Submarine discharges of groundwater from Lajes Graben – Terceira, Azores

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Abstract
Groundwater resources are the main source of water supply for the 55000 inhabitants of Terceira Island in the Azorean archipelago. Two principal types of groundwater bodies occurs on Terceira island: a basal water body (saturated zone), composed by freshwater floating on a displacing marine salt water, and perched water bodies, associated with impermeable levels like paleosoils and weathered pyroclastic deposits. Recharge of the basal water body results directly from percolating rainwater or by underground leakage from perched water bodies.
In the Lajes graben, located in the NE sector of the island, the groundwater exploration is basically made by wells that intercept the basal aquifer, corresponding to a total volume of $2{,}01 \times 10^6$ m^3/year. The tree perched groundwater bodies identified – Fontinhas, Lajes 1 and Lajes 2 - are just punctually exploited for agricultural purposes.
The recharge volume of groundwater in Lajes graben, considering the precipitation and river flow infiltrations in Fontinhas fault, demonstrate that the submarine basal springs discharge flows are in the range of 12 and 13 hm^3/year, which is circa 16% of the precipitation in the graben and the surrounding Serra do Cume. This means that a value higher than 30% of Lajes graben aquifer recharge can be discharged into the basal springs, either at the coast or in the surrounding submarine domain.

Introduction
Terceira is one of the nine islands of Azores archipelago located in the North Atlantic Ocean, between 38º N and 27º 24' W (Figure 1). Lajes graben is located on the northeast sector of Terceira Island and is one of the main areas exploited for water supply due to the large transmissivity of the aquifer formations and the low altitude, which facilitates the access to the basal aquifer. Lajes graben is also one of the main recharge areas of this basal aquifer and due to the large permeability of its formations and flat topography infiltration is very high and surface runoff almost absent. This large permeability, coupled with the reduced thickness of the basal aquifer accounts for punctual upconing and saline intrusion phenomena. It is from long time known that this basal aquifer discharges at the coastal area, and this has been used by water supply traditional systems as large tidal wells and tidal springs. It is also known, especially by the fishermen, that submarine springs occur and might be important ecological sites for marine ecosystems. Due to the increased demand in water supply and especially attending to the possible modifications in such demands due to climate changes, it is important to know how much water is discharged through these submarine springs, which role they play in the functioning of oceanic ecosystems, namely its importance for the sustainability of fish populations, and which amount of water can be exploited inland without compromising the ecological role of such submarine springs, that is, to progress towards the definition of "ecological rates" to preserve these springs and at the same time increase the sustainable availability of water for human demand.

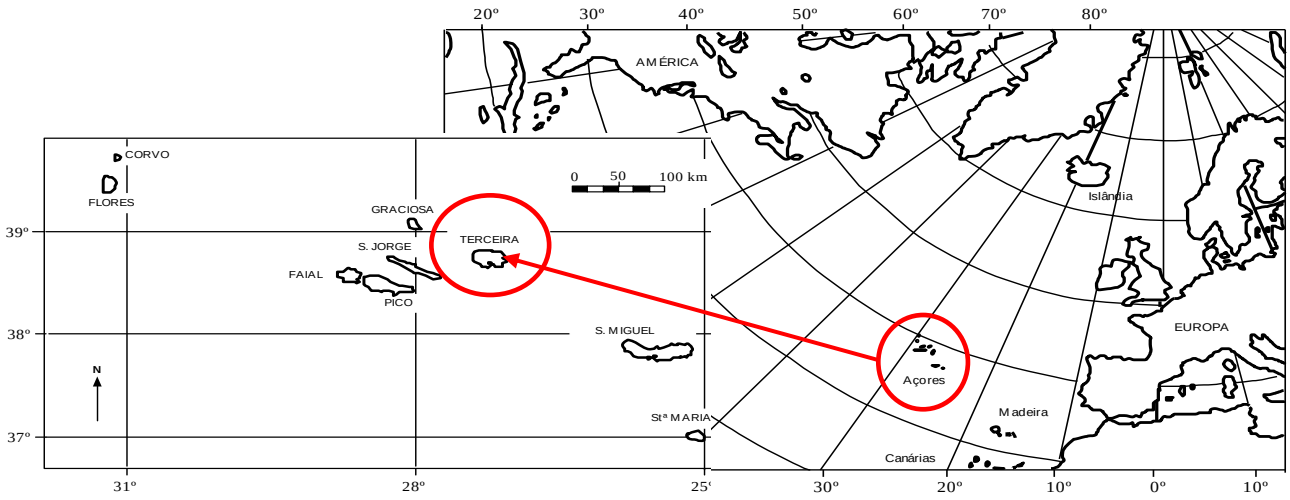

Figure 1. Azores islands location in the North Atlantic and Terceira location in the Azorean archipelago

1. Hydrology

1.1 Climate

The climate of the Azores islands is largely governed by the North Atlantic Gulf steam, with a cold and rainy period between October and March and a relatively warm and wet period during the rest of the year. According to the data of Lajes Air Field Meteorological Station the average annual temperature in Lajes graben is about 17 ºC, with a maximum of 25 ºC in August and a minimum of 11ºC in February. The annual precipitation ranges between 810 mm and 1210 mm, with the lowest values in the SE area (Figure 2).

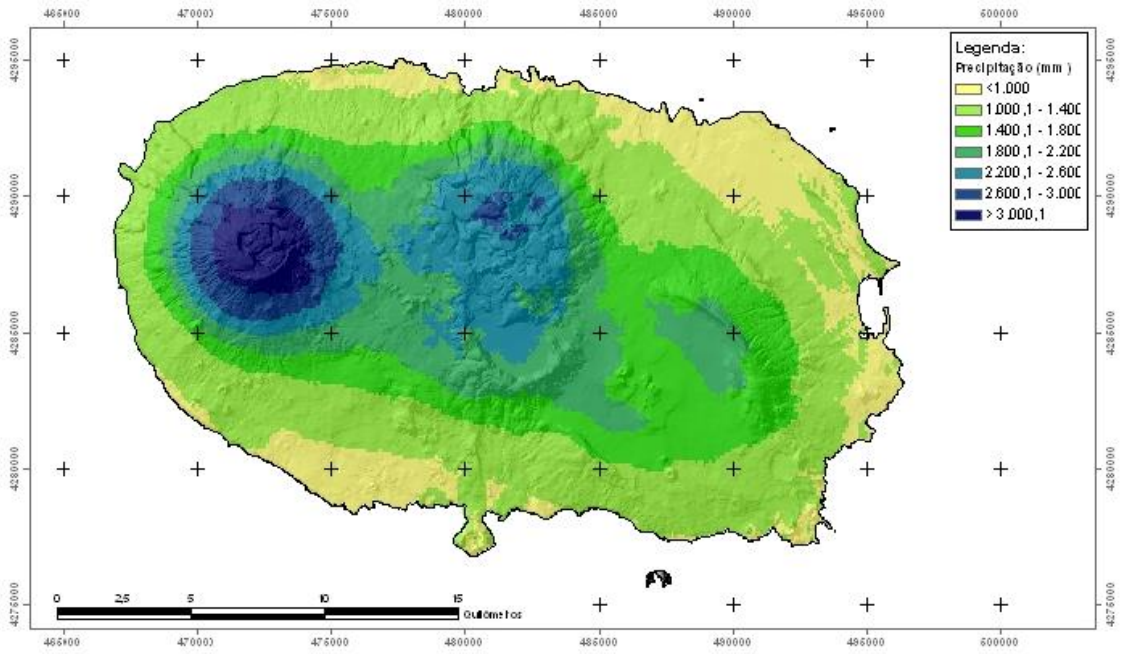

Figure 2- Distribution of precipitation on Terceira Island (Azores). Source: http://www.climaat.angra.uac.pt

The annual rainfall variations are significant, with high values between October and March (71%) and the lowest between May and August (16%). The relative humidity is always high, with a monthly average above 77%. Consistent with other Azorean islands, climatic parameters at Terceira Island are significantly overprinted with the elevation. In general the temperature gradient is changing about 0,6º C/100 m of elevation (Bettencourt,1977), with a small increment in the northern slopes of the island (Azevedo, 1996).

2. Hydrogeologic Setting

2.1 Geomorphology

Terceira island is built by tree volcanic massifs: the composite volcanoes of Cinco Picos, located in the eastern portion of the island, Guilherme Moniz-Pico Alto in the center and Santa Barbara in the western sector. The Cinco Picos composite volcano (151,1 km^2) is the oldest emerged volcano of Terceira island, with about 2,5 m.y. (Lloyd and Collins, 1981). Its morphology is characterized by the tectonic grabens of Lajes to the NE and Grota do Vale to the SW and by the Cinco Picos caldera in the center. The mountains of Serra do Cume and Serra da Ribeirinha are located between these tectonic depressions, and actually represent the NE and SW slopes of the old volcano. The Lajes graben is a tectonic depression stretching between the slopes of the Santiago and Fontinhas faults. The floor is of this tectonic depression, with about 29,1 km^2, is truncated by additional smaller faults, that dissect this area into compartments. The line defined between the SE sector of the Lajes airport and Fontinhas marks the boundary of the two sectors of the Lajes graben: the northern, with land surface sloping to the northwest and the southern, with slope of the land surface to the southeast.

2.2 Tectonic

The North Atlantic region of the Azores is dominated by the triple junction between the *Mid Atlantic Ridge* (MAR), the *East Azores Fracture Zone* (EAFZ), and the *Terceira rift* (Machado, 1959). These tree structures, that limit the American, the Euroasiatic and the African plates, configure together the Azores micro-plate (Forjaz, 1988). The *Terceira rift* - the NE limit of the Azores micro-plate (Forjaz, 1988) - is a spreading centre that trends about 125º, composed of several en echelon rifted basins with submarine and subareal volcanoes. The composite volcano of Cinco Picos is an element of *Terceira Ridge*, witch is a structural volcano-tectonic lineament of the *Terceira rift* (Searle, 1980). Lajes graben is a tectonic depression of *Terceira Ridge*. The dominant direction of its faults – Fontinhas fault and Santiago fault – is NNW-SSE, parallel to the trend of this volcano-tectonic structure (Figure 3). The Santiago fault - the NE limit of Lajes graben - is marked by a sub-vertical scarp with an elevation of more than 100 m in some areas, which trends 141º. The Fontinhas fault that bounds Lajes graben to the SW is marked by rugged scarps with a sinuous profile, that trends between 115º and 148º. The floor of Lajes graben is truncated by a complex system of

faults, marking distinct compartments in the field. The main structures, the S. Lazaro fault and Barreiro fault that trends between 120º and 130º, are marked by scarps that define, respectively, the Juncal compartment at NE and the Fontinhas compartment in SW.

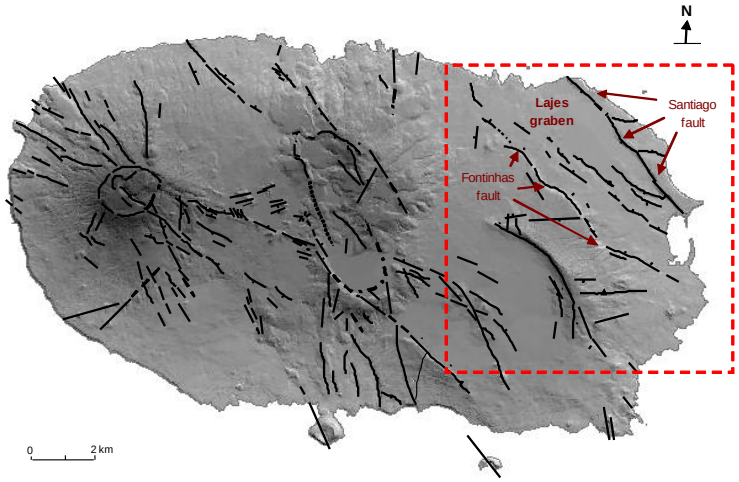

Figure 3. Main tectonic features of Terceira Island and Lajes graben (from Rodrigues, 2002).

2.3 Geology

Terceira is a young volcanic island built of quaternary volcanic rocks erupted by Cinco Picos, Guilherme Moniz and Santa Bárbara volcanoes and by vents alignments located in the central rift zone (Figure 4). According to Self (1976) and Self and Gunn (1976), the quaternary volcanic rocks can be divided into two groups: the lower Terceira group and the upper Terceira group, using as base of upper Terceira group Lajes and Angra Ignimbrites - with about 20 000 and 23 000 years old respectively. Lloyd and Collis (1981) subdivided these two groups into ten volcanic formations. The Lajes graben area presents a substrate essentially built with lower Terceira group of rocks: Cinco Picos trachybasalts, lower Terceira basalts, Lajes ignimbrites and upper Terceira basalts. The Cinco Picos trachybasalts are the oldest exposed rocks on Terceira and form the bedrock of the Cinco Picos strato-volcano and of the Lajes graben. It's composed by lava flows (ankaramitic basalts, hawaiítes and unsaturated trachytes) and subordinate tephras (lapilli, bombs and scoria). The presences of buried pedologic levels – *paleosoils* - provide evidence of volcanic quiescence periods. The lower Terceira basalts in the Lajes graben area correspond to basaltic lava flows and subordinate tephra, with origin in vents located in the flanks of Cinco Picos massifs. These materials overlie the Cinco Picos trachybasalts in Caldeira das Lajes and Cabo da Praia. The Lajes ignimbrites correspond to the youngest widespread ignimbrite on Terceira island (Self, 1976), erupted by the Pico Alto Volcanic Center. This formation presents different degrees of welding and a thickness inferior to 15 m, overlying in the Lajes graben an extensive paleosoil. The upper Terceira basalts is composed by basaltic lava flows and subordinate tephras with origin in vents disposed in Fontinhas fault (Pico Celeiro) and central fissure zone (W of Lajes village), overlaying the Lajes ignimbrites.

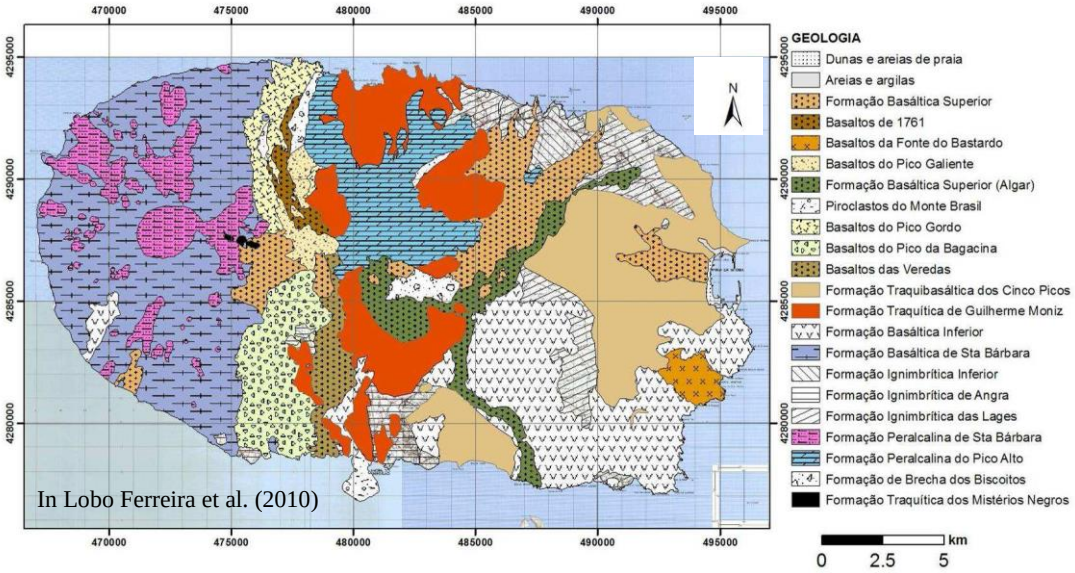

Figure 4. Geological map of Terceira island

2.4 Land use

The land use in the Lajes graben is primarily agriculture, especially pastureland, with important areas occupied by the Lajes airport, military agglomerations around and the urban villages of Praia da Vitória, Lajes and Fontinhas. The Lajes graben soils are mainly composed of Eutric Andossols (Pinheiro, 1990), characterized by a high infiltration capability (Faria, 1974). The vegetation is mainly grassland and agricultural fields.

2.5 Hydrogeology

Two principal types of groundwater bodies occurs on Terceira island: basal water body (saturated zone), floating on a displacing salt water, and perched water bodies associated with impermeable levels like paleosoils and weathered pyroclastic deposits.

The basal water body corresponds to a mass of freshwater that occurs at elevations slightly above sea level, floating on a deeper level of denser salt water which saturates the rocks below sea level (Ghyben-Herzberg lens). Fresh water flows constantly in all directions from the centre of the island towards the coast. A mixing area takes place at the interface between salt water and fresh water and seawater flows constantly in the opposite direction to compensate for the loss through the mixing zone. The average thickness of the freshwater in the Lajes graben is about 20 to 30 m (Frohlish and Berbereia, 2000), but it could be less in faulted areas. The principal source of fresh groundwater in the Lajes graben area, as for the eastern sector of the island, is the basal groundwater, which is actually explored by 13 drilled wells an amount of $2{,}05 \times 10^6$ m^3/year. The water however presents problems of saltwater intrusion, with high TDS, sodium, potassium and chloride concentrations. Recharge of the basal water body results directly from percolating rainwater or by underground leakage from perched water bodies. The infiltration varies greatly between the seasons of the year resulting in thickness fluctuation of the fresh water lens and vertical mixing of the fresh water with salt

water. The perched groundwater bodies occur above the basal aquifer and are trapped or impounded by relatively impermeable layers, as paleosoils or weathered pyroclastic deposits. The groundwater normally flows along these impermeable or semi-permeable layers until reaches its horizontal extend or discharges at the ground surface by springs. Natural storage in perched aquifers is generally small and the flow of perched water springs tends to be relatively unstable (Novo et al., 1997). Tree perched aquifers have been located in the Lajes graben (Rodrigues, 2002): (a) Fontinhas; (b) Lajes 1 and (c) Lajes 2. The Fontinhas aquifer occurs in the tectonic compartment between the Fontinhas fault and Barreiro fault. It has an average elevation of 115 m and is intercepted by some small wells. The Lajes 1 perched aquifer occurs in the NE sector of Lajes Graben (Juncal - Lajes Caldeira), dipping to NW, under the airport and the Lajes village. It has an average elevation of 42 m and is associated with a paleosoil with about 1 m of thickness covered by Lajes ignimbrite deposits and upper basaltic flows. The Lajes 2 perched aquifer is associated with a weathered pyroclastic layer that occurs at an elevation of 21 m between trachybasalts lava flows. The perched groundwater of Fontinhas, Lajes 1 and Lajes 2 is significantly less mineralized than in basal groundwater (table 1). In the Lajes 1 groundwater body, shared with the civil and military areas, there are limited spots with high concentrations of hydrocarbons, result of leaking of some storage tanks.

3. Water Balance

3.1 Precipitation

According the simulation of CIELO model (Azevedo, 1996), the annual precipitation in the Lajes graben ranges between 810 mm and 1210 mm and for Serra do Cume slopes changes between 1210 mm and 1810 mm. An average annual precipitation of 1050 mm and 1610 mm can be assumed as representative respectively for the entire Lajes depression and for the Serra do Cume eastern slopes.

3.2 Evapotranspiration

According the CIELO model the average annual evapotranspiration values estimated for the Lajes graben depression range between 636 mm and 791 mm and for Serra do Cume slopes, between 323 and 635 mm. An annual average of 700 mm 500 mm can be assumed as representative respectively for the Lajes graben depression and for Serra do Cume slopes.

3.3 Surface runoff

Most of the Lajes graben tectonic depression has an unstructured surface runoff system, without significant rivers. However is possible to individualise 5 hydrologic catchments, corresponding to small rivers. No measured data exists about surface runoff in the hydrologic catchments of Terceira and Lajes graben. Fontes et al. (1999) measured runoff in Cinco Picos massif and find a runoff coefficient that range between 0,01 and 0,17 respectively in grassland areas and during agricultural soil mobilizations. These values are similar to the runoff

coefficients considered by Heras (1974) for Gran Canaria and Wright (1989) for some Hawaiian islands. We believe that a runoff coefficient of 0,043 can be assumed as representative of the entire tectonic depression of Lajes graben considering the soil occupation and the low land declination. According to Fontes (1999) in Serra do Cume eastern slopes, the runoff coefficient is 0,10.

3.4 Groundwater Recharge

Groundwater recharge occurs in the Lajes graben from water percolation in the floor of the depression and from infiltration of water from small rivers in the Fontinhas fault. Based on water balance evaluation, the average annual amount of groundwater recharge in the Lajes graben area depression is approximately 335 mm/year; in Serra do Cume the recharge reaches circa 504 mm, due mainly through a reduction in the water consumed by the evapotranspiration. Assuming that circa 90% of the surface runoff generated from Serra do Cume infiltrates through the faults at the graben and reach the basal aquifer, this amount of water added to the water remaining in the aquifer after water withdrawal for all the several uses of Praia da Vitória county and Lajes air base is available for spring discharge at the coastal area and at submarine springs, which are known to exist. The values thus obtained reach am amount of 12 to 13 hm^3/year and this represents circa 16% of the whole precipitation in Serra do Cume and Lajes graben areas.

Water balance Summary

Water Budget Component	mm/year	hm^3/year*	%
Precipitation in the Graben	1050	37,8 – 42,0	100
Evapotranspiration in the Graben	700	25,2 – 28,0	66,7
Surface Runoff in the Graben	15	0,5 – 0,6	1,4
Groundwater recharge	335	12,6 – 13,4	31,9
Water withdrawal	43,0 – 47,8[a]	1,72	4,1 – 4,6[b]
Water surplus (discharged into coastal and oceanic springs)	286 – 293 [a]	10,3 – 11,7	27,2 – 27,9[b]
Precipitation in Serra do Cume	1060	31,8	100
Evapotranspiration in Serra do Cume	500	15,0	47,2
Groundwater recharge in Serra do Cume	504	15,1	47,6
Surface runoff in Serra do Cume	56	1,7	5,3
Water seeping through faults into the basal aquifer	50	1,5	4,7[c]
Total water surplus Lajes + Serra do Cume fault seeping (discharged into coastal and oceanic springs)	336 – 343	11,8 – 13,2	15,9 – 16,3[d]

[a] Lajes graben area between 36 and 40 km^2; [b] as percentage of precipitation in Lajes graben; [c] as percentage of precipitation in Serra do Cume; [d] as percentage of Serra do Cume + Lajes graben precipitation

3. Conclusions

This study reveals that submarine springs can be an important discharge system of basal aquifers. In Terceira island, the low lying tectonic depression of Lajes graben, composed of highly transmissive formations has a large infiltration coefficient, as is expressed by its disorganized river network. This means such area is a main recharge zone for the basal aquifer, and also an area of significant exploitation of this aquifer which, due to its short saturated thickness and high transmissivity, presents upconing and saltwater intrusion problems. Its tectonic setting plays an important role in the hydrogeological behaviour of the basal aquifer, with fault zones behaving either as preferential infiltration and flow zones or as impervious barriers, depending of its filling materials. This behaviour can be seen in the Fontinhas fault zone once reaching this fault almost all streams descending from Serra do Cume disappear into the graben terrains, so transforming this fault in a major conveyor of Serra do Cume's runoff into the basal aquifer. Recharge values in Lajes graben account for circa 32% (circa 13 hm^3/year) of the precipitation while Serra do Cume's runoff infiltrated along the Fontinhas border is circa 1,7 hm3/year, which represents circa 5,3% of precipitation in Serra do Cume. As a term of comparison, runoff in Lajes graben account just for 1,4% of Lajes precipitation, so expressing the higher permeability setting of this tectonic depression in contrast to the surrounding hilly terrains. Once water withdrawal is in the range of 1,72 hm^3/year – approximately the same as the runoff infiltrated along Fontinhas border – then almost all Lajes graben recharge becomes available for discharge along the coastal and submarine springs of the basal aquifer. Taking into account the total amount of precipitation in Serra do Cume and Lajes graben areas, it means that submarine and coastal discharges can be circa 16% of this precipitation total, which shows the importance of aquifer coastal and submarine discharges. These values also show the relative importance of the contribution of runoff from surrounding areas for Lajes graben water budget, in this case contributing to as much as the estimated yearly water withdrawal in Lajes graben. It also shows the importance of the tectonic setting and fault hydrogeological behaviour in aquifer functioning and in the establishment of hydraulic connections between this aquifer and the surrounding areas.

Bibliography:

Azevedo, E.M.B. 1996. Modelação do clima insular à escala local: modelo CIELO aplicado à Ilha Terceira. PhD dissert. Universidade dos Açores, Portugal.

Bettencourt, M.L. 1977. O Clima dos Açores como Recurso Natural, especialmente em Agricultura e Industria do Turismo. O clima de Portuga. Fasc. XVIII, INMG. Lisboa.

Forjaz, V.H. 1988. Azores Study Tour. Field Trip Guide: seminar on prediction earthquaques. Econ. Comm. For Europe-UN. Lisbon. 26 p.

Faria, F.X. 1974. Os solos da Ilha do Fogo (Arquipélago de Cabo Verde) Lisboa, Junta de Investigações Científicas do Ultramar, 1974. 146p. (Ensaios e Documentos, 129).

Fontes, J, C.; Pereira, L. S. and Smith, R. E. 1999. Assessing Land Use Hydrologic Impacts in the Volcanic Islands of Azores. In: Musy A., Pereira, L.S. and Fritsch, M. (eds.) Emerging Technologies for Sustainable Land Use and Water Management. 2nd Inter-Regional Conference on Environment-Water. Press Polytechniques et Universitaires Romandes, Lausanne - Switzerland: Paper 9.7 In: CD-ROM.

Frohlich, R.K. and Berbereia, V.J.D. 2000. Location of Groundwater Resources with Geoelectrical Depth Soundings - Terceira Azores. Department of Geosciences. University of Rhode Island.

Heras 1974. Water Resources of the Island of Gran Canaria. MOP/UNESCD Proyecto SPA/6Q/515. Informe Tecnica Final, Borrador del Proyecto.

Lobo Ferreira, J.P., Lwitão, T., Novo. M.N., Oliveira, L., Oliveira, M.M., Henriques, M.J., Martins, T. 2010. Análise e Parecer sobre a Situação Ambiental nas Áreas de Captação dos

Furos de Abastecimento do Concelho de Praia da Vitória – Açores. Relatório Final. Relatório 424/2010 – NAS, Lisboa, Laboratório Nacional de Engenharia Civil, 194 pp.
Lloyd, EF e Collis, SF. 1981. Geothermal Prospection – Ilha Terceira – Açores: Geological Report. Secretaria Regional do Comércio e Industria, Governo Regional dos Açores.
Machado, F., 1959. Submarine pits of the Azorean plateau. Bulletin of Volcanology, Vol 21, 109-116.
Novo. M.N., Lobo Ferreira, J.P., Cota Rodrigues, F. 1997. Estudo Hidrogeológico das Nascentes do Cabrito (Ilha Terceira - Açores), Relatório LNEC (Lisboa: Laboratório Nacional de Engenharia Civil, 1997).
Pinheiro, J.V.F.,1990. Estudo dos Principais Solos da Ilha Terceira. PhD tesis. ISA. Universidade Técnica de Lisboa.
Rodrigues, FC. 2002. Hidrogeologia da ilha Terceira (Açores – Portugal). PhD dissert. Universidade dos Açores, Portugal.
Searle, R., 1980. Tectonic pattern of the Azores spreading center and triple junction. Earth and Planet Sc. Letters, Vol. 51, 415-434.
Self, S.1976. Recent Volcanology of Terceira, Azores. Ll. Geol. Soc. London. 132: 645-666.
Self, S. and Gunn, B. 1976. Petrology, Volume and Age Relations of Alkaline and satured Peralkaline Volcanics from Terceira Island, Azores. Contr. Min. Petrol., s.n., 54 (4): 293-313.
Wright, T.L., Takahashi, T.J. 1989. Observations and Interpretation of Hawaiian Volcanism and Sismicity, 1799-1995. An Annotated Biography and Subject Index. Honolulu University of Hawaii.