African Journal of Microbiology Research Vol. 5(31), pp. 5554-5559, 23 December, 2011
Available online http://www.academicjournals.org/ajmr
ISSN 1996-0808 ©2011 Academic Journals
DOI: 10.5897/AJMR10.739

Full Length Research Paper

Factor analysis as an example of qualitative and quantitative method for modeling hydrogeochemical processes of coastal sedimentary basin of Togo

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Accepted 15 July, 2011

The present study examined the hydrochemical facies of groundwater present in the Coastal Sedimentary basin of Togo around drinking water supply. The study aim at explaining the controlling processes responsible for various facies. The parameters including pH, electrical conductivity (EC), K, Na, Ca, Mg, Cl, HCO_3, SiO_2, SO4 and NO_3 in water samples were analyzed and based on standard procedures. The data obtained were subjected to R-mode factor analysis. Two factors were extracted. Factor 1 include EC, Na, Cl, Ca, SO_4 and K and explained 59.88% of the total variance, Cl and EC and reflected the signature of saline water incursion. Factor 2 has high loading values of pH, HCO_3, SiO_2 and NO_3 which explained 34.76% of the total variance. pH and HCO_3 are the processes of natural rainwater recharge and water-soil/rock interaction process which eventually as acid-rain recharges aquifers in the vicinity. The presence of nitrate in groundwater reflects the anthropogenic impact of domestic sewage, industrial waste, uncontrolled landfill waste, fertilizers, and manure on the study area. This paper demonstrates the effectiveness of factor analysis in evaluating hydrochemical processes in coastal and industrial areas.

Key words: Coastal aquifers, factor analysis, water supply, nitrate, hydrochemical modeling.

INTRODUCTION

Water pollution arising from the presence of foreign substances (organic, inorganic, bacteriological or radiological) which tends to degrade the quality of water has become an issue of serious concern. Reliance on rain water is almost impossible and most surface water sources in Lome and its environs are polluted. Government and individuals have resorted to groundwater to satisfy major water needs. There is the general perception that water from boreholes are good for drinking and general household utilisation and the majority of people in the study area are no exception to this assertion. It is therefore crucial that periodic checks are performed on groundwater to establish its potability for consumption.

Many of the groundwaters in the coastal aquifer are suffering from seawater intrusion by over-abstraction and water quality degradation due to urbanization and agricultural activities. Intrusion of saline waters in coastal regions occurs naturally, and can be exacerbated due to exploitation of coastal aquifers as water sources (Calvache and Pulido-Bosch, 1997; Barker et al., 1998; Petalas and Diamantis, 1999; Martinez and Bocanegra, 2002; Ozler, 2003). Groundwater contamination by anthropogenic activities, such as urbanization and agricultural activities is another major problem in coastal aquifers. Numerous publications have reported that urban

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development on coastal aquifers directly or indirectly affect the groundwater quality (Zilberbrand et al., 2001; Foppen 2002; Faye et al., 2004). Likewise, agricultural activities also contribute to groundwater quality deterioration (Lowrance et al., 1997; Fakir et al., 2002; Cardona et al., 2004).

Aquifers play an ever increasing role in water resources systems as well as in systems developed for specialized purposes such as energy storage. The function of an aquifer in a water supply system varies. It may serve as a source of water, a medium of storage, or a means of upgrading water quality (Schwarz, 1989). As a source of water, an aquifer may be used as a single source or in conjunction with surface sources, as a regular complementary source to meet water quantity and quality requirements. It may also serve as a backup source in dry seasons or dry spells. Aquifers may be used as an enduring renewable source of meteoric water, or as a temporary source of mined juvenile water, for example to bridge the gap during the development of schemes for import of water which have a long gestation period.

As a storage facility, aquifers are used for artificial recharge of excess flows in wet seasons or wet spells, or when irrigation demand is low. As a means of water quality upgrading, aquifers are used to take advantage of various processes occurring naturally in groundwater: filtration, aeration, mixing with indigenous water, and providing retention time for biodégradation, decomposition of organisms and die-off of pathogenic microorganisms (Schwarz, 1989). Thus aquifers serve as natural filtration and oxidation plants to renovate and polish reclaimed waste water (Soil Aquifer Treatment - SAT) or to purify surface water with high pollution loads, by artificial recharge or induced recharge.

Early studies on the characterization of groundwater facies and chemical evolutionary history utilized graphical representations of major ionic composition of groundwater (Piper, 1944; Stiff, 1951; Schoeller, 1962; Hem, 1989). These schemes were useful in visually describing differences in major-ion chemistry in groundwater and classifying water compositions into identifiable groups (Freeze and Cherry, 1979), which are usually of similar genetic history.

The scientific studies concerning the hydrogeochemical processes are one of the most important and frequent objectives in hydrogeology (Mande et al., 2011). Therefore, the proper recognition of processes responsible for chemical diversity of groundwater in a given place and time is the main goal of hydrogeochemical studies. The hydrogeologists have practiced the varied tools to achieve this aim, and the statistical modeling is one of the most accurate. Recently, factor analysis has been used with remarkable success as a tool in the study of groundwater chemistry. Factor analysis assumes that observed variables are products of linear combinations of some few underlying sources variables known as factors. It therefore attempts to findout these factors, which can explain a large amount of the variance of the analytical data. The effectiveness of factor analysis in hydrochemical studies has been aptly demonstrated in several studies. These include the delineation of zones of natural recharge to groundwater in the Floridan aquifer (Lawrence and Upchurch, 1983), the delineation of areas prone to salinity hazard in Chitravati watershed of India (Briz-Kishore and Murali, 1992) and the delineation of effluent contaminated groundwater at two industrial sites at Vasakhapatnam in India (Sabbarao et al., 1995).

In this paper, it is shown that factor analysis is a useful and suitable method to easily achieve this goal, because this modeling allows for qualitative and quantitative recognition among the hydrogeochemical diversity of groundwater in a given population, including the percentage share. The effectiveness of this method in groundwater chemistry discrimination over the traditional piper and stiffs schemes stems from its ability to reveal hidden inter-variable relationships and allows the use of virtually limitless numbers of variable, thus trace elements and physical parameters can be part of the classification parameters. By its use of raw data as variable inputs, errors arising from close number systems are avoided. Also because elements are treated as independent variables, the masking effect of chemically similar elements that are often grouped together is avoided (Dalton and Upchurch, 1978).

The objective of this paper is to use physico-chemical parameters to determine the drinking water quality from boreholes in the Coastal Sedimentary Basin of Togo, using factor analysis statistical technique. This paper will aid in ensuring better water resource management in Region of Gulf and its environs.

Geological and hydrogeological aspects

Gulf region covers an area of about 3300 km^2. It lies between longitudes 0°55.837' E and 1°36.827' E and latitudes 6°11.683 N and 6°36.302' N. It is bounded in the South by the Guinea Coast, in the West by the Republic of Ghana and in the East by the Republic of Benin. The region falls within tropical climate. Annual average rainfall is 800 mm. It experiences an average temperature of 27.4°C. The vegetation cover is dominated by swamp forest, wetlands and tropical swamp forest comprising of fresh waters and mangrove. The region is located on coastal sedimentary rock mainly of sand and alluvium.

The drainage system is characterized Lagoons and waterways while it is drained by river Mono in the East, the Lake Togo and several lagoons (Aneho lagoon, Togoville lagoon and vogan lagoon) in the south-central and seasonal streams.

The aquifer system of Gulf region lies solely within the Dahomey sedimentary basin and extends almost from Accra in Ghana, through the Republic of Togo and Beninto Nigeria. In Gulf region the aquifer is confined beneath younger sediments and is divided into three, with

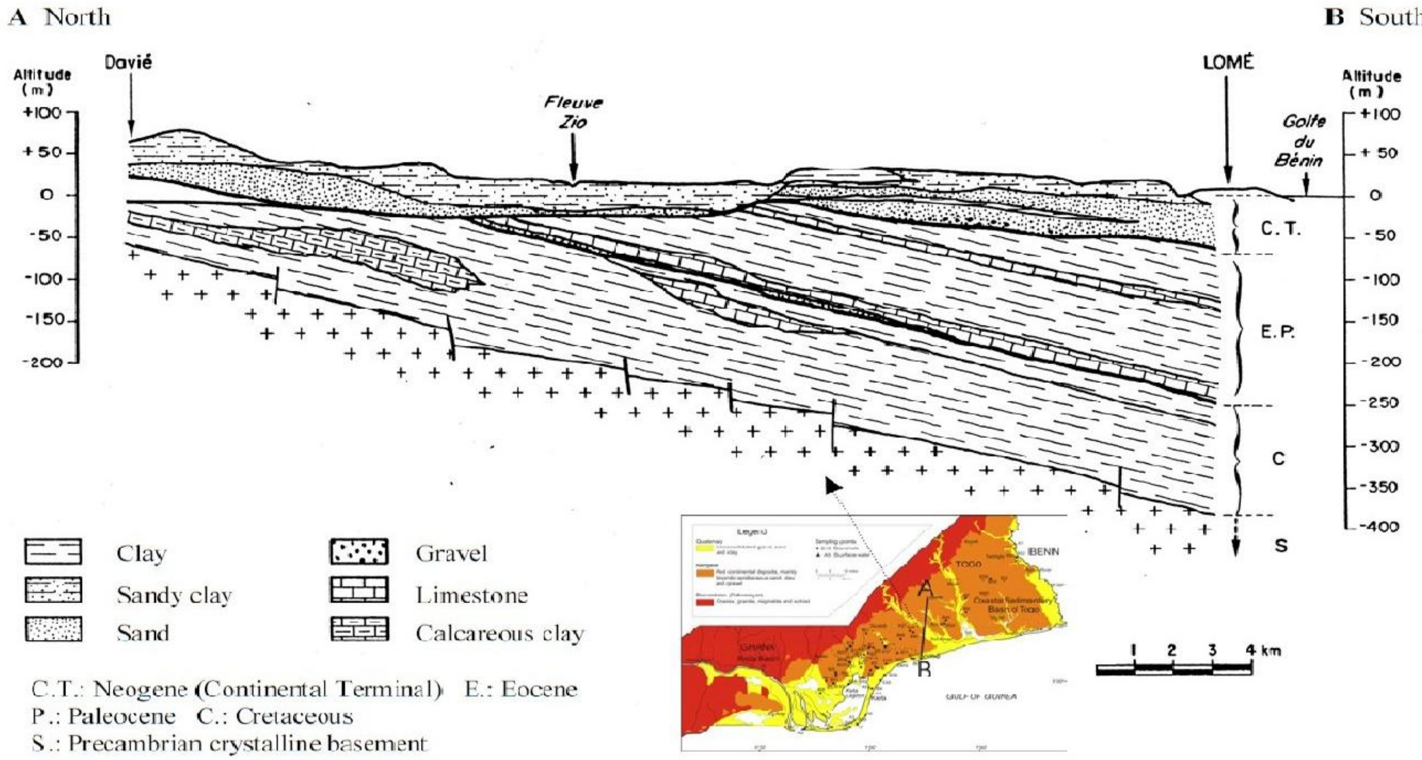

Figure 1. Geological north - south cross-section of cretaceous-quaternary sediments from the western part of the Coastal Sedimentary Basin of Togo. The location of the cross-section is shown on the inset.

the first aquifer representing the continental terminal (CT), the second aquifers being within the Eocene – paleocen (EP) aquifer while the third aquifer represents the cretaceous (C). The coastal sedimentary basin (CSB) consists of soft, very poorly sorted, clayey sands, pebbly sands, sandy clays, gravel, limestone and calcareous clay. Their thickness increases from north to south and can be up to 350 m. (Figure 1).

Many of boreholes in Gulf region obtain their water from the CT and EP. In these aquifers, there is a lot of lateral variation in lithology and water quality. The aquifer thickens from its outcrop area in the north to the south with increase in sand formation to the south. Groundwater salinity in the aquifer changes from north to south with salt water intrusion. In the Northern and central parts of the region is fresh water-bearing aquifer while, in the Southern coastal belt is the salt water-bearing aquifer. Groundwater flow shows a general North to south.

METHODS

Sampling

In 2009 to 2010, the seasonal observations of chemical composition of groundwater have been carried out. 23 sampling points in continental terminal and 6 sampling points in the Eocene-Paleocene which were selected to provide a uniform distribution over most the drinking water supply area (Figure 2).

Chemical analysis

The polyethylene bottles were used to collect the samples of groundwater. The values of temperature, electrical conductivity and pH were measured directly in the field. After delivery of water samples to the laboratory, the concentration of ions (Cl^-, HCO_3^-, SO_4^{2-}, NO_3^-, Ca^{2+}, Mg^{2+}, Na^+, K^+, Fe^{2+}, Mn^{2+} and SiO_2) have been measured using various methods based mainly on the normalized AFNOR (Afnor, 1996)

Statistical data processing

Eleven standardized chemical parameters (Table 2) have been used in factor analysis transformation. During the standardization processing all values of selected variables are replaced by standardized values (where 0 is mean value, -1 and 1 is standard deviation). In principal components transformation (PCA), the principal factors have been distinguished. The first separated factor explains the most common part of the variance among variables and each next a lesser part of the variance. Moreover, the transformation correlation matrix of factor loadings has been created. Factor loadings have varied from –1 to 1 value, but based on (Lambrakis et al., 2004), values <-1; -0, 7> and <0, 7; 1>) have been accepted as a significant on 0, 05 significance level. In order to take on clear configuration of factor loading the “varimax” strategy of rotation has been used (Manly, 1998). The number of factors for all calculated matrix have been retain on the base of the statistical scree test (Stat Soft 1984 to 2010). Next, the percentage participation of the particularly factors was calculated. The calculated result of 94.64% of chemical diversity of water was explained. The rest of is the random noise, impossible for interpretation by this method (Drever,

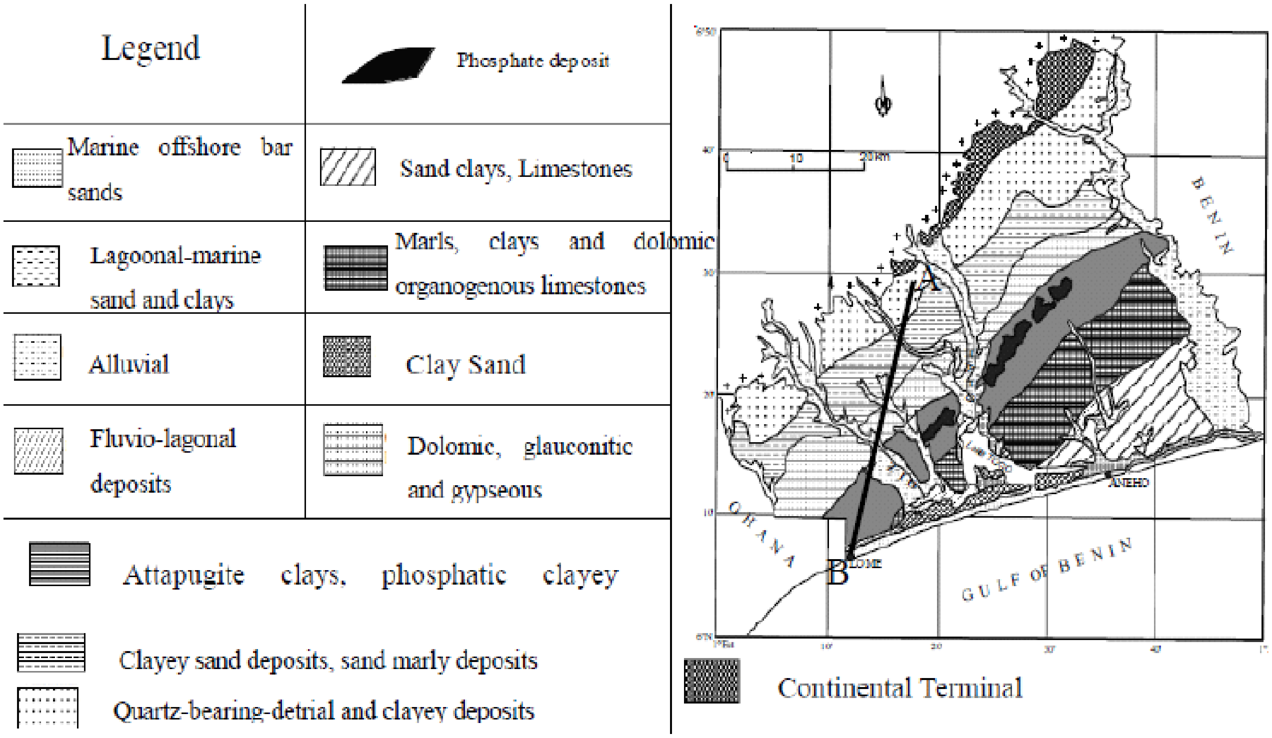

Figure 2. Geological map of coastal sedimentary basin of Togo.

1997; Manly, 1998; Dragon, 2002). The results of factor analysis have been interpreted in the relation to the natural and or anthropogenic processes (Drever, 1997). All statistical analysis was calculated using the SPSS 16.0 Software.

Saturation index modeling

The hydrogeochemical SI (saturation index) model for water under study has been done to verify the results of factor analysis using the AquaChem 5.1 software (waterloo, Inc 2009). Hydrogeochemical modeling may confirm the correctness of factor analysis' results. The values of saturation indices (SI) have shown the results of modeling among the others. SI > 0 evidences that the particular mineral phases may precipitate from the solution. SI < 0 indicates that some minerals can be dissolved. Values close to zero indicate the equilibrium conditions between water solution and the mineral phases.

RESULTS AND DISCUSSION

Table 1 presents a descriptive statistics of the hydrochemical data of the study area.

Result of factor analysis of the groundwater chemistry data indicates two factors that can be related to various controlling processes presumed to have produced the different water species. Table 2 shows the varimax rotated factor matrix consisting of the component factors, the loading of variables on each factor and percentage of data variance explained by each factor. These two factors account for 94.64% of the total variance in the dataset.

Factor 1 has a high loading of EC, Na, Cl, Ca, SO_4, Mg and K and explains 59.88% of the total variance (Table 2). The concentration of Na, Cl and K in seawater is much greater than in continental water. This factor can be ascribed to the intrusion of seawater into the aquifer system which increases the concentrations of these ions and hence values of the dissolved solids.

Factor 2, which explains 34.76% of the total variance, includes SiO_2, NO_3, pH and HCO_3 (Table 2). This factor reflects the signatures of natural water recharge and water-soil/ rock interaction. Surface water charged with atmospheric and biogenic CO_2 infiltrates into the subsurface and aggressively attack calcite, dolomite, aluminosilicates including feldspars and micas present in the formation (Figure 1) (SI values are < 0) liberating cations such as Ca and Mg into the water and leaving residues of clay minerals. A consequence of this incongruent dissolution is a rise in pH and in HCO3 concentration of the water (Freeze and Cherry, 1979).

Saturation index modeling has been investigated in the area of Gulf region and its environs. The hydrogeochemical processes may describe the varied numbers of factors. The most important among the analyzed parameters has been the dissolution taking place in the transient system of water flow. The occurrence of easily weathering and or dissolving minerals such as calcite, dolomite and anhydrite and aragonite may have enhanced this process (SI values are< 0). In general, the ions Ca^{2+}, Mg^{2+}, SO_4^{2-} have been strongly connected with

Table 1. Descriptive statistics of the hydrochemical data of the study area. All units are in mg/L, except for electrical conductivity (EC, µS/cm).

Parameter	Max	Min	Mean
pH	7.45	5.14	5.8821
Temp	29.2	24.4	26.909
EC	4580	327	1519.13
Ca	192	32	70.922
Na +K	790.67	35.842	232.29
Mg	103	5.52	34.71
Cl	1618.8	28.4	442.05
SO_4	335.14	24.3	111.93
HCO_3	355.02	13.42	84.268
NO_3	47.49	0	19.705
SiO_2	42.1	17.5	32.9

Table 2. Varimax rotated factor loading matrix for groundwater chemistry data in Gulf Region and its Environs.

Parameters	Factor 1	Factor 2
Mg^{2+}	0.995	
$Na^{+} + K^{+}$	0.994	
EC	0.993	
Cl^{-}	0.981	
Ca^{2+}	0.979	
SO_4^{2-}	0.957	
HCO_3^{-}		0.961
SiO_2		-0.953
pH		0.950
NO_3^{-}		-0.793
% of Variance	59.88	34.76
Cumulative %	94.64	

Table. 3. Results of SI modeling.

Parameter	Max	Min	Mean
SI(Anhydrite)	-1.3029	-2.6957	-2.0745
SI(Aragonite)	0.0803	-3.8526	-2.3034
SI(Calcite)	0.2243	-3.7084	-2.161
SI(Chalcedony)	0.3699	0.0224	0.25287
SI(Dolomite)	0.406	-7.3204	-4.2828
SI(Goethite)	7.3389	1.1288	3.6084
SI(Gypsum)	-1.1	-2.4936	-1.8629
SI(Hematite)	16.685	4.2849	9.2332
SI(Pyrite)	-65.632	-101.22	-79.596
SI(Quartz)	0.7928	0.4533	0.67607
SI(Siderite)	-0.4918	-4.4032	-2.8671
SI(Talc)	-0.3879	-13.469	-8.2541

with Factor 1 as these ions are the main constituents among the above listed minerals (Table 3).

The presented example of modeling based on multivariate statistical analysis has confirmed and qualitatively improved our general knowledge regarding to hydrogeochemical studies. The results of factor analysis have shown the percentage participation of these processes and the significance among each of them in the formation of groundwater chemistry.

Conclusion

The interpretation of the results due to the factor analysis depends mainly on the investigator, his experience and the knowledge about researched area. The result of the multivariate statistical analysis, as applied to the chemical data set of groundwater in the Coastal Sedimentary Basin of Togo provides an insight into the underlying controlling hydrochemical processes in the area. Two factors (1) (EC, Na, Cl, Ca and K), (2) (pH, HCO_3, SiO_2, and NO_3) extracted from the dataset represent the signatures of saltwater incursion, and interaction with the geological matrix in the groundwater. Factors 1 and 2 represent ions with dominant concentrations and therefore the main contributors to the groundwater salinity. The recent drive toward industrialization and the attendant urbanization in Lome city means a greater demand for groundwater in the area. New groundwater abstraction schemes are recommended preferably in areas with low values of Factors 1 and 2. This paper demonstrates the effectiveness of factor analysis in sorting out otherwise ambiguous hydrogeochemical processes in groundwater quality.

ACKNOWLEDGEMENT

This work was supported by the 863 Program (Grant No. 2007AA06A410) of the Chinese Ministry of Science and Technology and the Studies of Safety Evaluation and Pollution Prevention Technology and Demonstration for Groundwater Resources in Beijing (Grant No. D07050601510000). The analytical data reported were supplied by the Central Laboratory of Togolese Water Company (TdE)

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