Groundwater salinization in the Azores archipelago (Portugal): an overview

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ABSTRACT

Groundwater salinization due to mixture with seawater is one of the major pressures on water resources quality in the Azores archipelago and often leads to failure to comply with national water quality regulations. In order to study this process, a groundwater chemistry data set made of 54 samples from wells in the basal aquifer systems was assembled. It depicts the effects of salinization: samples are mainly from the Na-Cl type and conductivity measurements (in the range 127-9670 μS/cm) suggest the occurrence of high mineralized waters. In many waters Na^++K^+ exchange by Ca^{2+}+Mg^{2+} reactions are associated to the mixing mechanism.

INTRODUCTION

The Azores archipelago is located in the North Atlantic Ocean, between latitudes 36°55´43″N to 39°43´23″N and longitudes 24°46´15″W to 31°16´24″W. Comprising nine islands of volcanic origin, the archipelago has an area of 2333 km^2, and about 240,000 inhabitants. Being an autonomous region from the Portuguese republic has specific authority to define its own policies for water resources management.

Groundwater salinization in coastal regions causes severe constraints to water supply and economic losses to society worldwide. Therefore, studies of the main drivers and consequences of seawater intrusion have resulted in many publications in the international literature. In the Azores archipelago, groundwater abstraction in wells drilled in coastal aquifers is very important for water supply, and quality problems have been reported.

The present study characterizes the major-ion chemistry of the basal aquifer system on the majority of the islands from the Azores, in order to study the effects of mixture between freshwater and seawater and the evolution of the groundwater composition.

HYDROGEOLOGICAL SETTING

Groundwater in the Azores occurs in two major aquifer systems: (1) the basal aquifer system corresponds to freshwater lenses floating on underlying saltwater, and (2) the altitude aquifer system, that corresponds to perched-water bodies.

The basal aquifer system lies in the coastal area of the several islands, generally presenting a very low hydraulic gradient. Exploitation of the basal aquifer systems occurs mainly from wells,

which began to be drilled in the late 1950s to reinforce the water supply, and groundwater abstraction relies almost exclusively on the basal aquifer system in islands like Pico or Graciosa. Specific well capacity ranges between 1.40×10^{-2} L/s.m and 266.67 L/s.m (median=32.3 L/sm). Transmissivity values also present a large range, with values between $1.7x10^{-5}$ and $4x10^{-1}$ m^2/s (median=$3.7x10^{-2}$ m^2/s). The highest transmissivity values are from wells drilled in recent basaltic lava flows, which generally have interbedded unconsolidated clastic (*clincker*) levels.

GROUNDWATER SALINIZATION IN THE AZORES

Methodology and data presentation

A hydrogeochemical database of 54 drilled wells spread along Santa Maria, São Miguel, Terceira, Pico, Graciosa, and Faial was compiled from recent analytical work, complemented by additional data from previous studies. The well depths range from 25 to 284 m. The wells are located at a distance from the coast that ranges from 300 to 5825 m.

Groundwater represented in the dataset has a highly variable mineralization, reflected by the electrical conductivity measurements, which range from 127 to 9670 μS/cm (median= 862 μS/cm). Higher values are generally observed on Santa Maria, São Miguel, Pico, Graciosa and São Jorge islands. Waters are mainly slightly acidic to slightly alkaline, with a pH ranging between 5.63 and 8.50 (median=7.40). On Graciosa, Pico, and Faial wells present pH values usually above 7.

Plotting the major-ion composition in a Piper-type diagram shows that the majority of the waters are of the Na-Cl type, despite a few samples that actually present Mg-enrichment in the cationic triangle and HCO_3-enrichment in the anionic triangle (Figure 1). In fact, water mineralization is mainly controlled by Cl^- and Na^+ content, which accounts respectively for 10.8% to 45.1% and 15.7% to 53.2% of the relative ion content in the groundwater. These major ionic species in solution are positively correlated (r = 0.989), and their contribution to the overall chemical composition of the groundwater can also be shown by the good correlations between Cl^- or Na^+ and water conductivity (respectively r = 0.939 and r = 0.935).

Discussion

Results suggest the influence of sea salts in the groundwater compositional evolution, which is essentially explained by seawater intrusion into wells. The seawater fraction in groundwater composition, calculated assuming a binary mixture and Cl^- as a conservative ion, reaches a maximum of 22.5% (average=2.2%) The majority of the samples present a seawater fraction lower than 3.3%, but nine wells are in the range of 3.4% to 9.9%, mainly from Pico (44.4% of this group of wells) and São Jorge islands (22% of this group of wells). One well located in Santa Maria has a seawater fraction in the 19.9%-23.2% range.

The magnitude of seawater intrusion can also be inferred from the calculation of the Revelle coefficient (1941), which ranges between 0.31 and 46.6 (median=2.9), with about 53.7% of the studied wells presenting values greater than 2.

In order to depict the hydrogeochemical mechanisms associated to the mixture process the method suggested by Appelo and Geinaert (1991) was applied, which implies, in advance, to calculate the theoretical composition expected considering only the occurrence of a mixing process between freshwater and seawater, through the numerical expression proposed by

Appelo and Postma (1993). This methodology shows that the composition of most samples is plotted above the mixing line, thereby reflecting the influence of $Na^{+}+K^{+}$ exchange by $Ca^{2+}+Mg^{2+}$. Cation exchange reactions are often associated with water salinization processes, which explain the enrichment or depletion of cations in solution (Appelo and Postma 1993). These results are consistent with the base exchange index, provided by the ratio rCl-r(Na+K)/rCl (Custodio and Llamas 1983).

A few samples depict a bicarbonate enrichment, above the expected values considering only the mixture with seawater, which was already described for Pico island case study and for the mineral waters that discharge from the basal aquifer system in the Azores. This enrichment is attributed to silicate weathering that, despite the dilution effect of sea salts in the higher mineralized waters, and volcanic inputs.

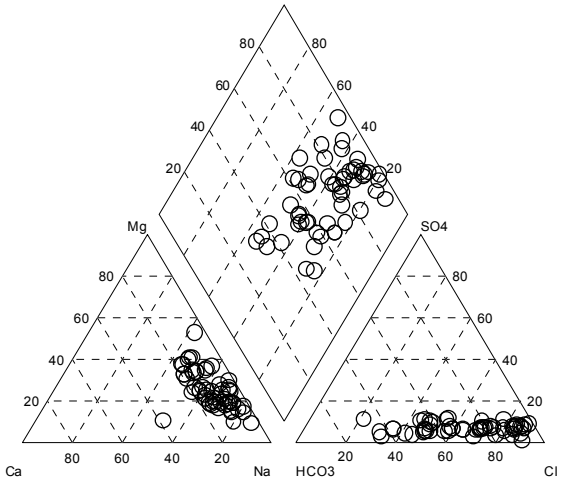

Figure 1. Major-ion composition represented by means of a Piper-type diagram.

Temporal evolution and compliance with quality regulations

In order to characterize groundwater salinization over time, an extensive collection of Cl^{-} content in wells was made possible through unpublished and published reports since the early 1960s. These time-series plots depicts the evolution of salinization in the basal aquifer systems and can be useful to check compliance with drinking water quality standards (Figure 2).

The Cl^{-} content in the majority of the wells located on Graciosa and Pico exceeds recommended Portuguese Drinking Water Standards (PDWS) (5.64 meq/L or 200 mg/L) during the observed period (Figure 2). In opposition, the majority of the wells located on Santa Maria and São Miguel complied with the referred PDWS value.

Major increases in Cl^{-} content are also found on Graciosa (wells 27, 30) and Pico (wells 33, 35), which is suggested to be a result of inadequate pumping rates. This effect is clear, considering the cyclic trend depicted by well 9 on São Miguel, where sharp increases in Cl^{-} content are clearly observable, mainly in the summer period, in response to higher pumping rates.

CONCLUSIONS

Groundwater in basal aquifers systems from the Azores is mainly of the Na-Cl type and present electrical conductivity in the range 127 - 9670 μS/cm, higher than values observed in perched-water bodies. Seawater fraction reaches a maximum of 22.5%, with higher values observed in

Pico and São Jorge. As well as the contribution of seawater, other processes may modify groundwater composition, such as cation exchange reactions and silicate weathering.

Salinization is a major pressure to water resources in the Azores and one of the most demanding questions for water managers. As a result of groundwater salinization, major-ions in solution frequently exceed national drinking water standards, leading on some islands to well abandonment, with severe economic losses and constraints to water supply.

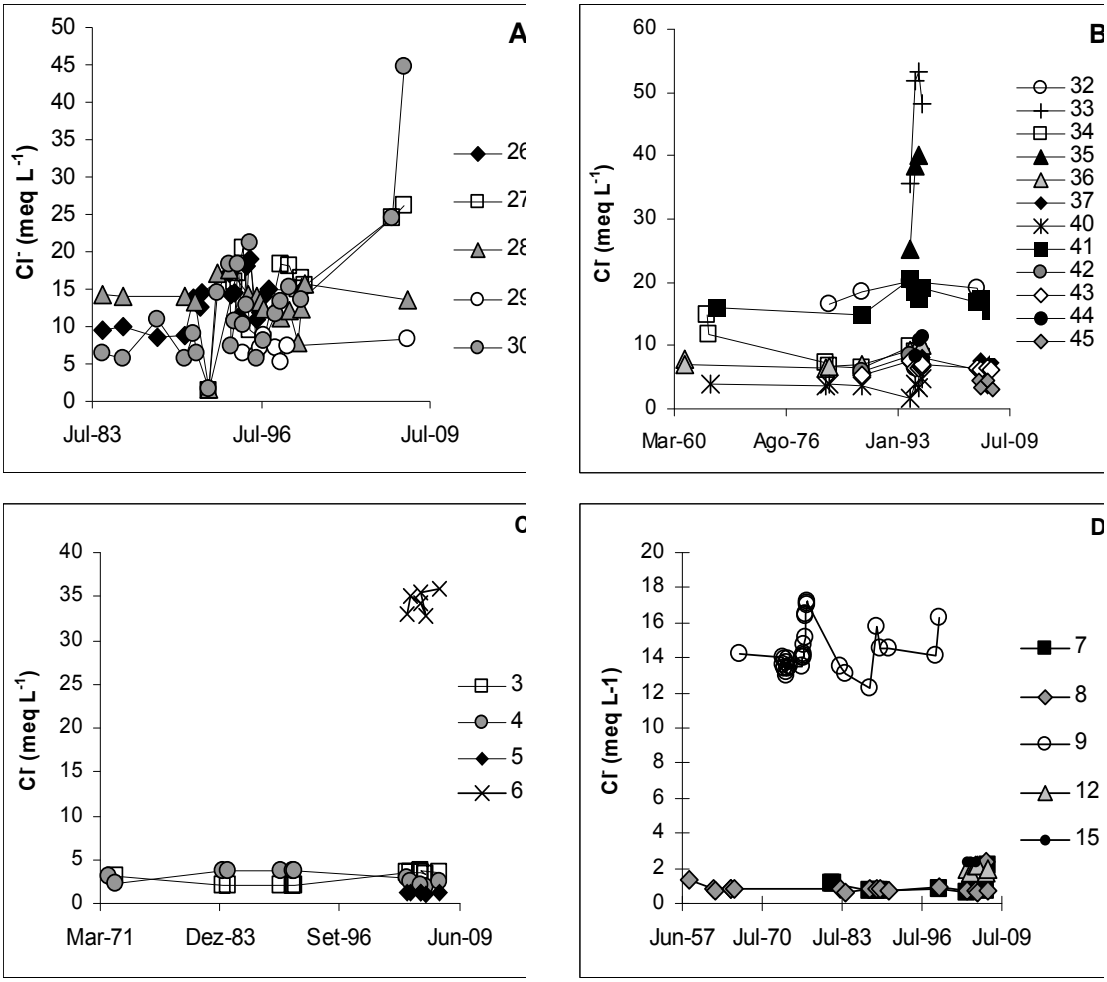

Figure 2. Cl^- time-series for wells in Graciosa (A), Pico (B), Santa Maria (C) and São Miguel islands (D).

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