Journal of African Earth Sciences 131 (2017) 284–300

Contents lists available at ScienceDirect

Journal of African Earth Sciences

journal homepage: www.elsevier.com/locate/jafrearsci

Assessment of chemical quality of groundwater in coastal volcano-sedimentary aquifer of Djibouti, Horn of Africa

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ARTICLE INFO

Article history:
Received 25 October 2016
Received in revised form
6 April 2017
Accepted 10 April 2017
Available online 21 April 2017

Keywords:
Hydrogeochemistry
Salinization processes
Multivariate statistical analysis
Geochemistry methods
Volcano-sedimentary aquifer
Djibouti

ABSTRACT

This research is conducted to evaluate the current status of hydrogeochemical contaminants and their sources in groundwater in the volcano-sedimentary aquifer of Djibouti. Groundwater samples were mostly collected from the volcanic and inferoflux aquifers and then were analyzed for quality on physicochemical parameters (EC, pH, Temperature, Cl^-, SO_4^{2-}, HCO_3^-, NO_3^-, Na^+, Ca^{2+}, Mg^{2+}, K^+, Br^-, F^-), minor and trace elements (Li, Ba, B, Sr, Si, Al, Cr, Fe, Mn, Mo, Pb, Co, Cu, Ni, Zn, Ti, V, As, Se). The interpretations of hydrochemical data are shown numerically and graphically through the Piper diagram such as the multivariate statistical analysis, binary diagram, the calculation of the saturation indexes, the index of base exchanges and ratio of Na^+/Cl^-, SO_4^{2-}/Cl^-, HCO_3^-/Cl^-. The seawater ratio and ionic deviation in the groundwater were calculated using the chloride concentration. These processes can be used as indicators of seawater intrusion progress. This study reveals three groundwater quality groups and how the quality of water supply has been deteriorated through the process of seawater intrusion. The seawater intrusion extends into the Gulf basalts aquifer that covers nearly 12% of the whole area according to some observations. Some toxic elements present in drinking water (As and Se) have already exceeded the maximum permissible in almost the entire of the Gulf basalts aquifer affected by seawater intrusion. Indeed, some correlations were found between As, Se, with electrical conductivity and among other minor and trace elements such as Br, B, Sr, Co and Cr. It indicates that all these elements are mainly controlled by naturel/geogenic processes.

The Principal component Analysis and the Hierarchical Cluster Analysis have led to the confirmation of the hypotheses developed in the previous hydrochemical study in which two factors explain the major hydrochemical processes in the aquifer. These factors reveal first the existence of an intensive intrusion of seawater and second the mechanisms of contamination through the recharge processes of groundwater.

Consequently, the assessment of water quality and the determination of the risk of water contamination by pollution seems to be very useful for an effective management of groundwater resources, and also for preventing salinization and minimizing the phenomena of seawater intrusion.

1. Introduction

The continuous and severe increase of water demands, due to the rapid population growth, have led to overexploitation of groundwater (Jameel and Sirajudeen, 2006), and have severely depleted its quantity and quality. Numerous recent hydrogeochemical studies confirm that salinity is one of the main causes of deterioration of groundwater quality of coastal aquifers subjected to an arid climate (Belkhiri et al., 2012; Bouchaou et al., 2008; Cardona et al., 2004; Djabri et al., 2008; El Yaouti et al., 2009; Fakir et al., 2001; Ghabayen et al., 2006; Moussa et al., 2012a; Vengosh et al., 2005; Zghibi et al., 2014). Cruz-Fuentes et al. (2014) listed many several mechanisms explaining salinization processes in the coastal areas such as seawater intrusion, concentration by evapotranspiration, hydrogeological

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http://dx.doi.org/10.1016/j.jafrearsci.2017.04.010
1464-343X/

characteristics of the aquifer, water-rock interaction and human influence.

Belonging to an arid coastal area, the groundwater resources of Djibouti suffering quality degradation resulting from over-exploitation due to accelerated urbanization. This degradation is stated by an increase in the salinity of the groundwater (Bouh, 2006; Houssein and Jalludin, 1996). Indeed, since the early 1960s, the water supply in the city of Djibouti was based exclusively on the exploitation of the basaltic aquifer of Djibouti. Recharge of the aquifer occurs rarely by the wadis's flow. Because due to the climatic conditions surface of basalts are impermeable and infiltration occurs exclusively in sedimentary formations located in the wadi bed (Jalludin and Razack, 1994). This direct storm-water infiltration in the superficial formations represents a major risk of groundwater contamination. The waters of these aquifers are in contact with red clay, alluvial sediments, altered basalt and basaltic scoria (Houmed Gaba, 2009). These basaltic rocks naturally contain significant quantities of metals in the form of oxides, carbonates or sulfide. Floor and Román-Ross (2012) reported the natural source of these trace elements that includes hydrothermal activity, host rock interaction, volcanic ash and leaching from soils. In fact, heavy metals can be relegated and mobilized by the phenomena of leaching, salinization or a change in acid-base conditions. That's why groundwater in volcanic aquifer of the Main Ethiopian Rift contains a high concentration of trace elements exceeding the concentration found in groundwater anywhere in Europe (Reimann et al., 2003).

The objectives of this paper are, first of all to determinate the part of the aquifers that can be currently affected by seawater intrusion due to the overexploitation of the groundwater reserve, and second of all to examine the relationship between groundwater chemistry and geology in the volcanic aquifers. So, in order to better understand the dominant processes governing spatial variation in chemical composition of the groundwater, a hydrogeochemical and statistical studies have been carried out.

2. Materials and methods

2.1. Study area

M%£µseismic activities and important networks of tectonic fractures are observed in Djibouti (Fig. 1). The study area is levelled with three volcanic series. These are the initial series of the Gulf of Tadjourah, the series of Somali basalts farther south, and the series of Goumarre basalts that intrude into the Somali basalts. The Gulf Basalts (2.8–1 Million of years (My)) of the Djibouti plain unevenly cover the Somali basalts (9–3.4 My) in the South as well as the Dalha basalts (9.3–4 My) and the Mabla rhyolites (15 My) on the West (Jalludin and Razack, 1997).

The Gulf Basalts include tholeïtic basalts impoverished in light rare earths (LREE) stemming from the Hayyabley volcano, which origin is attributed to the impoverished deep terrestrial mantel of plume type, and basaltic castings enriched in LREE coming from the current axis of the Gulf which are associated to the magmatic intrusions fed locally by eruptive centres of fissural type (Daoud, 2008). They are often inserted with detrital sedimentary levels of marine and continental origin, scorias, and paleosols (Gasse et al., 1983). The Dalha basalts series consists of a regular pile of basalt flows from a few meters to more than 10 m in thickness, with intercalations of acid lavas, mainly ignimbrite, but also of pumice and rhyolite flows inserted with sedimentary lake formations and detrital limestone (Demange and Stieljes, 1975). Between the traps are inserted scorias and paleosol which can exceed a few meters, marking the cessation of volcanic activity.

On the East coast, there is a littoral plain forming a band of a few kilometres wide that collects the floods of various wadis (Ambouli, Atar, Damerjog and Douda) as well as all the elements transported by these wadis. The sediments coming from deltaic cones of the wadis form accumulations of blocks and more or less unrefined basaltic pebbles inserted by silt. The thickness of these deposits can reach 18–20 m (Gasse et al., 1983). The wadi stream beds are covered by recent alluviums which form the inferoflux aquifer. These stream beds would be the place of underground flow of superficial stream bed waters and connections with the basaltic subsoil water. The inferoflux aquifer plays an essential role in the refilling of the basaltic aquifer (Jalludin, 1993).

The structure and hydrogeology of the costal system in Djibouti are typical of a multilayer complex system. Obviously, due to drilling distribution on aquifer, the piezometry distribution is best known in the East part of the study area. Indeed, the static level of the PK20 section is about 60 m of altitude. But the hypothesis of a continuous groundwater flow leads to confirm the presence of a transition zone between the main collection area along the coast in the East part of the study area where the static levels do not exceed 2 m and the PK20 section where the drillings AW1 and AW2 indicate respectively static levels of 20 m and 9 m. Moreover, taking into consideration the hydraulic relation between the basaltic aquifer and the alluvial reservoir it is conceivable to find downstream an intake of the static levels observed at PK20 to pass to the westward part of the aquifer at the WEA section among the basalts of Dahla where the static levels exceed an altitude of 200 m.

In fact, Bouh (2006) states that there is a high hydraulic gradient between 5 and 7‰ in the PK20 section (Aw1, Aw2, F3b, Fu, F7, Fu2b). This hydraulic gradient remains high along the contact NS of both aquifers upstream of Chabelley. Towards the eastern zone where is situated the main collection area, piezometric levels decrease rapidly and we notice extremely weak hydraulic gradients around 0.2‰ which means high transmissivity. So, piezometric observations demonstrate the replenishment of the alluvial groundwater and basalt groundwater by inferoflux groundwater during floods. So a direct relationship exists between the wadi aquifer, the basaltic aquifer and the alluvial reservoir in the coastal area of Djibouti.

2.2. Groundwater sampling and analytical methods

For this study, a spatial sampling strategy was planned taking into consideration hydrogeological, geological and geochemical studies of the areas. To analyse the major ionic constituents (Cl^-, SO_4^{2-}, HCO_3^-, NO_3^-, Na^+, Ca^{2+}, Mg^{2+}, K^+, Br^-, F^-), minor and trace elements (Li, Ba, B, Sr, Si, Al, V, Ti, Cr, Mn, Fe, Mo, Co, Cu, Ni, Pb, Zn, As, Se) some groundwater samples were collected during dry season in May 2011 and March 2012 from 26 sites, including 13 shallow boreholes of the Gulf basalt aquifer, 9 hand dug wells of the inferoflux aquifer in the Ambouli Wadi, and 4 samples from the Dalha basalts aquifer (Table 1). The groundwater resources supplied to Djibouti city are essentially located in the fractured Gulf and Somali basalts aquifers. The peri-urban farmers living around the Ambouli Wadi, located on the South of Djibouti, use shallow wells most of the time for agriculture purposes, particularly for irrigation. The drinking water used in Arta and Wea towns is extracted from the Dalha basaltic aquifer. Each sample was filtered through a 0.45 µm filters (cellulose acetate membrane) and stored in four polyethylene bottles. For every sample, one bottle was immediately acidified with ultra-pure acid (HNO_3) for the determination of cations whereas the others were left unchanged to determine the presence of anions. The physical parameters (pH, electrical conductivity, and the temperature) were measured *in situ* using multi-parameter WTW Universal Conductivity Meter. In the laboratory, all samples were immediately kept in a freezer to