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Multivariate statistical evaluation of the hydrochemical facies in Aba, Southeastern Nigeria

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Abstract

The quality of groundwater in terms physio-chemical and bacteriological characteristics in Aba was evaluated using multivariate statistical techniques. Six sources of pollutant were identified: Factor 1 (colour, conductivity, TDS, suspended solid, total solid, and potassium), Factor 2 (chloride, calcium hardness, magnesium, calcium and total hardness), Factor 3 (temperature and total coliform), Factor 4 (nitrate and chlorine), Factor 5 (pH and iron) and Factor 6 (bicarbonate and sulphate). Factors 1, 2, 5 and 6 may be due to natural phenomenon arising from seawater intrusion, dissolution of bedrock, infiltration and chemical weathering respectively. Pollution coming from factors 3 and 4 can be attributed to human activities resulting from faecal contamination and fertilizer application respectively. These factors determines the hydrochemical facies of groundwater in the area. Controlled extraction of freshwater from the aquifer and a well planned sanitary system is recommended for the area. The effectiveness of multivariate statistical techniques in the characterization of hydrochemical facies of the coastal plain-sand aquifers has been demonstrated in this study.

Keywords: Multivariate statistical techniques, groundwater quality, Aba, Southeastern Nigeria.

Introduction

Hydrochemical facies determinations are useful tools for determining the flow patterns, origins and chemical histories of groundwater masses. They are used to describe the bodies of groundwater in an aquifer that differ in their chemical composition. The facies are a function of the lithology, prevailing climatic condition, topography, resident time, solution kinetics, flow pattern of the aquifer and anthropogenic interference (Abdullah, et al., 2004). Hydrochemical facies can be classified on the basis of the dominant ions in the facies by means of diagrams and graphs (Piper, 1944). These methods combine chemically similar elements together and large data are usually cumbersome to handle. The demerit of the traditional Piper trilinear diagram has been overcome in this study by these techniques. Whereas the Piper diagram shows only one mixing trend, these statistical techniques allow interpretation of multiple mixing trends. Thus, it provides greater precision in identifying groundwater hydrochemical facies and interpreting their origins.

Brief review of two multivariate statistical techniques used in this study

Multivariate statistical techniques can help to simplify and organize large data sets to provide meaningful insight (Lambarkis, et al., 2004; Gupta, et al., 2005; Zeng and Rasmussen, 2005). In the present study, two multivariate statistical techniques were used to evaluate the concentrations of physio-chemical and bacteriological data from groundwater samples in Aba. The statistical software package SPSS 16.0 for windows (SPSS Inc., Chicago, IL, USA, 2009) was used for the multivariate statistical calculations. The principal component analysis (PCA) and factor analysis (FA) were used in this study to categorize the groundwater hydrochemical facies in the area.

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Principal component analysis.

Principal component analysis (PCA) calculates latent, new variables by a combination of the original variables, representing the multidimensional data structure in an optimal way. The direction of the first principal component, PC1, to which the studied objects are projected, is calculated in the way that the maximum variance of the studied objects is preserved. Then the second principal component, PC2, orthogonal to the PC1, is calculated using the same principle so that it again preserves the maximum possible residual variance. Further principal components (PCs) can be determined just continuing this same concept (Reghunath, *et al.*, 2002; Soylak, *et al.*, 2002; Praus, 2005).

Factor analysis

Factor analysis is a statistical method used to describe variability among observed variables in terms of a potentially lower number of unobserved variables called factors. In other words, it is possible, for example, that variations in three or four observed variables mainly reflect the variations in a single unobserved variable, or in a reduced number of unobserved variables. Factor analysis searches for such joint variations in response to unobserved latent variables. The information gained about the interdependencies between observed variables can be used later to reduce the set of variables in a dataset (Prasad and Narayana, 2004; Amadi and Olasehinde, 2008).

Factor analysis is related to principal component analysis (PCA) but not identical. This is due to the fact that PCA performs a variance-maximizing rotation of the variable space; it takes into account all variability in the variables. In contrast, factor analysis estimates how much of the variability is due to common factors called communality. The two methods have the potentials to reveal hidden inter-variable relationships and allow the use of virtually limitless numbers of variable. Thus trace elements, physical parameters and bacteriological parameters are part of the factorization. Parameters are treated as independent variables; the shielding effects of chemically similar elements that are combined together such as potassium and sodium by using Piper diagram are avoided (Abdullah and Aris, 2005).

The effectiveness of PCA and FA in Hydrochemical studies has been successfully demonstrated in the delineation of zones of natural recharge to groundwater in the Florida aquifer (Lawrence and Upchurch, 1983), the delineation of areas prone to salinity hazard in Chitravati watershed of India (Briz-Kishore and Murali, 1992) the delineation of effluent contaminated groundwater at two industrial sites at Vasakhapatnam in India (Sabbarao, *et al.*, 1996) and characterization by factor analysis of the chemical facies of groundwater in the deltaic plain-sands aquifers of Warri, western Niger Delta, Nigeria (Olobaniyi and Owoyemi, 2006).

The exponential growth of human population and industries in Aba has introduced a wide range of complex organic and inorganic wastes into the urban environment (Amadi, 2009). Due to high precipitation and relative humidity in the area, leachate from the dumpsites migrates through the porous and permeable aquiferous unit into the shallow water-table. Owing to the poor sanitary situation in Aba metropolis, groundwater contamination via anthropogenic interference cannot be completely ignored.

In this study, PCA and FA techniques were applied to the hydrochemical data set collected from Aba, Abia State, Southeastern Nigeria to ascertain its suitability for domestic, agricultural and industrial uses.

Location and physiography of the study area

The study area has a moderately flat terrain with good road network and is majorly drained by Aba River (Fig. 1). The area has two distinct seasons: a dry season which lasts from November to March, and a rainy season which lasts April to October. The dry season is often punctuated by a few scattered rains especially in February. The study area lies between longitude 5°30'E to 5°45'E and latitude 6°15'N to 6°30'N.

Geology and Hydrogeology of the area

The area is underlain by the Benin Formation of Miocene to Recent age (Fig. 1). The formation is made up of very friable fine to coarse grained sand with minor intercalations of clay. The Benin Formation is composed mostly of high-resistant fresh water bearing continental sand and gravel with clay and shale intercalations (Onyeagocha, 1980). Petrographic study on several thin sections ((Onyeagocha, 1980) shows that quartz makes up more than 98 % of all grains but Avbovbo (1978) indicated greater percentage of other skeletal materials including feldspar. The general thickness of the Benin Formation is variable and ranges from 200 m at the northeastern end to about 2000 m at the depocenter (Avbovbo, 1978).

The study area is underlain by a thick unconfined aquifer of regional extent depth to water table ranging from 4 m to 28 m (Amadi, 2007). The hydraulic conductivity (K) of the unconfined aquifer varies from 4.9 m/day to 43.9 m/day with a mean value of 19.7m/day while transmissivity are generally more than 500m²/day (Uma, 1986). The hydraulic gradient varies from 0.0007 in the recharge area to about 0.005 in the discharge area while the average linear groundwater velocity is in the range of 40m/yr to 400m/yr (Uma, 1986). Recharge into the unconfined aquifer is through direct infiltration of rain water. The annual groundwater recharge ranges from 22% to 30% while the average annual rainfall in the area is about 2500mm (Uma and Egboka, 1987).

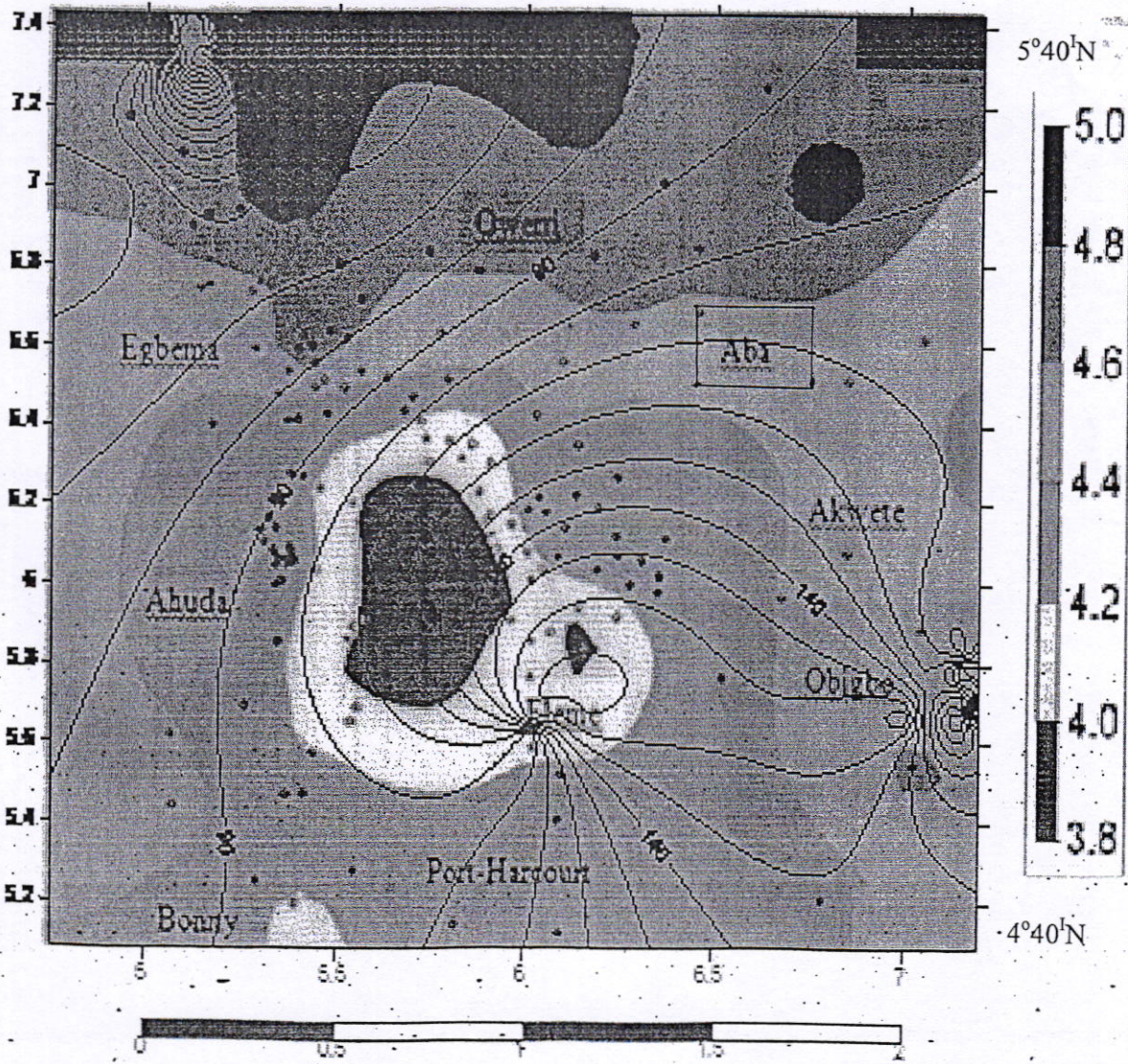


Fig. 1 pH concentration map of parts of Eastern Niger Delta

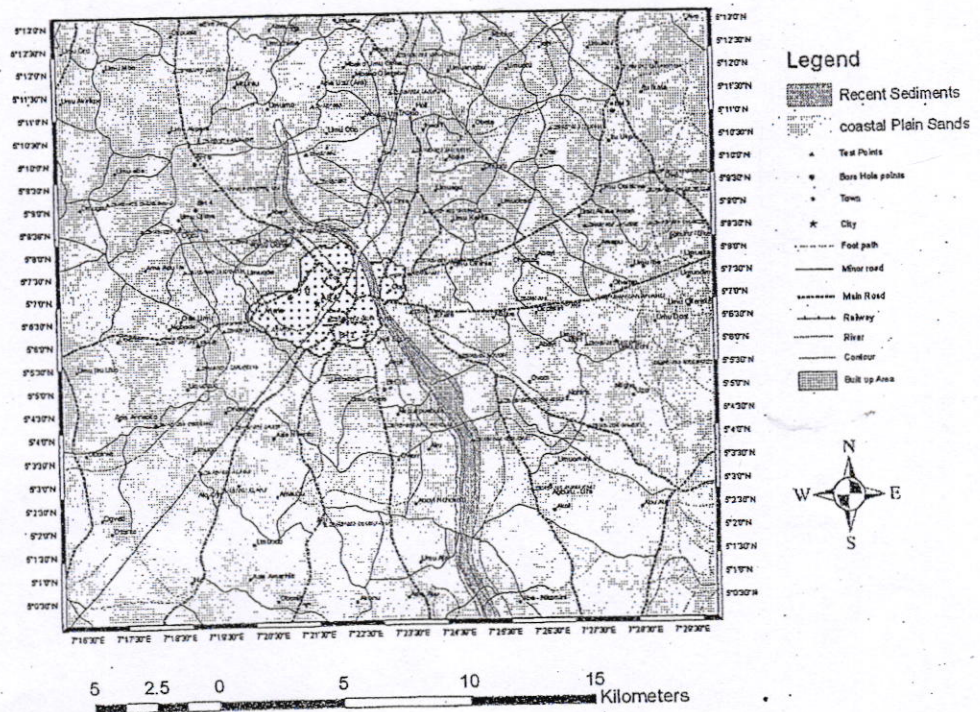


Fig. 1: Hydrogeological Map of Aba and Environs (Modified from NGSA, 2004)

Materials and methods

Field work

The values of the longitude, latitude and elevation of the sampling points were used to generate the digital terrain model (Fig. 2) and contour map (Fig. 3) of the area using Surfer-8.0 and ArcView GIS-3.2a softwares. While in the field, physical parameters such as pH, electrical conductivity, temperature were measured in the field using standard equipments (APHA, 1995).

Sampling and laboratory analyses

After field parameters stabilized, the groundwater samples were field filtered using 0.45 μ m pore-sized membrane filters and collected in high-density polyethylene (HDPE) bottles so as to prevent atmospheric contact with groundwater samples (Fredrickson, 1997). Samples for cation analyses were acidified with two drops of concentrated trioxonitrate (V) acid. Cations were analyzed by inductively coupled plasma-

atoms emission spectrometry (ICP-AES), and anions were analyzed by Dionex DX 500 ion chromatography. Fe was determined with an ICP-OES (Spectro Ciros CCD) whereas ICP-MS (Perkin-Elmer ELAN 6100) was employed for Mn determination. The accuracy of the analyses was estimated from the ionic balance error (Freeze and Cherry, 1979) which is within 5% for all samples.

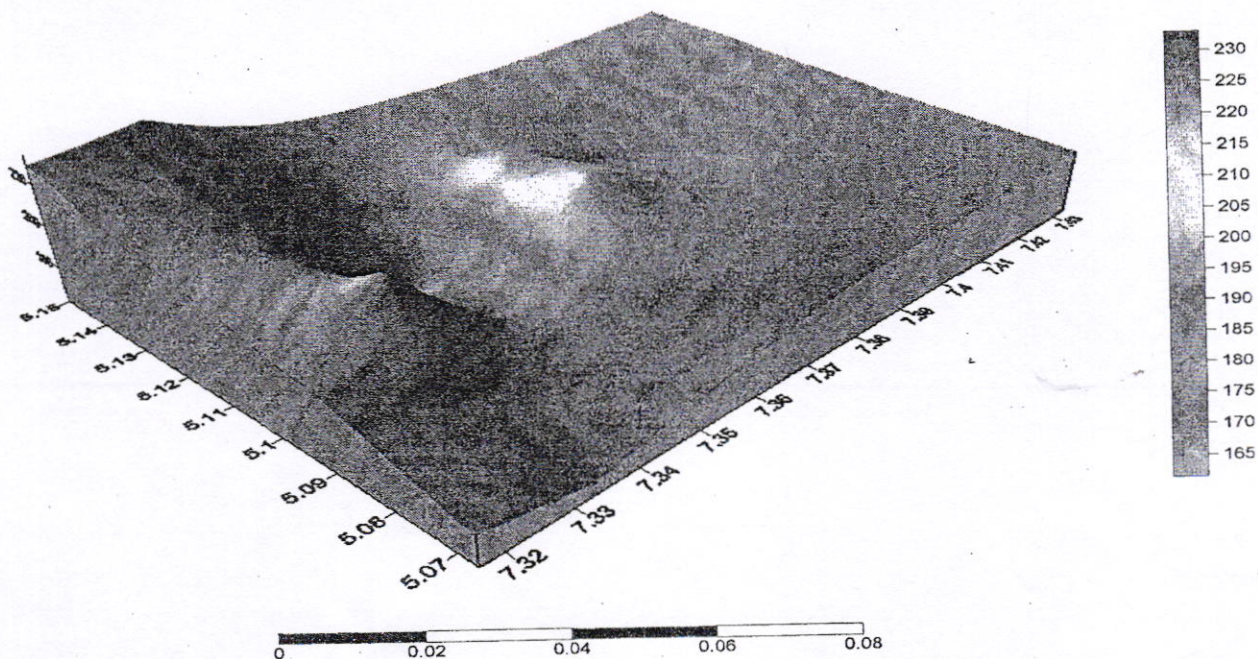


Fig. 2: Digital Terrain Model (DTM) of Aba (Source: Amadi, 2009)

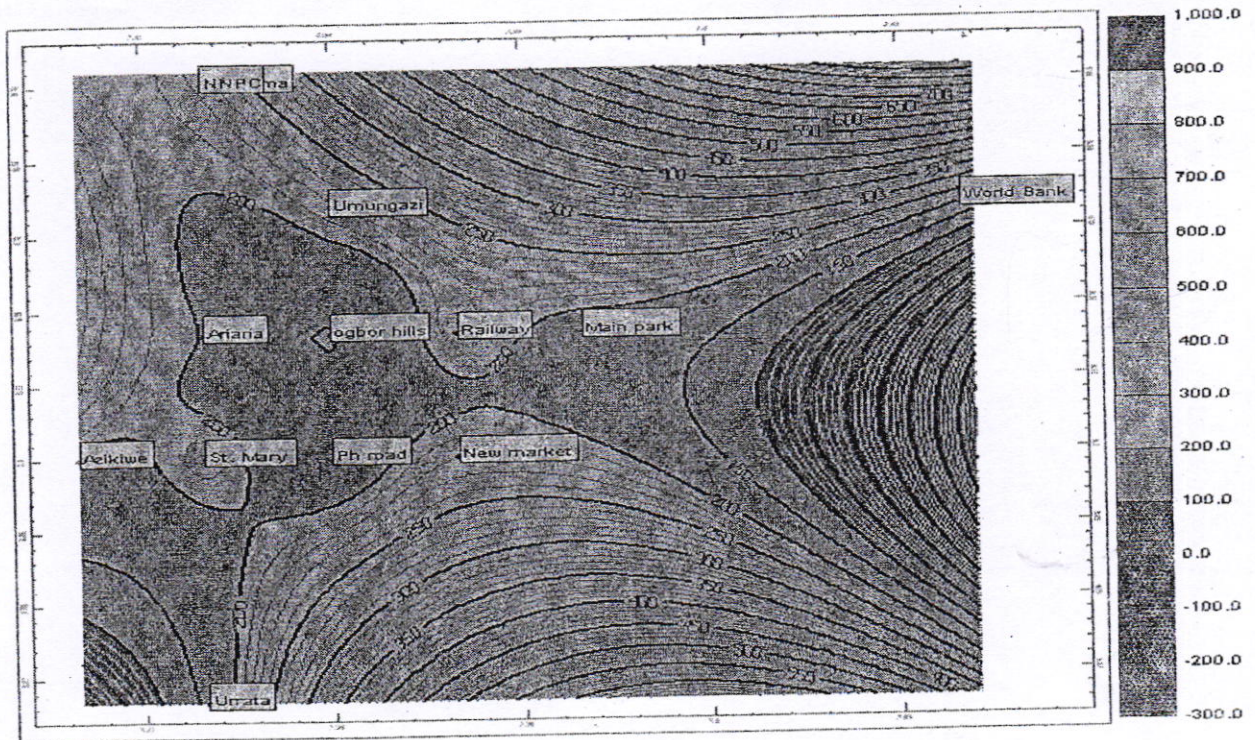


Fig. 3: Contour map of the area (Source: Amadi, 2009)

Results and discussion

In the application of principal component analysis (PCA) to groundwater quality data (Table 1) from Aba, a correlation matrix was used. The reason was that variables were different in scale (as suggested by Chatfield and Collins, 1980). The results of principal component analysis of the data are presented in Table 2. The six subsequently derived components from this table were rotated according to varimax rotation in order to make interpretation easier (Table 3). Table 3 also yields six factors, which may be interpreted as having vital importance to the groundwater quality status.

Table 1: Descriptive Statistics of Groundwater Chemistry in Aba

Parameter	Minimum	Maximum	Mean	Std.Deviation
Temperature (°C)	29.00	30.00		29.60 0.49
Colour (TCU)	4.00	34.00		15.01 8.32
pH	5.20	6.00		5.59 0.24
Conductivity (µs/cm)	9.00	458.00		121.93 126.82
TDS	5.80	297.70		76.27 778.95
Suspended Solid	4.00	81.00		38.92 23.68
Bicarbonate	11.00	54.00		26.74 13.38
Chloride	1.50	37.50	16.93	8.87
Manganese	0.01	0.30		0.09 0.92
Iron	0.06	0.35	0.19	0.09
Sulphate	2.00	13.00	5.87	3.04
Nitrate	5.60	31.10		16.39 8.52
Calcium Hardness	11.70	83.00		39.59 20.96
Total Solid	24.00	378.00		124.20 100.84
Magnesium	1.60	9.80		4.42 2.55
Calcium	4.70	33.20	15.73	8.39
Total Hardness	19.00	125.00	58.49	31.26
Potassium	3.30	38.00	16.31	9.92
Chlorine	0.01	0.60	0.17	0.15
Sodium	0.00	1.78	0.36	0.52
Total Coliform	38.00	715.00	219.67	191.81

*(All measurements are in mg/L, except otherwise indicated), TDS: total dissolved solid

Table 2: Principal component loadings of Aba groundwater data

Parameter	CP-1	CP-2	CP-3	CP-4	CP-5	CP-6
Temperature	-0.045	0.794	0.291	0.382	0.108	0.13
Colour	0.392	-0.173	0.200	-0.671	-0.152	-0.401
pH	0.557	-0.023	0.096	0.416	0.063	0.480
Conductivity	0.908	0.006	0.335	-0.089	0.151	0.107
TDS	0.901	-0.027	0.357	-0.115	0.118	0.043
Suspended solid	0.773	0.333	0.419	-0.136	0.250	0.103
Bicarbonate	0.470	0.359	-0.017	-0.418	-0.512	-0.128
Chloride	0.412	-0.766	0.193	-0.164	-0.060	0.226
Manganese	-0.218	-0.294	0.014	-0.259	0.821	0.141
Iron	0.286	0.084	-0.031	0.640	-0.275	0.432
Sulphate	0.262	0.299	-0.391	-0.349	-0.052	0.577
Nitrate	0.657	-0.358	0.058	0.258	-0.289	0.317
Calcium Hardness	0.815	-0.073	-0.515	0.019	0.092	0.086
Total Solid	0.865	0.138	0.367	-0.209	0.150	0.021
Magnesium	0.794	-0.033	-0.542	0.214	0.025	0.066
Calcium	0.815	-0.084	-0.519	0.026	0.097	0.092
Total Hardness	0.824	-0.065	-0.531	0.091	0.073	0.034
Potassium	0.625	0.127	0.450	0.039	-0.288	0.248
Chlorine	0.059	-0.301	0.497	0.377	-0.035	0.562
Sodium	-0.039	0.814	-0.63	-0.344	-0.028	0.115
Total Coliform	0.345	0.437	0.031	0.362	0.392	-0.459
Eigenvalue	7.802	2.976	2.646	2.347	1.704	1.654
% of Variance	37.151	14.172	12.602	11.178	8.115	7.878
Cumulative %	37.151	51.323	63.925	75.103	83.218	91.096

In order to reduce the contribution of variables with minor significance, thus, we simplify the data structure. The number of principal components (PCs) considered for each situation was mainly decided on the basis of the percentage of explained variance. The decision of when to stop extracting factors basically depends on when there is only very little 'random' variable left, which means that the extraction of a new factor does not significantly improve the overall information. Only factors with eigenvalue higher than one were selected. This was in agreement with Chatfield and Collins (1980), who stated that components with an eigenvalue of less than one should be eliminated so that fewer components are dealt with. That is except a factor contributes to improve the overall information at least as much as the equivalent of one original variable, we drop it. This criterion is also similar to the Screen-test, which is a graphical method that plots the eigenvalues until the place where the smooth decrease of the eigenvalues appears to level off to the right of the plot (Chatfield and Collins, 1980). Since all the communalities are higher than 0.73, it may be assumed that all the variables were described to an acceptable level. It can also be seen from Table 3 that these six principal components accounted for 91.10% of the total pollution variance of the groundwater original data.

Table 3: Aba groundwater data factor loadings after the varimax rotation

Parameter	Factor-1	Factor-2	Factor-3	Factor-4	Factor-5	Factor-6
Temperature	0.175	-0.201	0.890	0.086	0.138	0.090
Colour	0.534	-0.003	-0.528	-0.360	-0.259	0.301
pH	0.386	0.238	-0.012	0.154	0.692	-0.114
Conductivity	0.905	0.327	-0.113	0.089	0.181	0.035
TDS	0.905	0.315	-0.149	0.085	0.137	0.081
Suspended solid	0.941	0.172	0.208	0.062	0.069	-0.005
Bicarbonate	0.366	0.205	0.003	-0.209	-0.213	0.756
Chloride	0.333	0.501	-0.836	0.152	0.170	-0.092
Manganese	0.065	-0.064	-0.124	-0.091	-0.334	-0.871
Iron	0.019	0.115	0.061	-0.058	0.905	0.217
Sulphate	0.090	0.302	0.072	-0.057	-0.067	0.884
Nitrate	0.272	0.448	-0.276	0.603	0.226	0.223
Calcium Hardness	0.255	0.955	-0.067	0.025	-0.005	0.069
Total Solid	0.943	0.265	-0.025	0.033	0.049	0.086
Magnesium	0.192	0.906	-0.050	-0.063	0.323	0.083
Calcium	0.251	0.957	-0.075	0.031	0.007	0.057
Total Hardness	0.240	0.956	-0.064	-0.001	0.112	0.072
Potassium	0.610	0.116	0.083	0.468	0.002	0.429
Chlorine	0.110	-0.131	0.027	0.898	-0.031	-0.090
Sodium	0.123	-0.102	0.496	-0.479	-0.058	0.604
Total Coliform	0.320	-0.323	0.581	-0.230	0.109	-0.032
Eigenvalue	5.199	4.740	2.824	2.207	2.084	2.075
% of Variance	24.760	22.574	13.447	10.509	9.926	9.880
Cumulative %	24.760	47.334	60.781	71.290	81.216	91.096

As a general guide in interpreting factor loadings, Comrey and Lee (1992) suggested a range of values to interpret the strength of the relation between variables and each factor. Loading of 0.71 and above are considered excellent, 0.60 very good, 0.55 good, 0.45 fair and 0.32 poor. For this work, component loadings (correlation coefficients) larger than 0.60 was taken into consideration in the interpretation (as suggested by Mahloch, 1974). This implies that, the most significant variables in the components represented by high loadings have been taken into consideration in evaluating the components. In addition to the significance of high loading values, there exists a difference between the components: the components with larger variances are more desirable since they give more information about the data. When the variances (eigenvalues) of the components are examined in the related tables, it can be seen that principal components are in decreasing order of importance with respect to their variances.

An interpretation of the rotated six principal components in Table 3 is made by examining the component loadings noting the relationship to the original variables. The following factors have been computed for the hydrochemical aspect of the groundwater:

- i) Factor 1: colour, conductivity, TDS, suspended solid, total solid, and potassium
- ii) Factor 2: chloride, calcium hardness, magnesium, calcium and total hardness
- iii) Factor 3: temperature and total coliform
- iv) Factor 4: nitrate and chlorine
- v) Factor 5: pH and iron
- vi) Factor 6: bicarbonate and sulphate

Factor 1 accounted for 24.76% of the total variance and was characterized by the association of colour, conductivity, total dissolved solid (TDS), suspended solid, total solid, and potassium. There is significant correlation ($r = 0.971$, $p < 0.01$) between factor 1 and the salinity of groundwater, indicating seawater/freshwater mixing.

Factor 2 contains chloride, calcium hardness, magnesium, calcium and total hardness, which accounts for 22.57% of the total variance. Similarly, the variable association was a mark to the role of seawater intrusion into the aquifer. Seawater intrusion is one of the major problems of groundwater pollution coastal aquifer. Uncontrolled abstraction of the groundwater further aggregates the problem.

Factor 3 comprises of temperature and total coliform, accounting for 13.45% of the total variance. The presence of bacteria counts/total coliform in groundwater is an indication of contamination by animal faeces and their presence is temperature controlled. This is one of the problems of urbanization resulting from poor sanitary condition such as unlined soak-away and pit-latrines.

Factor 4 explains 10.51% of the total variance, involving nitrate and chlorine. This is as a result of agricultural activities (especially fertilizer application) in the area. High nitrate concentration in water causes cyanosis and asphyxia (blue-baby syndrome) in infants under 3 months.

Factor 5 involves pH and iron with 9.93% of the total variance. The source of iron in groundwater is weathering process of minerals. The area is characterized by low pH and this encourages chemical weathering leading to the formation of laterites which compose chiefly of iron and aluminum oxides. The presence of iron in lateritic soils is responsible for the reddish-brown or yellow colour to the soil. The iron in the laterite gets to water-table through infiltration and leaching process from the overlying lateritic formation. The low pH in the area enhances the corrosion of the iron/steel pipes used in the construction of most boreholes in the area thereby increasing the iron concentration in the groundwater. Excessive iron in the body does not cause any health hazard, only the turbidity, taste and appearance of the water will be affected.

Factor 6 has the lowest loading with bicarbonate and sulphate accounting for 9.88% of the total variance. The presence of bicarbonate and sulphate is through the dissolution of the bedrock in the course of movement. Clay and lignite contains sulphate which can enrich the groundwater by natural/anthropogenic means. The bicarbonate enrichment in the groundwater is related to the dissolution of calcite in the bedrock in the area.

Conclusion

The groundwater in Aba has been evaluated using multivariate statistical techniques. Six sources of solutes were significant. Contaminants coming from factors 3 and 4 can be attributed to human activities resulting from faecal contamination and fertilizer application respectively while the origin of factors 1, 2, 5 and 6 may be due to natural phenomenon arising from seawater intrusion, dissolution of bedrock, infiltration and chemical weathering respectively. These factors controls the hydrochemical facies of groundwater in the area.

Recommendation

Controlled extraction of freshwater from the aquifer and a well planned sanitary system is recommended for the area. Due to the high coliform count in the groundwater, boiling of the water before drinking is advocated as most bacteria count cannot withstand heat or high temperature. The water should be treated for acidity before drinking so as to improve the pH of the water. Federal Ministries of Water Resources and Abia State Water Cooperation should employ a holistic approach to drinking water supply risk assessment and management. National public health authorities should establish drinking water norms and standards and develop an efficient water resources management. Groundwater quality management through education of the public on health implications of water pollution and enforcement of necessary law that would help the protection of groundwater system is recommended.

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