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# Groundwater recharge processes in the Nasia sub-catchment of the White Volta Basin: Analysis of porewater characteristics in the unsaturated zone

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ABSTRACT

Vertical infiltration of precipitation has been examined in this study for the purpose of evaluating groundwater recharge processes in parts of the Nasia sub-catchment of the White Volta Basin. As recharge is an essential component in the detailed assessment of groundwater resources potential in a basin, evaluating its processes is vital in determining the spatial and temporal variability of the resource. Stable isotope data of precipitation, groundwater, surface water and porewater in the area suggest that the local precipitation is largely enriched compared to global meteoric water. This is consistent with the prevailing local conditions in the region and ties in with observations in other parts of the sub-region. The groundwater and porewater data indicate that prior to, and in the process of infiltration and final percolation into the saturated zone, rainwater undergoes evaporative enrichment such that the finally recharged water plots along an evaporation line with a much shallower gradient and intercept compared to the global meteoric water line and the local meteoric water line. The isotope data further suggest that through the shallow unsaturated zone, a significant fraction of the initial precipitation would have been evaporated by a depth of 3.0 m. Evaporation rates in the range of 38–49% have been estimated for the depth range of 0–3.0 m based on the porewater stable isotope data. Details of the procedures and implications of high evaporation rates within such shallower depths are presented and discussed. Groundwater recharge rates estimated from the chloride mass balance technique report values in the range of 73.26 mm/yr (390 $Mm^3$/yr)–109.89 mm/yr (585.27 $Mm^3$/yr), with an average of 94 mm/yr (500.6 $Mm^3$/yr). These translate into 6.6–10.9% of annual precipitation. Based on the current population trends and per capita water demand of 50 L per capita per day, this study finds that the estimated recharge rates exceed the demand 59 times. This suggests significant promise for developing groundwater resources for climate-proof livelihood support projects in the terrain. However, much more detailed hydrogeological assessments are required to constrain the effects of lateral and vertical lithological variations on the availability of the recharged groundwater for immediate abstraction and use. The study also observes that since evaporation is one of the main dynamic processes influencing the fraction of the initial precipitation that finally reaches the saturated zone, projected increases in temperature during the next decade may increase evaporation rates of infiltrating rainwater leading to reduced groundwater rates.



## 1. Introduction

Groundwater recharge is an important parameter in the basin-wide assessment of groundwater resources potential and for scoping the resource for large scale commercial development. A variety of techniques have been used universally for evaluating

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groundwater recharge processes and for estimating quantitative recharge to facilitate proper resource management and governance. Natural and hydrochemical tracers have been copiously used in the literature to identify the source and age of groundwater in aquifers (Flusche et al., 2005), investigate salinization of freshwater aquifers (Kim et al., 2003), assess groundwater recharge processes (Al-Gamal, 2011), and for differentiating groundwater types (Mukherjee et al., 2007) amongst other applications. Tracer techniques therefore provide vital information for the initial conceptualization of hydrological processes at the basin level and are critical in accurate determination of groundwater recharge regimes and mixing processes of water from different reservoirs. By their nature, stable isotope tracers preserve the conditions of the natural environment of rainwater, and can therefore be used to infer sources and qualitative age of groundwater. Oxygen-18 signatures for instance, are not affected by typical rock–water interactions at temperatures below 50 °C (Lawrence and Taylor, 1972; Drever, 1988). It is thus useful in tracing hydrological processes and for assessing mixing processes of waters of different origins. Since they are conservative tracers, oxygen-18 and deuterium are useful for studying the relationship among precipitation, porewater, and groundwater and for evaluating infiltration processes in the unsaturated zone (e.g. Gazis and Feng, 2004; Cheng et al., 2014). Zimmermann et al. (1966) provided a classical analysis of the effects of evaporation on the stable isotope characteristics of porewater and proved that deuterium is enriched near the soil surface, and decreases exponentially with depth of sampling. Other researchers have since observed similar patterns and have thus used this behavior of isotopes in soil water to distinguish the effects of evaporation and transpiration on infiltrating rainwater (e.g. DePaolo et al., 2004; Cheng et al., 2014). The propagation and attenuation of isotopic profiles down the unsaturated zones provide convenient basis for evaluating the movement of water in the unsaturated zone. As such, vertical isotope profiles of porewater in the unsaturated zone have been used to investigate recharge mechanisms and rates (e.g. McConville et al., 2001). Barnes and Turner (1998) suggest that mixing processes, water uptake by plants and hydrodynamic dispersion processes do alter the meteoric signal of water in the unsaturated zone particularly in humid environments. Thus, time series variations of stable isotopic signatures of unsaturated zone material have been observed in several places and copiously reported (e.g. Maloszewski et al., 2002; Wenninger, 2007).

In Ghana and other sub-Saharan African countries, sustainable socioeconomic development appears to hinge on the maintenance of robust irrigation systems that are resilient to the impacts of climate change/variability over time. It has been understood over time that groundwater has several characteristic features that render it useful for climate-proof irrigation activities almost everywhere in the country. However, the successful development and management of groundwater resources for such large scale abstractions will require the appropriate scientific research to provide the basis for decision making. Establishing the recharge regimes is of considerable importance in resource assessment and management. Stable isotopes have been used for similar investigations in other parts of the world (e.g. Mendonca et al., 2005; Négrel et al., 2007; Yao et al., 2009) to constrain groundwater recharge sources and evolution through time and space. In all these researches, the authors have made attempts to estimate evaporation rates of precipitation in transit from the unsaturated zone to the saturated zone. Through these estimates and subsequent analyses of water budgets, estimates of groundwater recharge are made. However in Ghana, this methodology has not been widely applied to quantitatively estimate groundwater recharge at the basin level. There have been notable applications of stable isotope data for the determination of the sources of groundwater recharge (e.g. Pelig-Ba, 2009; Adomako et al., 2010) in some parts of Ghana. Adomako et al. (2010) proceeded to estimate variations in groundwater recharge from time series porewater stable isotope data using the piston model. Yidana (2013) performed a comparative analysis of evaporation rates of surface water bodies and groundwater relative to fresh precipitation in an analysis of water budgets in the entire Voltaian basin. In the entire country, there has been no such study that evaluates the progressive increase in porewater evaporation rates through the unsaturated zone using stable isotope data. Furthermore, on the global scale, the clear separation of transpiration rates from evaporation rates through the combined use of natural hydrochemical tracers and stable isotope data has not been performed at the basin scale. In this current research, an attempt is made to estimate the percentage of the water lost to evapotranspiration which can be attributed to transpiration alone. This is because in the tropical environment, transpiration is an important aspect of the water budget.

In the Nasia sub-catchment of the White Volta Basin in particular, characterization of the groundwater recharge regime has not been performed to the required degree to provide the basis for a holistic numerical conceptualization of the hydrogeology of the terrain. In this research, porewater isotopic characteristics in the Nasia sub-catchment of the White Volta Basin are evaluated to enhance understanding of vertical infiltration processes in the unsaturated zone. Evaporation rates estimates, based on the stable isotope signatures of infiltrating water within the shallow subsurface, are discussed in relation to quantitative estimates of groundwater recharge based on the chloride mass balance methodology. The advantage of this methodology arises from the fact that it makes it possible to determine the effect of the unsaturated zone processes and the fraction of the initial precipitation that would have been lost to evaporation during its transit from the unsaturated zone to the saturated zone. The utility of the chloride mass balance technique will lead to a determination of the fraction of infiltrating precipitation remaining at every depth of the sampling.

## 2. Study area

### 2.1. Location

The Nasia basin (Fig. 1) is one of the nine (9) sub-basins of the White Volta Basin in Ghana. It is the drainage of one of the left bank tributaries of the White Volta and located on the north-eastern part of Ghana (Adu, 1995). The area lies entirely within the Northern Region of Ghana. The West Mamprusi and East Mamprusi District are respectively located at the western and eastern parts of the basin, whilst the southern flanks are covered mainly by Savelugu – Nanton, Gushegu and Karaga Districts. The drainage of Nasia basin has a catchment area of about 5326 $km^2$. The Nasia Basin is sparsely inhabited and according to the 2010 population and housing census, the total inhabitants of the basin was approximately 359,888 (GSS, 2010).

### 2.2. Topography, climate and Vegetation

The topography of the study area is generally flat with a few scattered hills like the Gambaga escarpments. The Nasia basin is located within the Interior Savannah Ecological Zone and as such, the vegetation comprises an ecological association in which grasses are dominant. The present vegetation is a fire sub-climate developed through a long period of degradation and modification by human activity, especially, through farming and burning (Adu, 1995). Degraded savannah occurs in uncultivated areas with