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Groundwater level monitoring and recharge estimation in the White Volta River basin of Ghana

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ABSTRACT

Recharge quantification is an important pre-requisite for effectively managing groundwater resources as recharge estimates are needed to determine sustainable yields of groundwater aquifers for rational and sustainable exploitation of the resource. In this study, the water table fluctuation method has been applied in the White Volta River basin of Ghana (approx. 46,000 km^2) to estimate seasonal fluctuations in groundwater levels in the basin and subsequently to estimate recharge to the groundwater for the 2006 and 2007 water years. Results show high seasonal and spatial variability in the water level, with a range of 1240–5000 mm in 2006, and 1600–6800 mm in 2007. Seasonal rainfall was found to be the main source of recharge to the aquifers in the basin as water level rise occurred only in the rainfall season. Recharge to groundwater in the White Volta basin was estimated to vary between 2.5% and 16.5% of the mean annual rainfall, with a mean recharge of 7–8%.

1. Introduction

The importance of freshwater is increasing very rapidly due to the fast growth in the world's population, resulting in the increased demand for the resource world-wide. Notwithstanding the rising demand, the amount of freshwater available on earth is limited and unevenly distributed. According to UNEP (2002), about one third of the world's population live in countries with moderate to high water stress with disproportionately high impacts on the poor. The study observed that, with the current projected human population growth, industrial development and expansion of irrigated agriculture in the next two decades, water demand will rise to levels that will make the task of providing water for human sustenance more difficult.

According to a recent study by UNICEF/WHO, safe water supply coverage in sub-Saharan Africa (SSA) is estimated to be about 56% of the total population (WHO/UNICEF, 2005). The low coverage was explained by lack of investment in new infrastructure and population growth. Major sources of water supply for domestic, agricultural and industrial uses in arid and semi-arid areas in SSA include surface water (e.g., streams and rivers, lakes, ponds, dugouts, impoundment reservoirs, rainwater harvesting) and groundwater (e.g., springs, boreholes and hand-dug wells). Due to high spatial and temporal variability associated with rainfall in SSA, surface water sources are mostly unreliable, subject to high evaporative losses, easily polluted, and insufficient to meet the rising demands. Groundwater sources are well suited to meet the dispersed demand of the growing rural population, which forms the larger proportion of the total population.

In the White Volta basin of Ghana, groundwater use is of fundamental importance and a key resource for economic and social development. In 2005, about 44% of the basin inhabitants depended on groundwater sources for domestic water supply (Martin and van de Giesen, 2005). The figure may be higher in recent times. Generally, the microbiological and chemical quality of the basin's groundwater is good for multipurpose use except for few areas where iron and excessive fluoride concentration are problematic. Over the past three decades, exploitation of groundwater in the basin has increased substantially for reasons including a policy by the Government of Ghana to set up water supply schemes for small towns and rural areas, based entirely on groundwater sources, and the quest of some inhabitants of the basin, mostly youth, to increase their income through dry season irrigated vegetable production. This has put stress on the resource in some localities, particularly, in the northeastern parts of the basin. While groundwater offers the opportunity to improve water supply coverage at relatively lower cost and with greater flexibility, it is of great importance to improve our knowledge of the resource for rational and sustainable development, use and management.

Evaluation of groundwater involves several factors of which the recharge is paramount. Quantification of the recharge rate is prerequisite for efficient and sustainable management of groundwater (Scanlon et al., 2002; Chand et al., 2005). Quantification of the

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recharge is needed for example, to estimate the sustainable yield of groundwater aquifers. Knowledge of aquifer sustainable yield is important for rational and sustainable exploitation of the groundwater resource (Sanford, 2002; Sophocleous and Schloss, 2000; Gonfiantini et al., 1998; Scanlon et al., 2002).

The objective of this study was to monitor the groundwater levels in the White Volta river basin of Ghana and to use this information to estimate recharge to the groundwater aquifers in the basin.

2. Recharge estimation methods

Estimating groundwater recharge in arid- and semi-arid-regions can be difficult, since in such areas the recharge is generally low compared to the average annual rainfall or evapotranspiration, and thus difficult to determine precisely (Scanlon et al., 2002; Beekman and Xu, 2003). Recharge processes vary from one place to another, and there is no guarantee that a method developed and used for one locality will give reliable results when used in another. Therefore, it is necessary to identify the probable flow mechanisms and the important features influencing the recharge in a locality before deciding on the recharge method to use (Lerner et al., 1990). The recharge to a groundwater aquifer cannot be easily measured directly, and usually estimated by indirect means (Lerner et al., 1990). The accuracy of the indirect estimates is usually difficult to determine, and therefore it is recommended that recharge should be estimated using multiple methods to obtain more reliable values (USGS, 2008; Scanlon et al., 2002; Lerner et al., 1990). A wide variety of methods exists for estimating groundwater recharge, which have been designed to represent the actual physical processes of the recharge.

Recharge estimation methods can be classified according to (i) hydro-geological provinces (Lerner et al., 1990), (ii) hydrologic zones (Scanlon et al., 2002; Beekman et al., 1996; Bredenkamp et al., 1995), (iii) physical, numeric modeling, and (iv) tracer techniques (Scanlon et al., 2002; Lerner et al., 1990; Kinzelbach et al., 2002). Scanlon et al. (2002) classified recharge methods on the basis of three hydrologic zones of studies namely surface water, unsaturated zone and saturated zone. Each of these zones provides a different set of data that can be used to estimate the groundwater recharge. Within each of the hydrologic zones, the recharge techniques were further classified into physical techniques, tracers and numerical modeling.

Methods based on surface water studies include physical methods, e.g., channel-water budget, seepage meters and baseflow discharge; tracer methods, e.g., stable isotopes of oxygen and hydrogen; numerical modeling methods, e.g., deep percolation model and water budget equation. Methods based on the unsaturated zone studies include physical methods, e.g., lysimeters, Darcy's law and zero-flux plane; tracer techniques, e.g., bromide, ^{3}H, and visible dyes, ^{36}Cl, and Cl; numerical modeling methods, e.g., soil water storage routing, quasi-analytical approaches and numerical solutions to the Richards equation. Recharge estimation methods based on the saturated zone studies are physical methods, e.g., water table fluctuation and Darcy's law; groundwater dating using traces such as CFC, $^{3}H/^{3}He$, and ^{14}C; and groundwater flow modeling. A detailed description of each of the above-mentioned techniques can be found in Scanlon et al. (2002), Scanlon et al. (2003), and Lerner et al. (1990).

The water table fluctuation was used in this study because it gives more reliable estimates irrespective of the recharge mechanism prevailing in an area, weather piston or preferential flow. Its applicability in terms of temporal scale is wide, from a day to years. In addition, the method is easy to use, has low data needs and cost relatively low (USGS, 2008).

3. Water table fluctuation

The water table fluctuation (WTF) method is one of the most widely used techniques for estimating groundwater recharge over a wide variety of climatic conditions (Scanlon et al., 2002; Hall and Risser, 1993; Healy and Cook, 2002). The use of the method requires knowledge of specific yield and changes in groundwater levels over time. Healy and Cook (2002) have attributed the wide use of this method to the abundance of available groundwater level data and the simplicity of estimating recharge rates from temporal fluctuations or spatial patterns of water levels. The WTF method is best suited for estimating recharge rates over short time periods in areas with shallow unconfined aquifers that display sharp rise and fall in water levels (Scanlon et al., 2002). The method has no assumptions regarding movement of water through the unsaturated zone and, therefore, the presence of preferential flow paths does not restrict its use. Recharge estimates with the WTF technique are actual and therefore more reliable, compared to potential recharge estimates given by other methods.

The WTF method is based on the assertion that rises in water levels in unconfined aquifers are due to recharge water arriving at the water table, and that all other components of the groundwater budget, including lateral flow, are zero during the recharge period (Scanlon et al., 2002; Healy and Cook, 2002). The recharge rate can be estimated as the product of the water level rise and the specific yield of the groundwater aquifer material. Mathematically, the recharge can be expressed as:

$$R = S_y dh/dt = S_y \Delta h/\Delta t \quad (1)$$

where R is groundwater recharge (mm/time); S_y is specific yield (dimensionless); Δh is peak rise in water level attributed to the recharge period (mm); and Δt is the time of the recharge period.

Major assumptions inherent in this technique include: (i) rise and decline in levels of the water table in shallow unconfined aquifers are solely due to recharge and discharge of groundwater; (ii) the specific yield of aquifer is known and constant over the time period of the water table fluctuation; and (iii) the pre-recharge water level recession can be extrapolated to determine water level rise (Healy and Cook, 2002). These assumptions are not always the case and could be drawbacks of this method in some situations. For instance, changes in groundwater levels may not always be as a result of recharge or discharge. It could be caused by other factors such as evapotranspiration, changes in atmospheric pressure, presence of entrapped air and earth tides, or as a response to changes in stream stage for wells that are very close to streams (Delin et al., 2006). Previous studies have shown that obtaining a specific yield that is representative of a large area can be difficult. Besides, specific yield values vary with time as opposed to the assumption of a known and constant specific yield (Delin et al., 2006; Loheide et al., 2005; Sophocleous, 1985).

There are no strict limits as to the range of recharge that can be estimated with the WTF method. Scanlon et al. (2002) gives annual recharge rates estimated using the WTF technique as ranging from 5 mm in the Tabalah Basin of Saudi Arabia to 247 mm in a small basin in eastern United States. In West Africa, the WTF method have been used by Martin (2005) and Sandwidi (2007) to estimate the annual groundwater recharge in the Atankwidi basin in Ghana (13–143 mm) and the Kompienga dam basin in Burkina Faso (44–244 mm).

4. Study area

The study area, the White Volta River basin of Ghana, is located in northern Ghana (Fig. 1) and falls within the boundaries of latitudes 8°30′ and 11°N, and longitudes 0.0° and 2°30′W. The study