)$$

Table 1 shows the water quality status based on the WQI value for each water sample. 0-25 shows excellent water while anything above 100 is unsuitable for drinking purposes.

Table 1. Water quality index (WQI) and status of water quality

Water quality index level	Water Quality status
0-25	Excellent water
26-50	Good water
51-75	Poor water
76-100	Very poor water
>100	Unsuitable for drinking purpose

Source: [22]

The leachate pollution index can be calculated using the Equation 5 when all 18 leachate pollutions parameters are known:

$$LPI = \sum_{i=1}^n w_i p_i \quad (5)$$

Where

LPI = The weighed additive leachate pollution index
 W_i = The weight of the ith pollutant variable
 P_i = The sub-index value of the ith leachate pollutant variable
 n = Number of leachate pollutant variables used in calculating LPI and n=18.

Leachate parameters sum = 1 [23]. Nine (9) parameters were used in this study which summed up to 0.496. The sub-index values were determined from the sub-index curves of the respective parameters.

But when the data for all the 18 leachate pollutant variables required to calculate the LPI is not available, the LPI can be calculated with the available pollutants using Equation 6:

$$LPI = \frac{\sum_{i=1}^m w_i p_i}{\sum w_i} \quad (6)$$

This method was applied in this report since all eighteen leachate parameters were not used in determining the LPI.

2.1 Sampling Technique

Leachate Samples were collected using sampling bottle that were thoroughly washed and dried. Leachate was collected from the base of the pit into One-litre polyethene bottles. The leachate had drained out by gravity. One leachate sample was collected and this was designated as Leachate Sample (LS). 10 Leachate parameters were analysed from the leachate sample collected from the open dump embedded in the borrow pit in the centre of the community. These parameters were chosen based on the method developed by [23]. The parameters used in this study are: Chromium, Iron, TDS, copper, nickel, lead, mercury, arsenic, chlorides and pH.

Groundwater samples were taken in one-litre polyethene bottles. Prior to collecting the samples, the water from the borehole was allowed to run for five minutes to ensure groundwater parameters were unchanged. Then, the sampling bottles were rinsed with the groundwater three times before collecting the samples. The water was taken from a point before the water enters the reservoirs (water tanks) used to store them. A plumber dismantled the piping works to enable water collection to be done directly from the source. This was done to prevent any form of contamination from the water storage reservoirs and to ensure the integrity of the samples. Borehole samples were designated by borehole 1 (BH1), borehole 2 (BH2) etc.

Eighteen (18) water samples were collected from boreholes in Rumuola community for this study. The sampling points were distributed around the community with the aid of the GIS software. The

samples were collected and analysed using standard methods for TDS, pH, Nitrate, sulphate, nickel, arsenic, mercury, iron and total hardness.

To model, Arc map (ARCGIS 10.5) software was used. This software forecasted values at unsampled locations for each parameter investigated while also creating interpolated surface maps which shows the distribution of the pollutants across the study area and highlights areas with low and high concentrations. The methods that were explored in this project were Ordinary kriging, Cokriging, Empirical Bayesian Kriging and Inverse Distance Weighting and the best methods were chosen by cross-validation.

The secondary data that was used for the study is the Nigerian Standard for Drinking Water Quality (NSDWQ) and The Federal Environmental Protection Agency Act 1988 No. 58. This was used to determine the safe limits for the physicochemical parameters of drinking water and safe limits of effluent (leachate) discharge in ground and surface water.

3. RESULTS AND DISCUSSION

Table 2 shows how the LPI was determined. W_i is the weight and P_i is the sub index value as derived from the study done by [23]. The determination of LPI was done using Equation 5. The leachate had a pH of 6.2. The concentration of arsenic in the leachate sample was 0.579 mg/l, which is higher than the effluent discharge limit of 0.1 mg/l. Every other leachate parameter had values that were below the effluent discharge limits specified by Nigeria's federal ministry of environment. LPI was determined using Allapat's method as outlined in Equations 5 and 6. The calculated LPI value was 5.31 and this shows that the pollution potential of the leachate is very low.

Table 3, shows the distribution of the parameters through the selected sampling points. The lowest pH values were observed in BH 4, 8 and 20 with a value of 3.6. The range of values was from 3.6 to 4.2 across the region. The acceptable pH range as specified by the NDWQS is 6.5-8.5 but the water samples analysed were below that range, which is an indication of acidity. Arsenic concentrations were very high in all the boreholes sampled with values ranging from 0.16 to 1.57 mg/l. Whereas, the acceptable level of arsenic in drinking water is 0.01 mg/l. Nickel concentrations were also generally high in the region ranging from 0.013-0.144 mg/l.

Table 2. Leachate pollution index calculation

Parameter	Concentration(mg/l)	Weight (W_i)	Sub-Index Rating (P_i)	W_iP_i
Chromium	0.005	0.064	5	0.32
Iron	0.158	0.045	5	0.225
TDS	108	0.05	5	0.25
Copper	0.004	0.05	5	0.25
Nickel	0.114	0.052	5	0.26
Lead	0.012	0.063	5	0.315
Mercury	0.01	0.062	6	0.372
Arsenic	0.579	0.061	5	0.305
Chlorides	20.5	0.049	5	0.245
pH	6.2	0.055	7	0.385
Total		0.551		2.927
			LPI	5.31216

Table 3. Water quality input data for water quality index

Parameter	BH1	BH3	BH4	BH5	BH6	BH7	BH8	BH9	BH11	BH12
pH	4.0	4.2	3.6	3.9	4.0	4.0	3.6	3.8	3.8	4.0
TDS	45	20	140	87	77	118	125	80	110	86
Nickel	0.016	0.013	0.024	0.027	0.028	0.026	0.03	0.028	0.03	0.035
Iron	0	0	0	0	0	0	0	0	0	0.061
Arsenic	0.394	0.375	0.779	0.433	0.76	0.16	0.885	0.615	1.29	0.981
Mercury	0	0	0	0	0	0	0	0	0	0
Sulphate	0.75	0.365	0.75	1.81	7.58	7.96	8.73	0.558	1.33	31.4
Nitrate	1	0.079	2.72	1.44	1.16	2.14	3.03	2.02	2.16	0.074
Hardness	6.2	3	13	12.8	6.4	16.6	24.8	8.4	15.2	2
WQI	345	327	680	381	664	144	773	539	1124	858
Parameter	BH13	BH15	BH16	BH17	BH18	BH19	BH20	BH21	LCP	
pH	4.2	3.8	4.2	4.0	4.1	3.7	3.6	3.8	6.2	
TDS	78	60	45	43	34	96	79	40	108	
Nickel	0.027	0.028	0.031	0.031	0.027	0.027	0.029	0.028	0.144	
Iron	0	0	0.036	0	0	0	0	0	0.158	
Arsenic	1.01	1.17	1.38	1.15	1.25	1.57	1.57	1.48	0.579	
Mercury	0	0	0	0	0	0	0	0	0	
Sulphate	2.67	0.75	6.71	0.558	0.75	0.942	0.558	0.654	7	
Nitrate	1.99	1.38	0.254	1.11	0.859	1.79	1.76	0.674	0.424	
Hardness	7.2	8.2	5.4	7	4.2	8.4	13	5.8	66	
WQI	881	1020	1203	1003	1089	1366	1367	1289	533	

The WQI values were determined using Equation 4 and results presented as Table 4. When compared with Table 1, it is observed that the water in the entire region is unsuitable for drinking because they all had values greater 100.

Hassan [4] outlined the conditions that need to be met for a prediction model to be selected over others. The mean error of the selected model should be nearest to zero, root mean square error should be lowest and root mean square standard error should be nearest to 1. Table 5 presents the best interpolators of the water quality parameters. The best method for modelling pH, sulphate, nitrate and TDS was EBK. This was probably because EBK does not

use one variogram as kriging does in fitting the model but applies many variograms thereby reducing the error introduced by assuming the initial variogram is the right one [16]. For nickel and hardness ordinary kriging was observed to be the better modelling technique. IDW was best used to predict iron and arsenic While WQI was best modelled by cokriging. Cokriging models WQI better because it is a calculated parameter and it is determined with parameters that have the highest correlation with WQI values, thereby increasing the accuracy.

The best fit models were used to produce surface interpolation plots for the various water quality parameters measured. Figs. 1-9 shows

the spatial distribution of the water quality parameters over the region. The colors were chosen to symbolize a cold to hot effect. The blue color represents a cold region or a region of mild effects, while the red color represents a hot region or a region of adverse effects.

Table 4. Water quality index around rumuola community

Source	WQI value	Interpretation
BH1	345	Unsuitable for drinking
BH3	328	Unsuitable for drinking
BH4	681	Unsuitable for drinking
BH5	381	Unsuitable for drinking
BH6	665	Unsuitable for drinking
BH7	144	Unsuitable for drinking
BH8	774	Unsuitable for drinking
BH9	539	Unsuitable for drinking
BH11	1125	Unsuitable for drinking
BH12	858	Unsuitable for drinking
BH13	881	Unsuitable for drinking
BH15	1020	Unsuitable for drinking
BH16	1203	Unsuitable for drinking
BH17	1004	Unsuitable for drinking
BH18	1090	Unsuitable for drinking
BH19	1367	Unsuitable for drinking
BH20	1367	Unsuitable for drinking
BH21	1289	Unsuitable for drinking



Fig. 1. pH distribution in the study area



Fig. 2. TDS distribution in the study area

Table 5. Best-fit model for interpolating groundwater parameters

Parameter	Method	Mean error	Root mean square error	Root mean square standard error	Status
pH	Ordinary Kriging	0.019	0.583	1.007	
	IDW	0.056	0.616		
	EBK	0.017	0.572	0.978	best fit
TDS	Ordinary Kriging	0.490	23.405	0.803	
	IDW	2.262	24.974		
	EBK	-0.505	22.987	0.958	best fit
Nickel	Ordinary Kriging	0.001	0.028	1.014	best fit
	IDW	0.003	0.030		
	EBK	0.002	0.029	0.995	
Iron	Ordinary Kriging	0.005	0.043	1.011	
	IDW	0.002	0.040		best fit
	EBK	0.002	0.040	0.976	
Arsenic	Ordinary Kriging	0.022	0.444	1.052	
	IDW	0.005	0.043		best fit
	EBK	0.022	0.459	1.016	
Sulphate	Ordinary Kriging	0.185	8.130	1.090	
	IDW	0.278	7.737		
	EBK	0.123	7.654	0.992	best fit
Nitrate	Ordinary Kriging	0.019	0.701	0.992	
Nitrate	IDW	-0.004	0.640		
Hardness					
Nitrate	EBK	0.000	0.634	0.951	best fit
Hardness	Ordinary Kriging	-0.047	14.067	1.335	best fit
Hardness	IDW	1.493	15.912		
WQI					
Hardness	EBK	0.433	15.288	1.023	
WQI	Ordinary Kriging	15.242	399.699	1.094	
WQI	IDW	-10.220	411.896		
WQI	EBK	16.070	398.469	1.004	
	Cokriging	-2.012	382.270	1.062	best fit



Fig. 3. Nickel distribution in the study area

Based on the interpolation maps, areas near the western part of Rumuola community had very acidic groundwater with a pH of about 3.6. TDS

increased steadily from east to the west although all values were below the maximum concentration of 500 mg/l for TDS in drinking

water. Nickel values were high at western and eastern boundaries. Arsenic concentrations across the community were above 0.01 mg/l which is the permissible concentration. Sulphate and nitrate concentrations were within permissible limits and did not pose any threat to the groundwater of the community. Hardness

increases from the south-east up to the northwest region but all concentrations are below the standard value of 150 mg/l. WQI values are all above safe limits with values peaking at 1367. The southern region of the map displayed the worst water quality index values while the “best” water quality is seen in the northwest areas.

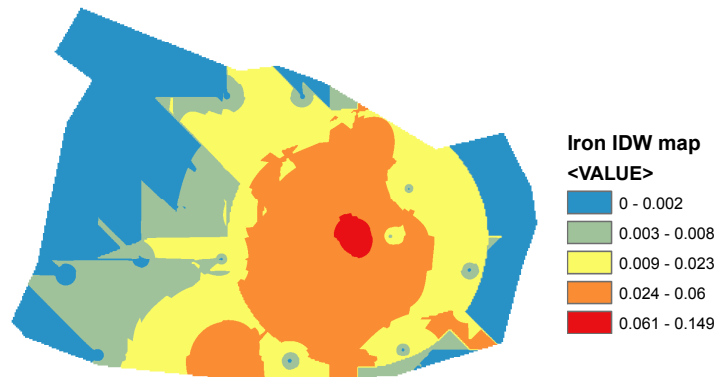


Fig. 4. Iron distribution in the study area



Fig. 5. Arsenic interpolation in the study area



Fig. 6. Sulphate distribution in the study area



Fig. 7. Nitrate distribution in the study area



Fig. 8. Hardness distribution in the study area



Fig. 9. WQI distribution in the study area

4. CONCLUSION

Findings showed that the LPI with a value of 5.31 has low pollution potential in line with the study done by [23]. Arsenic was the only leachate parameter to exceed the standard limit of 0.1 mg/l with a concentration of 0.579 mg/l in the leachate sample. Arsenic is considered

carcinogenic and is termed by some as the world's most hazardous chemical [24]. Other leachate parameters like pH, nickel, nitrate, sulphate, TDS, chloride, chromium, magnesium and lead were all within limits specified by The Federal Environmental Protection Agency Act 1988 No. 58.

The groundwater across Rumuola was generally acidic with values from 3.6-4.2. There was a high positive correlation between pH/nickel and pH/hardness. TDS, Iron, mercury, sulphate, nitrate and hardness levels were all below maximum limits. Nickel and arsenic values were above the acceptable limits for drinking water. The lowest concentration of arsenic that is allowable in drinking water is about 0.01 mg/l but the maximum concentration in the groundwater around Rumuola was 1.57 mg/l. The lowest arsenic concentration in the boreholes being 0.16 mg/l was still above drinking water limits. Nickel was observed to have a value of 0.033 mg/l and is above the limits of 0.02 mg/l in drinking water. According to SON and NIS [25], nickel is a carcinogenic element. The water quality index ranged 144 and 1367 which are all greater than 100. This means that the groundwater across Rumuola community is unsuitable for drinking. The best interpolation models for the groundwater quality parameters are as follows: EBK for pH, TDS, Sulphate and nitrate; Ordinary kriging for Nickel and Hardness; IDW for Iron and arsenic; Cokriging for WQI.

Advanced treatment methods should be explored to reduce the concentration of the toxic metals and to reduce acidity of the water to levels where they do not cause any harm to the residents who rely on this water for cooking and drinking.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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