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Groundwater Assessment at Santiago Island (Cabo Verde): A Multidisciplinary Approach to a Recurring Source of Water Supply

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Abstract Groundwater resources are in many parts of the world the only source for private domestic, agricultural and public water supply. Subsurface has also become major recipient of wastewater and solid waters especially in the developing countries. Overexploitation of coastal aquifers and pollution are among the main problems related to groundwater resources assessment and management in Santiago Island (Cabo Verde). Brackish groundwater is the only available water type in the region that is being provided to numerous parts of the Island such as Praia Baixo, Montenegro, and Charco for agriculture and human supply. Solute and isotope data obtained in different groundwater systems were used in the identification of groundwater resources degradation. In order to understand the influence of the anthropogenic activities on the water quality and the main origin of the salts in groundwater, a statistical approach (Principal Components Analyses—PCA) was performed on the physico-chemical data. The results obtained indicate water–rock interaction mechanisms as the major process responsible for the groundwater quality (mainly calcium-bicarbonate type), reflecting the lithological composition of the subsurface soil. Also, anthropogenic contamination was identified, in several points of the island. Isotopic techniques ($\delta^{2}H$, $\delta^{18}O$ and ^{3}H content) combined with geochemistry provided comprehensive information on groundwater recharge, as well as on the identification of salinization mechanisms (e.g. seawater intrusion, salt dissolution, and marine aerosols) of the groundwater systems, at Santiago Island.

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1 Introduction

Groundwater resources in arid and semi-arid regions play a vital role on the socio-economic development. Often, surface waters are either seasonal or non-existent and groundwater becomes the only dependable source of water supply. Besides, due to water scarcity problems, saltwater intrusion, with the consequent damages of coastal aquifers, is one of the natural hazards that can have enormous consequences in agriculture based societies and linked urban development.

The estimation of the amount of recharge or the quantification of the water resources is fundamental for the sustainable management of the hydrological resources. As an alternative to a merely hydrodynamic approach, geochemical and isotopic investigations of the aquifer systems have often proven to be quite successful in determining groundwater recharge, flow paths and renewal times in arid and semi-arid regions (Edmunds and Walton 1980; Salem et al. 1980; Cook and Walker 1996; Ojeda 2001; Weyhenmeyer 2002). The advantage of such approach is that the chemical and isotopic data can provide integrated information of all water that enters the system, thereby largely eliminating local differences and short-term variability observed in the hydrodynamic data.

Overexploitation of coastal aquifers and pollution are among the main problems related to groundwater resources assessment and management in Santiago Island (Cabo Verde archipelago). As a consequence to the scarce precipitation and difficulties in the water administration in the Santiago Island, the fresh water management is in a fragile balance with the seawater at coastal areas. On land, due to groundwater exploitation in the valleys near the coast, a careful monitoring of the fresh-salt water interface is being carried out in order to avoid saltwater pumping. One of the measures that are being implemented by the Cabo Verde national water authority is the rule that these public boreholes are allowed to work 2 to 3 h per day to supply water to the population, and no new boreholes are allowed to be drilled near the coast. The impact of such measures is enhanced since most part of population at Santiago Island lives by the ocean and has agriculture as the main activity. Surface waters are either seasonal or non-existent, and groundwater becomes the recurrent source of water supply.

Increased salinity and vulnerability to pollution at Santiago Island aquifers, mainly regarding the coastal zones encouraged the local Government to seek for external assistance in the framework of a bilateral cooperation between Cabo Verde and Portugal. The groundwater salinity, its origin and prevention are important components of the groundwater problem, especially in the context of deterioration of water quality resulting from pollution or overexploitation. Besides the application of isotopic techniques, water/rock interaction studies allow a better understanding of the groundwater salinity origin in the area.

The major challenge of this study is to distinguish saline groundwaters of different origins resulting from eventual seawater of different generations. For this purpose, both chemical and isotopic techniques were applied. Over the past 40 years, isotope methods have proven to be of unique value in understanding the origins of salinity as well as salinization processes. Joint measurements of chloride and sodium, when combined with the stable isotope (δ^2H and δ^{18}O) contents of groundwaters have provided a powerful technique in numerous studies of the evolution of groundwater salinity as well as recharge/discharge relationships (Edmunds 2005a; Gonfiantini and Simonot 1987; Grassi et al. 2007).

2 Study Area—Local Geology and Hydrogeology

Located in the South-eastern part of Cabo Verde archipelago, Santiago Island presents climatologically and hydrogeological features typical of Sahelian regions were the seasonal changes are related to the Inter Tropical Front (ITF). The precipitation events over the region are associated with the movements of the ITF (I.N.G.R.H. 1994). At Santiago Island, the rain distribution is irregular, varying between 190 to 320 mm/year at low levels near the coast and at the highest mountains, respectively. The wet period is distributed from August to November (Lobo de Pina et al. 2005; I.A.E.A. 2007). The temperature values show a small fluctuation, around 6°C between mean winter season (minimum value around 22°C at February) and the mean summer season (maximum value about 27°C at September). Also the wind is rather constant during all over the year, with a main direction of N–NE; the highest

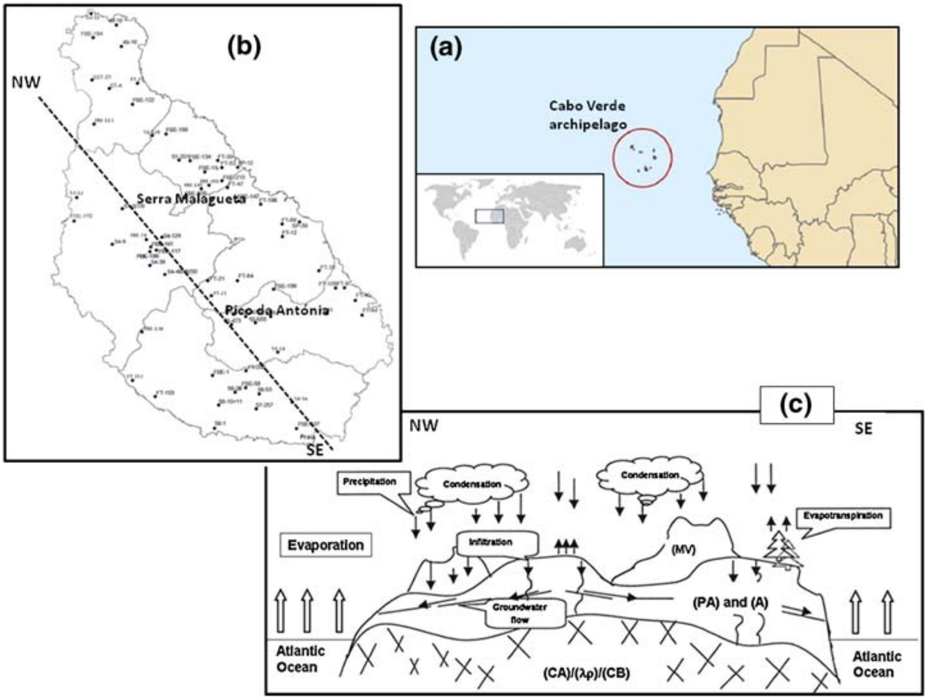

Fig. 1 **a** and **b** Santiago Island showing the location of the sampling points and the NW–SE cross section; **c** schematic NW–SE cross section displaying the hydrogeological conceptual model of Santiago Island (adapted from Lobo de Pina et al. 2005)

intensity usually is measured from January to May. The regular winds that cross the Island play an important role in the diffusion and transport of marine aerosols, one possible source to the income of salts to the groundwater systems.

The rocks type occurrence in Santiago Island has a volcanic origin being mainly composed by a vulcano-stratigraphic sequence, as first reported by Serralheiro (1974), and later improved by Matos Alves et al. (1979), which has been used as the basic support for hydrological and hydrogeological resources research. The main geological units with hydrogeological interest are the following: (1) the Eruptive complex of Pico da Antonia (*PA*) and (*A*); (2) The Monte das Vacas formation (*MV*) and (3) the recent sedimentary Quaternary formations (*a*). The most important reservoir of fresh water is the PA formation presenting terrestrial and submarine facies (pillow-lavas) (Fig. 1).

The storage coefficient of the eruptive complex Pico da Antonia (PA and A formations) is relatively high (mean transmissivity values between 10^{-1} and 2×10^{-2} m^2/s (Lobo de Pina et al. 2005); permeability avoids a rapid drainage of the scarce water supply with high feed rate. These geological units cover an impermeable formation known as the Base Unit (CA/$\lambda\varrho$/CB, see Fig. 1) composed by Ancient Internal Eruptive Complex (AIEC). The Flamengo and the Conglomeratic-Brechoide formations, represent the two components of the AIEC, characterized by a generalized alteration level, with high rate of compactness and low permeability (Fig. 2).

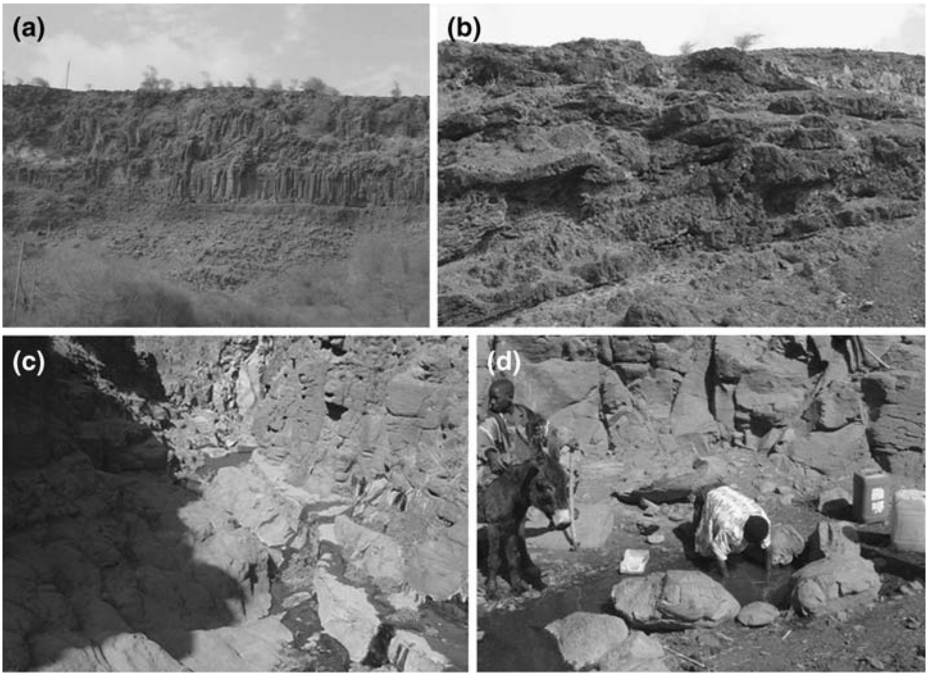

Fig. 2 Santiago Island geological environment. **a** prismatic basalt; **b** PA formation, sub-aerial facies; **c** geological contact between the prismatic fissured basalt and the compact basalt (impermeable) where **d** the Águas Podres spring issue

According to Monteiro Santos et al. (2006) the drilling and the pumping tests carried out by the National Institute of Water Resources Management (Instituto Nacional de Gestão de Recursos Hídricos (INGRH)), indicated that the pillow lava layers, with their fissures and holes, constitute the hydrogeological formation with the highest productivity (approximately 40 m^3/h), being the stabilization reached during the first minutes. Besides, the study performed at Monte das Vacas formation (MV), composed by pyroclastic material cones, pointed out that this formation present good vertical flow component and high degree of permeability and porosity and in Tarrafal area a mean value of 10% of porosity was obtained (POCI/CTE/GEX/55399/2004 R & D Project 2004). The Monte das Vacas formation outcrops principally at Santiago Island peaks (Pico da Antónia and Serra Malagueta), areas with the highest precipitation recorded. Due to its permeability of this formation, the infiltration is favoured. The infiltrated water is rapidly drained to lower levels of Monte das Vacas formation, reaching the Ancient Internal Eruptive Complex (AIEC), with low permeability and high rate compactness.

3 Sampling and Methods

Three groundwater-sampling campaigns were performed at Santiago Island, November 2005, February 2006 and November 2006 (Fig. 3). The groundwater samples were collected from boreholes and springs for isotopic analyses (δ^2H, $\delta^{18}O$ and ^3H). Electrical conductivity ($\mu S/cm$), pH and temperature (°C) were measured in situ. The ^2H and ^{18}O results are reported in δ notation and were measured with the accuracy of 1‰ for δ^2H and 0.1‰ for $\delta^{18}O$. The δ^2H and $\delta^{18}O$ were determined three times for each sample in order to increase the precision analysis. The measurements were carried out using a mass spectrometer SIRA 10 VG-ISOGAS using the methods proposed by Friedman (1953) and after modified by Tanweer et al. (1988), Tanweer (1990) and Epstein and Mayeda (1953) for ^2H and ^{18}O, respectively. The tritium content was determined using the electrolytic enrichment and liquid scintillation counting method (Packard TRI-CARB 2000 CA/LL). The error associated with the ^3H measurements (around 0.7 TU) varies with the ^3H concentration in the sample (I.A.E.A. 1976). All isotopic determinations were performed in the Instituto Tecnológico e Nuclear, ITN – Chemistry Department, Sacavém, Portugal.

During the fieldwork exercise carried out in the study area between December 2005, and November 2006, no groundwater samples were collected for chemical analyses, due to the fact that chemical data were available in the framework of previous campaigns carried out at Santiago Island by other researchers. The chemical data can be found in Lobo de Pina (2009).

4 Results and Discussion

Hydrogeochemical studies (chemical and isotopic composition of waters) can be used to (1) identify mixing of surface water/groundwater, (2) to quantify the contribution of different sources to the recharge of the hydrological systems and (3) estimate the groundwater mean residence time (Pilla et al. 2003). The relation between Na and Cl determined in the groundwater samples is characteristic of coastal groundwaters

Fig. 3 Schematic map of Santiago Island, with the localization of the groundwater sampling points

affected in most cases by seawater intrusion processes. However, leaching of marine sediments could be another source of groundwater Na–Cl salinity and in the case of Santiago Island the income of Na–Cl can also be connected to the marine spray.

Several of the salinity sources, such as seawater from surface brines, are associated with "liquid solutions" presenting a specific isotopic composition, which is distinct from that of meteoric waters. These particular isotopic signatures are often much better preserved in the aquifer environment than in the salinity components, which may undergo processes like ion exchange and precipitation, for example. From dissolution, flushing of dry salts or even mixing with seawater, only a small chemical distinction exists between the origins of salinity in groundwater.

From the isotopic point of view, it is possible to identify the salts origin within the groundwater system, since the mechanisms of dissolution or leaching of salts will not result in any change in the water's isotopic composition, yet observed in seawater intrusion processes (Gasparini 1989; Zouari et al. 1999). The isotopic approach is particularly useful near coastal areas where all the salinity was ultimately originated from the marine environment, so that, little chemical distinction exists between salinity originating from sea-spray or from direct sea-water encroachment, from surface lagoons or from interstitial waters. Isotope hydrology techniques are effective and unique tools for obtaining information on recharge conditions and aquifer hydrodynamics, The behaviour of oxygen and hydrogen stable isotopes in the meteoric waters is related with various environmental parameters, which characterize a given sampling point (e.g. altitude above sea level, distance to the coast, air temperature and rain amount). The distribution of $\delta^{18}O$ and $\delta^{2}H$ in precipitation mimics the topography of the regions, presenting depleted values at high altitudes, lower temperatures and higher distances from the coast (Dansgaard 1964). The source of salts of brackish to highly mineralised groundwater systems can be identified by the pattern defined in the plot isotopic composition as a function of the water mineralization (electrical conductivity or Cl^- content), also in case of processes as dissolution and leaching of salt, enrichment by evaporation or mixing of fresh with saline water or seawater.

Furthermore, a different approach to the isotopic and physico-chemical data was attempted. Principal Components Analysis (PCA) was applied in the study area using all data available from the boreholes and springs collected in the several water systems. All physical and chemical parameters obtained concerning these systems were used in this statistical method of analysis. The goal of this approach was to discriminate the relationship between the systems, the samples and the different parameters, in particularly those in small concentrations that sometimes are neglected and could be derived from the Human impact activities or leaching of secondary minerals, present in the water resources (Melloul 1995).

4.1 Water Chemistry

During the fieldwork exercise carried out in the study area between December 2005, February and November 2006, no groundwater samples were collected for chemical analyses, due to the fact that chemical data were available in the framework of previous campaigns carried out at Santiago Island by various other workers. Their results shows that the mean temperature of the groundwater samples is in the order of 25.4°C, with the highest values of about 30°C, and the lowest around 22°C. Electrical conductivity (EC) was also measured. The values obtained range approximately between 130 and 9400 μS/cm. The groundwater samples collected in the central part of Santiago Island, such as Pico da Antónia or Serra Malagueta, belong to the Na-HCO_3 type, pointing to the influence of the geological matrix (volcanic terrains; Table 1). On the other hand, the highest salt content is found in the valleys, areas of intense agriculture practices (sugar cane, banana and papaya fields), indicating a salt increase associated with excessive pumping of the aquifer systems (Fig. 4).

Most of the samples presenting high sodium and chloride content are ascribed to the valleys situated at the coastal areas, indicating most probably that seawater intrusion as the main mechanism responsible for the groundwater salinity. Nevertheless, the influence of marine aerosol cannot also be excluded as one of the salinity sources. The two hypothesis of the origin of salts in the groundwater should be considered,

Table 1 Geochemistry of the groundwaters from Santiago Island (data from Lobo de Pina 2009)

Sample reference	pH	EC (µS/cm)	SiO$_2$ (mg/L)	Na (mg/L)	K (mg/L)	Ca (mg/L)	Mg (mg/L)	Cl (mg/L)	SO$_4$ (mg/L)	NO$_3$ (mg/L)	HCO$_3$ (mg/L)
49-18[a]	6.80	2,750	25.2	477.0	26.8	41.6	75.8	638.1	100.2	5.4	278
SST-10[b]	7.20	1,362	31.1	146.0	30.8	56.0	53.5	241.1	36.4	26.8	244
SST-21[b]	7.30	504	35.6	77.9	12.9	17.6	15.6	70.9	n.m	21.5	186
49-16[a]	6.98	2,020	24.3	379.6	9.9	25.6	45.7	205.6	127.5	48.3	537
FBE-150[b]	7.60	478	22.5	58.4	30.8	16.0	10.7	49.6	9.1	21.5	188
FBE-131[b]	6.33	396	32.5	68.1	10.9	17.6	13.6	42.5	36.4	10.7	164
FBE-113[b]	7.10	459	31.6	77.9	15.9	20.8	8.7	49.6	9.1	16.1	195
FBE-161[b]	7.50	617	43.3	97.3	21.8	20.8	15.6	78.0	0.0	42.9	183
FBE-117[b]	7.20	448	54.1	68.1	9.9	17.6	12.6	63.8	13.7	59.0	100
51-123[a]	7.60	506	28.9	97.3	7.9	32.0	24.3	49.6	63.7	8.0	227
FBE-188[b]	7.00	627	29.8	68.1	7.9	43.2	29.2	70.9	18.2	26.8	227
51-201[a]	7.20	527	36.1	77.9	8.9	27.2	23.3	56.7	9.1	21.5	220
SP-12[b]	6.78	2,680	28.0	262.8	22.8	108.8	115.7	638.1	81.9	42.9	110
FT-40[b]	7.20	1,394	38.3	136.3	8.9	72.0	59.3	283.6	45.5	37.5	161
FT-44[b]	7.14	2,060	31.6	292.0	16.9	75.2	66.1	510.5	72.8	24.1	164
54-6[a]	7.20	949	33.4	87.6	16.9	51.2	38.9	99.3	54.6	21.5	268
54-128[a]	8.00	545	40.6	77.9	18.9	25.6	15.6	70.9	4.6	96.5	127
FT-78[b]	6.95	2,980	38.3	243.4	11.9	131.2	138.0	751.5	10.0	53.6	90
PT-29[b]	7.00	2,110	45.1	438.0	9.9	8.0	43.7	127.6	227.6	21.5	661
55-555[a]	8.00	433	38.3	37.0	10.9	19.2	20.4	70.9	18.2	16.1	176
FT-21[b]	7.10	1,351	36.1	243.4	24.8	6.4	53.5	85.1	81.9	0.0	566
FT-9[b]	7.10	1,020	33.8	97.3	7.9	35.2	39.9	141.8	36.4	59.0	156
FT-12[b]	7.05	1,311	35.6	107.1	8.9	35.2	60.3	226.9	27.3	37.5	176
FT-59[b]	7.00	913	37.9	77.9	9.9	72.0	45.7	113.4	27.3	37.5	315
FT-202[b]	7.20	384	37.9	58.4	11.9	17.6	15.6	49.6	4.6	16.1	149
FBE-58[b]	7.30	362	37.0	68.1	6.9	19.2	14.6	49.6	45.5	16.1	144
51-6/7/8[a]	7.62	695	40.1	97.3	31.8	30.4	20.4	78.0	63.7	42.9	247
58-53[a]	7.10	417	33.8	68.1	9.9	22.4	14.6	56.7	18.2	18.8	144
58-257[a]	7.20	440	35.2	58.4	10.9	19.2	14.6	49.6	4.6	13.4	164
58-1[a]	7.40	410	32.5	34.1	6.0	24.0	16.5	56.7	4.6	16.1	161
58-23[a]	7.30	405	33.8	68.1	8.9	17.6	15.6	56.7	9.1	16.1	161
FBE-1[b]	7.90	366	30.7	30.2	6.9	20.8	14.6	42.5	n.m	16.1	144
58-10/11[a]	7.60	384	19.8	36.0	6.9	20.8	13.6	49.6	n.m	13.4	144
FT-39[b]	6.90	1,439	42.8	175.2	13.9	54.4	69.0	262.3	54.6	21.5	276
FT-153[b]	7.40	987	36.1	77.9	16.9	27.2	47.6	106.4	18.2	10.7	249
FT-47[b]	7.22	1,622	37.0	175.2	22.8	36.8	82.6	297.8	63.7	48.3	222

n.m. not measured

[a] Spring

[b] Borehole

since the relationships between Na and Cl are extremely valuable for assessing the source of salinity in groundwater (Cartwright et al. 2004). The Na/Cl ratio varies between 0.63 and 5.29, while the Cl content range from 1.20 up to 21.20 meq/L. According to Cartwright et al. (2004), the oceanic ratio is 0.86 and the samples with high Na/Cl ratios observed in groundwater with low salinity values could be explain from weathering of plagioclase (Fig. 5), however this hypothesis seems not be very realistic in Santiago island since the chemical analyses performed in different rock samples from the different geological formations show a Na$_2$O percentage varying

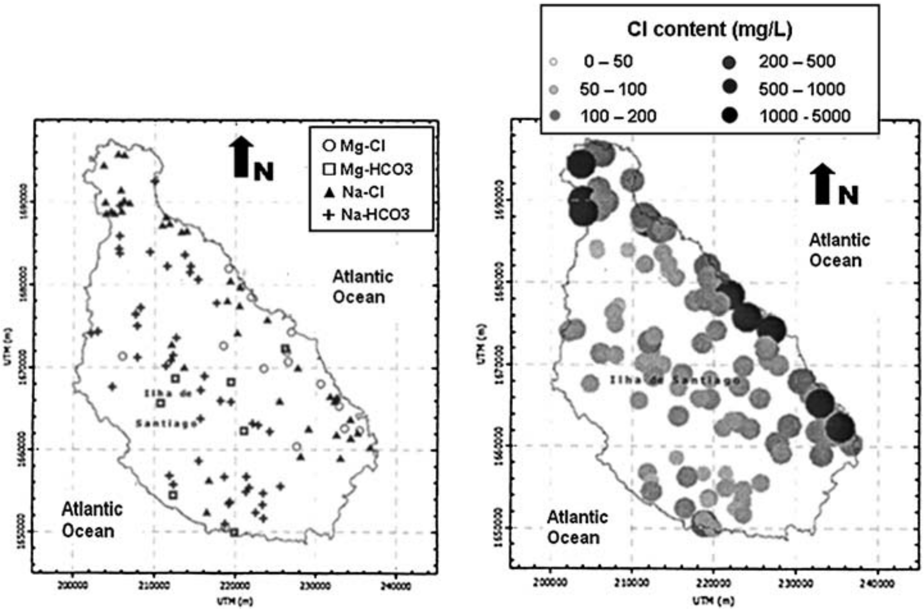

Fig. 4 Geochemical facies and Cl content at Santiago Island (adapted from Lobo de Pina et al. 2005)

1.19 and 2.76 (I.N.G.R.H. 1994). Another source for the increase of Na should be investigated.

Natural salinity boundaries exist in aquifers due to geological factors controlling the maximum depth of circulation, as well the interface between marine and fresh water. Climatic factors strongly control salinity, so that continuous low rate of recharge in arid areas, lead to a widespread salinity of groundwaters (Edmunds 2005a). Anthropogenic pollution increases recharge salinity directly, or indirectly due to agricultural activities and over pumping, leading to the incursion of saline groundwater into freshwater aquifers. These situations can be well observed at

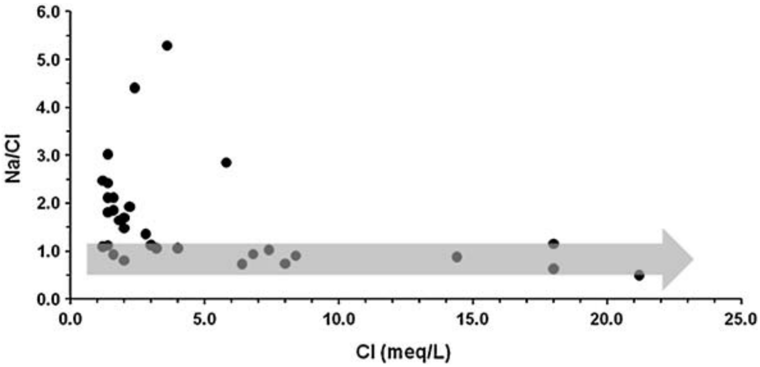

Fig. 5 Na, Cl concentrations in Santiago Island Groundwater (data from Table 1). Na/Cl ratio vs Cl content. The arrow show predicted trend for marine salts dissolution and mixing with sea water

Santiago Island. On the other hand, the removal of native vegetation causes the rise of regional water tables, which may lead to increase groundwater salinity due to the combined effects of mobilising salts stored in the unsaturated zone, promoting leakage of saline water from underlying aquifers (Cartwright et al. 2004).

Groundwater chemical composition of Santiago Island was represented in a Piper Diagram using the available data from previous surveys in the region (Fig. 6). Two trend lines were identified associated with two main processes: (1) groundwater evolution/mineralization controlled by the seawater spraying and by mixing with underlying seawater in the Quaternary formations, particularly in valley areas; (2) water–rock interaction, representing the most important mechanism in the geochemical evolution of groundwater signatures within the aquifers systems.

No correlation was found between the geochemical evolution and (1) the particular geological layer or (2) the type of sampling point (spring or borehole). However, trends with geochemical significance were established between the total ions and Mg, SO_4, Ca, HCO_3, Na and Cl contents (Fig. 7). Once the total ions content reaches values around 30 meq/L, the ion content seems to become stationary or in some cases even decreases. This behaviour probably indicates that the groundwater samples have reach saturation values with respect to Ca and Mg carbonates and gypsum. The low content in Na and Cl is followed by a small range in the Total Dissolved Solids (TDS) values, and increase as TDS values increase, indicating that the higher salinization of the groundwaters should be related to NaCl dissolution.

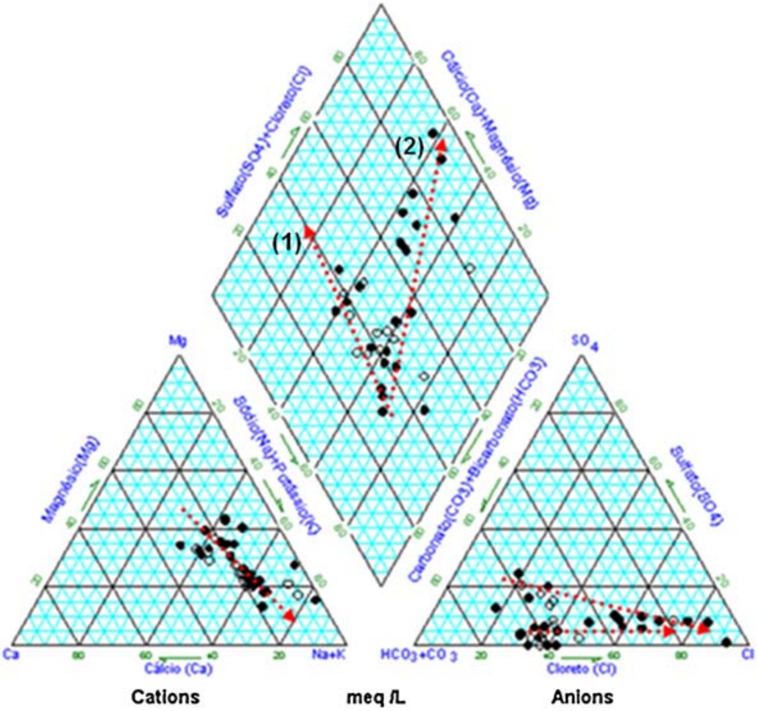

Fig. 6 Piper diagram for the studied groundwater samples. *Empty circle* spring waters, *filled circle* stands for borehole waters. Groundwater geochemical evolution patterns (1) associated to seawater spraying and mixing with seawater; (2) mostly derived from water–rock interaction mechanisms

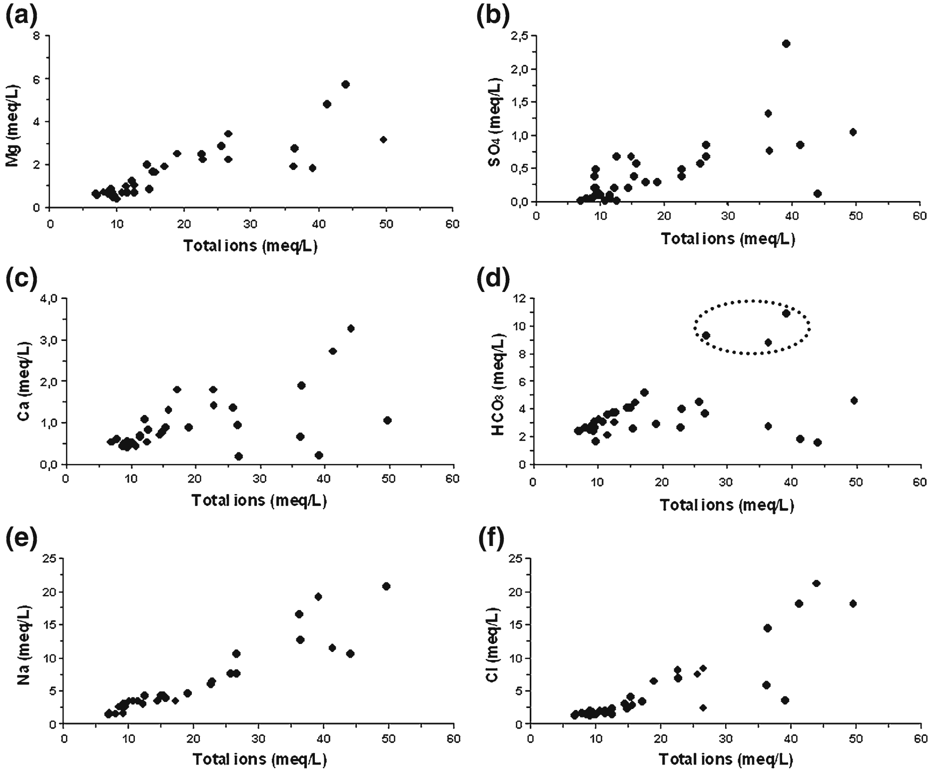

Fig. 7 Major ion composition diagrams of the groundwater samples collected at Santiago Island, exploiting different aquifer systems, versus total ions concentration (meq/L)

The area affected by seawater intrusion or influence by marine aerosol appears to be moving from the coastline forward to the interior of the island, as supported by the recent increase in the groundwater electrical conductivity data. The high salt content within the groundwater systems appears to be ascribed to agricultural zones (in the valley areas) located in the coast surroundings. The salt increase measured in the groundwater is consistent with intense exploitation of the groundwater resources and the scarcity of precipitation. The salt increase leads to a potential opening for soil salinization and alkalinisation, with the inherent soil deterioration and loss of productivity.

4.1.1 Principal Components Analysis

Principal Components Analyses (PCA) was useful to discriminate the relationship between the systems, the samples and the parameters, in particularly those in small concentrations that sometimes are neglected and could be derived from the Human impact activities, (Melloul 1995).

The physical and chemical parameters were used in this statistical method of analysis using STATISTIC 8 code (Statsoft Inc. 2008). The base matrix is composed by 36 cases and 11 variables. PCA requires three or more times the numbers of

Table 2 PCA for the Santiago Island water samples (factor loadings using varimax normalized)

	PC 1	PC 2	PC 3
EC	0.831	0.541	0.015
SiO_2	−0.118	0.056	−0.869
Na	0.488	0.826	0.049
K	0.235	0.265	−0.052
Ca	**0.924**	−0.134	−0.022
Mg	**0.920**	0.262	−0.013
Cl	**0.943**	0.196	0.035
SO_4	0.156	**0.927**	0.008
NO_3	0.364	−0.157	−0.694
HCO_3	−0.189	0.907	0.074
Altitude	−0.585	0.035	−0.613
Total variance (%)	37.46	26.20	14.78

The bold values represent loadings significant at 90% confidence level

cases, relative to the number of variables, like in the present study. Three factors with eigenvalues over 1 were obtained (Table 2). The eigenvalues can be used to determine an optimum number of principal components associated with the variation in the data. Component 1 (PC 1) accounts for 37% of the total variance and appears to characterize the water–rock interaction processes, responsible for the high loadings in Ca, Mg and Cl. Nevertheless, the high contribution of Cl in this component could be attributed not only to marine spray, but also to Cl concentration (by evaporation) from atmospheric precipitation. The weight of Cl in this factor is rather different from that of Na, bearing in mind that Cl content in the local volcanic rocks is rather low (Matos Alves et al. 1979). Therefore, this factor could be faced as a mark of the groundwater evolution in Santiago Island. The second component, PC 2, represents 26% of the total variance, standing for the high loadings in SO_4, HCO_3 and Na. This factor could be ascribed to the influence of anthropogenic input

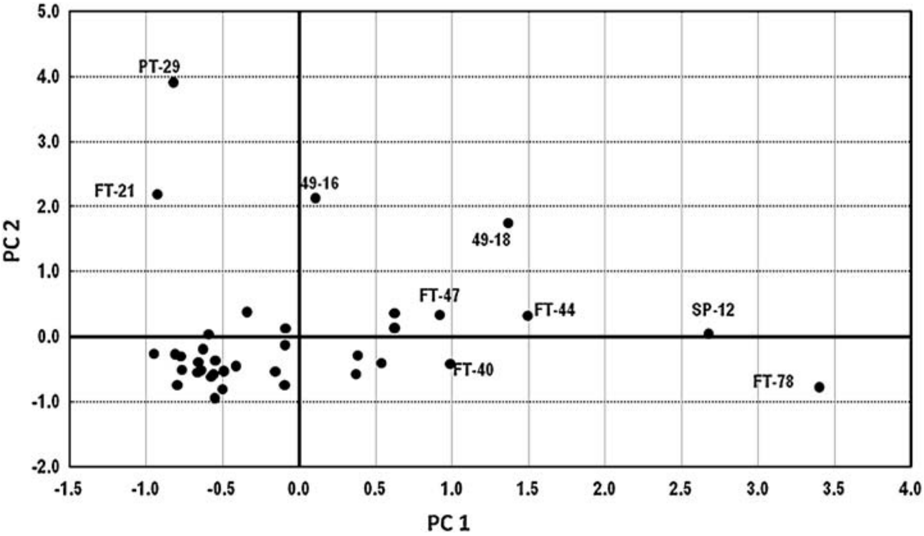

Fig. 8 PC2 versus PC 1 for the groundwater samples from Santiago Island

(agriculture activities introduction of SO_4 associated to insecticides and fertilizers in the agricultural fields, particularly within the banana and papaya plantations). The PC 3 is dominated by the inverse relation between the original rock matrix (e.g. SiO_2, K, Ca and Mg) and external contributions (e.g. Na, Cl and SO_4) associated with the proximity to the coastline.

Using the factor loadings and plotting PC 2 as a function of PC 1 (Fig. 8), the separation between two groups of water samples 49-18, SP-12, FT-40, FT-44, FT-78, FT-47 and 49-16, FT-21, PT-29 was found to be unambiguous. The first group presents the higher influence of Ca, Mg and Cl (Table 3). These water-sampling points are distributed along the coastline, representing the most evolved water–rock interaction processes. The second group of water samples are located in the

Table 3 Factor loadings of the water samples for the principal components

Sample reference	Factor loading PC1	Factor loading PC2	Factor loading PC3
49-18	1.3646	1.7445	1.3362
SST-10	0.6219	0.1375	0.3389
SST-21	−0.4933	−0.5243	0.3329
49-16	0.1041	2.1318	0.6666
FBE-150	−0.4152	−0.4453	1.4686
FBE-131	−0.8110	−0.2660	0.4685
FBE-113	−0.6584	−0.3845	0.5885
FBE-161	−0.6291	−0.1835	−1.8205
FBE-117	−0.6419	−0.5096	−3.0160
51-123	−0.5941	0.0384	1.0210
FBE-188	−0.1571	−0.5306	0.6907
51-201	−0.5493	−0.3639	−0.0051
SP-12	2.6754	0.0495	0.1577
FT-40	0.9872	−0.4100	−0.2322
FT-44	1.4906	0.3287	0.5084
54-6	−0.0909	0.1344	0.1483
54-128	−0.0959	−0.7384	−2.5667
FT-78	3.3968	−0.7734	−0.8334
PT-29	−0.8209	3.9120	−0.9019
55-555	−0.9510	−0.2587	−0.8082
FT-21	−0.9283	2.1886	0.0770
FT-9	0.3704	−0.5722	−0.2584
FT-12	0.5380	−0.4017	0.0435
FT-59	0.3809	−0.2830	−0.1323
FT-202	−0.7684	−0.5077	−0.2420
FBE-58	−0.7749	−0.2932	−0.0293
51-6/7/8	−0.3434	0.3879	−1.0780
58-53	−0.5599	−0.5685	0.3834
58-257	−0.5774	−0.6090	0.5610
58-1	−0.5008	−0.8042	0.7972
58-23	−0.6647	−0.5441	0.3900
FBE-1	−0.7977	−0.7368	0.3041
58-10/11	−0.5522	−0.9386	1.8368
FT-39	0.6218	0.3688	−0.2935
FT-153	−0.0924	−0.1193	0.6249
FT-47	0.9163	0.3444	−0.5267

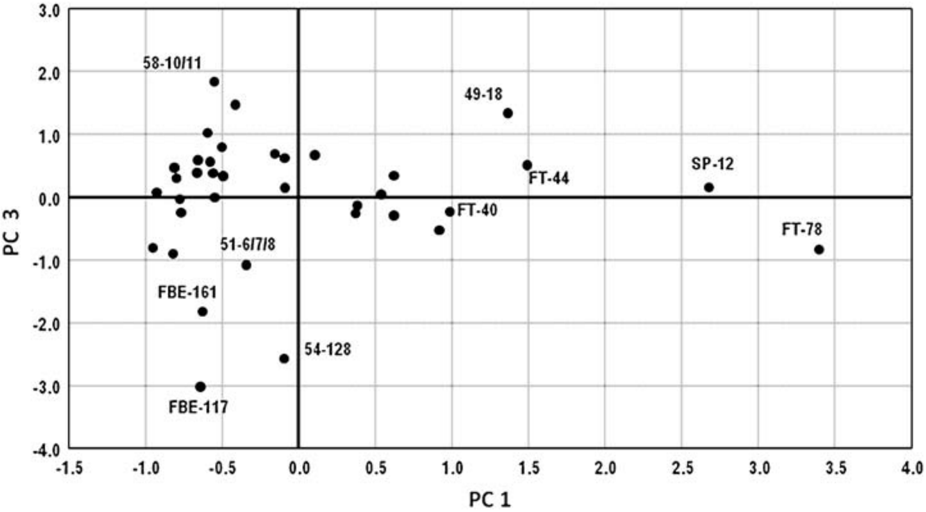

Fig. 9 Principal components analysis: PC 3 vs PC 1

middle of Santiago Island, within the recharge areas of the aquifers systems, in places with local small agriculture activities can be found, reflecting a short residence time and with the water–rock interaction processes in initial stage. On the other hand, this group of samples is reflecting a strong influence of the second Principal Component. The increase in SO_4 influence in the samples is pointing to the human impact in the water resources, as supported by the weight of SO_4 in PC2 (influence of pesticides and fertilizers). On the other hand, the distribution of the first group of water samples near and on the PC2 axis is strongly related with intense agriculture activities observed along the valleys near the coast.

PC 3 represents 14.78% of the total variance of the system and should be treated as a silica index which most probably associated with weathering and water–rock interaction processes. The samples FBE-117, 54-128 and FBE-161 are situated within the central part of Santiago Island, where the influence of Cl content by marine spray and/or seawater intrusion is negligible (Fig. 9).

Figure 10 shows a plot of PC 3 as a function of PC 2. From the figure, a few layers was observed. These groundwater samples (e.g. PT-29, FT-21, 49-16, 49-18) are mostly are located in places with low or even inexistent agriculture practices.

Table 4 shows the plot of the correlation matrix obtain using all parameters obtained in the groundwater samples. From Table 4, high influence of groundwater–seawater mixing processes is noted. Also, it was deduced that the anthropogenic activities and influence in the water resources in Santiago Island are with local impact this is enhanced by the weak correlation coefficient between the nitrates and sulphates content in the water systems.

4.2 Environmental Isotope Approach

Close to 120 groundwater samples were taken from boreholes and springs during three field work campaigns at Santiago Island (Fig. 3). The isotopic composition of

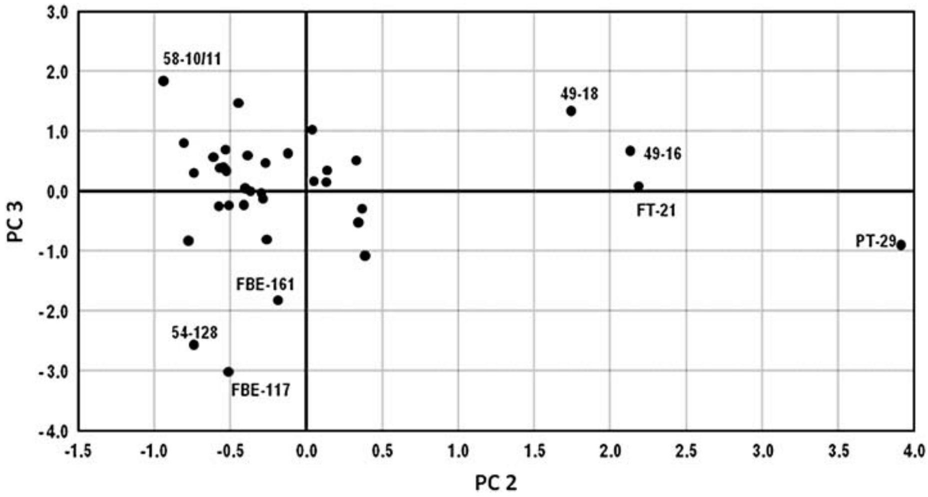

Fig. 10 Principal components analysis: PC3 vs PC2

the groundwater samples collect at Santiago Island range from −4.98 to −2.61‰ in $\delta^{18}O$ and from −44.6 to −14.9‰ in δ^2H, with a mean isotope content of -3.88 ± 0.53‰ in $\delta^{18}O$ and -25.9 ± 5.4‰ in δ^2H vs V-SMOW ($n = 115$). The isotopic content obtained is close to the average isotopic composition over the Island as discussed by Akiti (1985), suggesting that the infiltrated meteoric waters were not subjected to previous evaporation mechanisms.

Two groups of groundwater samples were identified from the diagram $\delta^{18}O$ vs. δ^2H (Fig. 11). One group is composed of the groundwater samples collected in the eastern part of Santiago Island, in most cases located near the coastline. The other group is ascribed to high-altitude sampling sites, i.e. most of the sampled points are located in the central part of the Island. Based on this pattern, we have tried to identify a possible correlation between the altitude of the sampling sites and the isotopic composition. However, no strong correlation was found between the altitudes of the sampling points with the several parameters available (see Table 4).

Table 4 Correlation matrix

	EC	SiO_2	Na	K	Ca	Mg	Cl	SO_4	NO_3	HCO_3	Altitude
EC	1.00										
SiO_2	−0.08	1.00									
Na	0.87	−0.09	1.00								
K	0.30	−0.09	0.28	1.00							
Ca	0.68	−0.06	0.29	0.11	1.00						
Mg	0.91	−0.03	0.62	0.24	0.83	1.00					
Cl	0.91	−0.13	0.67	0.28	0.81	0.91	1.00				
SO_4	0.61	0.03	0.83	0.16	0.05	0.36	0.31	1.00			
NO_3	0.19	0.36	0.03	0.09	0.31	0.22	0.20	−0.05	1.00		
HCO_3	0.32	0.02	0.61	0.14	−0.24	0.10	−0.07	0.78	−0.20	1.00	
Altitude	−0.45	0.50	−0.25	−0.01	−0.51	−0.50	−0.47	−0.11	0.08	0.01	1.00

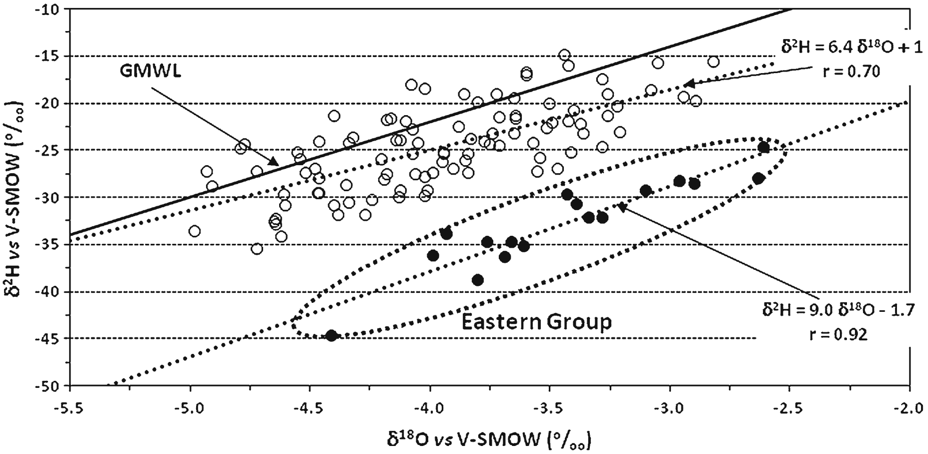

Fig. 11 δ^2H vs δ^{18}O for the sampled groundwaters

One possible explanation for this isotopic "division" (e.g. eastern group) could be related with infiltration/recharge under different climatic conditions. The hypothesis of the existence of a palaeoclimatic effect within these two groundwater groups should be formulated. The observed isotopic shift might be associated to the preferential storage of isotopically depleted water in the polar ice caps. The isotopic composition of the oceans is assumed that have changed by 1.3 to 1.6‰ in ^{18}O and about 10‰ in deuterium during glacial times (Rozanski 1985; Chappell and Shackleton 1986).

The significance of stable isotopes (^{18}O and ^{2}H) as climatic fingerprints and their application to palaeohydrologic and palaeoclimatic studies have been discussed by various workers world all over among which are was focused in different works all over the world (Darling et al. 1997; Gonfiantini et al. 1974; Edmunds and Wright 1979; Salem et al. 1980). The present day representative values in oxygen-18 and in deuterium observed in precipitation may be used as sensitive indicators of change and complexity in past temperature, precipitation patterns and air mass circulation. Past rainfall storage as palaeo-groundwater provide evidence of former climatic conditions (Rozanski et al. 1992). Climatic changes are expressed primarily as (1) isotopic depletion relative to modern groundwaters with reference to the meteoric water line (2) change in the deuterium excess, signifying changes in humidity in the air mass as it detaches from its primary oceanic source moving over arid zones (3) local condensation and evaporation effects within clouds or in falling rain. According to Edmunds (2005b), the large freshwater reserves in some basins of modern arid zones are therefore a priori indicators of wetter climates. Furthermore, in shallow aquifers higher salinity is mainly a legacy of the onset of more arid conditions during the past 4,000 years. The combined use of chloride and stable isotopes (δ^{18}O and δ^2H) of groundwater provide a powerful technique for studying past rainfall and evaporation cycles in groundwaters.

In order to identify climate signatures within the sampled groundwaters, the isotopic composition was plotted as a function of the chloride content. The available data was used in the identification and characterization of geochemical evolution and identification of salinization mechanisms (Fig. 12).

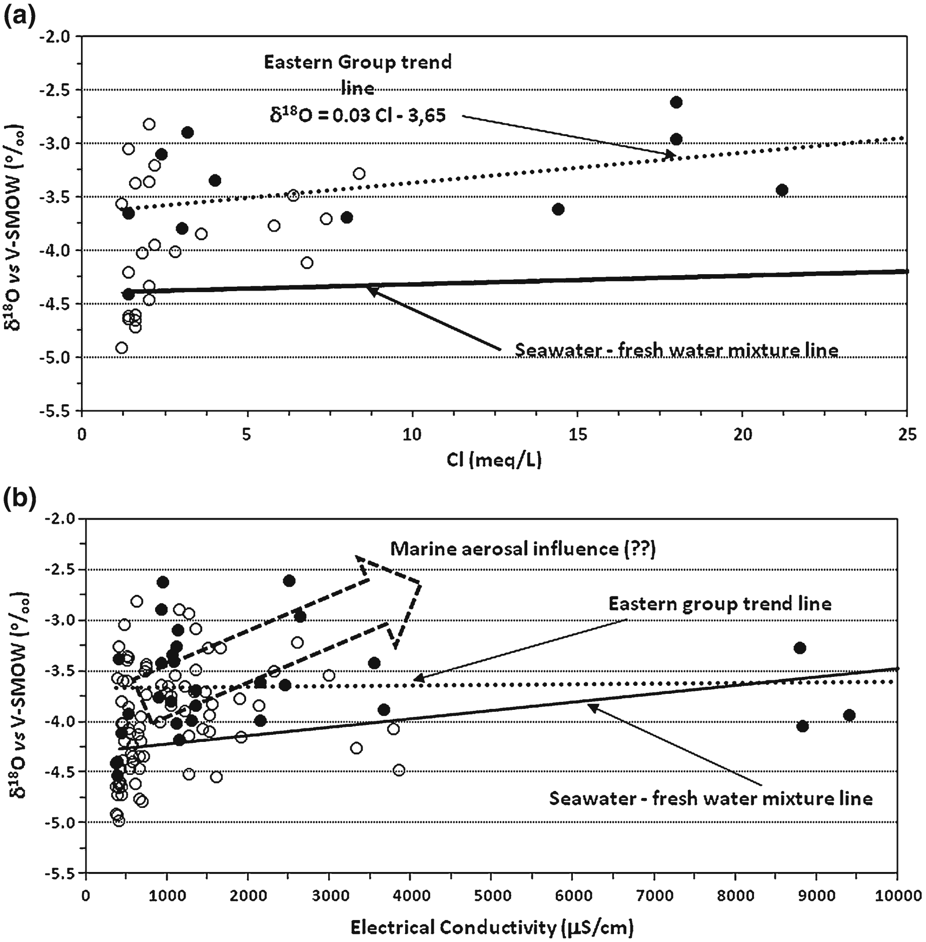

Fig. 12 **a** $\delta^{18}O$ vs Cl contents and **b** vs electrical conductivity of the sampled groundwaters

In the $\delta^{18}O$ vs Cl plot (Fig. 12a) the samples falls within the fan-shaped field whose boundary lines allowed the evaluation of the isotopic range of a possible meteoric recharge to the aquifer system, having this group of samples $\delta^{18}O$ values in the range of −5.0 to −4.0‰. The Cl enriched waters, are characterized by a more enriched stable isotopic content, approximating the probable seawater mixing trend line rather well. It should be stated that this trend line is more detectable within the eastern group of groundwaters. Further, this mixing pattern is also evident when the $\delta^{18}O$ values are plotted as a function of the electrical conductivity. The enrichment in heavy isotopes is followed by an increase in the electrical conductivity values (Fig. 12b). In the diagram of Fig. 12b, the trend line of the eastern group is not parallel to the X-axis as in the diagram of Fig. 12a. In both diagrams, a number of samples reveal a significant enrichment in ^{18}O, which cannot be explained only due to seawater intrusion. The pattern presented by this group of groundwater samples might in part be explained by direct infiltration of irrigation waters undergoing significant evaporation during

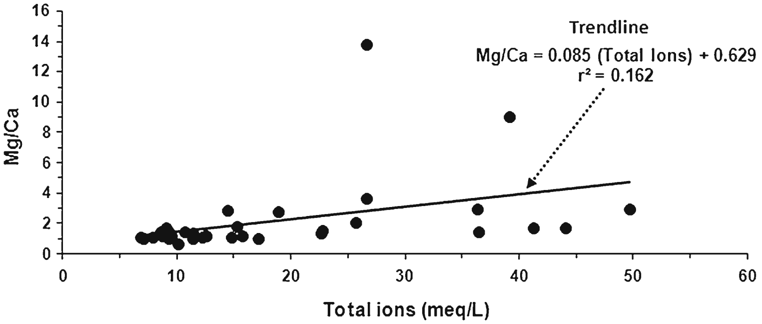

Fig. 13 Mg/Ca ratios versus total ions in the sampled groundwaters

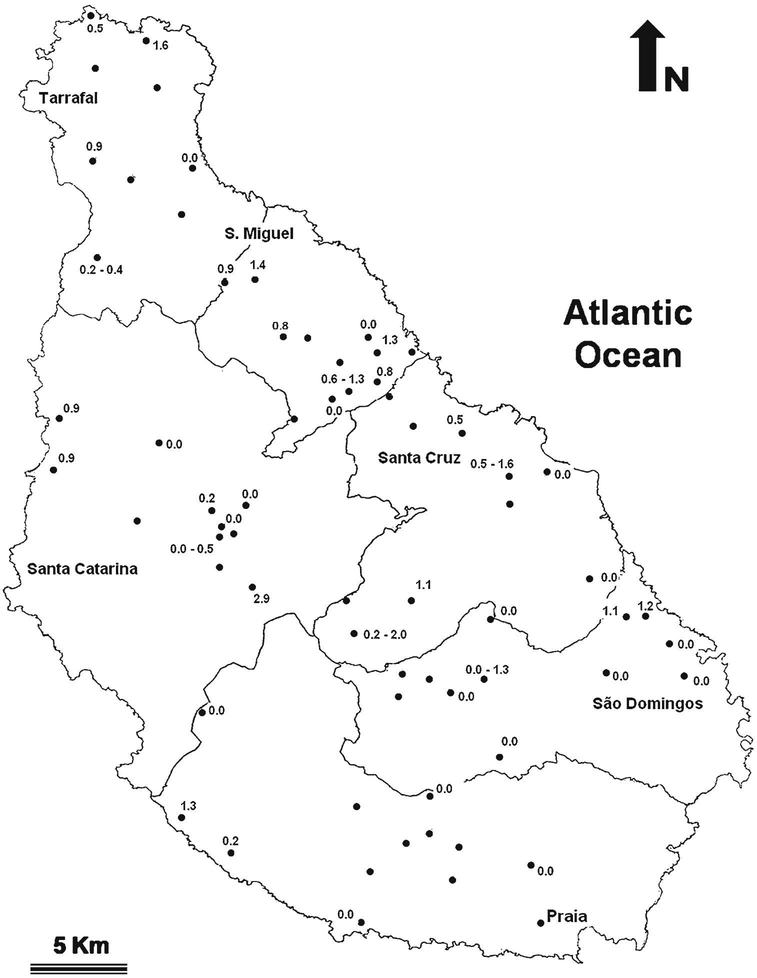

Fig. 14 Schematic map of Santiago Island, with the tritium content measured in the groundwater samples

the dry periods. On the other hand, within this group of waters, the influence of marine aerosol cannot be excluded since the isotopic enrichment is also followed by an increase in the Cl and Na content (see Fig. 5). Additionally based on the Mg/Ca ratios of the groundwater samples the hypothesis of extended water–rock interaction responsible for a change in seawater chemical composition (e.g. decrease in the Mg/Ca ratios) was formulated. The hypothesis of the occurrence of ancient seawater trapped in the geological formations responsible for the salinization increase is still in open since the results were not conclusive (Fig. 13).

The tritium content was measured in the all groundwater samples; the values obtained vary between 0 ± 0.6 and 3 ± 0.6 TU. Majority of the samples points that have no tritium (higher residence time) are located near the coastline, supporting the hypothesis of a larger flow path (Fig. 14). No correlation was however found between tritium concentrations either with the altitude of the sampling sites or with the electrical conductivity since the major part of the groundwater samples present no tritium in their composition. Unfortunately, no long series of ^{3}H content in rainfall of the area are available on the Cabo Verde archipelago. In fact, due to the absence of ^{3}H and the lower content found in remaining groundwater samples, it is difficult to estimate the turnover rates of the groundwater. Nevertheless, according to the work performed by Akiti (1985) in the N part of the island (Tarrafal) a mean residence time of 30 years was attributed. Moreover, according to that author, 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 water slowly from joints and fractures (Akiti 1985).

5 Concluding Remarks and Outlook

Groundwater is of major importance in providing not only private domestic and agricultural use, but also public water supply in many parts of the World. On the other hand, the subsurface has also become major recipient of wastewater and solid waters especially in the developing Countries. Concomitant widespread indications of groundwater degradation caused by extreme exploitation and or insufficient pollution control are evident.

The results of the study carried out in the semi-arid area of Santiago Island and Cabo Verde Archipelago are presented. Combinations of geochemical and isotopic methodologies were applied to describe the origin and evolution of groundwater in coastal aquifers in this region. The major challenge in this study was to distinguish saline water of different origins and seawater of different generations. The results point out that, the land extent of seawater intrusion and the influence of marine aerosol appear to be moving backwards. These results are supported by the recent increase in the groundwater electrical conductivity data towards the interior of the Island. The high salt content in groundwater systems is mostly ascribed to agricultural zones in valleys areas and seaside surroundings, interconnected with intense overexploitation of the groundwater resources and the scarcity of precipitation.

Based on the PCA results the hydrogeochemical variance of the water samples appears to characterize first the water–rock interaction processes, responsible for the high loadings in Ca, Mg and Cl. Followed by the influence of marine spray /seawater intrusion. PC3 represented by the high loadings in SO_4, HCO_3 and Na, should be ascribed to the influence of anthropogenic input (agriculture activities introduction of SO_4 associated to insecticides and fertilizers in the agricultural fields, particularly within the banana and papaya plantations).

The isotopic pattern presented by the groundwater samples can part be explained by the fact that they have been more or less subjected to evaporation. In fact, the more positive $\delta^{18}O$ groundwater values could be related to direct infiltration of irrigation waters undergoing significant evaporation, during the dry periods. On the other hand, within this group of waters, the influence of marine aerosol cannot be excluded since the isotopic enrichment is also followed by an increase in the Cl and Na content. It is concluded that effective management of the groundwater resources in Santiago Island requires a future detailed assessment of available water resources through a multidisciplinary approach including isotopic, chemical and geophysical surveys.

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