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The Stable Isotope Characteristics of Groundwater in the Voltaian Basin – An Evaluation of the Role of Meteoric Recharge in the Basin

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Abstract

This study finds that groundwater recharge in the shallow aquifer system of the Voltaian Basin is recent meteoric water which has undergone evaporative enrichment of the heavier isotopes of the main components of the water molecule as it transits the vadose zone. Apparently, low annual relative humidities and high temperatures in the basin have led to lower slope and intercept of the Local Meteoric Water Line than is observed in the Global Meteoric Water Line. This assertion is consistent with the observation that annual relative humidity variationsin the basin are in the range of 65% – 85% even during the rainy season. Surface flows are considerably enriched in terms of the heavier stable isotopes of oxygen and hydrogen, suggesting severe evaporation. Using the stable isotope data of the surface flows and the estimated isotopic signature of the most probable source rainwater, this study finds that the rate of evaporative losses of water from the surface waterbodies ranges between 29.5% and 84.7%. This much evaporation of surface water is significant and suggests that surface water dams may not be sustainable water sources for commercial irrigation in the long term. Groundwater in the basin is relatively heavier than the local meteoric water. This is attributed to low but variable infiltration rates of rainwater, high temperatures, and low humidities in the basin. Evaporative loses of infiltrating water in the basin have been estimated to range between 19.8% and 70.6%. A hydraulic connection between aquifers in the basin and surface flows could not be conclusively established on the basis of the isotope data alone in this study.

Keywords

Evaporation; Groundwater; Recharge; Rainwater; Voltaian

Introduction

The application of environmental tracers to provide leads in hydrological studies is conventional practice and is useful in assisting in the initial conceptualization of hydrological systems at local and regional levels. The utility of natural tracers is amply exemplified in contaminant hydrogeological studies [1,2], studies of the residence times of groundwater in basins [3,4], analyses of sources of groundwater recharge and groundwater evolution through time and space [5-11], determination of the hydraulic properties of some aquifers [12], tracing hydrological flow paths [13] amongst several others. Probably the most published application of tracers in hydrological studies has involved the analyses and studies of groundwater recharge and the evolution of groundwater along flowpaths. In particular, stable isotopes of hydrogen and oxygen, which are the components of the water molecule, have been identified as effective tracers of the sources and evolution of water bodies. This is because they are quite conservative and are therefore able to preserve conditions that prevailed at the period and location of recharge. It is on this basis that they are key indicators of paleo and meteoric groundwater recharge, and mixing conditions. Stable isotopes of oxygen and hydrogen are particularly useful as tracers of hydrological processes in aquifers since their signatures or compositions are not affected by rock-water interactions at the usual low groundwater temperatures [6]. In the light of this, fluctuations in the ratio of the heavier to the lighter isotopes of oxygen ($^{18}O/^{16}O$) have been used over the years to provide insights for the identification of hydrological sources and flow paths under different conditions, and for estimating mean catchment residence times [13].

In Ghana, few cases of the application of isotopes in hydrological studies have been reported in the literature [14-19]. Such studies have attempted to characterize different aspects of the hydrological conditions of specific basins in the country. The findings have been diverse in their utility of the isotope tracers. The research of Jorgensen and Banoeng-Yakubo [15] for instance was instrumental in situating the role of saline water intrusion in the seasonal fluctuations in groundwater salinity in the shallow unconfined aquifer system of the Keta Basin in Southeastern Ghana. In doing this, the researchers made use of the unique isotopic signatures of recent meteoric water, seawater, and evaporated meteoric water. Similarly, Acheampong and Hess [20] related groundwater recharge in the southern part of the Voltaian Basin to recent meteoric water. They contended from the analysis of isotope data that groundwater in the shallow aquifer system originates from recent rainwater which has endured evaporative enrichment of the heavier isotopes. It was also suggested that although a hydraulic connection between the adjacent Volta Lake and the aquifers in the area is possible, there is no evidence of significant downward infiltration and percolation of lake water into the aquifers. This finding is contrary to earlier concepts of the hydrological situation around the Voltaian that had suggested that apparent hydraulic connections between the shallow aquifer systems of the Southern Voltaian encouraged some amount of groundwater recharge from the Lake. This study, however, did not discount the reverse situation of groundwater recharge of the Lake through baseflow, as the isotopic signature of the Lake water was observed to be considerably heavier. It was on the basis of this observation and other field relationships that Yidana [21] conceptualized the hydrogeological system of the Southern Voltaian for numerical groundwater flow modeling. The study of Adomako et al. [17] in the Densu Basin in southern Ghana assisted in conceptualizing the groundwater recharge regime in the basin.

The Voltaian Sedimentary Basin underlies over 45% of the total landmass of Ghana [22] and covers most of the communities vulnerable to the effects of climate change/variability especially in

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relation to the availability of water resources for productive uses. The development of climate proofed economic projects in the area is tied to the development and sustainable management of groundwater resources in the basin. An evaluation of the groundwater recharge regime and quantitative estimates of recharge from various sources constitutes an important aspect of assessing the resource for commercial development. In this study, isotope tracers are being used to study the groundwater recharge regime in relation to recent precipitation and surface water bodies in the area. This is part of initial efforts at characterizing the hydrogeology of the entire basin for regional numerical simulation.

The Study Area

The study area lies between latitudes 6°48’N and 10°26’N and longitudes 0°30’E and 1°16’W (Figure 1). It is characterized by two major agro-ecological zones namely the interior savannah in the north and the rain forest in the southeastern portions of it. The forest savannah zone interfaces these two major ecological zones in the basin. Annual rainfall ranges from 1000 - 1100 mm (1 m–1.1 m) in the north to around 1500 - 1600 mm (1.5 m–1.6 m) in the south [23]. The annual evapotranspiration values in the area are high in the north ranging from 1800 - 1900 mm (1.8 m–1.9 m) to about 1400 - 1500 mm (1.4 m–1.5 m)in the south [23]. The topography is generally undulating being relatively flat in the north to slightly rugged in the south. The major economic activities of the people include farming, fishing and trading. Peasant agriculture is the mainstay of life in the area. This enterprise is largely rain-fed. Therefore successes are based on the reliability of the rains. Two major seasons (the rainy/wet and dry seasons) have been identified in the area. Historically, the rainy season has been known to range from May to October every year [24], with the peak in August. The rest of the year is relatively dry with occasional rains. However, due to the current fluctuations in weather patterns, attending the effects of climate change/variability, the rainy season is highly erratic and unpredictable. It is on account of this that rain-fed agriculture cannot be sustained in the long run.

In much of the basin, daily temperatures are generally high (above 35°C or 308 K) except in the harmattan season (November-February) when the temperatures can get as low as 20°C (293 K) or less, especially during the night. The mean monthly temperatures vary from about 36°C (309 K) in March/April to about 27°C(300 K) in August. Relative humidity is high during the rainy season (65-85%) but may fall to as low as 20% during the dry season. Daily sunshine duration is about 7 hours except in the rainy days of June to September when it ranges from 6.9 hours to 4.7hours [24].

The hydrogeology of the basin is captured in the new hydrogeological zonation of Ghana [25]. Different aspects of the hydrogeology of the basin are also contained in earlier reports of Acheampong [26], Acheampong and Hess [27], Yidana et al. [28], Yidana [21], Attandoh et al. [29] amongst others. The terrain is composed of diverse kinds of sedimentary rocks which have been affected by the Pan-African tectonic events [22] and are therefore partially metamorphosed. Primary permeabilities have therefore been partially destroyed and aquifer parameters are based on the presence and pervasiveness of secondary permeabilities created in the wake of fracturing and/or weathering of the rocks to create ingresses for enhanced groundwater recharge, storage, and transmission. Where the fracturing and/or weathering are intense and considerably pervasive, the hydrogeological conditions are quite enhanced and the rocks serve as good aquifers. The weathered zone is variably conductive due to the variability in the clay content. The thickness of the overburden is variable depending on the location and can be as high as 50 m or more in places. Some of the shallow wells are completed in the weathered zone and have reported mixed fortunes in terms of their yield. Averagely, success rates in drilling prolific wells within this zone have been less than 60% [25]. This is because the parameters that control groundwater storage appear to be discrete entities of variable spatial extents. Recent drilling projects by the Ghana Water Resources Commission through the Hydrogeological Assessment Project (HAP) suggested that well yield is considerably enhanced at higher depths, although there is no significant

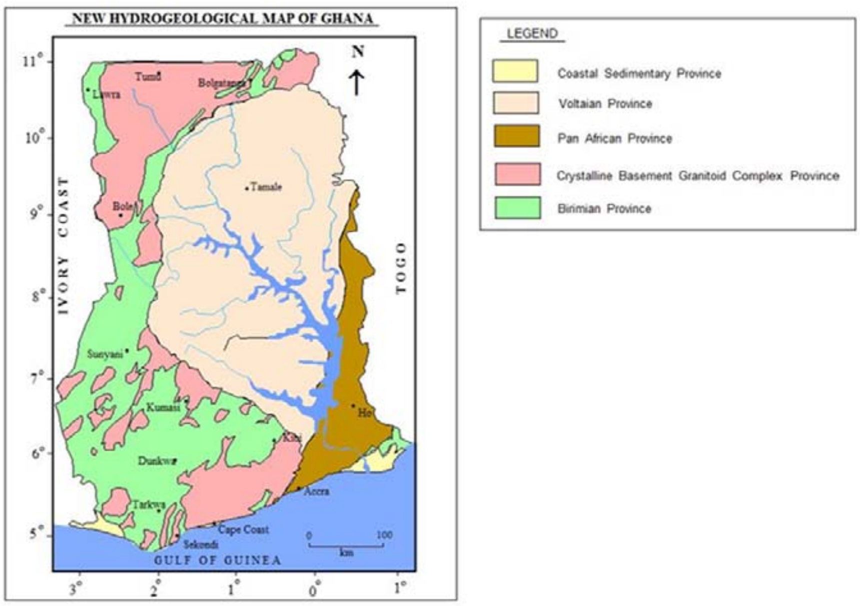

Figure 1: Map of the hydrogeology of Ghana showing the Voltaian Province (modified after Banoeng-Yakubo et al., 2010).

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relationship between well depth and yield. This offers opportunities for commercial development of the aquifers for irrigation purposes. Some flowing artesian wells have been reported in some of the current drilling projects.

Methodology

Groundwater and some streams in parts of the Voltaian were sampled for the purpose of analyzing for the stable isotope contents. The usual physical parameters (pH, Electrical Conductivity, EC, Total Dissolved Solids, TDS, and Temperature) were measured onsite. Rainwater samples were also taken in Tamale (almost at the center of the terrain) during the rainy in 2012. Samples for the isotope analyses were collected unfiltered in previously sterilized polyethylene bottles and filled to the very brim. Special care was taken to ensure that no air bubbles were trapped in the bottles. The samples were stored away from light in a cool dry container and then transported to the laboratory for analyses. All analyses were conducted in the laboratory of the Ghana Atomic Energy Commission, GAEC in Kwabenya near Accra.

The Liquid Water Isotope Analyzer (LWIA) was used to analyze for stable isotopes of oxygen and hydrogen ($\delta^{18}O$ and $\delta^{2}H$). $\delta^{18}O$ and $\delta^{2}H$ values were expressed in the conventional "delta" (δ) notation, which is the per mil (‰, parts per thousand) difference in the ratio of the less abundant isotope to the most abundant isotope in the sample relative to a reference standard V-SMOW, originally defined by the International Atomic Energy Agency, IAEA.

The historical data were originally acquired following similar sampling and analytical protocols. For the isotopes, data of 23 rainwater samples were acquired, together with 35, 210, and 9 samples respectively for streams, groundwater, and the Volta Lake were used for this study.

The resulting data was subjected to detailed analyses involving the use of some biplots and interpreted in the light of the Global Meteoric Water Line, GMWL [30].

Results and Discussions

General trends in the isotopic data

Box-and-Whisker plots of the isotope data for all the water media are presented in Figure 2. It is obvious that for both isotopes, the most enriched data are those of the Volta Lake, and other surface flows whilst the most depleted samples are obviously the rainwater samples. It is also clear that the streams and rainwater samples exhibit the highest variability in terms of data distribution. In the case of the rainwater samples, the observed variability may be related to the variabilities in the conditions prevailing at the various sampled locations. Twelve (12) of the rainwater data were obtained out of samples which were taken during the end of the major rainy season and the dry season in the southern Voltaian in 1994. The observed high variability may be partly attributed to these seasonal effects. The nature of the streams sampled (ephemeral or perennial), spatial location, amongst others are partly responsible for the observed pattern of the data from the streams and ponds. A cursory analysis of the streamflow data suggests that the largely perennial streams and ponds sampled are much more enriched in the heavier isotopes of both elements than is observed for the ephemeral ones, whose signatures bear close similarities with those of the rainwater data. The stream water samples also included floodwaters of the Nabogo sub-basin which were taken during the most recent sampling campaign. These are generally lighter in terms of their isotopic compositions and are similar to the signatures of recent rainwater in the area. The rainwater samples from the southern Voltaian are the most enriched. These samples were taken close to the end of the rainy season in the area, and were therefore apparently affected by the amount effect. The groundwater data appear to be the most homogeneous of all the datasets used in this study. The apparent homogeneity may be attributed to the fact that the factors responsible

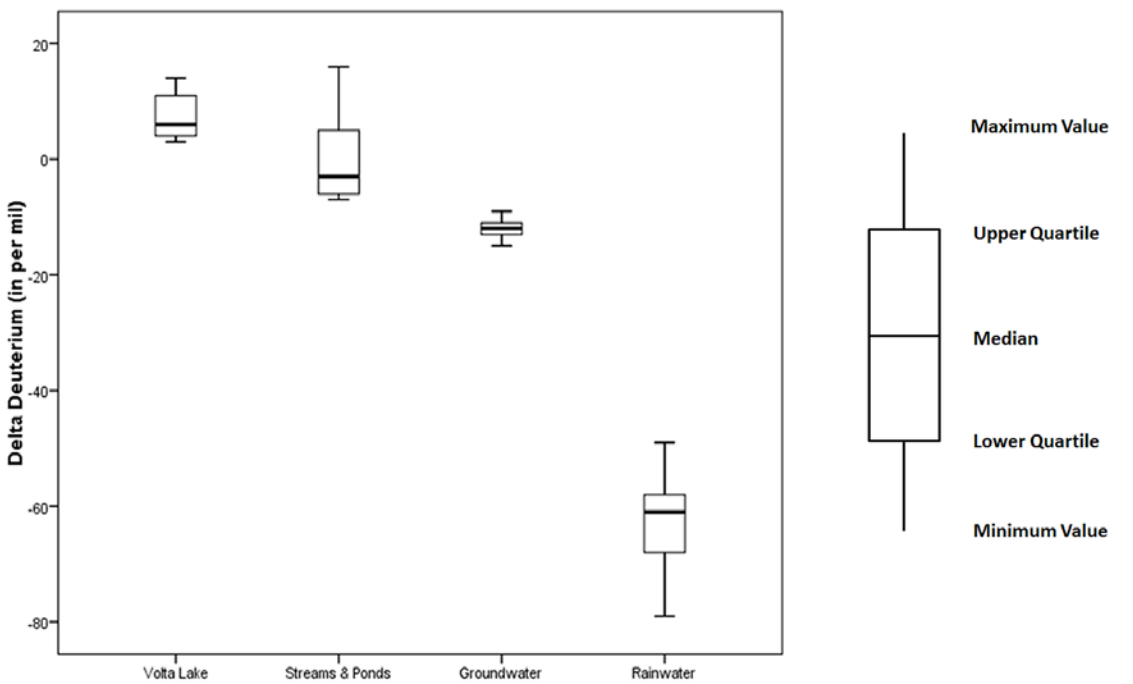

Figure 2a: Box plots for the $\delta^{2}H$ for the different water types sampled.

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for the variation in the stable isotope data of groundwater are largely similar in the north and in the south of the terrain. The Lake water data are the most enriched in the heavier isotopes as is obvious in Figure 2. This is attributed to the full exposure of the lake to high atmospheric temperatures and low humidities throughout the year. Kinetic fractionation processes attending evaporation result in the enrichment of the residual water in the lake. In addition to reflecting the effects evaporation of recent precipitation, the lake water also represents mixed isotopic signatures from several precipitation events at different places over several seasons since the Volta Lake is known to receive recharge from a network of several tributaries. The Lake water data also appears to be relatively homogeneous. This may reflect similarities in the characteristics of all its recharge sources and/or the limited nature of the sampling.

The Local Meteoric Water Line for the Voltaian Basin

The characteristics of local precipitation within the Voltaian Basin are adequately captured in the Local Meteoric Water Line, LMWL, developed from the precipitation data. Figure 3 presents the relationships amongst the different water bodies sampled in terms of their isotopic compositions. The rainwater samples plot on a line defined by Equation 1, which defines the LMWL for the Voltaian Basin. The slope and intercept are both lower than those of the Global Meteoric Water Line, GMWL [30] (Equation 2). The lower slope and intercept of the LMWL relative to the GMWL suggests some enrichment of the heavier isotopes in the current study area relative to those of the GMWL. The slope is similar to the LMWL suggested by Pelig-Ba [16] who used a limited number of rainwater samples from the Northern parts of the basin (Equation 3), but the intercept is quite different.

$$\delta^2H = 7.28\delta^{18}O + 4.77 \quad (1)$$

$$\delta^2H = 8\delta^{18}O + 10 \quad (2)$$

Significant departures from the intercept of the GMWL may be due to two major factors: (1) where the intercept is higher than 10, it suggests contribution of a re-evaporated vapor phase to the raining cloud [31-33]; (2) when the slope is lower than 8, kinetic fractionation during evaporation of the rain droplets below the cloud base in dry conditions [31-33] may be responsible. In the current study, the considerably lower intercept suggests evaporation of the raindrops during rain events. This process occurs especially when the relative humidity is lower than 100% [34] and where temperatures are high. In the basin, relative humidities fall in the range of 65% - 85% during the rainy season [24] and can therefore lead to significant kinetic fractionation attending the evaporation of raindrops. This observation ties in with the results of Acheampong and Hess [20] in the southern Voltaian where the observed intercept was 4.3. Evaporation under a relative humidity of less than 100% will result in a slope of 5 ± 2 on a δ^2H- $\delta^{18}O$ plot [20,34,35].Temperature, amount of rainfall, and relative humidity all play important roles in influencing the isotopic signature of precipitation [36]. The amount effect could also have played a role in the enrichment of the heavy isotopes, especially with the samples taken from the southern part of the Voltaian. Some of the most enriched rainwater samples were taken in the southern part of the terrain during the end of the major rainy season into the dry season. During these months, the rainfall events are usually brief and of small amounts with heavier isotopes.Equation 1 is considerably different from that of the LMWL for the Accra Plains area [14], and that for the Densu Basin [19]. The differences in intercept probably arise from differences in humidity during the periods of the rain and the proximity of the Accra Plains to the sea. However, the observation in this study, whereby both the slope and intercept of the LMWL are lower than those of the GMWL is consistent with observations in other parts of the Sahel Savannah, and suggests that most of the precipitation events occur at relative humidities lower than 100%.

Characteristics of surface waters in the basin

The data from the stream and pond samples appear more enriched than those of rainwater samples. The data fall on an evaporation line defined by Equation 3whose slope is lower than that of the LMWL, and even lower than that of the GMWL. This observation is attributed to evaporative enrichment of the heavier isotopes of both elements. Evaporation of surface water bodies causes an enrichment in the heavier isotopes of the residual water, resulting in slopes of the δ^2H-

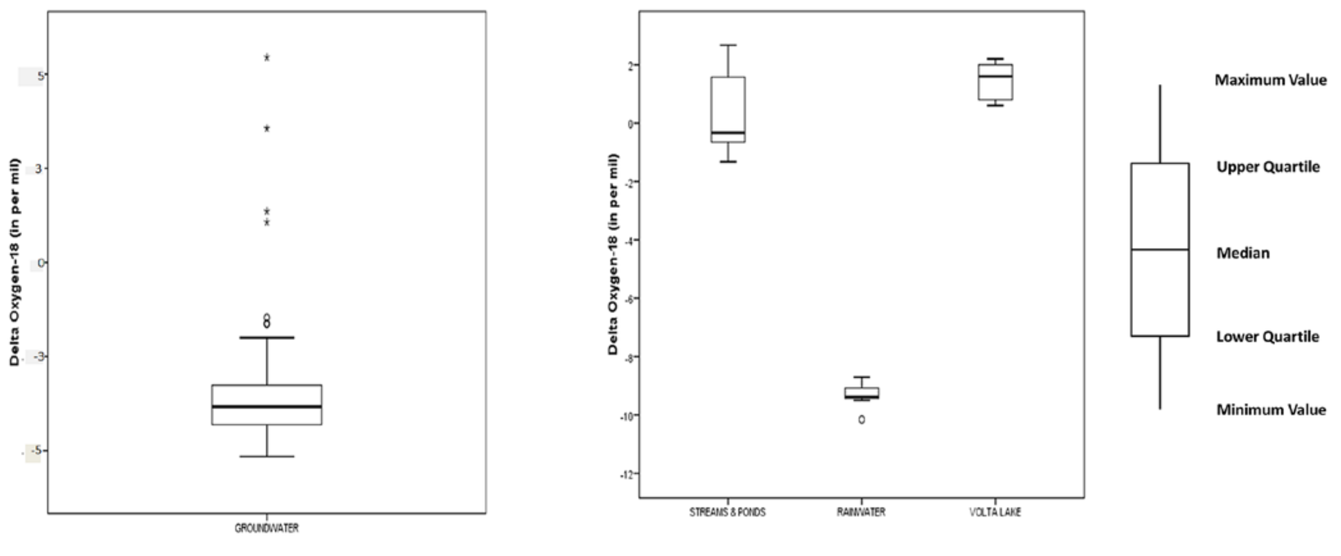

Figure 2b: Box plots for $\delta^{18}O$ data from the different water types sampled.

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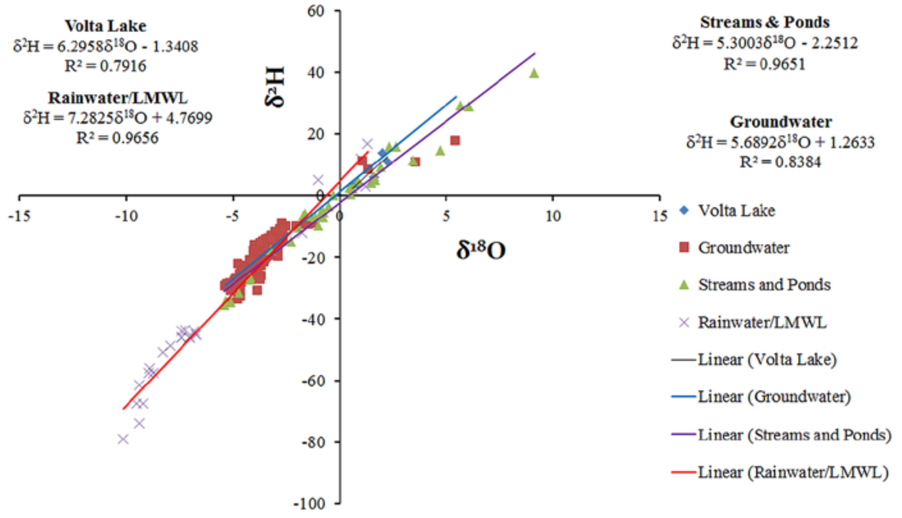

Figure 3: A biplot of $\delta^{18}O$ – δ^2H showing regression relationships for rainwater, surface water, groundwater, and the Volta Lake.

$\delta^{18}O$ diagram in the range of 4 and 5.5 [37]. Fractionation processes attending evaporation of open surface water bodies is known to characterize the isotopic composition of lakes and temporary ponding of water in small surface depressions [38] of the kind observed in the study area. In such cases, the slopes of the regression equations for δ^2H- $\delta^{18}O$ depends on the atmospheric conditions prevailing during the period of the evaporation [34]. Generally, the slope increases with increasing humidity and decreases when the humidity drops. In the case of the study area, where the humidity is almost always lower than 100% throughout the year and much lower during the dry season, it is expected that slopes of such relationships will be considerably low. There are clear differences in the isotopic signatures of the ephemeral streams sampled and the largely perennial ones, as the latter present much more enriched data than the former. The perennial streams represent mixed precipitation waters for different years and seasons. In addition, due to their open nature and general exposure to atmospheric conditions, they are much more prone to evaporative enrichment arising from high ambient temperatures and low relative humidities prevailing in the areas. The ephemeral streams on the other hand, are relatively less enriched and largely represent the signature of precipitation of the season just preceding the sampling event. Figure 4 indicates the position of the surface water evaporation line (SWL) relative to the LMWL. Simultaneous solution of the SWL and LMWL will provide the signature of the precipitation at the time of recharge of the streams and ponds sampled. This assumes that the LMWL developed in this study represents the general characteristics of recent precipitation in the basin. Continuous sampling of rainwater at several locations within the basin over long periods of time may have been more representative of the true character of rainwater in the basin. In Figure 4, the two lines intersect at a point where δ^2H and $\delta^{18}O$ are respectively -23‰ and -4.0‰. This is the signature of the rainwater that recharged the streams and other surface impoundments sampled in the study area. Kinetic fractionation is an important factor responsible for isotopic enrichment arising from evaporation processes in open surface water [37].

$$\delta^2H = 5.3\delta^{18}O - 2.25 \quad (3)$$

The isotopic signature of precipitation at the time of recharging the surface water bodies sampled, and the average humidity conditions were used to determine the approximate rates of evaporation from these surface water bodies. The procedure used is akin to that proposed by Craig and Gordon [39] and adopted in several recent researches. The fraction of precipitation lost to evaporation, *f*, is given by Equation 4 [33,40].

$$f = 1 - \left(\left(\delta_L - \delta^*\right)/\left(\delta_p - \delta^*\right)\right)^{1/m} \quad (4)$$

δ_p is the isotopic signature of the source water for the streams and ponds sampled; δ_L is the isotopic composition of the streams and ponds sampled; the indices, m and δ^* are respectively given by Equations 5 and 6 [33,41-43].

$$m = \frac{\left(h - \varepsilon/1000\right)}{\left(1 - h + \varepsilon_k/1000\right)} \quad (5)$$

$$\delta^* = \left(h\delta A + \varepsilon\right)/\left(h - \varepsilon/1000\right) \quad (6)$$

h, δ_A are respectively the relative humidity and isotopic signature of ambient air/vapor.

Gonfiantini [34] defined the isotopic enrichment arising from kinetic isotope fractionation (ε_k) and total isotope enrichment factor (ε). Kinetic fractionation factors for ^{18}O and ^2H are respectively defined by Equations 7 and 8.

$$\varepsilon_k{}^{18}O = 14.2\left(1-h\right)\ ‰ \quad (7)$$

$$\varepsilon_k{}^{2}H = 12.5\left(1-h\right)\ ‰ \quad (8)$$

The total fractionation factor is then given by Equation 9.

$$\varepsilon = \varepsilon_{eq} + \varepsilon_k \quad (9)$$

Where $\varepsilon_{eq} = 1000\left(1 - \alpha^{-1}{}_{w-v}\right)$

$$10^3 \ln \alpha_{w-v}{}^{18}O = -2.0667 - 0.4156\left(10^3/T\right) + 1.137\left(10^6/T^2\right) \quad (10)$$

$$10^3 \ln \alpha_{w-v}{}^{2}H = 52.612 - 76.248\left(10^3/T\right) + 24.844\left(10^6/T^2\right) \quad (11)$$

α_{w-v} is the equilibrium fractionation factor between vapor and water for oxygen and hydrogen isotopes respectively. It is a function of

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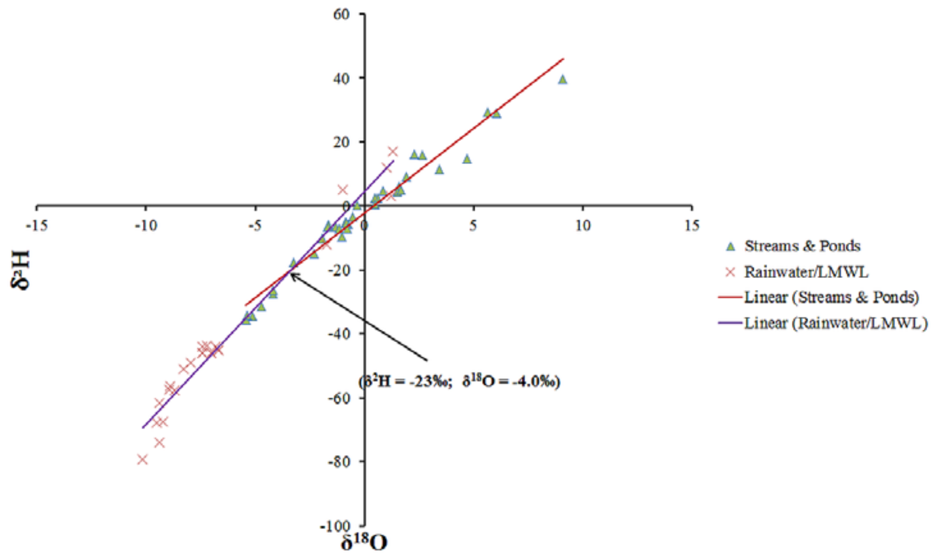

Figure 4: Relationship between the LMWL and SWL in the study area.

temperature (T) [44] as indicated in Equations 10 and 11.

δ_A is a difficult parameter to measure. In most practical cases, it is estimated from other parameters. Peng et al. [45] suggested a relationship between initial precipitation and δ_A (Equation 12). This relationship assumes that initial precipitation (IP) is in isotopic equilibrium with the precipitating vapor during the course of the precipitation.

$$\delta_A \cong \delta_{IP} - 10^3\left(\alpha_{w-v} - 1\right) \tag{12}$$

Due to high temperatures and low relative humidities, it is expected that first rains will normally be relatively enriched in terms of the heavy isotopes of hydrogen and oxygen. The earliest rainwater sample available from the study area for this study was taken in Donkorkrom in the Southern Voltaian in the month of February and returned data of 1.3%‰ and 17‰ for $\delta^{18}O$ and δ^2H respectively. These were used to solve Equation 12 to determine the isotopic signature of water vapor responsible for the rains. The corresponding isotopic signature of water vapor in ambient air is -7.84‰ and -59.31‰ for $\delta^{18}O$ and δ^2H respectively.

The percentage of precipitation that evaporated to result in the observed signatures of stream and pond water samples was then computed. It ranges between 29.5% and 84.7% in the Voltaian Basin. The apparent wide range in the estimated evaporation rates suggests significant temporal and spatial variability in the prevailing atmospheric conditions in the basin. This is consistent with the observed high temperatures and low humidities during much of the year, and ties in with the high evapotranspiration rates estimated for most parts of the basin. The high and low ends of the range respectively depict what pertains in the dry and rainy seasons in the basin. Possible sources of error in these estimates include the likelihood of sampling water of different sources in the surface water outlets monitored for this study, as well as the uncertainties in the estimates of the relative humidities, and isotopic composition of ambient air water vapor. These high evaporation rates also suggest that damming of surface flows for the purpose of supplying water for dry season irrigation in the basin may not be sustainable due to the high evaporation rates. Indeed this has been the observation in the basin as surface impoundments have been drying out before the end of the dry season.

Isotopic characteristics of groundwater and estimated groundwater recharge

The groundwater data fall on an evaporation line defined by Equation 13. It obviously has a lower slope and deuterium excess than the GMWL, and is thus indicative of the effects of high evaporation rates attending high temperatures, low relative humidities, and slow infiltration rates through the top surficial material. Hydrometeorological conditions vary widely in the terrain. The nature and thickness of the overburden material and the prevailing weather conditions ultimately determine the fraction of precipitation that finally reaches the saturated zone as direct groundwater recharge from precipitation.

$$\delta^2 H = 5.69^{18}O + 1.29 \tag{13}$$

The groundwater isotope data used for this study also exhibits some variability between the northern and southern parts of the basin. Such slight variabilities may be attributed to slight differences in the processes of evolution of rainwater through the overburden to the saturated zone. The slope of the Local Groundwater Line (LGWL) is comparatively lower than those observed for the LMWL in Equation 1. This suggests that infiltrating rainwater underwent some enrichment of the heavier isotopes prior to recharge and/or during the process of infiltration and percolation through the unsaturated zone to the saturated zone. Relative to the surface water line (Equation 3), the LGWL appears to be relatively less enriched. This is because the streams and ponds sampled are much more exposed to high effects of evaporation than groundwater in transit. Acheampong and Hess [20] developed a LGWL for the Voltaian aquifers in the south. In comparison with the result of this current study, the line of Acheampong and Hess [20] has a higher slope and intercept, suggesting that the basin wide dataset presents a relatively much enriched signature compared to the localized study of Acheampong and Hess [20]. Although this study did not perform extensive

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monthly sampling and analysis of groundwater samples, the data used is much more representative of the character of groundwater in the entire basin since it includes data from both the north and south, and the two major seasons (wet and dry seasons) of the year. The comparatively lower slope and intercept reflects the variability in the factors influencing groundwater isotopic signatures in the entire basin. Groundwater isotopic composition is relatively unaffected by rock-water interactions at the usual low groundwater temperatures [6] especially where the residence time is low. This is especially the case with silicate mineral weathering, which has been noted as the major source of variation in groundwater hydrochemistry in the basin [28]. It is usually for this reason that stable isotopes are reliable tracers of the source and evolution of groundwater over time and / or space. In the Voltaian basin, the thickness of the overburden and the fraction of it that is clayey, play essential roles in determining the rate of infiltration and the percentage of precipitation that reaches the saturated zone. Where the clay content is significant, the rate of infiltration and downward percolation of groundwater through the unsaturated zone to the saturated zone is quite low, and whilst the infiltrating water is close to the surface, it is prone to the effects of high temperatures and low humidity. It is therefore likely to be quite enriched when it finally reaches the saturated zone. An estimation of the fraction of the initial precipitation water that goes into the atmosphere as a result of evaporation will therefore provide indications of estimates of groundwater recharge from precipitation.

The simultaneous solution of the LGWL and LMWL will provide the isotopic signature of the source precipitation water for the aquifers in the area. Such a solution is achieved at the point of intersection of the two lines (Figure 5). The two lines meet at a point where the $\delta^{18}O$ and δ^2H are respectively -2.3‰ and -12‰.This is the character of recent precipitation and falls within the range of the data obtained from the precipitation samples used for this study. Estimates of the fraction of precipitation that evaporated in the course of infiltration and percolation were made through procedures similar to those used for the surface water. The estimated range of evaporation is 19.8% to 70.6% of the initial component of precipitation that begins infiltration to the subsurface. Although the level of evaporation of precipitation in transit to the saturated zone appears to be understandably lower than observed for the streams and ponds, it is quite high and attests to the assertion that rainwater infiltration and percolation to the saturated zone is a slow process, largely due to low vertical hydraulic conductivity of the material in the overburden. Direct groundwater recharge from precipitation in the basin is therefore expected to be quite reduced at most places.

Interaction between surface flows and groundwater in the basin

An understanding of any possible relationship between surface flows in streams and ponds on one hand and the aquifers in the basin on the other hand, will form an important aspect of characterizing the hydrological system. The streams generally present enriched water compared to groundwater. This suggests that any hydraulic connection between surface flows and the aquifers in the basin favors groundwater discharge into the streams and not the converse, which would have led to much more enriched isotopic signatures of groundwater than has been observed in this study. An attempt has been made to determine the isotopic signature of any groundwater source of streamflow in the area. Again, this was determined through a simultaneous solution of the SWL and LGWL (Figure 6). This resulted in -9.0‰ and -49‰ respectively for $\delta^{18}O$ and δ^2H respectively. This is certainly outside of the range of isotope data for the groundwater in the basin as captured in this study. The implication is that groundwater does not contribute to local stream flow in the basin. The observed isotopic signature of the source water for the streams is consistent with the signature of current rainfall in the area, and suggests that if there is any relationship between the surface flows and subsurface water, it is certainly the fact that both receive recharge from current precipitation in the basin.

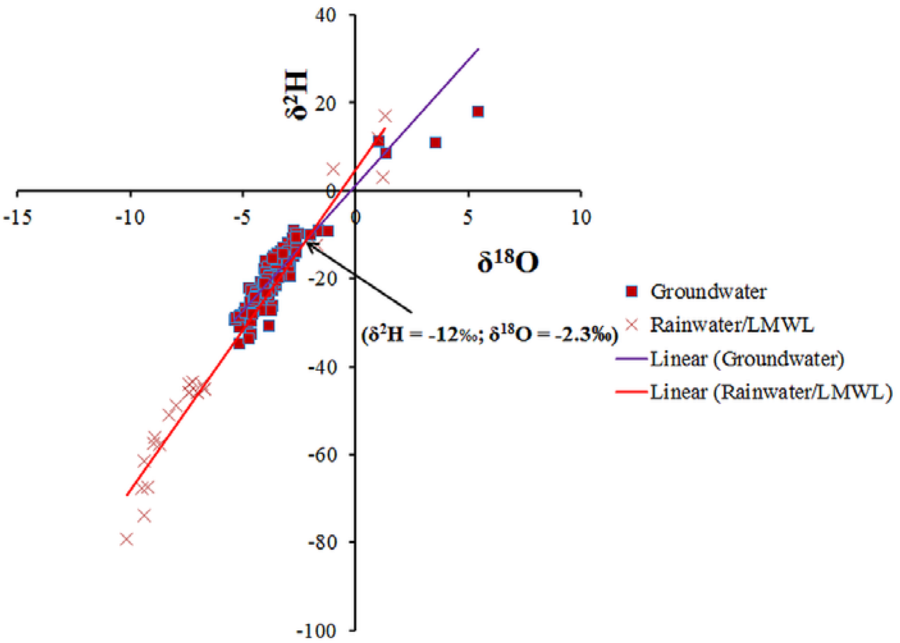

Figure 5: Relationship between the LGWL and LMWL for the study area.

Another major surface water body of significant importance is the Volta Lake, which had hitherto been believed to contribute to subsurface flows in the basin. However, as indicated by Acheampong and Hess [20] and is also obvious in the current study, the isotopic signature of the Lake water is too enriched to have been a recharge source for groundwater. On the other hand, the reverse process is likely. This study investigated the possibility of groundwater discharge into the Volta Lake by determining the signature of any source groundwater recharging the lake. As is indicated in Figure 7, the evaporation line for the Volta Lake intersects the LGWL at a point where the $\delta^{18}O$ and $\delta^{2}H$ are respectively 4.0‰ and 25.0‰. This means that any groundwater of the current isotopic signature, recharging the lake would have been significantly enriched during the process. The likelihood of such a process is unclear and will be investigated

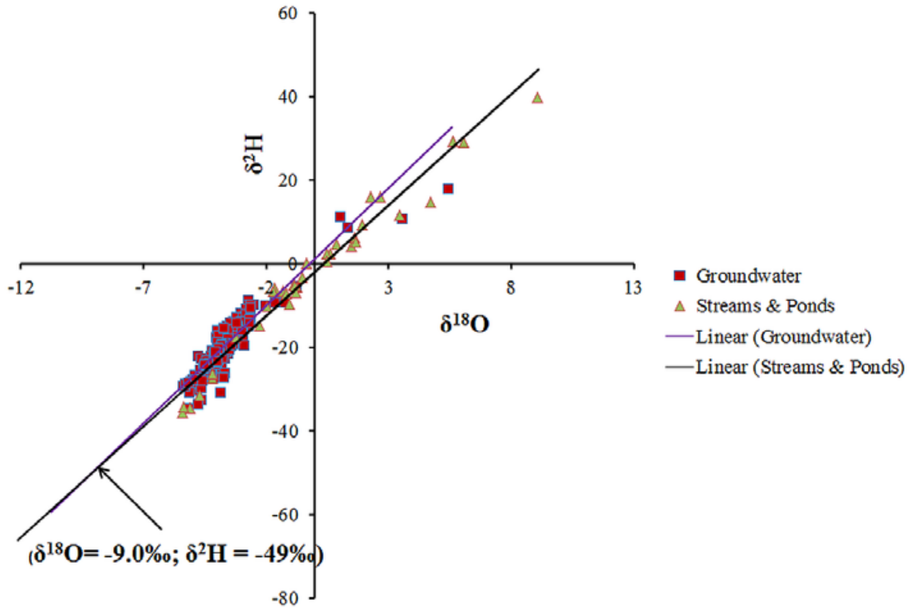

Figure 6: Relationship between the LGWL and SWL for the study area.

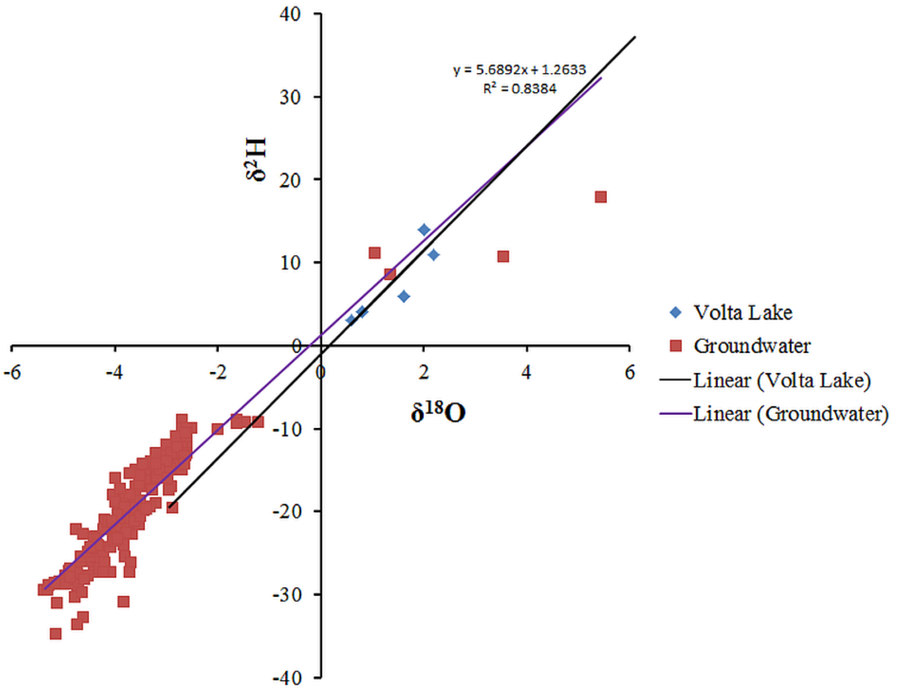

Figure 7: Relationship between the LGWL and the Lake Water Line.

through other vigorous field investigations, backed by detailed hydrochemical and isotopic analyses.

Conclusions

This study finds that groundwater recharge in the Voltaian Basin is meteoric water which has been enriched due to high levels of evaporation of infiltrating rainwater in the process of infiltration and percolation through the unsaturated zone to the saturated zone. The rate of evaporation of recharging water has been estimated to range between 19.8% and 70.6% and suggests that direct groundwater recharge from infiltrating rainwater is considerably variable in the terrain, and is limited by the vertical hydraulic conductivity of the intervening material between the surface and the saturated zone, low humidities, and high annual average temperatures in the basin. The variations in the clay content of the material of the unsaturated zone plays an important role in determining the rate of infiltration of rainwater. Where there is high clay content, infiltration rates are much reduced and the water is much more prone to the effects of high temperatures and prevailing low relative humidities. Surface water bodies in the terrain are considerably much more evaporated than groundwater and exhibit a high level of variability, suggesting differences in the residence times of the sampled water as part of this study. The isotope data indicates considerable enrichment relative to local meteoric water from the basin, and suggests evaporation rates in the range of 29.5% and 84.7% from the surface water bodies. There is no evidence from the stable isotope data alone, to suggest any hydraulic connection between the aquifers in the basin and surface flows.

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