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Using stable isotopes to characterize groundwater recharge sources in the volcanic island of Madeira, Portugal

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SUMMARY

The hydrogeology of volcanic islands remains poorly understood, despite the fact that populations that live on them rely on groundwater as a primary water source. This situation is exacerbated by their complex structure, geological heterogeneity, and sometimes active volcanic processes that hamper easy analysis of their hydrogeological dynamics. Stable isotope analysis is a powerful tool that has been used to assess groundwater dynamics in complex terrains. In this work, stable isotopes are used to better understand the hydrogeology of Madeira Island and provide a case-study that can serve as a basis for groundwater studies in other similar settings. The stable isotopic composition ($\delta^{18}O$ and $\delta^{2}H$) of rain at the main recharge areas of the island is determined, as well as the sources and altitudes of recharge of several springs, groundwater in tunnels and wells. The water in tunnels was found to be recharged almost exclusively by rain in the deforested high plateaus, whilst several springs associated with shallow perched aquifers are recharged from rain and cloud water interception by the vegetated slopes. Nevertheless some springs thought to be sourced from deep perched aquifers, recharge in the central plateaus, and their isotopic composition is similar to the water in the tunnels. Recharge occurs primarily during autumn and winter, as evidenced by the springs and tunnels Water Lines (WL). The groundwater in wells appears to originate from runoff from rain that falls along the slopes that infiltrates near the streams' mouths, where the wells are located. This is evident by the evaporation line along which the wells plot. Irrigation water is also a possible source of recharge. The data is compatible with the hydrogeological conceptual model of Madeira. This work also shows the importance of cloud water interception as a net contributor to groundwater recharge, at least in the perched aquifers that feed numerous springs. As the amount of rainfall is expected to decrease until the end of the century and water supply to become scarcer, cloud water interception might become an increasingly important aspect of Madeira Island hydrology.

1. Introduction

Understanding the hydrogeological functioning of a region is fundamental for the sustainability, protection and management of its water resources. Volcanic islands represent only a small fraction of the Earth surface due to their small area, however their inhabitants are usually heavily dependent on groundwater sources for water supply, both due to the hydrological setting and aggravated by the impracticability of proceeding to water resources transfers from other regions. Therefore, the study of volcanic islands hydrogeology, especially in those regions that are densely populated, is extremely important (Custódio, 1978; Cruz and Amaral, 2004; Cruz and Silva, 2001; Ingebritsen and Scholl, 1993; Lau and Mink, 1995; Peterson, 1972, 1993; Scholl et al., 2002; Stieltjes et al., 1988).

The development of conceptual groundwater models in most volcanic islands is challenging due to their geological complexity and the difficulty in obtaining data on their internal structure (Izquierdo, 2014). Stable isotope analysis is a powerful tool to investigate volcanic islands in order to: (1) determine areas of and calculate altitudes of recharge, (2) determine recharge periods and sources, and, (3) offer an insight in the groundwater flow paths (Carreira et al., 2010; Heilweil et al., 2009; Hildenbrand et al., 2005; Herrera and Custodio, 2008; Lee et al., 1999, 2007; Mandal et al., 2011; Scholl et al., 2002). Typically, rain becomes depleted in the heavier isotopes with increasing altitude due to decreasing

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temperature and rainout of the air mass (Clark and Fritz, 1997; Gat, 2010), thus a strong negative correlation between altitude increase and isotope enrichment is found in several regions (Lee et al., 1999; Prada et al., 2015a; Scholl et al., 1996, 2002). This relationship makes the estimation of recharge altitudes of groundwater discharged in a homogeneous geological setting a relatively straightforward exercise (Parisi et al., 2011). However, there are several aspects that challenge this simplistic approach such as the variation of rain isotopic composition throughout the year, which reflects variations in temperature, air humidity, air mass source, evapotranspiration, and rainfall amount and type (Aráguas-Aráguas et al., 2000; Clark and Fritz, 1997; Dansgard, 1964; Gat, 1996, 2010), s surface runoff, irrigation water and snow and glacier melting (Earman et al., 2006; Fernández-Chacón et al., 2010). Besides, in regions where orographic fog is common (like in mountainous islands), cloud water interception by vegetation may also contribute to groundwater recharge (Prada et al., 2010a, 2010b; Scholl et al., 2002, 2011; Scholl and Murphy, 2014). Cloud water interception normally occurs when a cloud intercepts the topographic surface (fog), and the water droplets in suspension adhere to the vegetation and thereafter coalesce into heavier droplets that drop to the ground surface. This is a phenomenon, also known as fog precipitation that takes place in areas where dense, moist fog, wind and vegetation occur simultaneously, and for enough time (Bruijnzeel et al., 2005; Eugster et al., 2006; Prada, 2000; Scholl et al., 2011). In mountainous environments where these features are common, cloud water interception has a visible impact in the water budget. This effect may be direct, as a net contribution to recharge and/or runoff (Aravena et al., 1989; Ingraham and Matthews, 1988, 1990, 1995; Prada et al., 2010a; Scholl et al., 2002; Scholl and Murphy, 2014) and/or indirect, by attenuating ecological water stress during dry periods and by reducing evapotranspiration, due to higher air humidity, lower temperatures and decreased insolation (García-Santos and Bruijnzeel, 2011; Reinhardt and Smith, 2008; Ritter et al., 2009; Sperling et al., 2004).

Madeira is a densely populated island (c. 265 000 inhabitants) as well as a well-known touristic destination (more than 1 million visitors per year) located in the North-Atlantic, whose water supply is heavily dependent on groundwater and, on a smaller scale, on surface runoff (SRA, 2014; Prada et al., 2003). As rainfall is projected to be reduced by as much as 30% until the end of the century as a result of climate change (Santos and Aguiar, 2006; Tomé, 2013), and, consequently water availability (Prada et al., 2015b) the study of the groundwater resources occurring in Madeira is instrumental for an efficient and sustainable exploitation and management. Several studies on Madeira water resources have been conducted in the past few years (Figueira et al., 2013; Prada, 2000; Prada and Silva, 2001; Prada et al., 2003, 2005a, 2005b, 2009, 2015a, 2015b). Prada et al. (2010a) and Fernandes et al. (2010) have already hinted about the contribution of cloud water to groundwater recharge in Madeira. Figueira et al. (2013) have discussed some of the implications that this water source may have in the sustainability of the laurel montane cloud forests of the island, an endangered ecosystem designated as a World Heritage Site by the United Nations Educational, Scientific and Cultural Organization (UNESCO, 2015).

In this work, the isotopic composition of rain and groundwater from different hydrogeological features such as springs, tunnels and wells is used to interpret the regional hydrogeology. The objectives are to: (1) verify if cloud water is a component of groundwater recharge, (2) estimate recharge altitudes, and (3) validate the hydrogeological conceptual model of Madeira. We present a case study on the application of isotope analysis in a volcanic island hydrogeology setting whose findings are valuable to other volcanic settings throughout the world.

2. Madeira Island characterization

2.1. Geological and climatic setting

The Madeira Island is located in the eastern central North Atlantic, about 700 km west of the African coast and 850 km southwest of Portugal Mainland (Fig. 1). The island is bound by latitudes 3 2°38′N–32°52′N and longitudes 16°39′W–17°16′W and has an area of approximately 737 km^2. It is the aerial portion of a volcanic edifice that rises from the ocean floor from depths of around −4000 m a.s.l. (above sea level) up to an elevation of 1861 m a.s.l. at Pico Ruivo.

The climate in Madeira is influenced by the location and intensity of the Azores High (Cropper, 2013; Cropper and Hanna, 2014; Herrera et al., 2001; Prada et al., 2015a). The northeastern trade winds, associated with the eastern branch of the Azores High predominate throughout the year mainly during spring and summer. During autumn and winter the island is also affected by heavy rainfall from low pressure systems and associated fronts that cross the North Atlantic or are originated between the island and the Iberian Peninsula (Lima and Lima, 2009; Prada et al., 2003). At the regional scale, the climate and weather patterns are influenced by local factors, such as topography, altitude, solar radiance and wind exposure. This results in local microclimates, in the manifestation of altitudinal gradients of temperature and rainfall, and in climatic differentiation between the windward (north) and leeward (south) slopes (Cropper, 2013; Prada et al., 2003, 2015a). Annual precipitation varies between 513 mm in the southeastern coastline and about 3000 mm in the central high areas (Prada et al., 2003 – Fig. 1C). Mean air temperature decreases with increasing altitude and spans from 19.4 °C in the southern coastline to 9.1 °C in the central high areas. Annual mean air humidity varies between 75% and 90%, with the exception of the southern coastline, where air humidity varies between 55% and 75% (Prada et al., 2003).

A frequent windward orographic cloud belt occurs as a result of the contraction and expansion of clouds transported by the trade winds and of the adiabatic cooling of the air mass as it crosses over the mountain range (Prada et al., 2009, 2015a). It is within these fog immersed areas that cloud water interception occurs (Figueira et al., 2013; Prada et al., 2009, 2012, 2015a).

2.2. Hydrogeological setting

Groundwater is the most important source for water supply in Madeira. Water is withdrawn from springs that discharge from perched aquifers (60%; ~3500 L/s), from tunnels (20%; ~1150 L/s) and drilled wells (20%; ~1200 L/s) the latter withdrawn from the basal aquifer. Prada et al. (2003) defined a conceptual hydrogeological model for Madeira, where two major domains are considered, namely perched and basal groundwater (Fig. 2). Basal groundwater corresponds to a fresh water lens floating on seawater. The model shows that there is a hydraulic connection between the coastal basal groundwater and inland areas with a steep increase of the hydraulic gradient, that is related to: (1) volcanic rocks becoming older and less permeable toward the interior of the island, (2) abundant low permeability dikes that are intruded vertically slow the movement of water toward discharge points, and (3) the groundwater flow from inland recharge areas, where the piezometric level exceeds 1000 m a.s.l., toward the shoreline.

The abundance of dikes in the central part of the island, usually less permeable than the rocks they intrude, can impound basal groundwater to high altitudes (Fig. 2). As a result, groundwater can be found at shallow depths in the high plateaus, where recharge mainly occurs. Water accumulated in different