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Groundwater in hard rocks of Benin: Regional storage and buffer capacity in the face of change

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SUMMARY

Groundwater plays a major role in supplying domestic water to millions of people in Africa. In the future, the ability to increase reliable water supplies for domestic and possibly irrigation purposes will depend on groundwater development. Groundwater storage is a key property because it controls the buffering behavior of the aquifer as it is subjected to time-varying conditions such as increased pumping or land-use change. However, quantitative knowledge of groundwater storage in Africa is very limited. This lack of knowledge is a major concern in hard rocks, which cover about 40% of the surface area of Africa. This paper presents a unique quantitative assessment of groundwater storage in different types of hard rocks and a first estimate of the capacity of hard rock aquifers to buffer changes in climatic and anthropogenic conditions. Our study area in Benin (West Africa) is composed of various grades of metamorphic rocks. We used the latest developments in the application of the magnetic resonance geophysical method to confront the methodological difficulty of quantifying groundwater storage. We successfully conducted 38 magnetic-resonance measurements in eight (8) different geological units; each measurement was quantitatively interpreted in terms of groundwater storage. We determined the groundwater storage of our study area to be 440 mm ± 70 mm (equivalent water thickness). To assess the buffer capacity of aquifers, we compared groundwater storage to groundwater discharge. Groundwater discharge is the sum of natural discharge plus human abstraction. We estimated natural discharge (i.e. deep drainage plus evapotranspiration) from water table fluctuations monitored in six (6) piezometers. Human abstraction was calculated based on the number of operating boreholes and their average daily abstraction. We found that human abstraction (0.34 mm/year ± 0.07 mm) is far less than natural discharge (108 mm/year ± 58 mm). We conclude that increased abstraction due to population growth will probably have a smaller impact on storage than observed land-use change, which may lead to a change in the evapotranspiration rate. We calculated buffer capacity as the ratio of current storage to total discharge, and obtained a result of 6 years ± 47 months. This buffer capacity confirms groundwater's ability to buffer changes. Finally, our study is intended to promote a more quantitative approach to assessing groundwater resources in Africa and to support our ability to adapt to current and future changes.

1. Introduction

Increasing reliable water supplies throughout Africa is an urgent need. As of 2012, more than 320 million Africans did not have access to safe drinking water (WHO/UNICEF JMP, 2014). Expanding irrigation to enhance food security is also a growing necessity because per capita food consumption is largely inadequate (Alexandratos and Bruinsma, 2012; Pfister et al., 2011). Moreover, most countries where population is expected to grow rapidly in the future are the same countries that have high levels of malnourishment (Alexandratos and Bruinsma, 2012) and also limited drinking water access.

Groundwater already plays a major role in supplying water to millions of people in Africa: the proportion of the population that depends on groundwater for its daily water supply is estimated at about 75% (UNEP, 2008). In the future, the ability to increase reliable water supplies will also depend on the development of groundwater, which is generally the only perennial water source

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in arid and semi-arid areas. Groundwater offers several advantages over surface water (e.g. groundwater is less vulnerable to pathogenic contamination, its development is cheaper and can be scaled to allow in-field application on demand); one of its most important advantages is its much slower response to climate variations (Taylor et al., 2009). Thus, increasing appropriate groundwater supplies in Africa can significantly increase the resilience of rural communities to climate variability (Calow et al., 2010).

Estimates of groundwater storage are needed for quantifying groundwater resources (MacDonald et al., 2012) and for assessing the impact of climate and land-use changes on water resources (Taylor et al., 2013). Indeed, the amount of water stored in the rock reservoir plays a major role in the transient response of the aquifer to conditions that vary over time. The greater the groundwater storage, the higher the buffering capacity of the aquifer (all else being equal) and the slower the impact of changes caused by variation in pumping, recharge, or evapotranspiration (i.e. climatic and anthropogenic changes). Groundwater storage in unconfined aquifers is calculated by multiplying the saturated thickness times the specific yield (De Marsily, 1986). Data regarding saturated aquifer thickness are widely available from numerous boreholes drilled in Africa during recent decades (e.g. Courtois et al., 2010). However, in Africa reliable quantification of specific yield is quite rare; the first quantitative Africa-wide map of aquifer storage presented by MacDonald et al. (2012) is based on 283 aquifer summaries, only two (2) of which contain in-situ specific yield measurements. Although not exhaustive (e.g. Compaore et al., 1997; Vouillamoz et al., 2005) the collation and review by MacDonald et al. (2012) clearly identify the lack of specific yield data. As underlined by Taylor et al. (2013), the result is a profound lack of knowledge regarding the quantity of groundwater storage in most aquifers.

The lack of groundwater storage estimates result from the fact that it is difficult to estimate in situ the volume of water that an aquifer will release through pumping (MacDonald et al., 2012). Indeed, conducting field experiments costs time and money because it requires the drilling of several boreholes and the setup of long-duration pumping experiments (e.g. Butler et al., 1999; Kruseman and de Ridder, 2000). Moreover, researchers have questioned the appropriateness of parameters derived from the interpretation of pumping experiments in both heterogeneous aquifers (e.g. Wen et al., 2010; Wu et al., 2005) and unconfined aquifers (e.g. Mao et al., 2011; Neuman and Mishra, 2012). Finally, comprehensive pumping experiments are difficult both to conduct and to interpret in complex environments; for this reason they are rarely, if ever, used for routine work in Africa. This is particularly true for hard rock aquifers even though hundreds of thousands of boreholes have been drilled in these aquifers since the 80's within the framework of projects supported by the international community (starting with the first "Water Decade" in 1981 and continuing under the "Millennium Development Goals" initiative). Boreholes have usually been drilled for the primary goal of short-term water production but with minor emphasis on groundwater resources. Hard rock aquifers are of major concern because they crop out on more than 40% of the African surface area, where more than 220 million rural people now live (Calow et al., 2010) and because these aquifers can store only a limited quantity of water, estimated to be less than 1000 mm (MacDonald et al., 2012).

Our paper presents a new step in the quantification of groundwater storage in hard rocks in Africa by using a more comprehensive dataset than previous studies, and also by comparing groundwater storage of different hard rock types. We used the Magnetic Resonance Sounding (MRS) geophysical method to quantify specific yield and groundwater storage at 38 locations located on top of eight (8) different hard rock units in Benin. We then compared groundwater storage to natural groundwater discharge and human abstraction to assess the buffer capacity of aquifers in the face of climatic and anthropogenic changes.

2. Material and method

2.1. Study area

Hard rocks underlie 80% of Benin's surface area (Fig. 1). Different hard rock types crop out within short distances, thus facilitating the comparison of their hydrogeological properties. The hard rock aquifers of Benin were formed by the uplift of a mountain range during the last stage of the Pan-African orogeny (610–570 Ma); the range was eroded and later weathered in the warm and humid climate that prevailed in West Africa at the beginning of the Cenozoic (65 Ma) (Office Béninois des Mines, 1984). The weathering processes created a heterogeneous groundwater reservoir that is unconsolidated on top and fissured at depth. This groundwater reservoir is conceptually described as a two-layer reservoir in which the fissured layer immediately underlies the unconsolidated saprolite (Lachassagne et al., 2011). The boundary between saprolite and fissured layers is generally smooth because both layers result from the same weathering process.

We selected a study area (27,200 km^2) that overlaps the primary structural direction of Benin (i.e. N10° to N20°) to include the major geological units of the country (Fig. 1). The geology of our study window is composed of various grades of metamorphic rocks; the predominant rocks are schist, gneiss, and migmatite in the western and central part of the window and granitic rocks in the east (Office Béninois des Mines, 1984). The study window also overlaps the Upper Oueme Catchment (Fig. 1), which is being studied and monitored as part of the African Monsoon Multidisciplinary Analysis (AMMA) project (Lebel et al., 2010), thus providing additional hydro-meteorological data.

The geological history of the study area results in a rather flat landscape where weathered hard rock aquifers extend to a depth of a few tens of meters (GIZ, 2012). The climate is of the Sudanian type; mean annual rainfall is 1190 mm (Lelay and Galle, 2005) and Actual EvapoTranspiration (AET) ranges from 68% to 86% of annual rainfall (Séguis et al., 2011).

2.2. Calculation of groundwater storage

Our groundwater storage estimate is based on the use of a non-invasive geophysical method called Magnetic Resonance Sounding (MRS). We first used pumping tests to parameterize the MRS at six (6) experimental sites (Vouillamoz et al., 2014b) and we then performed MRS measurements at 43 locations throughout the target area to estimate specific yield. Finally, we used the calculated specific yield together with geological/hydrological data to estimate groundwater storage and buffer capacity.

Detailed descriptions of the MRS technique can be found in numerous publications (e.g., Behroozmand et al., 2014; Legchenko and Valla, 2002; Legchenko, 2013; Lubczynski and Roy, 2004). The major advantage of MRS as compared to other geophysical methods is that with MRS, the groundwater molecules themselves generate the signals that are measured, thus resulting in direct measurement of groundwater (Legchenko and Valla, 2002). The primary output parameters obtained after interpretation of a measurement are variation in depth of the MRS water content θ_{MRS} and decay time T_2^* of the MRS signal. MRS has been successfully used for characterizing aquifers since the 1990's (Vouillamoz et al., 2007) but the quantification of specific yield is a very recent and major step forward in the application of the MRS method (Vouillamoz et al., 2014a, 2012). Based on this new development in the use of MRS, Vouillamoz et al. (2014b) proposed