Hydro-Geochemical Mechanisms of Brackish Shallow Groundwater Development- Coastal Greater Accra Region, Ghana

F. A. Mensah¹*, S. K. Bartaya², B. Ofosu¹, T. A. Tagbor³ and S. K. Tiwari²

¹CSIR-Building and Road Research Institute, Kumasi, Ghana.
²Waddia Institute of Himalayan Geology, Dehradun, Uttarkhand – 240001, India.
³CSIR-Institute of Industrial Research, Accra, Ghana.

Authors’ contributions

This work was carried out in collaboration among all authors. Author FAM designed the study, managed the literature, wrote the first draft of the manuscript and effected most of the corrections after the review. Authors SKB and SKT supervised the work. Author FAM did the field sampling and laboratory analyses. Authors FAM and BO did statistical plots. Authors FAM and TAT organized the manuscript to journal format with guidance from author SKB and revised the plots after the review. All authors read and approved the final manuscript.

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ABSTRACT

This study investigated the processes influencing the chemistry of surface and shallow groundwater in tropical coastal environments - south east of greater Accra region of Ghana using GIS models and combination of geological and hydro geochemical techniques for sustainable management of freshwater resources and abundantly available brackish water resources. A total of 37 shallow groundwater and 11 surface water samples were collected and analysed for their physico-chemical constituents.

The samples were adjusted to room temperature after which the hydrogen ion concentration (pH), Total Dissolve Solids (TDS) and Electrical Conductivity were measured with a precision of 0.01 for both parameters using a La Motte, USA in unfiltered samples. The analysis of major and minor ions were performed using ion chromatography (DIONEX-ICS-1000 Series). The geographical locations of the samples were recorded with the aid of a handheld Global Position System (GPS).

*Corresponding author: E-mail: anamensgh@yahoo.com;
The analysed shallow groundwater indicates minimum salinity values of 70.2 psu/ppm, maximum salinity of 4398.3 psu/ppm with an average of 1571.4 psu/ppm whilst surface water has minimum salinity of 33.8 psu/ppm, maximum of 43574 psu/ppm with an average of 4972.6 psu/ppm therefore highly saline. The total minimum dissolved solid (TDS) concentrations is 87.5 ppm, maximum of 5160 ppm with an average of 1911.96 ppm for shallow groundwater and for surface water minimum of 38.4 ppm, maximum of 27100 ppm and average 3938.12 ppm.

Keywords: GIS; geochemistry; shallow groundwater; sustainable management; resource; brackish; coastal.

1. INTRODUCTION

In 1995, the Government came up with a policy (Ghana Vision 2020, 1998), which aimed at supplying all the rural communities with potable water mainly from groundwater sources by the year 2020. Also, at the United Nations Millennium Summit held between 6th and 8th September 2000 at the United Nations Headquarters in New York, 189 Heads of State adopted the Millenium Development Goals (MDGs), which set clear, numerical, time-bound targets for making real progress, by 2015 in tackling the most pressing issues facing developing countries. One of the MDGs is to cut by half the proportion of people without sustainable access to safe drinking water and sanitation by 2015 [1].

Recent studies suggest that we are on the verge of a freshwater crisis wherein demand relative to supply is projected to lead water scarcity for significant percentages of the global population in the relatively near future. It has been estimated that each person on the earth needs a minimum of about 1000 m$^3$ of water per year for drinking, hygiene, and growing food for sustenance; whether people get enough water to meet their needs depends primarily on where they live as the distribution of global water resources varies widely [2]. Almost half the world’s population lives within 60 km of the coast; 75% of large cities are located near coasts. Coastal aquifers are part and in many cases the only part of the water supply equation to these crowds. Unfortunately, as is the case with so many of our water supplies, we have (collectively) failed to look after these resources [3]. Coastal hydrogeologic systems, particularly in areas of modest rainfall, runoff, and recharge, are complex and difficult to decipher. The primary forcing function of less precipitation results in less erosion, smaller aquifers, slower groundwater flow rates and a predominance of brackish groundwater [4]. The coastal area of south eastern greater Accra Region, Ghana, has a similar setting, as shown in Fig. 1.

Aquifers don’t just stop at the shoreline. Both unconfined and confined aquifers extend beneath the sea, strata nearing to numerous 10s of kilometres across continents. There is a dynamic relationship between the land-derived fresh water, and sea water that enters the aquifer beyond the coast. Improved knowledge and exploitation of unconventional water resources will increase water safety and assist economic growth into the future. Putting in place the responsible development of brackish groundwater will help alleviate pressure on freshwater resources and mitigate potential water crisis in the years to come.

2. LITERATURE REVIEW

2.1 Brackish Groundwater

Brackish groundwater has a high concentration of total dissolved solids (TDS), including the common salt sodium chloride. It is often defined as water containing between 1,000 and 10,000 ppm TDS (Seawater contains about 35,000 ppm TDS, and the secondary standard for drinking water in the US is 500 ppm TDS), Brackish and saline groundwater frequently occur in hydraulic contact with fresh groundwater and can cause very considerable constraints upon the exploitation of the fresh water resources. Saou A., et al. [5], in their study used the analysis of major and trace elements in water in order to determine the origin of the high salinity in a basin and to describe their spatial and temporal evolution.

In understanding the response of a saline groundwater body to freshwater abstraction a knowledge of the total system including head controls, flows etc. is necessary which will clearly be of benefit in the management of other adjacent freshwater resources, though it is frequently a difficult proposition. Traditionally groundwater has been classified upon their TDS.
content which has been applied particularly to the non-fresh groundwater as given in Table 1.

Table 1. Groundwater classification. Source: J. W. Lloyd and J. A. Heathcote (1985)

| Class  | TDS (mg/l) |
|--------|------------|
| Fresh  | 0-1000     |
| Brackish | 1000-10000 |
| Saline | 10000-100000 |
| Brine  | >100 000   |

2.2 Occurrence and Origin of Groundwater Salinity

As a result of chemical and biochemical interactions between waters and the material through or over which they flow and to a lesser extent because of contributions from the atmosphere, the waters acquire salinity proportional to their flow experience. The salinities may be acquired within the ground as groundwater chemistry evolves or may be introduced during aquifer matrix deposition or subsequent groundwater or surface water movement. Because of the various ways in which salinity is imparted to a groundwater certain chemical signatures can be recognized which may also indicate the origin of the salinity [6].

2.3 Modern Seawater Intrusion

In estuaries and adjacent to coastlines modern seawater intrusion frequently occurs into aquifers either under natural flow controls or because of flows induced by abstraction.

Based on the sources of intruding water bodies, seawater intrusion can be divided into two types: intrusion of saline water derived from modern seawater, and intrusion of subsurface brine and saline water derived from paleo-seawater in shallow Quaternary sediments. There are some distinct differences in their formation, mechanism and damage. The subsurface brine intrusion is a special type, which can cause very serious disaster [7]. Various coastal environments in different coastal sections result in three types of intrusion: seawater intrusion, saline groundwater intrusion, and mixed seawater and saline water intrusion.

According to Carrera et al. [8], the progression of saltwater intrusion is sensitive to (1) coastal topography and water management, (2) type of inland boundary conditions [9], (3) geological heterogeneity of coastal aquifers, (4) initial salt distribution, and (5) relative sea level rise.

The recognition of modern seawater intrusion normally should not pose difficulties; however, it may be associated with saline groundwater of other origins or may have been modified by residence in the aquifer. In any case a reasonably comprehensive hydrochemical interpretation is worthwhile as it may shed light upon the mechanisms controlling intrusion or the rates of flow [6].

Fig. 1. Map with study area highlighted in rectangular box
2.4 Geology and Hydro-Geologic Setting

The coastal plain hydrogeologic province is underlain by semi consolidated to unconsolidated sediments ranging from cretaceous to Holocene in age in south-eastern Ghana and in a relatively small isolated area in the extreme south-western part of the country.

Rocks of the Dahomeyan System of Neoproterozoic era (550Ma) underlie the Accra Plains and southern parts of the Eastern and Volta Regions. They extend from Ho in the Volta region to Accra, the nation’s capital. The rocks consist mainly of crystalline gneiss and migmatite, with subordinate quartz schist, biotite schist and sedimentary-rocks remnants. The gneiss is generally massive and has few fractures. The two main varieties are silicic and mafic gneisses, which weather, respectively, to slightly permeable clayey sand and nearly impermeable calcareous clay. The generally impervious nature of the weathered zone and massive crystalline structure of the rocks limit the yields that can be obtained from hand-dug wells or boreholes [1].

2.5 Study Objectives

The study objectives included mainly using geochemical strategies to understand the processes and factors that control the evolution of water mineralization. Specifically:

- Determine hydrogeochemical structure,
- Interrelationship between surface water and groundwater,
- Configuration of fresh and saline water,
- Aid water management

3. MATERIALS AND METHODS

3.1 Study Area Description

The study locations in the Ada East and Ada West Districts of the Greater Accra Region of Ghana is between Latitudes 06°00” 25” N, 00°19”E and 05° 45” 30” N, 00°41” 40”E.

The area has wetlands and marshes, sand dunes and islands. The Songor wetland situated within the study area consists of a shallow brackish water lagoon (10-50 cm) with mudflats, riverine islands, a broad sandy beach southwards, flood plains with degraded mangroves and coastal savannah vegetation.

The lagoon is low-lying. The highest elevation above sea level is 75 m whilst the lowest elevation above sea level is 10 m. Maximum depth below mean sea level is 50 cm. (Ecological Mapping of the Songor Ramsar Site- Ghana National MAB Committee, 2009). There is a narrow sand dune along the coast with no cliffs on the smooth coastline. Further, shoreline recession through tidal activity also require management intervention.

The area receives about 750mm rainfall recorded at Ada Foah Meteorological Station. Temperatures are generally high ranging from 23°C to 33°C.

3.2 Methodology

A total of 37 groundwater samples from shallow wells used for human consumption derived from shallow aquifer and 11 surface water samples comprising 3 lagoon samples, 4 river samples and 4 stream samples, were collected. Prior to analysis all samples were stored under hygienic and required temperatures in the water chemistry laboratory of Geomorphology and Environmental Geology Group, Wadia Institute of Himalayan Geology. To negate such changes as chemical composition, samples were kept in potable ice chest under freezing conditions immediately they are obtained. Wheatstone [10] has shown that freezing has no adverse effect upon a wide range of determinants. After adjusting the samples to room temperature; the pH, TDS and electrical conductivity were measured with a precision of 0.01 for both parameters using a La Motte, USA in unfiltered samples. The analysis of major and minor ions were performed using ion chromatography (DIONEX-ICS-1000 Series).

3.2.1 GPS coordinates of samples locations

The geographical locations of the samples were recorded with the aid of a handheld GPS. On each samples point, three set of readings were taken after observing for about five minutes, the averaged value is taken as the coordinates. GIS maps of distribution of pertinent parameters are used to aid water management and to examine ideas about geologic structure, location and flowpaths of groundwater, interaction of surface water and groundwater, configuration of fresh and saline water, and possible areas to extract additional brackish groundwater to be treated for potable use and to describe their spatial and temporal evolution.
4. RESULTS AND DISCUSSION

4.1 Results

The results of the chemical analysis of the samples is presented in a summary statistics in Table 2. The relative abundance of cations in the groundwater is in the order Na>Mg>Ca>K and that of anions is Cl>SO₄>NO₃>HCO₃>Fl. Na and Cl are the dominant cation and anion respectively. Similar as was obtained by Mensah and Bartarya [11].

4.2 Discussion

4.2.1 Chlorides

Chloride is assumed to be a conservative tracer and the relationship between chloride and the other major and trace elements controlling chemical compositions of surface and shallow groundwater helps to well understand the processes of mineralization (salinity) increase. The relation Na-Cl is often used to identify the mechanisms of acquisition of salinity and marine intrusion. Na is lower and positively correlated with Cl (r²=0.998.) Fig. 2. A linear relation between Na and Cl represents simple mixing of the fresh groundwater with the seawater.

The high concentration of sodium and chloride in the groundwater could be related to the weathering of silicate rocks, and/or seawater intrusion. The dissolution of halite related to rock weathering/or likely evaporites from within alluvial sediments. This pattern is confirmed by low Na+/Cl⁻ molar ratios, ranging from 0.34 to 5.45. The ratio of Na+/Cl⁻ where equal to one indicates that halite dissolution could be responsible for the sodium concentration in the water samples. Based on the Na+/Cl⁻ ratios, the majority making up of the core of the study area was covered with ratios less than 1.5, which indicated halite dissolution whilst on the fringes outside the core of the study area exhibit ratios greater than 1.5 indicating the presence of silicate weathering contributing to sodium in the study area. There is identified a boundary where the two activities could be observed occurring at the same time. Groundwater salinity may also relate to the formation of salt layers by leaching from the soil surface during evaporation in and during dry seasons.

Fig. 2. Map of study area indicating drainage/stream channels, the songhor lagoon, volta river, sampling points, elevation and TDS values
In literature, the SO4/Cl ratio generally decreases with the decrease of the salinity of water and Mg/Ca ratio increases proportionally with the increase of salinity. It was noticed that SO4/Cl ratios Fig. 3. Varies from 0 to 0.86. The strongest values of SO4/Cl ratios (Fig. 4) are observed far and near the coastal area, indicating the complex origin of water mineralization (salinization), both marine and evaporatic. Mg/Ca ratio varies from 0.12 to 35.60 and increases with an increase in water salinity Fig. 5. The strongest values are observed in the near shore and afar from the coast.

Again the strong and positive correlations of Cl and K (0.915) and Cl and SO4 (0.875) Figs. 6 and 7 indicate the dissolution of evaporate (KCl) and/or infiltration of fertilizers applied in the form of potash (KCl) and sulfate salts. Sulphate reduction promotes the dissolution of carbonate minerals. This phenomenon could influence strongly the Mg/Ca ratio.

The interpretation of the results by using the correlation of major elements with chloride, variations of SO4/Cl, and Mg/Ca ratios showed and revealed zones with strong salinities as a result of marine water/or dissolution of evaporitic formations. Several factors control groundwater chemistry, which can be related to the physical situation of the aquifer, bedrock mineralogy and weather condition.

Hydro-Geochemical groundwater evolution of chloride ion tends to be most conservative in that it is readily removed from matrix materials but rarely precipitate under dilute solution conditions, from literature. Chloride concentrations therefore normally increase down the hydraulic gradient (Fig. 6) and with groundwater flow experience and residence. Chloride is a good indicator of groundwater flow direction and better permeability conditions. This phenomenon is observed where, the two circles increased mineralization (salinities) at lower elevations (<10 m) and decreased mineralization at higher elevations (>10 m) across study area in Fig. 8.

### 4.2.2 Conjunctive water use

The increasing acuteness of water scarcity problems, poor quality water and management of rising watertable worldwide, requires the adoption of a double approach of water supply
management and water demand management. The adoption of an integrated river basin management approach for elaborating policies and strategies of water resources development, management and conservation would help consider the water resources as one system and would avoid a water resources development approach focused only on surface water. This approach also facilitates the management of the resource itself, allowing a better understanding, by water users, of the hydrological issues involved. Governments tend to consider river basins as water resources management units and as a spatial basis for the formulation of water management strategies integrating all cross-sectoral issues such as water resources conservation, environment, water resources allocation, water demand management, etc. The conjunctive use of surface and groundwater is one of the strategies of water supply management which has to be considered to optimize the water resources development, management and conservation within a basin. Conjunctive use of surface and groundwater consists of harmoniously combining the use of both sources of water in order to minimize the undesirable physical, environmental and economic effects of each solution and to optimize the water demand/supply balance. Usually conjunctive use of surface and groundwater is considered within a river basin management programme - i.e. both the river and the aquifer belong to the same basin.

Fig. 4. Map of SO₄/Cl ratios across study area

Fig. 5. Map of Mg/Ca ratios across study area
Decrease in good quality water resources stresses the need of using surface water and groundwater resources conjunctively for water supply, irrigation etc. The conjunctive use permits the utilization of poor quality water, which cannot be used as such for potable use or irrigation due to its harmful effect.

Properly managed integrated water resources systems can yield more water with more economic rates than those separately managed surface-water or groundwater systems. Conjunctive use of surface water and groundwater has been extensively studied and a number of methods/techniques have been reported for supporting conjunctive water use planning and management [12,13,14,15,16,17,18,19,20].

5. CONCLUSION

Acquiring better knowledge and understanding of hydrogeological resources will allow policymakers to better decisions about how to manage brackish groundwater resources and protect aquifers, both brackish and fresh. The management challenge of increasing rural and municipal supply is to capture more of the fresh groundwater on its way to the ocean and extract some of the brackish groundwater for treatment using reverse osmosis. The deep multiple-depth well sites could be used to characterize the
geologic, hydrologic, and geochemical systems and to monitor seawater intrusion, land deformation, and effects on coastal systems.

6. RECOMMENDATIONS

Our objectives was to contribute to a better understanding of the process of increased mineralization in the shallow groundwaters in the study location and as a result make a few recommendations below in a way to promote brackish water management use in the region. They are:

1) National and local Governments to be more proactive to institutionalize Conjunctive water usage practices to save fresh water.
2) Irrigation development authority and water and sanitation ministry should play an active role to chalk out action plan for “conjunctive water use for agricultural purposes.
3) Further research on alternative crops which will be more profitable by using conjunctive water should be conducted.
4) Creating awareness amongst the farmers about practicing conjunctive water uses.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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