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Application of isotopic tracers as a tool for understanding hydrodynamic behavior of the highly exploited Diass aquifer system (Senegal)

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SUMMARY

The Diass horst aquifer system located 50 km east of Dakar (Senegal) is exploited in two main aquifers covered by a sandy superficial aquifer: the confined/unconfined Palaeocene karstic limestone and the confined Maastrichtian sandstone aquifer underneath. This system has experienced intensive groundwater abstraction during the last 50 years to supply increasing water demand, agricultural and industrial needs. The high abstraction rate from 1989 to 2009 (about 109,000 m^3/d) has caused a continuous groundwater level decline (up to 30 m), a modification of the groundwater flow and salinization in parts of the aquifers. The objective of the study is to improve our understanding of the system functioning with regards to high pumping, identify the geochemical reactions that take place in the system, infer origin and timing of recharge by using mainly stable ($\delta^{18}O$, δ^2H, ^{13}C) and radioactive (^3H and ^{14}C) isotopes.

Water types defined in the Piper diagram vary in order of abundance from Ca–HCO_3 (65%), Ca/Na–Cl (20%), Na–HCO_3 (3%) and Na–Cl (12%). Values of $\delta^{18}O$ and δ^2H for the superficial aquifer range between −5.8 and −4.2‰ and between −42 and −31‰, respectively. For the Palaeocene aquifer they range from −5.8 to −5.0‰ and from −38 to −31‰, respectively; values in the Maastrichtian aquifer are between −5.9 and −4.3‰ for $\delta^{18}O$ and −38 to −26‰ for δ^2H. Plotted against the conventional $\delta^{18}O$ vs δ^2H diagram, data from the upper aquifer exhibit a dispersed distribution with respect to isotopic fractionation while those of the Palaeocene and Maastrichtian aquifers are aligned parallel and slightly below/or on the Global Meteoric Water Line (GMWL) evidencing ancient waters which had evaporated during infiltration.

The low tritium (generally <0.7 TU) and ^{14}C (0.7–57.2 pmc) contents indicate predominance of older water being recharged during the Pleistocene and Holocene periods. However, few boreholes which exhibit high tritium (1.2–4.3 TU) and ^{14}C (65.7–70.8 pmc) values indicate some mixture with recent water likely through faulting and vertical drainage from the upper to deeper aquifers as well as lateral flow along flow paths to the piezometric depressions created by pumping.

1. Introduction

Each atmospheric precipitation event is unique as far as its deuterium and oxygen 18 content are concerned. As stable isotopes of the water molecule are nearly conservative, they preserve the signature of atmospheric condition and carry it to the subsurface. Therefore, they can help reveal the origin and age of groundwater. Stable isotopes oxygen-18 ($\delta^{18}O$) and deuterium (δ^2H) as well as radioactive isotopes tritium (^3H) and carbon-14 (^{14}C) have been proven to be important tools in answering important mechanisms in hydrogeology such as the origin of water, recharge and mixing processes, flow regime, residence time and changes in climatic conditions (Clark and Fritz, 1997; Zongyu et al., 2003; Mazor, 2004; Maduabuchi et al., 2006; Demlie et al., 2007; Bouchaou et al., 2009; Jirakova et al., 2009; Kumar et al., 2009). In the context of confined reservoirs with groundwaters revealing palaeorecharge and palaeoclimate conditions, several studies have been carried

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out around the world (Zongyu et al., 2003; Edmunds et al., 2006; Zhu et al., 2007; Jirakova et al., 2009; Huneau et al., 2011); they pointed out the importance of palaeorecharge and also difficulties in clearly delineating chronology and evolution of recharge history. These isotopes were also used to study the dynamics of overexploited aquifers including the origin of water and the hydraulic connectivity between superposed aquifers (Kamel et al., 2005; El-Naqa et al., 2007) as well as the origin and process of groundwater contamination in complex systems (Vengosh et al., 2002).

In Dakar, the Capital city of Senegal which concentrates about 23% (2,300,000 inhabitants of the total population) (estimation DPS, 2004) and large proportion of the industrial activities, water supply is ensured by surface water piped from the Guiers Lake (250 km distant from the capital) and groundwater resources. Among these, the Diass aquifer system contributes to a substantial proportion (36%) of the total water supply distribution due to growing demand as consequence of the rapid demographic growth.

Due to its importance in water supply, several works have been carried out since the early 1970s to better understand the geometry and structure, flow regime and chemical characteristics of this aquifer system (Martin, 1970; ARLAB, 1981, 1983; Fall, 1981; Faye, 1983, 1994). In addition, environmental isotopes are used to infer recharge (BRGM, 1971; IAEA, 1972; OMS, 1972; Faye, 1983, 1994; Travi, 1988; RAF, 1998; Sarr, 2000). These studies undertaken at the Senegal sedimentary basin scale pointed out the existence of palaeowaters that had been recharged during the late Pleistocene period as well as potential recharge zones in the outcropped Maastrichian aquifer located in the Diass horst and in the South East and East of the basin. In the Diass multilayer system, relatively high tritium contents and high ^{14}C activities in part of the region evidenced modern recharge likely occurring through the upper aquifer and percolation from the Palaeocene aquifer. Water yield of this upper aquifer is limited and it is just exploited by small, dug wells delivering water for some villages. Faye (1994) compiled previous data (BRGM, 1971; IAEA, 1972; OMS, 1972; Faye, 1983; Travi, 1988) and provided additional information by use of long periods radionuclides (series of uranium, ^4He, ^{36}Cl) and noble gases (He, Ne, Kr, Xe) to better understand the past and present Maastrichtian system functioning at the Senegal sedimentary basin scale. He argued that the Diass compartment had functioned as a recharge zone for the Maastrichtian aquifer between 4000 and 3000 years BP. This present study particularly focuses to the Diass aquifer to infer its functioning with regards to recharge processes and flow exchange in the context of high exploitation and particular complex geometry setting. In fact, since 1983, abstraction in the five pumping fields to supply Dakar and the localities of Mbour, Sébikotane, Pout increased from 63,000 to 97,000 m^3/day for the two aquifers. At present, the total pumping rate is estimated to be 109,000 m^3/d (National Water Society database) in addition to industrial and agricultural activities needs.

This high yield has caused a continuous groundwater level decline (more than 30 m in 50 years) in some parts of the system, a change in the flow regime and quality patterns which are evidenced by salinization of few boreholes located at Sébikotane and Mbour pumping fields (Madioune, 2012). This high demand and exploitation of the system coincided with the occurrence of drought conditions since the 1970s where inducing deficit in groundwater replenishment as well.

In this system, due to the complexity of the structure and the substantial groundwater abstraction, characteristics such as the hydraulic connectivity between the Palaeocene and Maastrichtian aquifers (vertically and horizontally), the relative significance of present day recharge as well as location of recharge zones need to be investigated.

The present study aims to improve our understanding of groundwater dynamics in order to foster more appropriate groundwater management with regards to high exploitation in the Diass aquifer system scale after 50 years of intensive pumping. Specifically, it intends to: (1) identify the geochemical reactions that take place in the system, (2) infer origin and timing of recharge. This will help to evaluate the recharge mechanism and system functioning needed for management purpose in order to ensure sustainability of the groundwater resources with regards to demand and water quality conservation.

2. Geology and hydrogeology

The study area is located at the western part of Senegal between Dakar and Thiès and extends a surface area of 1340 km^2 (Fig. 1a). It is characterized by a tropical climate with two distinct seasons: a dry season (from November to May) and a rainy season (from June to October). Climate data (precipitation, temperature, relative humidity, insulation and wind speed) during the period from 1977 to 2001 were collected from the Senegal National Meteorological Agency in Dakar Yoff, Thiès and Mbour wheather stations. The average annual precipitation and temperatures are 440 mm and 27 °C, respectively.

Rainfall spatial and temporal distribution is highly variable and since the 1970s, a rainfall deficit occurs through most of the Sahel zone (Mahé and Olivry, 1995; Paturel et al., 1998; Lebel and Ali, 2009) inducing deficit in groundwater replenishment (Aguiar et al., 2010; Madioune, 2012) as well as variations of the hydrologic regime (e.g. Sircoulon, 1987; Hubert et al., 2007; Mahé et al., 2010). Potential and actual evapotranspiration (1977–2001) calculated from the Penman method (Allen et al., 1998) are 2057 and 371 mm/yr, respectively (Madioune, 2012). The hydrography of the region consists mainly of lakes and fossil valleys (Fig. 1a).

The geological structure of the system is updated using hydraulic and petroleum boreholes data (271 in total), previous cross sections (Martin, 1970; Fall, 1981; Faye, 1983) and geological map (1:50,000) established recently by Roger et al. (2009). The system is bordered by the Ponty-Kayar fault in the West, the Atlantic Ocean in the North and South and the Thiès fault in the East. Table 1 resumes the geological and hydrogeological characteristics of the system aquifer. The hydrogeological map in Fig. 1a presents the top main aquifer.

The Diass aquifer system consists of a complex multilayer structure, compartmentalized by four major faults oriented NE-SW (Fig. 1a). These faults configure the region into a horst system with three compartments: the Diass compartment in the center (between Sébikotane and Pout fault) where the Maastrichtian sandstones outcrop surrounded by two Palaeocene karstic limestones compartments (Martin, 1970) namely the Sébikotane compartment in the West (between Ponty-Kayar and Sébikotane fault) and the Pout compartment in the East (between Pout and Thiès fault) (Fig. 1a). The geological formations from bottom to top are composed as follow (Martin, 1970; Fall, 1981; Faye, 1983; Roger et al., 2009) (Table 1):

- The Maastrichtian formations, they are heterogeneous both laterally and vertically and are composed of clay with interbedded sand, sandstone, calcareous sandstone and clayey sands at the top. Towards the West, they are mainly composed of clayey sediments.
- The Palaeocene consisting of a succession of marly and clayey calcareous and limestone. These latter formation are karstified in the Sébikotane and Pout compartment while in the Western part, they are made of clay and clayey limestone.
- The Eocene formations made up of marl and clay, they cover the Palaeocene limestone in the Sébikotane compartment and in the northern Pout compartment.