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Determination of the mineral stability field of evolving groundwater in the Lake Bosumtwi impact crater and surrounding areas

Yvonne Sena Akosua Loh [a, *], Sandow Mark Yidana [a], Bruce Banoeng-Yakubo [a, b], Patrick Asamoah Sakyi [a], Millicent Obeng Addai [a], Daniel Kwadwo Asiedu [a]

[a] Department of Earth Science, University of Ghana, Legon, Accra, Ghana
[b] Ministry of Lands and Natural Resources, Ghana

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ABSTRACT

Conventional graphical techniques, mass balance geochemical modelling, and multivariate statistical methods were jointly applied to hydrogeochemical data of groundwater from the fractured rock aquifer system, and surface water in the Bosumtwi and surrounding areas to reveal evolutionary trends and the characteristics of evolving groundwater in the area. Four clusters distinguished from the Q-mode hierarchical cluster analysis (HCA) comprised three main groundwater associations and one surface water group (lake water). Although both water resources are of low mineralization (TDS < 1000 mg/l), it was observed that the groundwater from the upper catchment with hydrochemical facies dominated by Na–Mg–HCO_3^-, evolves to Ca–Mg– and mixed cations HCO_3^- water types at the lower reaches. The lake water on the other hand is Na–HCO_3^- water type. Results from principal component analyses (PCA) and other geochemical interpretations distinguished three sources of variations in the hydrochemistry. Saturation indices of possible reactive mineral phases show groundwater undersaturation relative to albite, anorthite, aragonite, barite, calcite, chlorite, chrysotile, dolomite, gypsum, k-felspar and talc, and supersaturation with respect to gibbsite, kaolinite, Ca-montmorillonite and k-mica in the area. The PCA and other geochemical interpretation identify weathering of feldspars and carbonate mineral dissolution as predominantly influencing the hydrochemistry of the groundwater. Hydrolysis of the aluminosilicates causes the groundwater to reach equilibrium with kaolinite. In addition to dissolution of silicates, the chemical composition of the lake water has been influenced by evaporation and consequent carbonate saturation.

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* Corresponding author.
E-mail addresses: sloh@ug.edu.gh, sayloh14@gmail.com (Y.S.A. Loh).

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1. Introduction

The chemical composition of natural waters is controlled by a variety of factors that include the composition of rainwater, climate, topography, structure and mineralogy of host rocks and the geochemical processes that are operating within the aquifers. These factors can combine in various ways to give the water a characteristic fingerprint, consequently determining the purpose for which it can be used. Interpretation of hydrochemical data from regional aquifer sampling and analyses has provided useful leads to the understanding of groundwater evolution along flow paths (Gerla, 1992; Marfia et al., 2004; Salem et al., 2004). The literature is rich in several innovative methods to aid in the interpretation of the hydrochemical data. In addition to conventional graphical methods, the application of multivariate statistical techniques to physical and chemical data of natural waters to uncover latent characteristics that assist in groundwater and surface water evolution has been copiously documented in the literature (e.g. Thyne et al., 2004; Cloutier et al., 2006). The advanced statistical approaches commonly used in the geosciences are discretionary and are able to cluster hydrochemical parameters into groups, associations or hierarchies based on the variations in the datasets of those parameters. When used simultaneously with conventional graphical techniques, advanced statistical methods assist in identifying key hydrogeological processes that play in the transformation of the hydrochemistry of groundwater along flow paths (e.g. Guler et al., 2002; Thyne et al., 2004; Yidana et al., 2012). Stetzenbach et al. (1999) applied the multivariate statistical method; principal component analyses, to hydrochemical dataset and concluded that PCA is not only used to support previously studied hydrological systems but may in itself provide rapid and relatively cost effective methods to assess possible flow regimes in systems that have not been previously studied. Suk and Lee (1999) discretised and characterised the groundwater hydrochemical system of an area in Incheon, Korea, through cluster analysis using factor scores.

Over the last decade, mass balance hydrochemical modelling, particularly using PHREEQC, has proven a powerful tool for chemical simulation (Van der Kemp et al., 2000; Wurl et al., 2003; Dai and Samper, 2004; Lecomte et al., 2005). The method has been valuable in computing aqueous speciation and saturation indices from geochemical data to determine the reactive minerals within aquifers (e.g. Thyne et al., 2004; Yidana et al., 2008b; Ako et al., 2011). Saturation indices have been useful in evaluating the degree of equilibrium between water and aquifer minerals, distinguish different stages of hydrochemical evolution (Locsey and Cox, 2002) and assist in identifying which geochemical reactions are important in surface and groundwater hydrochemistry (Yidana et al., 2008a; Aghazadeh and Mogaddam, 2010). Whiles Busby et al. (1991) used the mass balance technique to quantify reactions controlling water chemistry along flow paths; Kuells et al. (2000) applied the technique to quantify mixing of end-member components in a flow system. Thyne et al. (2004) employed integrated statistical and mass balance methods to identify natural water/rock interaction and an anthropogenic component as the major processes controlling the hydrochemistry in aquifers along the Turkey Creek Basin, to determine the location and chemical signature of anthropogenic impact, and provide information about the aquifer properties. Similarly, Helstrup et al. (2007) identified the most relevant controls on the water quality within the Cretaceous-Eocene limestone aquifer of the Keta Basin of Ghana and the coastal sedimentary basin of Togo, using Q-mode hierarchical cluster analysis (HCA) and mass-balance modelling methods.

In most parts of Ghana, particularly aquifers underlying the Bosumtwi Impact Crater (BIC) and surrounding areas, there is general lack of hydrologic and hydrogeologic data which has resulted in great uncertainties in the understanding of the groundwater flow regimes and of the main processes that influence the hydrochemical evolution of groundwater. In fact since the construction of boreholes and use of groundwater in the study area, no investigations have been conducted over the years to accurately characterise the groundwater resources with respect to the hydrochemistry. Such a study will not only better define the mode of groundwater occurrence but will assist in understanding the behaviour of groundwater from recharge to discharge areas as this is key to developing an effective water use system. Again, this will consequently form the basis for a holistic numerical conceptualization of the hydrodynamics of the study area for proper assessment, planning and sustainable management of the water resources in the study area. Conventional methods, coupled with multivariate statistical, PHREEQC modelling and stability diagrams have been applied to hydrogeochemical data collected for this study to characterise the groundwater systems and evaluate the principal controls on groundwater and lake water hydrochemistry to present an enhanced understanding of the hydrology of the study area's watershed. It is envisaged that results from this research will assist policy/decision makers to develop a better management plan that will ensure sustainable use of the groundwater resources in the study area.

2. The study area

2.1. Geography

Lake Bosumtwi, a scenic natural inland freshwater meteorite crater lake, is located in the Ashanti Region of Ghana (Fig. 1). Located in a unique and attractive, partly forested area, it serves as a regional tourist site (Boamah and Koeberl, 2007). The Lake Bosumtwi area is an important geological site because it houses the largest, young (1.07 Ma) and well-preserved complex meteorite impact crater currently known on earth. The interior of the crater is filled by an 8 km wide Lake, Bosumtwi, which is 78 m deep and represents the only significant natural lake in Ghana and the West African subregion (Scholz et al., 2007). Several communities surrounding the lake have historically depended solely on fish from the lake as an important source of livelihood and also relied on perennial streams that flowed into the lake for drinking and domestic water supply needs.

The physical structure of the crater has been well described (e.g. Jones et al., 1981; Karp et al., 2002). The impact crater has a steep rim rising up to 300 m above present lake level. It is surrounded by an irregular circular depression forming a hydrologically closed basin with a rim-to-rim diameter of 10.5 km, as well as an outer ring of minor topographic highs with a diameter of about 20 km (Jones et al., 1981; Reimold et al., 1998) (Fig. 2). Characterised by a tropical rain forest environment, the climate is semi-equatorial with double maxima rainfall pattern between 1600 mm and 1800 mm with an average of about 150 rainy days in a year. The first major rainfall season starts from March and ends in July with a peak in June whilst the second rainfall season starts from September to November and peaks in October. The climate is warm with a fairly high and uniform temperature ranging from 32 °C in March and 20 °C in August. Relative humidity ranges between 70 and 80 percent (Turner et al., 1996). The original vegetation cover of semi-deciduous and rainforest has been degraded to mosaic of secondary forest due to extensive and repeated farming, illegal mining and lumbering. The drainage pattern of Bosumtwi District is dendritic. However, around Lake Bosumtwi, there is an internal drainage where the streams flow from surrounding highlands into the lake forming a dense network due to the double maxima rainfall regime.