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# Contribution of cloud water to the groundwater recharge in Madeira Island: preliminary isotopic data

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## Abstract

Situated about 600km southwest of mainland Portugal, in the North Atlantic, Madeira is the bigger and more populated island of the archipelago with the same name. It has a total area of 747km$^2$ and its northern slope forms a barrier that opposes the prevailing north-easterly trade winds, thus resulting in a very frequent windward fog belt, between 800-1600m a.s.l. Madeira has a 125km$^2$ area of indigenous altitude forests inside the windward fog belt, between 800-1600m a.s.l. This area is characterized by very steep slopes, mainly exposed to the prevailing winds. When combined, factors like steep slopes, great exposure to the humid trade winds and presence of forest vegetation facilitate fog precipitation. This is why we assume that fog precipitation is a generalized phenomenon throughout Madeira's northern slope area.

To ascertain whether or not fog water contributes to groundwater recharge, a study on the stable isotopic composition was made. For that purpose, assuming a difference between isotopic composition in rain and fog (fog being enriched in heavier isotopes $^2$H and $^{18}$O relative to rain at the same altitude and region), several samples of fog water, rain water and groundwater were collected for stable isotopic analysis. Groundwater was collected, according to from springs and tunnels representing perched and basal aquifers, respectively; fog water was collected on trees by hand by placing a funnel in a collection bottle and dabbing droplets which collected on the foliage, in rainless days of intense fog, under 98-100% relative humidity conditions, thus preventing sample evaporation enrichment; rain water was collected in containers with a 1cm thick layer of mineral oil to prevent evaporation, representing a sample of several rain events.

The preliminary stable isotopic compositions of fog, rain and groundwater samples collected are plotted in figure 1 along with the Global Meteoric Water Line (GMWL). The rain samples are the most isotopically depleted and fog samples the most enriched ones. Groundwater data is plotted in an intermediate position between the stable isotopic ratios for rain and fog waters.

The composition of groundwater may be explained by evaporation of the rain prior to infiltration. However, the isotopic composition of groundwater does not appear to depict any evaporative effects. So, the best explanation is that some of the fog water infiltrates and recharges the groundwater system of the Madeira Island, as observed in other regions.

## 1. Introduction

Situated at about 600km southwest of mainland Portugal, in the North Atlantic, Madeira is the biggest and more populated island of the archipelago with the same name. This volcanic island was originated more than 5.6 Ma ago by an oceanic hot-spot in the African Plate (Ech-Chakrouni, 2004). With a total of 737km$^2$, its rugged relief reaches a maximum altitude of 1861m a.s.l., at Pico Ruivo. The island forms an E-W oriented mountain range, resulting in a barrier to the prevailing north-easterly trade winds. The adiabatic cooling of the air masses that are pushed up the slopes of the island originates a very frequent windward cloud belt, between 800-

1600m a.s.l. This leads to events of thick, very moist and turbulent ground fog that can last for several days. Cloud water interception occurs when cloud droplets (essentially fog droplets of various sizes and sometimes drizzle) coalesce on foliar and woody surfaces as the cloud base passes through the canopy (Bruijnzeel *et al.*, 2005; Holder, 2003, 2004; Prada *et al.* 2009; Brauman *et al.*, 2010). In the absence of the vegetation, this water would not precipitate into the soil in significant quantities (Cunha, 1964; Davis and DeWiest, 1991). Different factors influence the amount of cloud water intercepted. Among these, cloud droplet size, cloud liquid water content, vegetation size and morphology, site exposure to wind and wind velocity are the most important. The cloud belt occurs in an area that is characterized by steep slopes, mostly covered by indigenous altitude forest (Prada *et al.*, 2008) and it is assumed that cloud interception is a common phenomenon along the area (Prada *et al.*, 2010).

Groundwater is the most important water supply source in Madeira. As such, knowledge about the island's water cycle is important for a correct management and evaluation of water resources. The objective of this work was to determine if cloud water contributes to groundwater recharge. Cloud water is normally enriched in the heavier isotopes $^{2}H$ and $^{18}O$ relative to rain at the same altitude and region (Ingraham and Mathews 1988, 1995; Clark and Fritz, 1997). By comparing the isotopic composition of both of them with groundwater, it is possible to determine if recharge occurs essentially through rain infiltration, or if it is a mixture of rain and cloud water.

## 2. Materials and Methods

Groundwater samples were collected, according to Clark and Fritz, (1997), from springs and tunnels throughout the island, representing perched and basal aquifers, respectively. Cloud water was collected on trees by hand by placing a funnel in a collection bottle and dabbing droplets which collected on the foliage, in rainless days of intense fog, under 98-100% relative humidity conditions, thus preventing sample evaporation enrichment. Rain water was collected in containers with a 1 cm thick layer of mineral oil to prevent evaporation according to Clark and Fritz (1997) and School *et al.*, (2002), representing a sample of several rain events. Both rain and cloud water were only sampled at altitudes above 1000m a.s.l., due to the fact that groundwater recharge mainly occurs above this level (Prada *et al.*, 2005).

## 3. Results and discussion

The preliminary stable isotopic compositions of fog, rain and groundwater samples collected are plotted in Figure 1 along with the Global Meteoric Water Line (GMWL), first described by Craig (1961). The rain samples are the most isotopically depleted and fog samples the most enriched ones. Groundwater data is plotted in an intermediate position between the stable isotopic ratios for rain and fog waters.

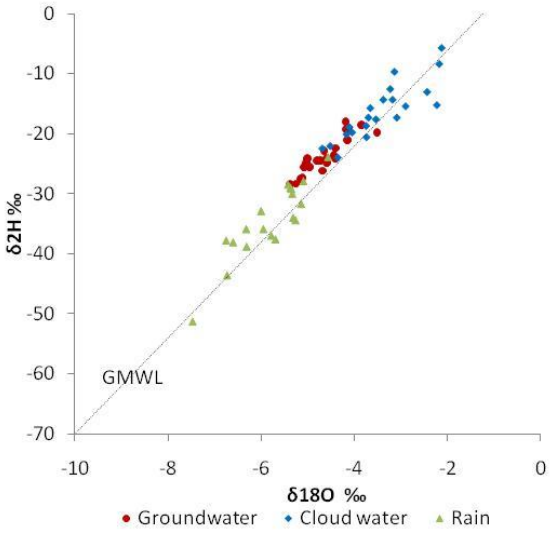


Figure 1: Graphic with plotted rain, cloud water, groundwater and the GMWL. Groundwater (red circles) is isotopically enriched when compared to rain water (green triangles). This shows evidence that cloud water is an alternative source of groundwater recharge.

The composition of groundwater may be explained by evaporation of the rain prior to infiltration. However, the isotopic composition of groundwater does not appear to depict any evaporative effects. So, the best explanation is that some of the fog water infiltrates and recharges the groundwater system of the Madeira Island, as observed in other regions by Ingraham and Matthews (1988; 1995).

## 4. Summary and Conclusions

The preliminary isotopic results show that groundwater in Madeira has a different isotopic composition from that of the meteoric water in the recharge area. There is evidence that at least some cloud water infiltrates and recharges the aquifers. Further analysis of the data is currently being performed. With this, we expect to refine Madeira's hydrological model through a better understanding of recharge altitudes, water origins and groundwater dynamics.

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