JOURNAL OF
ENVIRONMENTAL HYDROLOGY

The Electronic Journal of the International Association for Environmental Hydrology
On the World Wide Web at http://www.hydroweb.com

VOLUME 16 2008

THE HYDROCHEMICAL FRAMEWORK OF SURFACE WATER BASINS IN SOUTHERN GHANA

Sandow Mark Yidana

Department of Earth & Environmental Studies
Montclair State University, USA

Surface water resources play a crucial role in the domestic water delivery system in Ghana. In addition, sustainable food production is based on the quality and quantity of water resources available for irrigation purposes to supplement rain-fed agricultural activities. The objective of this research was to determine the main controls on the hydrochemistry of surface water resources in southern Ghana and assess the quality of water from these basins for irrigation purposes. R-mode factor and cluster analyses were applied to six hundred and twenty-five (625) data points from six river basins after the data was log transformed and standardized for homogeneity. The surface water chemistry in the south is controlled by the chemistry of rainfall, fertilizers from agricultural activities in the area, as well as the weathering of carbonate minerals. Silicate mineral weathering from the underlying sediments and rocks appears to play a minor role in the hydrochemistry at the regional level. In addition, an assessment of the irrigation quality of water from these basins suggests that the basins are largely low sodium-low to medium salinity basins, delivering water of acceptable quality for irrigation.

INTRODUCTION

In Ghana, the problems associated with rural and urban water delivery are enormous. The current state of performance of the water sector is rooted in the economic reforms which begun in the 1980s under the economic recovery program (ERP), the structural adjustment program (SAP)(1983-1993) and the program of action for the first medium term development plan (1997 to 2000) of Ghana, Vision 2020 (NDPC, 1998). Following the International Drinking Water Decade, it became necessary to introduce reforms in the drinking water supply sector in order to accelerate coverage of communities with safe drinking water. A new policy was put in place to ensure that the supply of water to rural communities was demand driven and community managed. Between 1996 and 1998, the government of Ghana as part of the Water Sector Rehabilitation Project, spent an average of US$1.95 million per annum while donor contribution went up to US$34.2 million in 1998 (Gyau-Boakye and Ampomah, 2003).

Most urban communities in the country depend on tap water from the river basins in the area. Where rural communities are close enough to urban centers, they also tap into the extensions of the urban water delivery system. In recent times, it has become abundantly clear that the sustainable socioeconomic development of the country is tied to the management of surface and groundwater resources for various uses in households, industry, irrigation and other purposes. The agricultural sector contributes significantly to the economy. Often times, this enterprise is rain fed and with the irregularity of rainfall patterns in recent times, reliance on rain fed agriculture can not support sustainable socioeconomic development of the nation. There is therefore a growing interest in developing the irrigation industry to support year round agricultural activities. This calls for an in-depth evaluation of the available surface and groundwater resources to support this enterprise. The management of surface and groundwater resources to meet growing needs begins with an analysis of the main controls on the quality of these surface water basins.

This paper evaluates the sources of variation in the hydrochemistry of seven river basins in southern Ghana using advanced statistical analysis, and assesses its quality for irrigation using salinity and sodicity plots.

SURFACE WATER SYSTEMS IN GHANA

Ghana is drained by three main river systems: the Volta, Southwestern and Coastal River Systems. They cover respectively 70%, 22% and 8% of the total drainage area. The Volta system is made of the Red, Black and White and the Oti River. The Southwestern Rivers comprise the Bia, Tano, Ankobra and Pra rivers, while the coastal river system is made of the Ochi-Amissah, Ochi-Nakwa, Ayensu, Densu and Tordzie/Aka rivers. The mean annual runoff from Ghana alone is 39.4 billion cubic meters, with the Volta, Southwestern and Coastal systems contributing 64.7, 29.2 and 6.1 percent respectively. This amount of runoff is enough to support most domestic and irrigation uses in the country if it is adequately managed. This research is focused on the Birim, Ankobra, Tano, Amisa, Pra, Ayensu and Densu basins. Figure 1 is a hydrological map of Ghana showing the locations of the river basins under discussion in this research. Also indicated is the underlying geology of the region of influence of these river basins.

The seven river basins are underlain by Precambrian igneous and metamorphic rocks which are typically referred to as the basement complex. These include a series of isoclinally folded metamorphosed sediments intercalated with metamorphosed tuff and lava. This series of metasediments is intruded by batholithic masses of granite and gneisses. The argillaceous

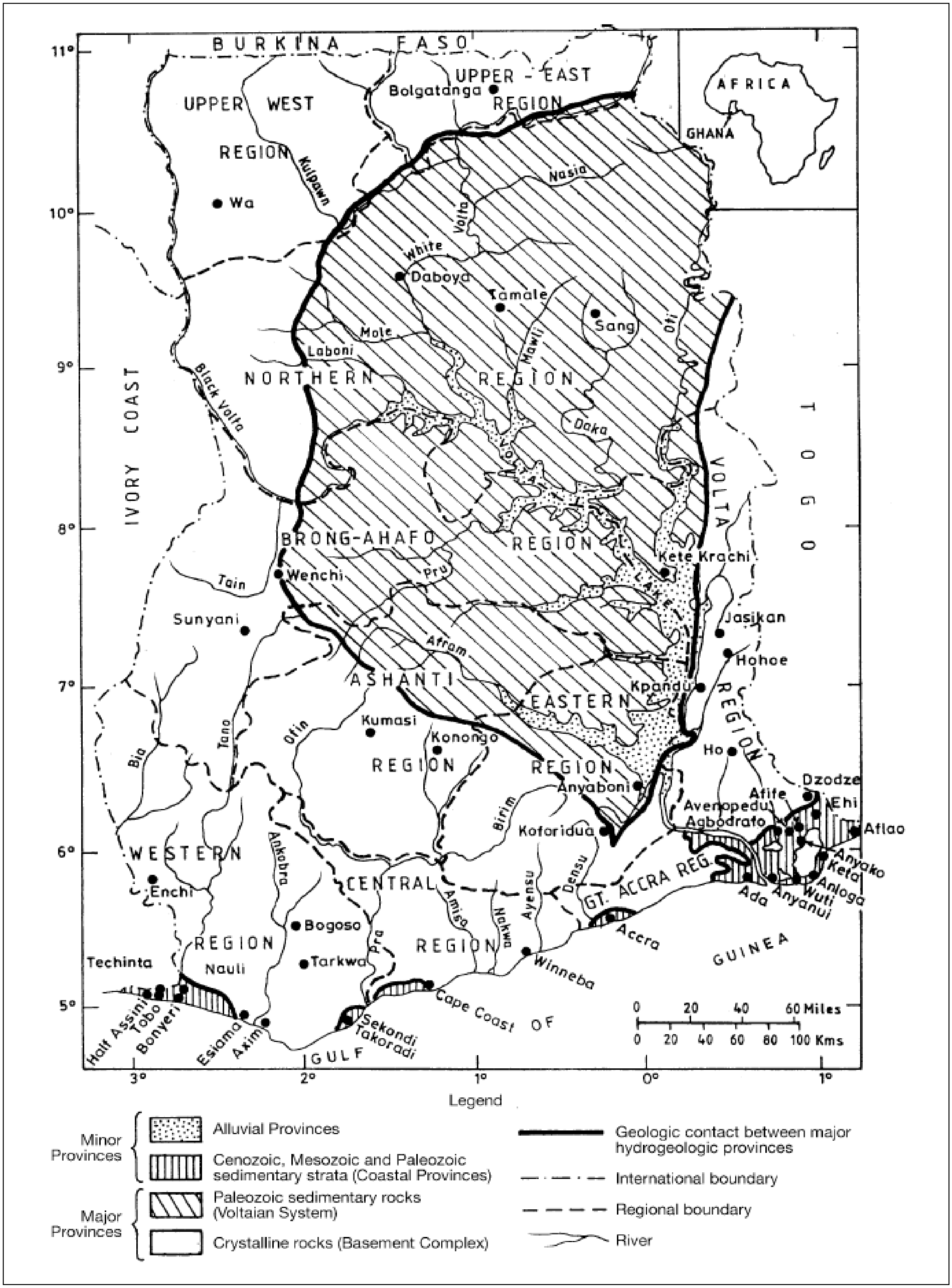

Figure 1. A relief and drainage map of Ghana showing the locations of all the river basins sampled for this research (Dapaah-Siakwan and Gyau-Boakye, 2000).

sediments were metamorphosed to schist, slate, and phyllites with interbedded greywacke (Dapaah-Siakwan and Gyau-Boakye, 2000). Other rock units found in the area are sandstones, quartzites, shale and conglomerate, resting unconformably on and derived from the metasediments and batholithic masses of rock discussed above. These are readily weatherable materials which have the potential to influence the hydrochemistry of rivers flowing on them.

The Densu River, the Pra River, the Ankobra River, and the Tano River all of which play important roles in the economy of Ghana, form what is known as the Akan Lowlands. The Densu River Basin, location of the important urban centers of Koforidua and Nsawam in the eastern lowlands, has an undulating topography. Many of the hills here have craggy summits, which give a striking appearance to the landscape. The upper section of the Pra River Basin, to the west of the Densu, is relatively flat; the topography of its lower reaches, however, resembles that of the Densu Basin and is a rich cocoa and food-producing region. The valley of the Birim River, one of the main tributaries of the Pra, is the country's most important diamond-producing area.

The Ankobra River Basin and the middle and lower basins of the Tano River to the west of the lowlands form the largest subdivision of the Akan Lowlands. Here annual rainfall between 1,500 and 2,150 millimeters help assure a dense forest cover. In addition to timber, the area is rich in minerals. The middle and lower Tano basins have been intensely explored for oil and natural gas since the mid-1980s. The lower basins of the Pra, Birim, Densu, and Ankobra rivers are also sites for palm tree cultivation.

The hydrochemistry of surface water resources is influenced by many factors including precipitation, underlying geology, organic matter decay and anthropogenic factors such as agricultural activities and mining. The degree of influence of each of the above factors depends on the location, the climate and season. The natural changes in the chemistry of a mass of water as it flows down a river, apart from the effects of mixing, are usually generally relatively small compared to changes that take place in the soil zone (Drever, 1988). This is because the residence time of water in a river is relatively short and because there is relatively little contact between the water and the solid phase. Such changes as usually occur are caused by biological processes and affect primarily the nutrients (nitrogen, phosphorus, and potassium), silica and certain trace elements (Drever, 1988).

LITERATURE REVIEW

Multivariate statistical tools have been used widely to study the sources of the variation in the hydrochemistry of surface and groundwater systems in recent times. Arguably, one of the most powerful tools that have gained widespread acceptance in the geo-environmental research community is multivariate statistical hydrochemical modeling. Precisely, factor and cluster analysis are the most widely applied tools in geochemical studies to decipher trends in data variation. Excellent examples of the application of factor analysis to solve hydrochemical problems are contained in Dalton and Upchurch (1978), Usunoff and Guzman-Guzman (1989), Briz-Kishore and Murali (1992), Grande et al. (1996), Huizar et al. (1998), Ceron et al. (1999), Suk and Lee (1999) and Sanchez-Martos et al. (2001). Multivariate techniques have been used to resolve hydrological factors such as aquifer boundaries, groundwater flow paths and hydrochemical parameters (e.g. Razack and Dazy, 1990; Join et al., 1997; Ochsenkuehn et al., 1997; Liedholz and Schafmeister, 1998; Wang et al., 2001 and Locsey and Cox, 2003), identify geochemical controls on the composition of water (Adams et al., 2001; Alberto et al., 2001) and separate anomalies such as anthropogenic impacts from background concentrations (Hernandez et al., 1991; Birke and Raush, 1993; Helena et al., 2000; Pereira et al., 2003). Multivariate statistical methods can be used in much the same way as a trilinear diagram, but with the advantage of being able to include additional ions to the major and also non-chemical data (van Tonder and Hodgson, 1986). If the variables measured for each groundwater sample include those variables that can be expected to differentiate groundwater by source, then multivariate data analysis can be used to formulate and test hypotheses of possible segregation among groundwater sources or mixing between aquifers (Steinhorst and Williams, 1985).

METHODOLOGY

The data used for this study include concentrations of the major ions: sodium (Na^+), potassium (K^+), calcium (Ca^{2+}), magnesium (Mg^{2+}), chloride (Cl^-), bicarbonate (HCO_3^-), sulfate (SO_4^{2-}) and nitrate (NO_3^-), as well as silica (SiO_2), electrical conductivity (EC), and pH. This data was compiled by workers of the Water Resources Research Institute (WRRI) of the Center for Scientific and Industrial Research (CSIR) of Ghana. Electrical conductivity and pH were measured directly in the field. The concentrations of the major ions and silica were determined in an approved laboratory in Accra after samples were collected at vantage locations along the river basins into plastic bottles and acidified to discourage bacterial action.

A total of six hundred and twenty five (625) data points were used for this study. The data was first tested for normal distribution since this is a requirement for optimal multivariate statistical analysis. The normal distribution criterion was not met for all the parameters. They were therefore log – transformed and then standardized to their respective z-scores. Standardization was achieved by using Equation 1.

$$z = \frac{x - \bar{x}}{s} \qquad (1)$$

where x and $\bar{x}$ respectively stand for the concentration and mean concentration of each parameter, and s is the standard deviation of each parameter.

Data standardization is preferred in cluster analysis since it gives equal weight to each variable in the multivariate analysis. Otherwise, the Euclidean distances calculated will be influenced most strongly by the variable that has the greatest magnitude (Güler et al., 2002).

R-mode hierarchical cluster analysis (HCA) was then applied to the standard z-scores using squared Euclidean distance as a similarity (dissimilarity) measure and the Ward’s linkage algorithm. The Statistical Package for Social Sciences (SPSS) (SPSS Inc., 2001) software package was used for both the R-mode HCA and factor analysis. A combination of squared Euclidean distance and the Ward’s linkage algorithm produces optimal results in R-mode cluster analysis. R-mode cluster analysis places a set of variables into distinct groups on the basis of their similarity or dissimilarity with each other in the field.

R-mode factor analysis with principal components and varimax rotation was then applied to the z-scores of the chemical parameters. The Kaiser criterion (Kaiser, 1960) was used to limit the number of factors (principal components) to those with an eigenvector sum of at least 1.00. Four factors were obtained after the first analysis with Kaiser Criterion and varimax rotation. However, upon close inspection, the last two factors did not constitute unique sources of variance from the geochemical point of view. Therefore the analysis was repeated with only three factors with varimax rotation. The contribution of each of the three factors to the variation in the geochemistry of each of the river basins was evaluated by taking the sum of the products of the loading of each variable under each factor.

RESULTS AND DISCUSSIONS

The results of the R-mode HCA is illustrated with the dendrogram in Figure 2. The dendrogram shows three distinct associations: the Na^+, Cl^- and Ca^{2+}, which probably represents the effects of precipitation; the K^+, Mg^{2+} and SiO_2 group which probably accounts for the effects of nutrients and the weathering of K-feldspar and mica from the underlying sediments; and the SO_4^{2-} and HCO_3^- group which also represents the effect of vegetation or organic matter on the surface water hydrochemistry.

The factor analysis resulted in three principal components representing three main sources of variation in the hydrochemistry at the regional level. These three components account for 67% of the variance in the hydrochemical data. Table 1 summarizes the results. Component 1 which has high loadings for Na^+, EC, K^+ and Cl^- is indicative of the effects of precipitation. Sodium and potassium are probably derived from their chloride salts derived from the atmosphere and the underlying sediments. The EC appears to vary in concert with sodium and potassium, suggesting that the sources of these ions are the main control on the general ionic enrichment of the surface water basins. Appelo and Postma (1993) suggest that Na^+, K^+ and Cl^- can also be enriched in natural waters due to the weathering of granites and magmatic rocks through which the water flows. In the weathering of igneous rocks, albite and potassium feldspars are usually the main sources of Na^+ and K^+ ions respectively. The weathering of albite and K-feldspars leads to enrichment of SiO_2 as well. If these silicate minerals were the main sources of Na^+ and K^+ ions, one would have expected

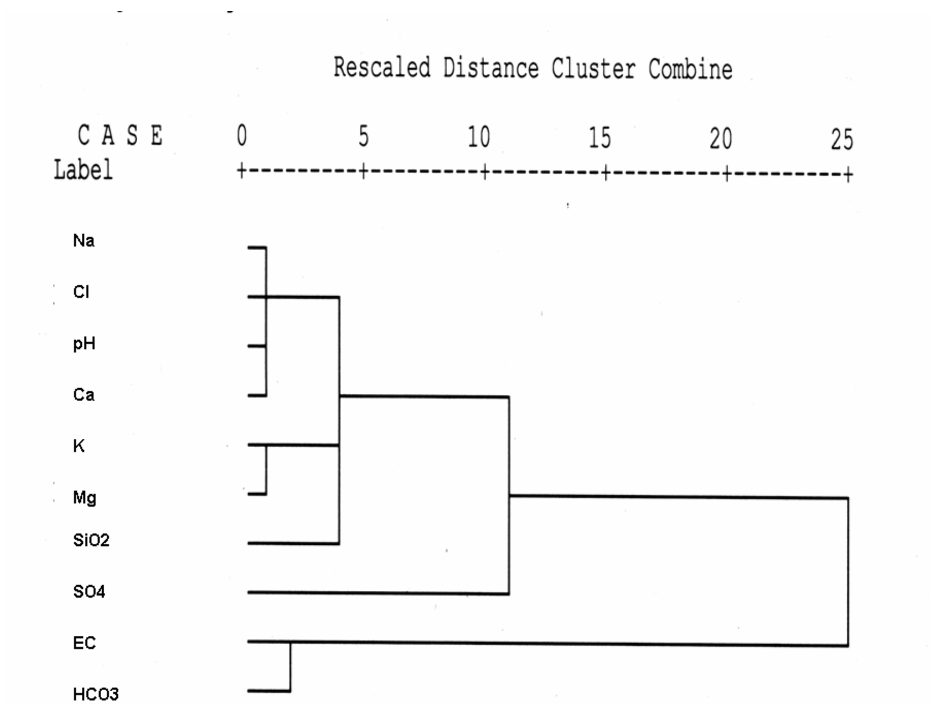

Figure 2. A dendrogram showing the results of the R-mode HCA on water chemistry data of surface water basins in southern Ghana.

Table 1. The results of factor analysis showing three main controls on the hydrochemistry of the surface water basins in southern Ghana.

	Component		
	1	2	3
pH	.079	.788	.228
Na	.934	-.036	-.018
EC	.702	.172	.570
Ca	.362	.038	.707
K	.785	.066	.250
Mg	-.124	.658	.300
Cl	.901	.066	.103
HCO3	.080	.111	.801
SiO2	.293	.732	-.362
NO3	.310	-.698	-.337
SO4	-.161	-.460	.112

SiO_2 to be correlated with them under the same component in the factor analysis. A plot of Na^+ against Cl^- is presented in Figure 3. The distribution of the scatter points indicates that whereas much of the sodium in the basins could be attributed to sodium chloride, there are probably other sources of the sodium cation in the system. More points occur in the scatter in the Figure 3 plot above the equiline than points below it, which suggests that chloride cannot account for all the sodium in the basins. The weathering of albite from the underlying sediments and rocks probably plays a secondary role in the enrichment of the Na^+ content of the basins. In Figure 4, a plot of the total cations, TC against Na + K shows that some points in the scatter plot above the Na+K = 0.33TC line, which suggests that silicate mineral weathering might be playing some role in the generation of the total cation base of the basins. Figure 5 supports this point, suggesting that in addition to silicate mineral weathering from the underlying geology, carbonate mineral weathering also plays a role in the hydrochemistry of the basins.

Magnesium, and SiO_2, (which are probable results of the weathering of micas in the underlying geology), show high absolute loadings under component 2. In addition, component 2 shows high loadings for NO_3^- and SO_4^{2-} which represent the effects of nitrate and sulfate fertilizers from agricultural activities in the neighborhood of the basins. There is extensive cocoa farming in the southern sector of the country and farmers do use nitrate and sulfate fertilizers extensively. The second component is therefore a mixed factor representing the effects of mineral weathering and agricultural activities. Component 3 is characterized by high loadings for Ca^{2+} and HCO_3^- which represent the dissolution of calcite from the underlying sediments. Figure 5 supports this fact as discussed above.

Surface water from these basins was also assessed for its suitability for irrigation purposes in the surrounding communities. The assessment was based on the combined effects of the sodium content compared to the total concentration of calcium and magnesium, and the salinity as measured by the electrical conductivity of the water. Sodium Adsorption Ratio, SAR, defined by Equation 2 is an index used to measure the sodium strength of irrigation waters.

$$SAR = \frac{m_{Na^+}}{\left(m_{Ca^{2+}} + m_{Mg^{2+}}\right)} \qquad (2)$$

where m_i is the concentration of species i in mmol/l.

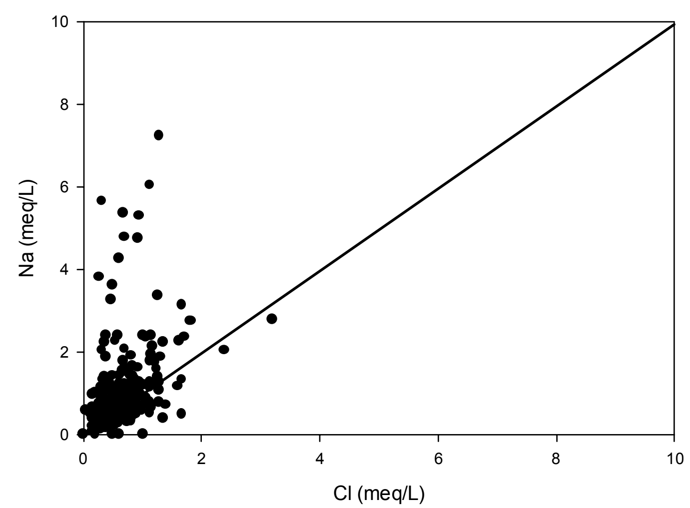

Figure 3. A plot of Na (meq/L) against Cl (meq/L) for the surface water basins in southern Ghana.

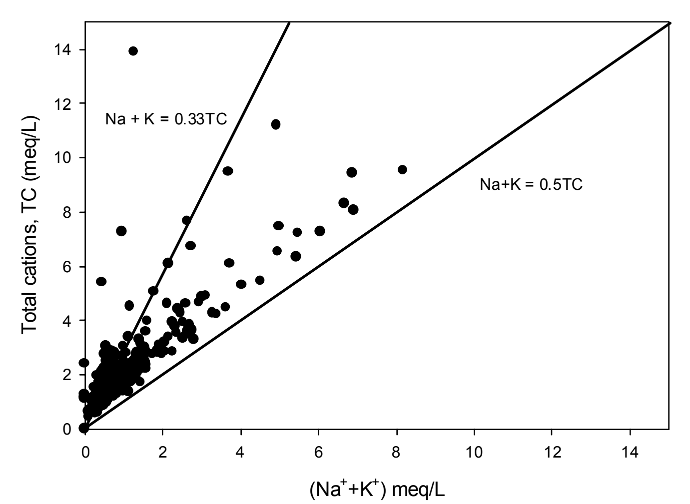

Figure 4. A scatter plot for total cations and the sum of Na^+ and K^+ in meq/L.

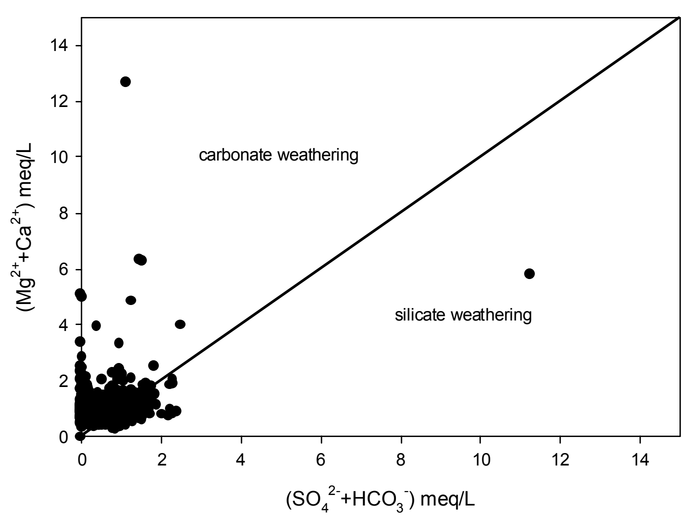

Figure 5. A scatter plot showing the sum of Mg^{2+} and Ca^{2+} in meq/L against the sum of SO_4^{2-} and HCO_3^- in meq/L.

Figure 6 is a plot of sodicity measured by the SAR against salinity as EC of the water from all the six river basins. Figure 6 is used to assess the irrigation quality of surface water from all the river basins under evaluation. This classification scheme is after the United States Salinity Laboratory, USSL (1954). It is obvious that more than 90% of the data plots within the low sodicity and low to medium salinity fields of the semi-log plot. The implication is that surface waters from these basins are generally of low sodium content and low to medium salinity. Excess sodium in waters produces the undesirable effects of changing soil properties and reducing soil permeability (Kelly, 1951). Sodium replacing adsorbed calcium and magnesium is a hazard as it can lead to significant damage to the soil structure. Waters of high sodium content and low calcium and magnesium concentrations can reduce the permeability of agricultural soils and reduce productivity on those soils. According to the USSL (1954) categorization scheme, water of low sodicity and low to medium salinity is generally of acceptable irrigation quality.

CONCLUSION

Data on the chemical parameters of surface water from some basins in southern Ghana was evaluated using multivariate statistical methods to determine the most significant processes that affect the hydrochemistry. This study finds that precipitation, agricultural activities and carbonate mineral weathering are the three most significant processes that determine surface water chemistry in the southern section of the country. The weathering of feldspars and micas from the underlying geology appears to play a minor role in regulating the chemistry of water in these surface water basins. This may largely be due to low residence times. The concentrations of the

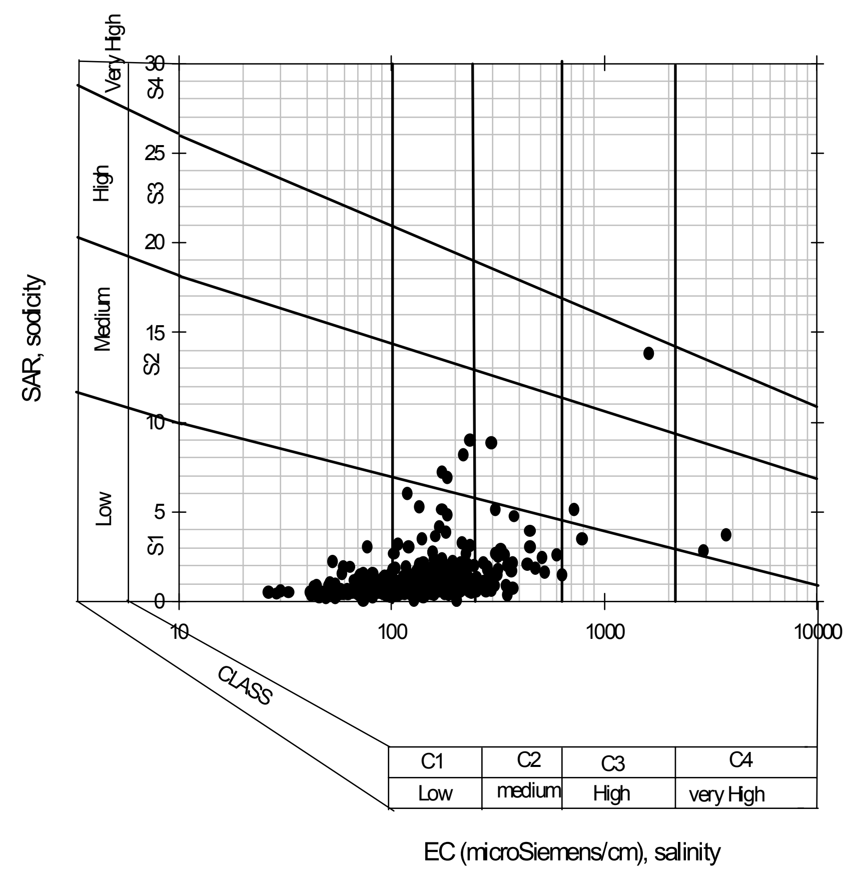

Figure 6. A plot of SAR against EC on a semilog axis (after USSL 1954).

major ions are generally within acceptable limits for most purposes. The sodium content and the EC were used to determine the suitability of water from these basins for irrigation activities in the area. On the basis of the USSL categorization system, this study finds that surface water from the six basins in southern Ghana is generally of acceptable quality for irrigation purposes. Most of the samples used in this study plot within the low sodicity, low to medium salinity fields.

REFERENCES

Adams, S., R. Titus, K. Pietersen, G. Tredoux, and C. Harris. 2001. Hydrochemical characteristics of aquifers near Sutherland in western Karoo, South Africa. Journal of Hydrology. V. 241 (1-2), pp. 91-103.

Alberto, W.D., D.M. del Pilar, A.M. Valeria, P.S. Fabiana, H.A. Cecilia, and D.L. Angles. 2001. Pattern recognition techniques for the evaluation of spatial and temporal variations in water quality, a case study: Suquia River Basin (Cordoba-Argentina). Water Resources Research. V. 35 pp. 2881-2894.

Appelo, C.A., and D. Postma. 1993. Geochemistry, Groundwater and Pollution. 2nd Eds. Balkema, Rotterdam.

Birke, M., and U. Rauch. 1993. Environmental aspects of the regional geochemical survey in the southern part of East Germany. Journal of Geochemical Exploration. V. 49 (1-2), 35-61.

Briz-Kishore, B.H., and G. Murali. 1992. Factor analysis for revealing hydrochemical characteristics of a watershed. Env. Geol. Wat. Sc. V.19 (1), pp. 3-9.

Ceron, J.C., A. Pulido-Bosch, and M. Bakalowicz. 1999. Application of principalcomponent analysis to the study of CO_2-rich thermomineral waters in the aquifer system of Alto Guadalentin (Spain). Hydrological Science. V.44(6), pp. 929-942.

Dalton, M.G., and S.B. Upchurch. 1978. Interpretation of hydrochemical facies by factor analysis. Groundwater. V.16 (4), pp. 228-233.

Dapaah-Siakwan, S., and P. Gyau-Boakye. 2000. Hydrogeologic and borehole yields in Ghana. Hydrogeology. V.8 pp. 405-416.

Drever, J.I. 1988. The Geochemistry of Natural Waters, Prentice Hall, Upper Saddle River, NJ.

Grande, J.A., A. Gonzalez, R. Beltran, and D. Sanchez-Rodas. 1996. Application of factor analysis to the study of contamination in the aquifer system of Ayamonte-Huelva (Spain). Groundwater V.34(1), pp. 155-161.

Güler, C., G. Thyne, J.E. McCray, and A.K. Turner. 2002. Evaluation and graphical and multivariate statistical methods for classification of water chemistry data. Hydrogeology. V.10, pp. 455-474.

Gyau-Boakye, P., and B.Y. Ampomah. 2003. Water pricing and water sector reformsinformation study in Ghana. Water International, V. 28 (1), pp. 11-18.

Helena, B., R. Pardo, M. Vega, E. Barrado, J.M. Fernandez, and L. Fernandez. 2000. Temporal evolution of groundwater composition in an alluvial aquifer (Pissuerga River, Spain) by principal component analysis. Wat. Resear. V.34, pp. 807-816.

Hernandez, M.A., N. Gonzalez, and M. Levin. 1991. Multivariate analysis of a coastal phreatic aquifer using hydrochemical and isotopic indicators, Buenos Aires, Argentina. In: Proceedings of the International Association on Water Pollution Research and Control's International Seminar on Pollution, Protection and Control of Groundwater, as published in Water Science & Technology. V.24, pp. 139-146.

Huizar, R., T. Mendez, and R. Madrid. 1998. Patterns of groundwater hydrochemistry in Apan-Tochac sub-basin, Mexico. Hydrological Sciences. V.43 (5), pp. 669-685.

Join, J.L., J. Coudray, and K. Longworth. 1997. Using principal components analysis and Na/Cl ratios to trace groundwater circulation in a volcanic island: The example of Reunion. Journal of Hydrology. V.190 (1-2), pp. 1-18.

Kaiser, H. F. (1960). The application of electronic computers to factor analysis. Educational and Psychological Measurement, 20, 141-151.

Kelly, W.P. 1951. Alkali soils – Their formation, Properties and Reclamation. Reinhold Publ., New York.

Liedholz, T., and M.T. Schafmeister. 1998. Mapping of hydrochemical groundwater regimes by means of multivariate statistical analyses. In: Proceedings of the Fourth Annual Conference of the International Association for Mathematical Geology, October 5 – 9, Ischia, Italy, ed. A. Buccianti, G. Nardi, and R. Potenza, 298 – 303. Kingston, Ontario, Canada. International Association for Mathematical Geology.

Locsey, K.L., and M. E. Cox. 2003. Statistical and hydrochemical methods to compare basalt- and basement rock-hosted groundwaters: Atheron Tablelands, northeastern Australia. Environmental Geology. V. 43 (6), pp. 698 – 713.

National Development Planning Commission (NDPC). 1998. The Ghana Vision 2020.Programme of Action for the First Medium-Term Development Plan (1997-2000). Accra.

Ochsenkuehn, K.M., J. Kontoyannakos, and P.M. Ochsenkuehn. 1997. A newapproach to a hydrochemical study of groundwater flow. Journal of Hydrology. V. 194 (1-4), pp.64-75.

Pereira, H.G., S. Renca, and J. Sataiva. 2003. A case study on geochemical anomaly identification through principal component analysis supplementary projection. Applied Geochemistry. V.18, pp.37-44.

Razack, M., and J. Dazy. 1990. Hydrochemical characterization of groundwater mixing in sedimentary and metamorphic reservoirs with combined use of Piper's principle and factor analysis. Journal of Hydrology. V.114 (3-4), pp. 371-393.

Sanchez-Martos, F., R. Jimenez-Espinosa, and A. Pulido-Bosch. 2001. Mapping groundwater quality variables using PCA and geostatistics: a case study of Bajo Andarax, southeastern Spain. Hydrological Science. V.46(2), pp. 227-242.

SPSS for Windows, Rel. 11.0.1. 2001. Chicago: SPSS Inc.

Steinhorst, R.K. and R.E. Williams. 1985. Discrimination of groundwater sources using cluster analysis, MANOVA, canonical analysis and discriminant analysis. Water Resources Research. V. 21(8), pp. 1149-1156

Suk, H., and K.K. Lee. 1999. Characterization of hydrochemical system throughmultivariate analysis: clustering into groundwater zones. Groundwater. V. 37(3), pp. 358-366.

USSL. 1954. Diagnosis and Improvement of Saline and Alkali Soils. USDA Agr. Handbook No. 60, Washington D.C.

Usunoff, E.J., and A. Guzman-Guzman. 1989. Multivariate analysis in hydrochemistry: an example of the use of factor and correspondence analyses. Groundwater. V. 27 (1), pp. 27-34.

van Tonder, G.J., and F.D.I. Hodgson. 1986. Interpretation of hydrogeochemical faciesby multivariate statistical methods. Water S. Afr. V.12(1), pp. 1-6.

Wang, Y., T. Ma, and Z. Luo. 2001. Geostatistical and geochemical analysis of surface water leakage into groundwater on regional scale: A case study in the Liulin karst system, northwestern China. Journal of Hydrology. V.246 (1-4), pp. 223-234.

ADDRESS FOR CORRESPONDENCE
Sandow Mark Yidana
Department of Earth & Environmental Studies
Montclair State University
Montclair, NJ 07043

Email: yidanas1@mail.montclair.edu