The role of 3D volcanic structures on seawater intrusion in Grande Comore Island inferred from geophysical investigations and groundwater modelling

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ABSTRACT

Grande Comore Island is located at the Northern end of the Mozambique Channel in the Southwestern Indian Ocean. Groundwater is the only safe water resource for drinking, but only one third of the population have access to this resource. Due to the steep slopes of this high and still active volcanic island, all existing wells are drilled in the coastal zone within 3 km from the shoreline and can reach up to more than 100m deep. Among them, only one third provide groundwater of acceptable salinity for drinking (less than 1 g/L), one third provide water of salinity comprised between 1 and 3 g/L, and the remaining third is generally disused due to salinities higher than 3 g/L. The development of groundwater in Grande Comore requires an improved understanding of the coastal volcanic aquifers, quantitatively and qualitatively. This work applies an integrated hydrogeological approach aiming at improving both the conceptual understanding of Grande Comore volcanic aquifers and the dynamics of seawater intrusion. This approach included (1) a review of the current hydrogeological knowledge regarding the structure, properties and conceptualisation of the island's volcanic aquifers, (2) the spatial characterisation of both aquifer structures and seawater intrusion in coastal areas, through the implementation of geophysical surveys comprising electrical resistivity tomography (ERT) and time-domain electromagnetic (TDEM) and (3) the quantification of the impact of typical volcanic heterogeneities on coastal groundwater salinity through numerical groundwater modelling. The simulations confirm the strong controls exerted by volcanic structures on saline intrusion dynamics as observed from geophysical investigations, in particular the presence of paleo-valleys filled by lava flows of contrasted hydrogeological properties.

INTRODUCTION

The Comoros volcanic archipelago is located midway between the west coast Madagascar and the African east coast, at the northern extremity of the Mozambique Channel, between Lat. S 11-13° and Long. N 43-46°. It covers a total area of 2033 km² including four mean islands. The westernmost island of Grande Comore is geologically the most recent [most of the rocks have less than 1 Ma], the largest [1024 km²] and the highest [2361 m]. The volcanism is still active at the Karthala Volcano [2361 m]. The island is mainly composed of two recent shield volcanoes of dominant basaltic type: (1) the massif of La Grille [1087 m], which covers the northern half part of the island, is of intermediate age [Middle Pleistocene], with a morphology characterised by gentle slopes and scattered by several cinder cones; (2) the massif of the Karthala, which covers a surface of about two thirds of the island in its centre, is an active shield volcano [Quaternary] characterized by a near-absence of weathering.

This work is aiming to understand and simulate the role of structural heterogeneities on the seawater intrusion dynamics in the recent volcanic aquifers. Geophysical methods are used for imaging the salt wedge geometry and numerical simulations allowed understanding the relations between geological structures and saltwater intrusion extension.

HYDROGEOLOGICAL SETTING

The Comoros archipelago has a humid tropical climate, including a hot and wet season and a cool and dry season. The annual rainfall varies from less than 1.5 m in the north-east up to more than 5 m in the south-west of the island (western flank of the Karthala). Runoff is very low (estimated annually at 5% of rainfall) and there are no permanent rivers.

The renewable annual groundwater volume of Grande Comore is estimated between 0.5 and 2 billion (10^9) cubic meters, resulting from an effective rainfall infiltration estimated between 57% and 63% of the annual rainfall. The combined annual abstraction of the currently 11 operating wells (out of the 55 existing) can be estimated at about 7 millions of m^3, which constitutes only 0.4 to 1.4% of the renewable annual groundwater resource. However, two thirds of the Island's water wells are naturally contaminated by saltwater concentrations higher than 1g/L.

In the coastal zone, the hydrodynamic properties of the basal aquifer, display exceptionally high values of transmissivities, hydraulic conductivities, diffusivities and well productivities. Most of the results, however, would not be representative of the most recent and highly productive units, where it is difficult to obtain significant drawdowns required for a reliable interpretation of the pumping tests. Aquifer storativities reflect unconfined to semi-confined conditions. Aquifers hydrodispersive properties that control solute transport, such as salt water, are not known. The high aquifer diffusivities result in both a low attenuation and a short time-lag of the tidal signal, which enhance the seawater encroachment, further exacerbated by a large tidal range [up to 3 m].

METHODS

A review of the available literature provided the current status of knowledge about the Grande Comore hydrogeological settings. Then, multi-techniques ground geophysical investigations carried out in 3 coastal zones enabled imaging the complexity of the geometry of the seawater interface in Grande Comore. These methods included Time Domain Electro-Magnetics [TDEM] soundings and Electrical Resistivity Tomography [ERT] profiles. These 2D measurements were taken with the Wenner-Schlumberger array, which has a relatively good signal/noise ratio (Dahlin and Zhou 2004) and is sufficiently sensitive to the geometrical features of seawater interface in coastal groundwater (Comte et al., 2010). Finally, a 3D numerical model using the code SEAWAT (Guo and Langevin 2002) was applied to investigate the theoretical effects of local aquifer heterogeneities associated to typical various volcanic structures on the patterns of seawater intrusion in the basal aquifer.

RESULTS

Geophysical investigations

The littoral domain in the most recent volcanic rock is characterized by variable resistivities resulting from both different lithologies and degree of seawater intrusion. On the flanks of the recent Karthala volcano, at shallow depths, the unsaturated basalts and the fresh groundwater are characterised by very high resistivities (>1000 Ω.m and 100-1000 Ω.m, resp.). At greater depths, the presence of saline/brackish groundwater results in very low resistivities (<100 Ω.m for brackish water and <10 Ω.m for salt water). On transects normal to the coast (Figure 1a), the interface between fresh and saline groundwater displays a very low dipping angle towards the island resulting from low hydraulic gradients and high permeabilities. In such recent volcanic areas, this low dipping angle of the seawater interface explains the apparent wide transition zone between saline and fresh groundwater and the occurrence of high degrees of salinities at relatively large distances from the sea. Transects parallel to the coast (Figure 1b) reveal large resistivity variations in the saturated zone (about 10 to 500 Ω.m), which suggests large variations of permeability, porosity and/or salinity associated to possible preferential flows resulting from the depositional structure of lava flows.

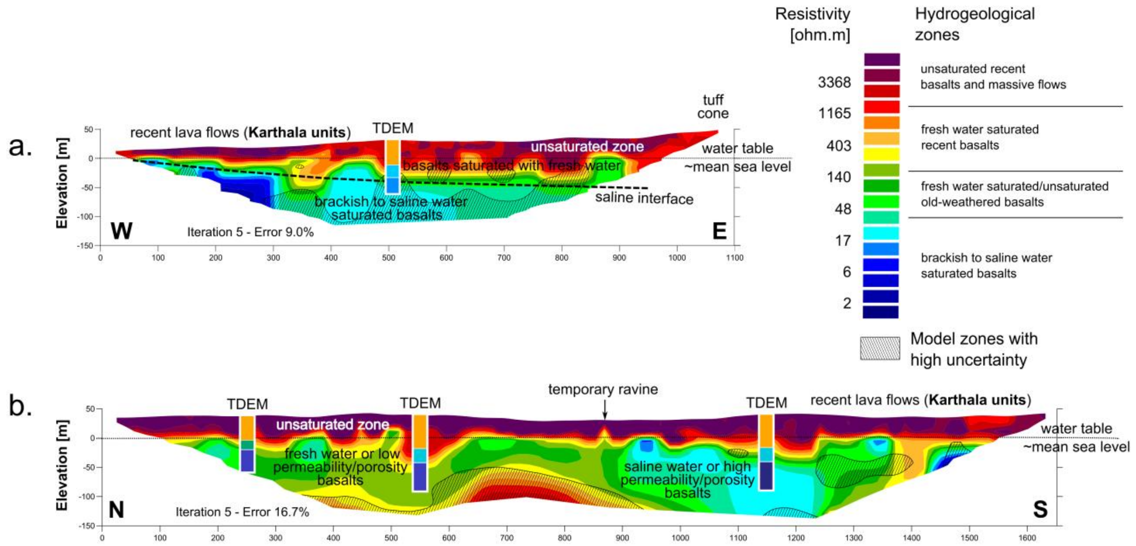

Figure 1 : Typology of the basal volcanic aquifers in Grande Comore interpreted from combining ERT and TDEM results – (a) section normal to the coast; (b) section parallel to the coast.

Theoretical simulation of the role of 3D volcanic structures on saline intrusion

The model hydrogeologic parameters and boundary conditions applied are representative of the youngest volcanic units of the Karthala volcano in Grande Comore. The homogeneous model (K_h=10^{-3} m/s; K_v=10^{-4} m/s) results in a smooth and regular transition zone between fresh and saline water displaying a low dipping angle towards the island (Figure 2a). The thickness of freshwater lying on transition levels reaches about 30m below sea level at 1.2 km from the shoreline, and about 75 m at 5 km. The local presence of a paleo-valley infilled with a massive, low permeability isotropic lava flow (K_h= K_v=10^{-5} m/s) results in a deepening of the transition zone beneath the paleo-valley, where freshwater thickness appears almost double (~50 m) at 1.2 km from the shoreline (Figure 2b). In contrast, the local presence of a paleo-valley infilled with a high permeability isotropic lava flow (K_h= K_v=10^{-2} m/s) results in the thinning of the freshwater levels, which disappear on a distance from the coast up to 2 km, particularly on the borders of the paleo-valley (Figure 2c). The width of the transition zone along the coast appears also significantly increased. Given the large diversity of volcanic units expected in young volcanic environment such as in Grande Comore, those theoretical simulations confirms the significant lateral variation of salinities observed in water wells along the coast in both La Grille and Karthala recent volcanoes. Those simulations support the hypothesis that local structures can strongly impact the seawater intrusion at the local/field scale.

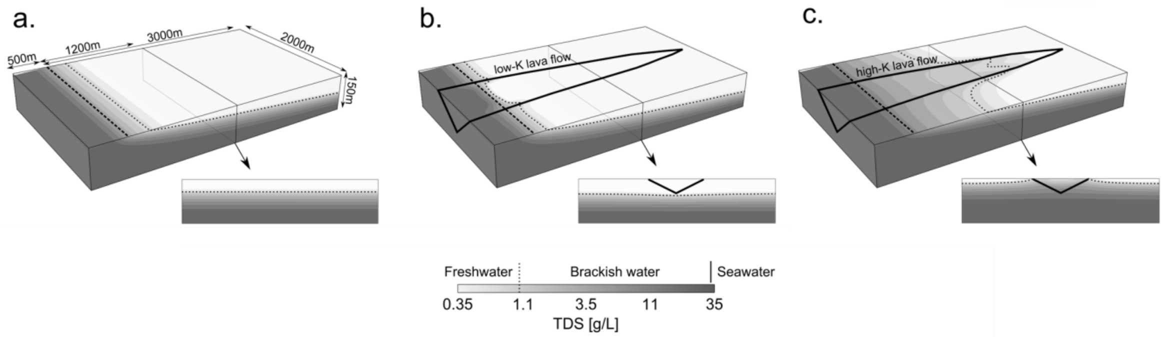

Figure 2 : Role of local heterogeneities on seawater intrusion in the coastal zone: (a) homogeneous model; (b) palaeovalley infilled with lower permeability (K) lava flow; (c) palaeovalley infilled with higher permeability lava flow. The top face is at mean sea level elevation. Dashed line is the coastline and dotted line is the contour 1 g/L corresponding to the WHO (2003) max salinity standard for drinking water. Vertical exaggeration x3.

DISCUSSION AND CONCLUSIONS

Strong hydrogeological heterogeneities have been observed in the recent volcanic aquifers. Geophysical results revealed a large diversity of geological heterogeneities and salinity variability in the coastal areas. Those areas are where all the water wells are located which is the result of the technical and economical difficulties for drilling boreholes in other areas where elevations are high and the water table is very deep. Groundwater modelling confirms that in the coastal zone the presence of channels of recent high-permeability lava flows enhances the saline invasion, while the presence of lower permeability lava flows tends to maintain the saline interface deeper. These findings reveal a potential for further developing the aquifers of the coastal zone of Grande Comore, where the knowledge of the geological structures appears crucial for accessing groundwater of acceptable salinity.

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