The effects of climate change on the hydrology and groundwater of Terceira island (Azores)

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ABSTRACT

Until recently the water flowing from rain fed springs was abundant enough on Terceira (Azores, Portugal) and groundwater exploration was limited to the Lajes basin. This paper discusses the effects of climate change on the hydrology of Terceira and presents an estimate of the size of the fresh water lens underneath the whole island of Terceira using fault orientation as an indication for conductivity anisotropy. Longer periods of drought are thought to be one of the effects of greenhouse warming for Terceira and the exploration and exploitation of the freshwater lens may become necessary.

INTRODUCTION

Terceira or 'Third' is the third largest island in the Azoran archipelago. There are currently large differences in annual rainfall across the island, depending mostly on altitude. The average rainfall along the coast is around 1000 mm/yr whereas on the top of the mountains average rainfall amounts to 3600 mm/yr. The volcanic rocks that form the island have a large hydraulic conductivity. This is demonstrated by Oxygen18 and Deuterium isotope studies that show that the transit time for rain water to exit at springs varies from 11 to 30 days (Novo *et al.* 1997). The fresh water lens, typical for any oceanic island, is exploited with wells in the Lajes basin on the South East part of Terceira. Some preliminary studies report a thickness of the fresh water lens in the Lajes basin of maximum 20 m (CH2MHILL, 2005). Relatively little is known about the subsurface of Terceira. The locations of faults and of dikes and of the interface between fresh and salt water as well as the hydraulic properties of the rocks are yet to be established.

EFFECTS OF CLIMATE CHANGE ON THE HYDROLOGY OF TERCEIRA

Many possible effects of climate change on the hydrology of Terceira are indicated in Figure 1. Due to sea level rise (SLR), some freshwater springs could disappear below the seawater line. The fresh water lens underneath the island will shrink due to SLR. Many of the springs that used to flow year round are already becoming ephemeral and they flow mostly in winter and much less or not at all in summer. This is in part explained by the land use change that took place in the last decades. The water that used to be stored in the peat soil of the forests is now released much faster to the ocean, since the trees and turf soil have been removed to make place for pasture. Some of the springs occur were 'hanging or perched aquifers' encounter a fault or impermeable layer. The perched aquifers have a decreased flow in periods of drought. The tides have a large effect on flow in the aquifer: tidal pumping is felt up to hundreds of meters from the coast (CH2MHILL, 2005). These movements bring in seawater that reduces the size of the fresh water lens by mixing and dispersion. SLR and increased storm frequency will make this effect just worse. SLR-related flooding of the low areas (Lajes basin, the harbour) will cause surface and groundwater salinization. Up-coning of salt water by pumping in the Lajes basin could increase as well.

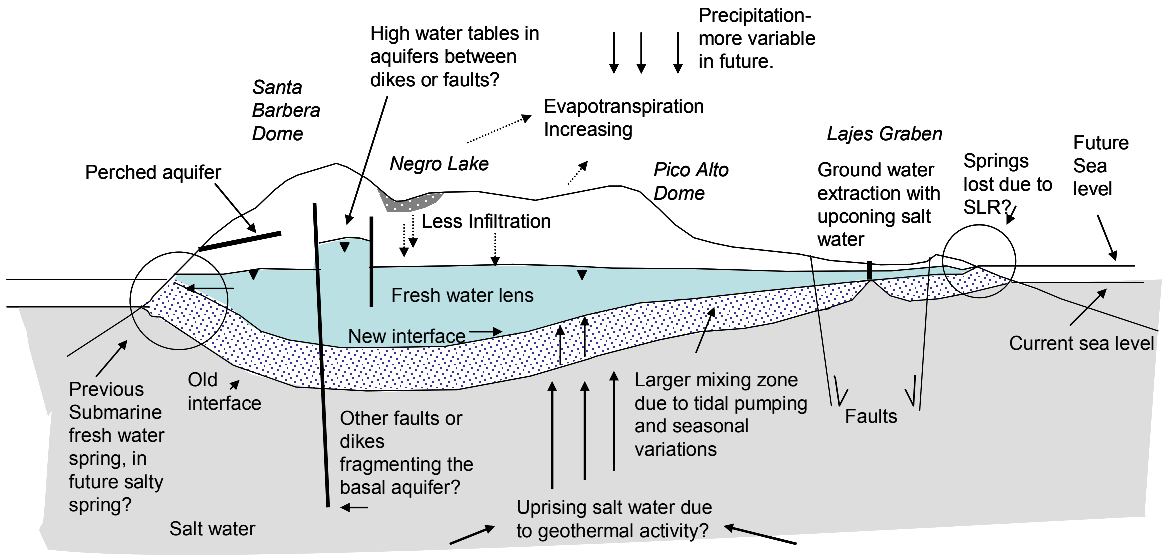

Figure 1. Implications of climate change on the hydrology of Terceira. Modified from Bjarnason, 1993.

THE SIZE OF THE FRESH WATER LENS IN FRACTURED BASALT

This study presents a first approximation of the size of the freshwater lens underneath Terceira to see if that could be a source of freshwater worthwhile exploring. We make some simplifying assumptions: (1) porosity is mostly fracture porosity; (2) the aquifer hydraulic conductivity and its anisotropy are determined by the fractures and faults visible on Figure 2a. The faults and fractures are oriented perpendicular to the extensive stress (Novarra *et al*. 2009) and assumed to be open conduits for flow. The depth of the interface between fresh and salt water, the length of the outflow face, and the shape of the lens are estimated with the equations presented by Bakker (2000). These equations are approximations of exact analytical solutions for the two dimensional steady flow below an elongated island with a source term (infiltration). The shape of the interface can be approximated by (Bakker, 2000):

$$y = -D\sqrt{1 - \frac{x}{(L+l)^2}} \qquad (1)$$

Where D = depth to interface in the centre of the island, a function of Kx, (horizontal conductivity) and recharge. L is the width of the island, and l is the length of the outflow face on the edge of the island, a function of Ky (vertical conductivity) and recharge (Bakker, 2000). Hydraulic conductivity for fractured basalt varies between 0.1 and 54 m/day (Wellhan and Reed, 1997) although higher conductivities of 1000m/day were used in flow models for Terceira (CH2MHILL, 2005). We assume at first that the vertical conductivity K_y is 54 m/day and we let Kx vary as a function of fracture orientation (see θ in Figure 2a). Kx is related to Ky by the cosine of θ. For an island width of 20 km and a homogeneous daily recharge of 1.5 mm/day (Rodriguez, 2002), the interface depth in the centre of the island varies between 333m (Kx=Ky) and 816m (Kx/Ky = 0.17).

A map of the interface (Figure 3a and b) is constructed with several profiles across the island taking into account not only fracture orientation but also density. The horizontal Kx is in this case multiplied by the number of fractures and faults that are encountered along the profiles and then corrected for orientation. Ky is kept constant at 54 m/day and so in this reconstruction

Kx/Ky>1. See Figure 2b for the interface depth for various ratios of Kx/Ky. With the help of Surfer ™ a contour plot is created of the interface. The resulting depth to the interface is greatest in areas with no faults and fractures and reaches a maximum value of 160 m.

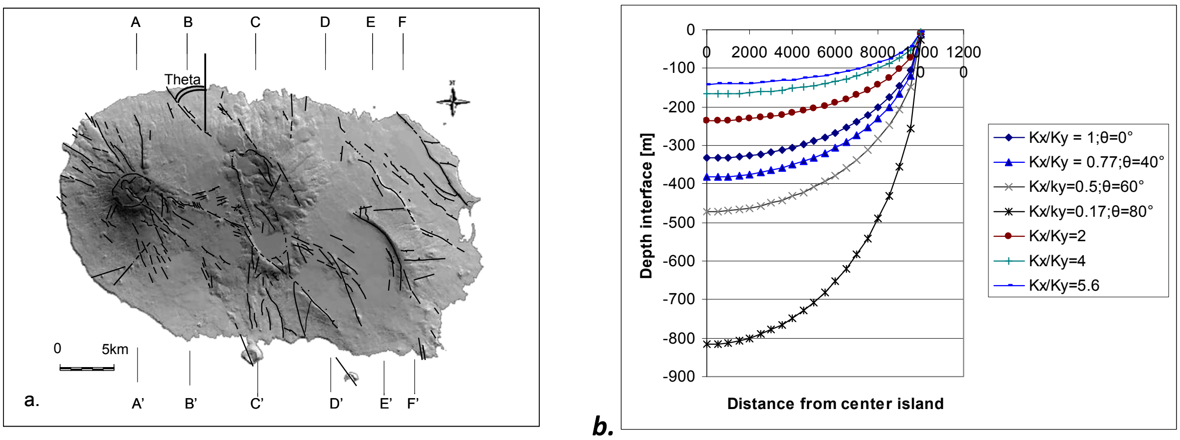

Figure 2a. The most important fractures and faults on Terceira from Rodriguez, 2002. b. depth to fresh- salt water interface for different Kx/Ky ratios.

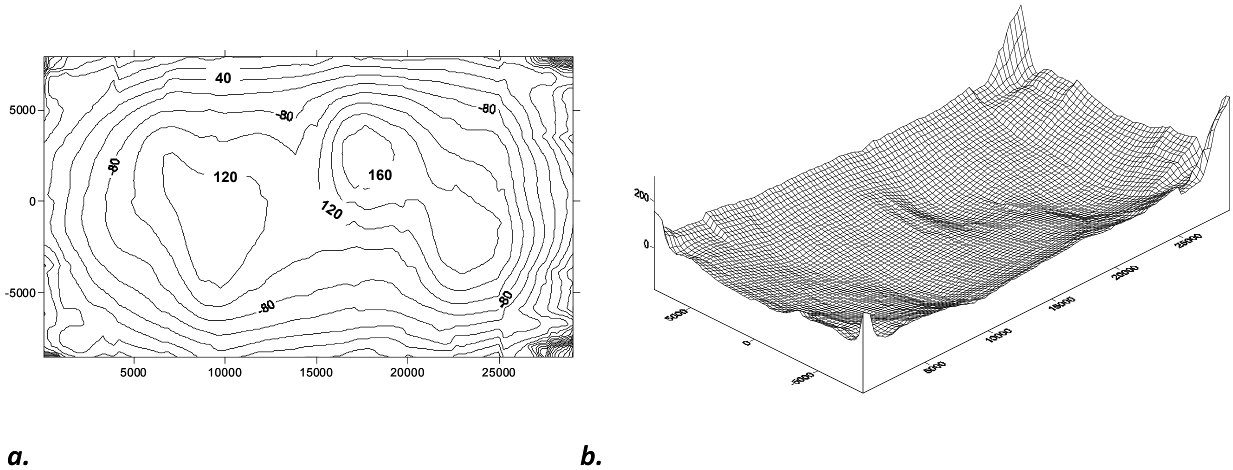

Figure 3a.Contourplot and b. 3D graph of the depth to the salt-fresh water interface based on fault orientation and fault density of Fig 2a, combining several profiles of Fig. 2b with Kx/Ky>1 in one plot .

DISCUSSION AND CONCLUSIONS

The fractures and faults in the volcanic aquifers of Terceira are very likely to cause strong conductivity anisotropy, since they have formed or are reactivated under an active tectonic stress field. Our calculations show that this anisotropy has repercussions for the size of the fresh water lens underneath the island. In order to obtain a more accurate estimate of the size of the fresh water lens than presented in this paper, a detailed characterization of the fractures and faults in the aquifer and their petrophysical properties is needed (e.g. Antonellini and Mollema, 2000 and references therein). Besides the type of fracture, also fracture density and orientation is required.

This maybe a difficult task since large parts of Terceira are covered with soil or recent volcanic deposits (Novarra *et al* 2009). In this paper we have projected a 3D problem on a 2D plane. To have a more realistic mathematical description of double density flow in a fractured aquifer, the third dimension should be taken into account as well as other factors ignored here such as layering, matrix porosity, spatially and temporally varying recharge and many more. Although characterizing and modelling a fractured aquifer, as the one underneath Terceira, is a complicated and expensive matter it may be worth the effort since climate change may cause periods of drought and reduce the traditional sources of freshwater on the island, such as perched aquifers, springs and wells in the Lajes basin. Terceira is too far from the mainland to import water and the only sources of fresh water have to be found on or below the island itself.

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