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Time-lapse electrical surveys to locate infiltration zones in weathered hard rock tropical areas

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ABSTRACT

In West Africa, infiltration and groundwater recharge processes in hard rock areas are depending on climatic, surface and subsurface conditions, and are poorly documented. Part of the reason is that identification, location and monitoring of these processes is still a challenge. Here, we explore the potential for time-lapse electrical surveys to bring additional information on these processes for two different climate situations: a semi-arid Sahelian site (north of Burkina and a humid Sudanian site (north of Benin), respectively focusing on indirect (localized) and direct (diffuse) recharge processes. The methodology is based on surveys in dry season and rainy season on typical pond or gully using Electrical Resistivity Tomography (ERT) and frequency electromagnetic (FEM) apparent conductivity mapping. The results show that in the Sahelian zone an indirect recharge occurs as expected, but infiltration doesn't takes place at the center of the pond to the aquifer, but occurs laterally in the banks. In Sudanian zone, the ERT survey shows a direct recharge process as expected, but also a complicated behavior of groundwater dilution, as well as the role of hardpans for fast infiltration. These processes are ascertained by groundwater monitoring in adjacent observing wells. At last, FEM time lapse mapping is found to be difficult to quantitatively interpreted due to the non-uniqueness of the model, clearly evidenced comparing FEM result to auger holes monitoring. Finally, we found that time-lapse ERT can be an efficient way to track infiltration processes across ponds and gullies in both climatic conditions, the Sahelian setting providing results easier to interpret, due to significant resistivity contrasts between dry and rain seasons. Both methods can be used for efficient implementation of punctual sensors for complementary studies. However, FEM time-lapse mapping remains difficult to practice without external information that renders this method less attractive for quantitative interpretation purposes.

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1. Introduction

Location of infiltration in Sahelian and Sudano-Sahelian areas is a key issue for understanding hydrological processes undergoing in West Africa. Hydrological modeling studies, from hill slope scale to watershed scale, need to locate and spatialize infiltration zones, as they are a key input for building the model geometry and processes-driven logics (Boucher et al., 2009; Comte et al., 2010). Moreover, model outputs need to be evaluated by comparison with field data. Those field data need to be monitored using in-situ sensors (tensiometers, moisture probes, piezometers) located at accurate places, being representatives of the process under study.

The present study focuses in hard rock areas, which cover large surfaces in West Africa. Countries like Burkina Faso, Ivory Coast, Ghana, Togo, Benin and Nigeria, among others, are mainly hard rock covered. They mostly rely on groundwater resources for population needs, particularly during dry seasons. The weathered part of the subsurface – considered as the storage part of the aquifers (Lachassagne et al., 2008) – are clayey to sandy, as a contrary to sedimentary context where more sandy subsurface is encountered. In Sahel, in the last decades, the loss of vegetation cover leads to an increase of wind and water erosion (Thiombiano, 2000; Karambiri et al., 2003). In Sahelian semi arid areas, the erosion of clayey soils favors the growth of crusted impervious surfaces (Ribolzi et al., 2006) and consequently creates favorable conditions to runoff processes. This leads to a hydrological behavior that concentrates water runoff in streams and rivers (Descroix and Amogu, 2012; Malam Abdou et al., 2015), where infiltration and aquifer recharge take place. This is the so-called indirect recharge process. In more humid areas (i.e. Sudano-Sahelian climate), with more vegetation cover, direct infiltration can take place everywhere, including slopes, but with variable intensity due to the laterally variable nature (clayey to sandy) of the soils (Richard and et al., 2013). This is the so-called direct recharge process. As a contrary to semi-arid areas, groundwater (or shallow sub-surface flows from perched intermittent aquifers) generally discharges into intermittent streams during the rainy season (Séguis, 2011).

For hydrologists, localization of infiltration in the weathered zone of hard rock is a challenging task. Several previous papers have studied infiltration and recharge using various means, including piezometric monitoring (Ruiz et al., 2009), geochemistry from borehole samples (Massuel et al., 2006), shallow moisture sensors at the hill slope scale (Richard and et al., 2013) or neutron probe monitoring in auger holes down to few meters (Hector et al., 2013). Some of those studies are using geophysics as a means to better implement the sensors at key places, considering the spatial variations of some geophysical parameters such as resistivity. Doing so there is still a question rising: are those places hydrologically active during the annual water cycle? In other words, is there any water movement within the vadose zone at those particular places?

Our study proposes to consider geophysical resistivity techniques to investigate whether it is possible, and to what extent, to use time-lapse electrical surveys to identify infiltration patterns both laterally at the surface (XY mapping) and at depth. Electrical resistivity varies with water content, water electrical conductivity and temperature. Time-lapse resistivity variations have been already investigated in several studies exploiting this behavior to describe various hydrological processes. For very shallow processes (i.e. less than 1 m), Descloitres et al. (2007) investigated rain infiltration in sandy soils and found that electrical resistivity ratio observed before and after the rain can reveal water tension variations. They used in-depth sensor data to constrain data interpretation. For annual processes, Descloitres et al. (2003), used time-lapse Electrical Resistivity Tomography (ERT) across an intermittent gully to monitor aquifer recharge. They were faced with some difficulties in recovering actual deep infiltration patterns due to unconstrained inversion process. Later on, Clément et al. (2009) proposed an enhanced interpretation of time-lapse ERT incorporating shallow infiltration patterns into the inversion to obtain more reliable results. This later study allows us to apply their time-lapse ERT methodology as a tool to track water paths into the vadose zone.

In the present study, we propose to apply both Direct Current (DC, including ERT) and frequency electromagnetism (FEM) resistivity techniques in time-lapse mode to investigate two contrasted experimental sites of sub-Saharian Africa, both located in hard rock areas.

For the first site, under semi-arid climate, annual time-lapse resistivity variations are enhanced because the long drying season makes the shallow soils electrically resistive while the rain season drastically decreases their bulk resistivity as evidenced in Descloitres et al. (2003). We chose a typical site in northern Burkina Faso, the Katchari-Dangadé test site, with the objective to obtain a detailed pattern of infiltration at depth across an intermittent gully using a time-lapse ERT survey. At this place, we expected an aquifer recharge during the rainy season. Our survey was controlled with neutron probe and resistivity monitoring in few boreholes in order to validate the geophysical interpretation.

For the second site, under Sudano-Sahelian climate, annual time-lapse resistivity variations may be weaker because the vadose zone remains humid even in dry season. It is a less favorable experimental condition, and therefore a convenient situation to test the sensitivity of our methods. We chose the experimental site of Ara Watershed, in northern Benin, where several studies have been performed since 1997 in the frame of the "AMMA-CATCH" long term hydrological observatory (http://www.amma-catch.org/). A time lapse ERT survey was also performed across a small intermittent gully. In addition, as the infiltration takes place not only at the gully area but also everywhere around, we experienced a time-lapse FEM apparent resistivity mapping around the gully. The results of the surveys allow us to draw some practical conclusions on the efficiency of time-lapse resistivity surveys to evidence infiltration processes in two contrasted climatic situations of West Africa.

2. Background on resistivity methods, experimental sites and surveys setup

2.1. Resistivity methods

Resistivity is a key parameter for groundwater studies since it varies primarily with groundwater conductivity and porosity in the saturated zone, and with water saturation, groundwater conductivity and porosity in the vadose zone (see Archie, 1942, for sandy materials). If clayey materials are also present, resistivity is also influenced by the ions capacity exchange of clayey minerals. At last, temperature can also influence resistivity.

The measure of soil resistivity is done using electrical or electromagnetic methods which can be used to collect 1, 2 or 3D data sets. For our study, we used Electrical Resistivity Tomography (ERT) for cross-sections imaging and frequency Electromagnetism (FEM) to map subsurface resistivity patterns. A detailed description of these methods is not under the scope of this paper but we give a brief overview below.