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Sete Cidades and Furnas lake eutrophication (São Miguel, Azores): Analysis of long-term monitoring data and remediation measures

J. Virgílio Cruz [a,*], Dina Pacheco [b], João Porteiro [c], Raquel Cymbron [b], Sandra Mendes [b], Andrea Malcata [b], César Andrade [a]

[a] CVARG — Centre of Volcanology and Geological Hazards Assessment, Department of Geosciences, University of the Azores, Apartado 1422, 9501-801 Ponta Delgada, Portugal
[b] Directorate-Regional for the Environment, Av Antero de Quental, 9C, 2° Piso, 9500-160 Ponta Delgada, Portugal
[c] CIBIO — Azores, Research Center in Biodiversity and Genetic Resources, Department of Biology, University of the Azores, Apartado 1422, 9501-801 Ponta Delgada, Portugal

HIGHLIGHTS

- Eutrophication of lakes in the Azores (Portugal) imply water quality deterioration
- Long-term monitoring data from Sete Cidades and Furnas lake is discussed
- Water chemistry influenced by anoxic environment in the bottom during summer
- Ratio TN/TP suggests an improvement in water quality due to remediation measures
- Internal P-loading influences trophic status

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ABSTRACT

Eutrophication of lakes in the Azores archipelago (Portugal) has been described since the 80s, and due to water quality deterioration several remediation methodologies were applied. Long-term monitoring data on water quality from Sete Cidades and Furnas lakes (São Miguel island) were analyzed in order to address that the success of the ongoing policy reverses their eutrophic status. Sete Cidades lake (4.46 km^2), made by two branches (so-called Green and Blue lakes), has a water volume equal to 58×10^6 m^3 and a depth in the range between 24 and 28.5 m. Furnas lake (1.87 km^2) has a volume equal to 14×10^6 m^3 and a maximum depth of 15 m.
In Sete Cidades lake mean water temperature and pH range respectively between 13.4 °C to 17.7 °C and 7.04 to 8.06. Instead, mean temperature in Lake Furnas ranges between 16.6 °C and 17.2 °C, with a pH between 7.36 and 7.84. Mean water conductivity shows that both lakes correspond to very diluted waters, with values between 98.1 and 136.5 μS/cm. Water chemistry is influenced by the monomictic character of the lakes, as anoxic environment in the hypolimnion due to O_2 consumption during the summer, when stratification prevents mixing along the water column, explains sharp increase in TP, TN, N-ammoniacal, Mn and Fe.
Major-ion content is rather constant along time, with some seasonal fluctuations, despite a decrease in SO_4 observed in Sete Cidades lake which is suggested to be a result of runoff diversion, a result also shown by the decrease of the molal ratio TN/TP in both studied lakes. Nevertheless, the application of the trophic state index (TSI_{TP}) does not suggest an improvement in what concerns trophic status, which is explained by the internal P-loading, a source that have to be managed by environmental authorities in the near future in order to revert eutrophication.

1. Introduction

Eutrophication of surface water bodies is a worldwide phenomenon, placing difficult challenges to all involved in water management due to water quality deterioration (Smith et al., 1999, 2006; Prepas and Charette, 2005; Smith and Schindler, 2009) which requires a multidisciplinary approach to deal with this problem (Orderud and Vogt, 2013) and imposes severe environmental costs (Pretty et al., 2003). Several case studies on this subject have been described worldwide addressing water (Zhukova, 2011; Huo et al., 2013; Khadka and Ramanathan, 2013) and sediment matrixes (Muri et al., 2013), as well as the eutrophication enhancement through climate change (Moss et al., 2011; Foley et al., 2012; Verspagen et al., 2014). Following the adoption of measures to prevent or reduce nutrient loads to water bodies, impacts

* Corresponding author.
E-mail address: jvc@uac.pt (J.V. Cruz).

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over water quality have been measured in several studies (Jeppesen et al., 2005; Kohler et al., 2005). The adoption of the Water-Framework Directive (WFD) by European Union member states also led to the development of new tools to deal wit eutrophication of water bodies (Cardoso et al., 2007; Arnaud et al., 2013).

An extensive survey conducted for the Azores Water Plan, that came to force on the 23rd of April 2003, has identified 88 surface lakes, occupying a total surface area of 9.5 km^2 (0.4% of the entire archipelago area). Two other identified lakes occur inside lava caves in Graciosa and Terceira islands. The volume of water contained in the Azores lakes is equal to 9×10^7 m^3, 93% of which corresponds to São Miguel lakes, 5% to Flores lakes, while the remaining corresponds to the lakes in Terceira, Pico and Corvo (DROTRH/INAG, 2001). Of all the lakes, the Sete Cidades lake (São Miguel island) contains 478×10^5 m^3 of water and is the most voluminous lake in the Azores (Pacheco et al., 2010). Half of these lakes are located inside explosive craters, namely in scoria cones (26.7%) or in hydrovolcanic craters (23.3%), while 16.7% of the lakes are located in the bottom of subsidence calderas. Therefore, 66.7% of the lakes are related to craters or calderas, which is common for volcanic lakes worldwide (Cruz et al., 2006).

The Azores archipelago is one of the seven outermost regions from the European Union. Located in the North Atlantic Ocean, between 37° to 40°N latitude and 25° to 31°W longitude, about 1500 km from Portugal mainland, the archipelago is made of nine islands of volcanic origin, spread along a WNW–ESE trending strip, about 640 km long (Fig. A — electronic supplementary material). It has a total surface area of 2322 km^2, but the dispersion and the fragmented character of the territory are shown by the islands' surface area, ranging from 17 to 745 km^2 (SREA, 2014) The islands have 247,440 inhabitants (data from year 2013; SREA, 2014), mainly living in São Miguel (56%) and Terceira (23%), associated with an irregular distribution of the population as depicted by the density in the several islands which range between 26.7 and 186.2 inhabitants/km^2 (SREA, 2014).

Surface water and groundwater pollution have been reported in the majority of the nine islands of the Azores archipelago due to the impact of agricultural activities, resulting in some cases in the failure to comply EU and national water quality regulations. Changes in the chemical and biological characteristics of lake waters are mainly the result of agricultural activities that are taken place in their watersheds, through excess nutrient loads as a result of the intensive fertilization as well as livestock manure. This is one of the most serious problems regarding surface water quality in the Azores archipelago, and only recently the consequences of eutrophication on lakes have received increased attention in the Azores archipelago (Porteiro, 2000; Santos et al., 2005; Ribeiro et al., 2008; Martins et al., 2008, 2012; Gonçalves, 1997, 2008; Pacheco et al., 2005, 2010; Pereira, 2013; Cruz, 2013).

As well as eutrophication-oriented research, other studies have been completed regarding water chemistry in lakes all over the Azores islands focusing on the interaction with the active volcanic environment (Martini et al., 1994; Cruz et al., 2006; Antunes, 2008; Antunes et al., 2010; Andrade, 2014). Despite their volcanic origin and the fact that the referred water bodies are mainly located in active volcanoes they can be considered as no active lakes, generally presenting neutral-diluted waters and belonging to class 6 according to the classification scheme provided by Pasternak and Varekamp (1997) and adapted by Rouwet et al. (2014). Therefore, and contrary to other case studies (Pedrozo et al., 2008), the contribution of volcanic nutrient input toward the trophic state of the studied lakes is considered to be negligible, as deduced from the overall water chemistry as well as from the low dissolved CO_2 content (Cruz et al., 2006). Nevertheless, the emission of CO_2 in Furnas lake was estimated to be in the range of 23 (summer) to 63 t/day (winter period) (12–32 t/km^2/day) and occurs mainly near the north margin where a fumarolic field is located, a fraction of which is suggested to be associated with a volcanic source (Andrade, 2014).

The objectives of the present paper are to present long-term monitoring data on water quality from Sete Cidades and Furnas lakes, located in São Miguel island, as well as analyze the success of the ongoing policy measures taken nowadays in order to reverse their eutrophic status, namely through water quality improvements. Long-term investigations may be crucial in tackling the problems arising from a vast number of interacting variables involved in the eutrophication processes, therefore allowing any trends to be addressed over time.

2. Studied area

2.1. Location and climate setting

São Miguel, the major island of the archipelago, located between 37°55′N to 37°04′N of latitude and 25°52′W to 25°08′W of longitude, with a length of 66 km and a maximum width of 16 km, has an area of about 744 km^2 and 138,638 inhabitants (year 2013; SREA, 2014). It belongs to the Azores Eastern group, and similar to the remaining islands, agriculture is one of the main economic activities in the archipelago, as shown by the gross value added to the regional product due to agriculture (8.6%; year 2010). Livestock is the main agricultural activity, as approximately 94% of the land occupied for agriculture use corresponds to pastures.

In the context of the altitudinal distribution of the Azores lakes, Lake Sete Cidades and Lake Furnas are located at a lower altitude, the former presenting an urban area in their drainage basin, as well as a more diverse use of land patterns, including recreation, agriculture, pasture and forested areas.

According to the classification defined by Thornthwaite (1948) the climate in São Miguel can be considered as humid to super-humid, and mesothermal with dry summers using the Köppen classification (Ricardo et al., 1977). Monthly average temperatures are higher in August, about 22 °C in the coastal area and 15 °C in the higher elevation areas and the coldest month is February, with temperature values between 14 °C, at the coast and 5 °C in higher altitude zones (Ricardo et al., 1977).

Average annual precipitation in São Miguel is equal to 1722 mm (DROTRH/INAG, 2001). The seasonal distribution is marked by a rainy season, and for example from the average annual precipitation of 958 mm that occurs in Ponta Delgada 76.3% of the total precipitation occurs between September and March. Monthly average precipitation is, in general, higher in January and lower in July and August.

2.2. Geological setting

The geology of São Miguel is dominated by three active central volcanoes (Sete Cidades, Fogo and Furnas), associated with highly explosive eruptions of magmas of trachytic nature, which explain the large Quaternary calderas that occupy the summit of these volcanoes (Booth et al., 1978; Moore, 1990; Guest et al., 1999; Pacheco et al., 2013). The recent activity of these volcanoes is mainly explosive in character, with plinian, subplinian, and phreatomagmatic activity, producing a high volume of pumice fall deposits, pyroclastic flows, surges, lahars and domes as well as trachytic lava flows.

Sete Cidades volcano is the westernmost of the three active central volcanoes of São Miguel island. This volcano occupies an area of 110 km^2 and presents a subaerial volume of 45 km^3 (Moore, 1990; Queiroz, 1998). This steeply volcanic cone, with an average slope of 12°, has a maximum altitude of 845 m and an average basal diameter of approximately 12 km. It presents a summit caldera corresponding to a 5 km diameter circular shaped depression, with an average depth of 300 m (Queiroz, 1998).

The Sete Cidades volcano caldera results from three main phases of collapses, dated from 36,000 years to 16,000 years and is a result of major eruptions given rise to important fall and flux of pyroclastic deposits. Several volcanic features can be observed inside the caldera,