Available online at www.sciencedirect.com
SciVerse ScienceDirect
Procedia Earth and Planetary Science 7 (2013) 113 – 117
Procedia
Earth and Planetary Science

Water Rock Interaction [WRI 14]

Isotopic and geochemical tracers in the evaluation of groundwater residence time and salinization problems at Santiago Island, Cape Verde

Paula M. Carreira[a]*, José M. Marques[b], Dina Nunes[a], Fernando A. Monteiro Santos[c], Rui Gonçalves[d], António Pina[e], António Mota Gomes[e]

[a]*Química Analítica e Ambiental, IST/ITN, Universidade Técnica de Lisboa, Estrada Nacional nº 10, 2686-953 Sacavém, Portugal*
[b]*Centro de Petrologia e Geoquímica. Instituto Superior Técnico, UTL, Av. Rovisco Pais, 1049-001 Lisboa, Portugal*
[c]*Universidade de Lisboa-IDL, 1749-016 Lisboa, Portugal*
[d]*Inst. Politécnico de Tomar, Quinta do Contador, Estrada da Serra, 2300 Tomar, Portugal*
[e]*Instituto Superior de Educação, Praia, Santiago, Cabo Verde*

Abstract

Stable isotopes ($\delta^{18}O$, $\delta^{2}H$) and tritium (^{3}H), together with geochemistry and geophysical data, were used for evaluating groundwater recharge sources, flow paths, and residence times in a watershed on Santiago Island, Cape Verde, West Africa. Stable isotopes indicate the predominance of high-elevation precipitation that undergoes little evaporation prior to groundwater recharge. Low tritium concentrations at seven sampling sites indicate groundwater residence times greater than 50 years. Higher tritium values at other locations suggest more recent recharge. Young ages indicate local recharge and potential groundwater vulnerability to surface contamination and/or salt-water intrusion. Geochemical results indicate that water–rock interaction mechanisms are the major processes responsible for the groundwater quality (mainly calcium-bicarbonate type), reflecting the lithological composition of subsurface soil.

Selection and/or peer-review under responsibility of the Organizing and Scientific Committee of WRI 14 – 2013

Keywords: Santiago Island, Cape Verde - West Africa; stable isotopes; groundwater age; groundwater quality; seawater intrusion.

1. Introduction

Salinization of groundwater resources is one the most widespread processes that degrades water-quality and endangers future water exploitation in coastal areas in particular in arid and semi-arid regions.

* Corresponding author. Tel.: + 351 219946179; fax: + 351 219946185
E-mail address: carreira@itn.pt

1878-5220 © 2013 The Authors. Published by Elsevier B.V.
Selection and/or peer-review under responsibility of the Organizing and Scientific Committee of WRI 14 – 2013
doi:10.1016/j.proeps.2013.03.063

The problem is intensified in coastal aquifers, where human activities result in accelerating water-quality deterioration in particularly in arid and semi-arid regions. Santiago Island is part of the Republic of Cape Verde, located about 500 km west of Senegal, Africa (Fig. 1a). Because of its proximity to the equator, seasonal average daily temperatures vary around 5°C throughout the year from 22–27°C and total annual precipitation ranges from 0–50 mm along the populated coastal areas to 400-1000 mm in the highlands (Pico da Antónia or Serra da Malagueta) and is extremely variable from year to year [1]. Most of the precipitation is lost due to evapotranspiration and runoff to the sea, caused by a combination of warm climate, thin soil cover, and steep topographic gradients. Surface-water resources are virtually non-existent; only a few small perennial streams. The majority of the population resides in rural areas and gets its livelihood from rain-fed agriculture. Nearly all of the water for consumption comes either from rainfall catchment structures or groundwater [1]. The semi-arid to arid climate of Santiago Island, with unreliable and erratic rainfall, leads to prolonged drought periods. In fact this situation is responsible for quasi-periodic and sometimes catastrophic aridity.

Under the R&D Project "HYDROARID – Evaluation of the Hydrogeological Potential and Sea Water Intrusion Monitoring in Semi-Arid Zones Using a Multitechnique approach: application to the Santiago and Maio Islands (Cabo Verde)", fieldwork campaigns were carried out at Santiago Island (Fig.1b). The aim of this study was to evaluate the application of environmental isotope and geochemical methodologies to find answers to hydrogeological questions such as: (i) What is the origin and mechanisms of groundwater recharge? (ii) What is the relation between shallow and deep aquifer systems? (iii) How severe is the saltwater intrusion problem? (iv) What is the apparent groundwater age?

2. Study Area—Local Geology and Hydrogeology

The Cape Verde archipelago experiences semi-arid climate, with a major influence provided by the Sahara desert on mainland Africa to the east (Fig 1). The rainy season extends from July-August to October-November, with precipitation being mainly orographic. Mean annual precipitation is 323mm, over its 1000 km^2 surface area. The water balance calculations indicate that runoff amounts to 18% of the precipitation which discharges directly to the sea, while just 13% of the precipitation becomes infiltration to the soil [1]. Three main hydrogeological units have been identified on Santiago Island, which are linked to the island's volcanic origins: (i) the oldest Basal Unit, a Lower Palaeogene - Middle Miocene complex consisting of compacted, low-permeability formations; (ii) the Intermediate Unit, a thick and extensive eruptive formation consisting of basaltic pillow lavas and pyroclastic rocks that is characterized by a high permeability and is the principal aquifer system; and (iii) the Recent Unit comprised of highly permeable pyroclastic cones through which input water readily leaks through into the Intermediate Unit. Alluvial sediments from the Pliocene-Pleistocene fill most of the stream valleys, especially in their terminal sections. Intensive agricultural practices occur within these fertile soil valleys [3]. In this particular hydrogeological environment low-permeability clay layers intercalated with sand formed by the weathering of the upper lava flows may also act as hydraulic barriers. Such horizontal and vertical flow barriers may cause perched groundwater, high-altitude springs, and/or groundwater compartmentalization resulting in a stepped and discontinuous water table (see Fig. 1c). Oceanic islands typically have a low-density freshwater lens of groundwater overlying higher-density brackish and saltwater. Under steady-state conditions, the freshwater hydraulic head is above sea level. The fresh water/brackish water boundary is generally controlled by pressure and density and is dependent on the balance between groundwater recharge and groundwater discharge. Therefore, aquifer drawdown associated with excessive pumping, may lower water levels in the aquifer and move the fresh/brackish water boundary upward and inland, causing salt-water intrusion

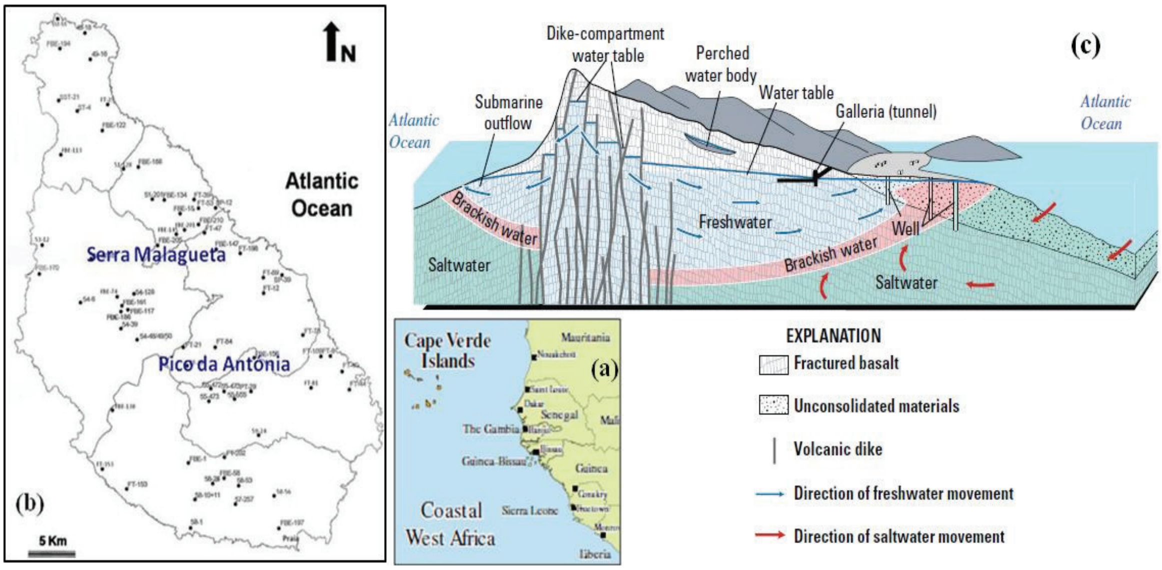

Fig. 1. (a) Location of Cape Verde [2]; (b) location of the sampling points on Santiago Island; (c) schematic cross section through a generic volcanic island [2].

3. Results and Discussion

Groundwater samples were collected and measured from November 2005 to November 2006, during three fieldwork campaigns. The groundwater samples were collected from boreholes and springs for isotopic analyses (δ^2H, $\delta^{18}O$ and ^3H). Electrical conductivity (µS/cm), pH and temperature (ºC) were measured *in situ*. Geochemical data were available in the framework of previous sampling campaigns carried out at Santiago Island by other authors and the data can be found in [1].

3.1. Geochemical results

No correlation was found between the geochemical composition of groundwater samples and the geological layers. Nevertheless, trends were observed between the TDS and Mg^{2+}, SO_4^{2-}, Ca^{2+}, HCO_3^-, Na^+ and Cl^- concentrations. Although TDS reaches concentrations around 30 meq/L, the ion content seems to level off or even decrease in some cases, indicating that the groundwater samples have reached saturation values with respect to Ca and Mg carbonates and gypsum. The low content in Na^+ and Cl^- is followed by a minor variation in TDS, indicative of NaCl dissolution.

The Na/Cl ratio in the groundwater samples varies between 0.63 and 5.29, while the Cl^- contents range from 1.20 up to 21.20 meq/L. The mean ocean value is 0.86 for this ratio; samples with a higher ratio and with low salinity values are likely to result from the weathering of plagioclase that would provide a source of additional sodium.

Around the island, high salt contents within the groundwater systems may be ascribed to agricultural zones (valley areas) located in the coastline surroundings [1].

3.2. Isotopic signatures

Stable isotope ratios fall within a fairly tight cluster on or near the global meteoric water line, with range from -4.7 to -2.6 $^{o}/_{oo}$ in $\delta^{18}O$ and from -44.6 to -15.8 $^{o}/_{oo}$ in $\delta^{2}H$ *vs.* V-SMOW, suggesting little evaporation prior to groundwater recharge, suggested by the isotopic deviation from the GMWL. No strong correlation was found between the altitude of the sampling sites and the isotopic composition of the groundwater. On the other hand, in the diagram $\delta^{18}O$ *vs.* $\delta^{2}H$ two groups of groundwater samples are identified: one group is composed by the samples collected in the eastern part of the island, in most cases located near the coastline and another group is ascribed to high-altitude sampling sites (Fig. 2a). Plotting the electrical conductivity (or the content in TDS, in Cl^{-}, in SO_4^{2-} or in Na^{+}) of the groundwater samples as a function of the oxygen-18 content, two evolution patterns can be observed (Fig.2b): one reflecting the mixture with seawater with a progressive enrichment in oxygen-18 and in the mineralization; and another trend reflecting influence of marine aerosol. Besides to this, another trend line can be observed in the diagram, defined only in the isotopic composition enrichment, which most probably is due to evaporation, the shift in the $\delta^{18}O$ values varies between approximately -5 and -2.8 $^{o}/_{oo}$. The waters have the same isotopic “history” but different geochemical signatures that depend on which process is dominant (weathering and permeability of the rocks and mixing with sea water and marine spray).

The tritium results range between 0±0.7 and 3±0.7 TU. No correlation was found linking tritium concentration with either the altitude of the sampling sites or with the electrical conductivity. In fact, due to the absence of ^{3}H and the lower content found in remaining points it is difficult to ascertain the turnover rates of the groundwater. Nevertheless, in the northern part of the island (Tarrafal), a mean residence time of 30 years can be estimated. Moreover, in the eastern part of Santiago Island, in Achada Baleia, it seems that the shallow boreholes were receiving contemporaneous recharge while the deep boreholes were receiving slow flowing groundwater from joints and fractures. Similar 3H results were obtained by [2] although the hydrogeological research was performed in S. Nicolau island part of Cape Verde archipelago, the results obtained, less than 0.3 TU, indicative of groundwater recharge occurring prior to the early 1950s.

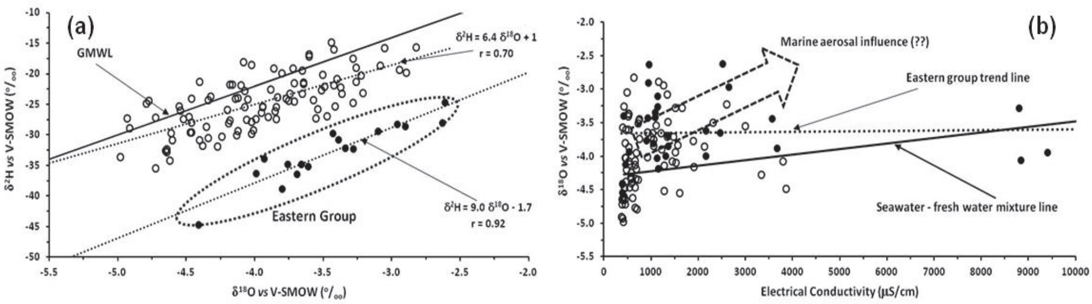

Fig. 2. Plot of (a) $\delta^{18}O$ *vs.* $\delta^{2}H$ and (b) $\delta^{18}O$ *vs.* electrical conductivity for Cape Verde groundwaters. The filled circles denote samples from the western portion of the island, whereas the open circles denote samples from other parts of the island. The line labeled GMWL is Fig 1a. is the ‘Global Meteoric Line of Craig [4].The two dotted lines are the trend lines of these two groups of groundwaters.

4. Conclusions

The combination of field measurements and environmental tracer data for groundwaters indicates variations in both vulnerability to contamination from anthropogenic sources or saltwater intrusion.

Isotopic and physico-chemical results point to a recent increase of groundwater mineralization towards the interior of the island. The high salt content is mostly ascribed to agricultural zones and seaside coastal surroundings, associated with intense overexploitation of groundwater resources and scarcity of precipitation. One possible explanation for the isotopic division (eastern group) could be related to infiltration/recharge under different climatic conditions.

References

[1] Pina AFL. Hydrochemistry and quality in the groundwater of Santiago Island – Cabo Verde. *PhD Thesis* 2009 (in Portuguese).

[2] Heilweil VM, Solomon DK et al. Oxygen, hydrogen, and helium isotopes for investigating groundwater systems of the Cape Verde Islands, West Africa. *Hydrogeology Journal* 2009; **17**: 1157–1174.

[3] Serralheiro A. Santiago Island geology (Cabo Verde). *Ph.D. Thesis* 1974 (in Portuguese).

[4] Craig H. Isotopic variations in meteoric waters. *Science* 1961; **133:** 1702-1703.