Chapter 5
River Water Characteristics After Recent Volcanic Eruptions in Southern Chile

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Abstract Within 9 days after recent volcanic eruptions in southern Chile (Cordón Caulle, Villarrica and Calbuco), we analysed the physico-chemical quality of riverine waters of nearby rivers. Sulphates, total suspended solids, fluorides and conductivity were higher at the turbid waters of affected rivers, while pH and silicates showed no significant differences between affected and non-affected rivers. The results of principal component analysis demonstrate a similar overall impact in all affected riversheds, independently of the volcanological characteristics of the erupting centres.

Keywords Volcanic eruptions · Riverine waters · Chile

5.1 Introduction

Volcanic ash and pumice are the most widely distributed products of explosive eruptions (Del Moral and Grishin 1999; Bertrand et al. 2014), affecting water quality and benthic biota of nearby rivers (e.g., Del Moral 1981; Miserendino et al. 2012; Lallement et al. 2014; Lallement et al. 2016). This is of concern for communities located in the influence zone of dispersion and fallout of those volcanic products. In such cases, authorities are generally unable to diminish public fears because of a lack of water quality information collected before volcanic eruptions.

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We provide here basic information on water characteristics of rivers affected by three recent volcanic eruptions in southern Chile: that of the Cordón Caulle (from 3 June 2011) and those of volcanoes Villarrica and Calbuco (from 3 March and 22 April 2015, respectively). We primarily focus on the short-term effects (4–9 days) of those large natural disturbances on the water quality of river systems located around the volcanoes.

On the 4th of June of 2011, after five decades of inactivity and 2 months of elevated seismicity, a new vent formed on the northern side of the fissural range of Cordón Caulle producing an ash and gas plume up to 14 km above sea level (Bertin et al. 2012). The Plinian-subplinian phases of the eruption (Volcanic Explosivity Index, VEI = 4) lasted until April 2012 and released during the first 27 h of the eruption about 0.5–1.0 km^3 of rhyodacitic tephra (0.2–0.4 km^3 Dense Rock Equivalent, DRE) (Bertin et al. 2012). In addition to tephra, the eruption produced later on an estimated 0.45 km^3 of rhyodacitic lava (70% SiO_2), which covered a surface nearly 7 km^2 (Bertin et al. 2012). Part of the lava flow extended north east of the vent in the drainage of Nilahue river (Tuffen et al. 2013). Due to the predominant westerly winds, tephra dispersion mainly occurred towards the east (Collini et al. 2013). The Gol Gol river, which drains from the southern flank of Cordón Caulle and discharges in Puyehue lake, and the Nilahue river, which drains from the northern flank of Cordón Caulle and discharges in Ranco lake, were the most affected by ash and pumice contamination (Bertrand et al. 2014).

Villarrica, Chile's most active volcano, is characterized by regular eruptive cycles associated with moderate explosive activity (VEI = 2) that occur periodically every few decades. 22 lahar-forming eruptions have been documented during the last 600 years (Van Daele et al. 2014). The eruptive cycle that culminated in March 2015 was initiated about three months earlier in December 2014 with increased anomalies in thermal activity and volcanic gas emission (Global Volcanism Program 2016; Aiuppa et al. 2017). In February 2015, sporadic Strombolian explosions sent tephra up to 5 m in size down the flanks and within 1 km from the crater. The increased activity climaxed on the morning of March 3 with a vigorous Strombolian activity and subsequent lava fountaining that rose 1500 m above the crater rim and lasted only about half an hour. This paroxysmal explosion (VEI = 2) produced an ash plume that reached an altitude of 9 km and drifted to the east. Explosive activity with ash plumes and lava spattering continued at decreasing levels throughout 2015 (Global Volcanism Program 2016). The explosion of March 3 produced heavy tephra fallout to the east and incandescent scoria flows mostly on the northern and eastern flanks of the volcano (Johnson and Palma 2015). Glacier melting generated moderate lahar activity in Zanjón Seco river drainage to the north west but a lahar more than 20 km long in the Pedregoso and Turbio river drainages to the north east (Flores and Amigo

2015; Johnson and Palma 2015). Estimates of the bulk non-DRE volume of emitted tephra vary between about 4 and 7 million of m^3 (Bertin et al. 2015a; Romero et al. 2016a). The erupted materials were mostly medium-K basaltic andesite in composition (Bertin et al. 2015a; Romero et al. 2016a).

The 2015 Calbuco volcano eruption cycle, the first in four decades, initiated with increasing seismic activity months prior to the April eruption (Sernageomin 2015a). Nonetheless, the intense subplinian explosive eruption of the 22nd of April 2015 (VEI = 4) came as a surprise in the absence of precursors in the days or hours preceding the event. A thermal anomaly and stronger seismic events were only detected minutes prior to the eruption (Sernageomin 2015a; Valderrama et al. 2015). The first eruptive pulse on April 22 lasted about 90 min and produced an ash plume that reached an altitude of nearly 17 km (Sernageomin 2015b). A second and more powerful pulse occurred the following day and lasted about 6 h, generating an ash plume of about 20 km that drifted initially towards the north east (Sernageomin 2015c). Collapse of the eruptive column produced pyroclastic density currents that travelled up to 6 km from the vent (Castruccio et al. 2016). A third and smaller pulse on April 30 generated a 4 km high ash plume, which deposited tephra towards the south east (Romero et al. 2016a, b) and only produced mm to sub-mm thick fall deposits near Lake Chapo and Ralún (Bertin et al. 2015b). The total bulk tephra deposit volume was estimated to be between 0.27 and 0.38 km^3, i.e. 0.12–0.15 km^3 DRE (Romero et al. 2016b; Castruccio et al. 2016). The erupted materials correspond mostly to porphyritic basaltic andesite (about 55 wt% SiO_2) (Romero et al. 2016b; Castruccio et al. 2016).

5.2 Methods

Four days after the start of the Cordón Caulle eruption, we collected water samples from six rivers on its northern flank and from two rivers on its southern flank (Fig. 5.1a). As for the eruptions of the Villarrica and Calbuco volcanoes, water samples were collected from four and five nearby rivers, respectively, nine and six days after the start of the eruptions, respectively (Fig. 5.1b, c). The following water parameters were recorded in situ with a multi-parameter probe: water temperature, potential hydrogen (pH) and electrical conductivity. We also collected water samples to measure levels of sulphates, silicates, fluorides and total suspended solids (TSS), which are expected by-products of volcanic eruptions (e.g., Stewart et al. 2006; Witham et al. 2005). To improve statistics, samples for TSS were collected as triplicates, while samples for the other chemicals were collected as duplicates. Results presented in Table 5.1 are average values of the triplicates and duplicates. All water samples were collected with Nalgene xp 1 L plastic bottles. The analysis for TSS, sulphates, silicates and fluorides were carried out according to the standard methods for the examination of water and waste water (APHA 2005).

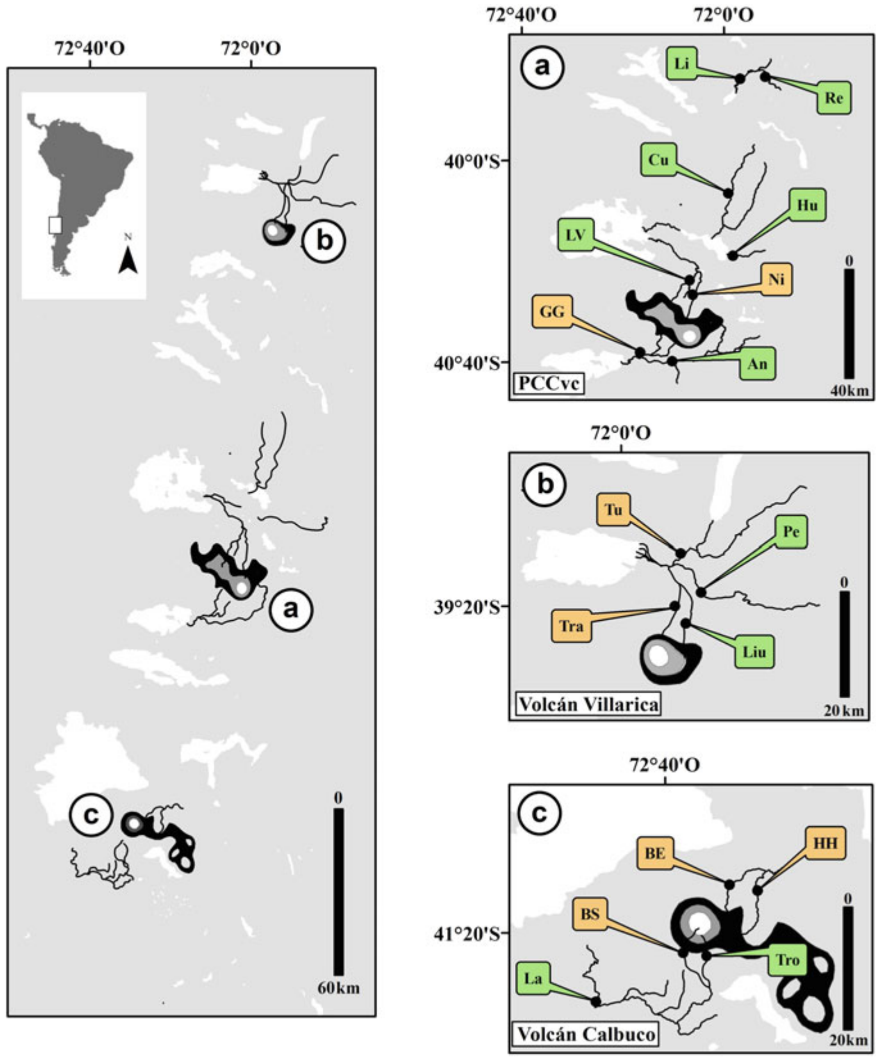

Fig. 5.1 Location map of sampled rivers in the vicinity of the Cordón Caulle (**a**), Villarrica (**b**) and Calbuco (**c**) volcanoes in southern Chile. River names are as follows: **a** Liquiñe (Li), Reyehueico (Re), Curringue (Cu), Hueinahue (Hu), Los Venados (LV), Nilahue (Ni), Gol Gol (GG) and Anticura (An) close to Cordón Caulle; **b** Turbio (Tu), Pedregoso (Pe), Trancura (Tra) and Liucura (Liu) near Villarrica; **c** Blanco Este (BE), Hueño Hueño (HH), Blanco Sur (BS), Tronador (Tro) and Lauca (La) near Calbuco. Turbid and clear water rivers labelled in brown and green, respectively (see text)

Table 5.1 Water characteristics of the rivers sampled near Cordón Caulle, Villarrica and Calbuco volcanoes

Category	Volcano	Rivers	Conductivity (µS/cm)	pH	TSS (mg/L)	Sulphates (mg/L)	Silicates (mg/L)	Fluoride (mg/L)
Turbid waters	Cordón Caulle	Nilahue	52.4	7.0	5750.5	18.4	12.5	0.47
		Gol Gol	91.1	9.5	3738.7	17.3	5.9	0.28
	Villarrica	Turbio	21.5	6.9	1246.1	8.9	15.1	0.2
		Trancura	57.3	8.2	33.0	5.3	25.2	0.08
	Calbuco	Blanco Este	132.6	7.7	1399.2	29.1	13.3	0.76
		Hueño Hueño	53.2	7.7	108.6	10.6	12.6	0.13
		Blanco Sur	26.0	7.8	1591.3	0.5	6.8	0.18
		Mean	62.0	7.8	1981.1	12.9	13.1	0.3
		Standard deviation	38.6	0.9	2066.8	9.5	6.4	0.24
Clear waters	Cordón Caulle	Los Venados	46.0	6.9	38.6	29.6	9.5	0.12
		Anticura	39.0	8.9	10.2	10.7	7.2	0.04
		Curringue	40.4	7.5	13.1	4.2	5.0	0.03
		Hueinahue	34.6	6.0	40.8	11.8	3.5	0.07
		Reyehueico	36.6	7.2	2.7	3.3	6.4	0.03
		Liquiñe	38.8	6.7	2.1	3.0	5.9	0.03
	Villarrica	Pedregoso	35.4	7.9	5.4	0.5	24.6	0.08
		Liucura	66.0	8.1	4.3	2.2	28.9	0.08
	Calbuco	Tronador	34.2	7.3	4.4	0.5	15.3	0.08
		Lauca	67.8	7.5	3.2	0.5	20.6	0.08
		Mean	43.9	7.4	12.5	6.6	12.7	0.06
		Standard deviation	12.6	0.8	14.8	9.0	9.1	0.03

Based on direct field observations, the rivers were preliminarily categorized in terms of the levels of turbidity as turbid and clear rivers (cf. Fig. 5.2). This visual classification is generally correlated with TSS measurements, which indicated that turbid rivers had high TSS loads (Table 5.1). Turbid rivers included the Nilahue and Gol Gol rivers near Cordón Caulle, the Turbio and Trancura rivers near Villarrica and Blanco Este, Hueño Hueño and Blanco Sur near Calbuco (Figs. 5.1 and 5.2). On the other hand, clear water rivers had green clean waters without noticeable load of TSS including tephra (Los Venados, Hueinahue, Curringue, Liquiñe and Reyehueico near Cordón Caulle, Pedregoso and Liucura close to Villarrica and Tronador and Lauca near Calbuco) (Fig. 5.2). To graphically explore the water characteristics variation amongst the set of studied rivers, we performed principal component analyses (PCA) on log-transformed data of the above-mentioned variables. Eventual statistically significant differences between turbid and clear rivers and source volcanoes were analysed with PERMANOVA by using the scores of the first two principal components that resulted from PCA. This procedure is particularly suited to study groups characterized by a large number of variables, since it runs a multivariate analysis with permutations to avoid possible biases. All the analyses were made with R (http://www.r-project.org/) by using the routines *vegan* and *ggbiplot*.

5.3 Results and Discussion

The results of the PCA show that less than ten days after the volcanic eruptions, the first two principal components explained nearly 70% of the variability of the data set (Fig. 5.3). The spatial segregation of turbid and clear rivers was statistically significant (PERMANOVA $R^2 = 19\%$; $p < 0.01$) and occurred along the first principal component, which explains 42% of the variance (Fig. 5.3a). That segregation was explained by the higher concentrations of sulphates, TSS, fluorides and higher conductivity for the turbid water rivers, being TSS and fluorides the main sources of differentiation (Fig. 5.3a and Table 5.1). The results of the statistical analyses do not show significant differences considering the overall data from each volcano (PERMANOVA $R^2 = 22\%$; $p < 0.135$) (Fig. 5.3b and Table 5.1), which may indicate that the differences found between rivers of turbid waters and clear waters constitutes a common pattern for all the volcanic eruptions analysed here. It follows that the response of the freshwater aquatic fauna could be quite different between nearby rivers on a given volcano (depending on turbidity). However it should be relatively similar for all clear rivers on one side and all turbid rivers on the other side, independently of their location.

Fig. 5.2 Representative images of turbid and clear water rivers at the study area. The rivers Nilahue, Gol Gol, Trancura and Blanco Sur were classified as turbid water rivers, while Hueinahue, Anticura, Liucura and Tronador were categorized as clear water rivers

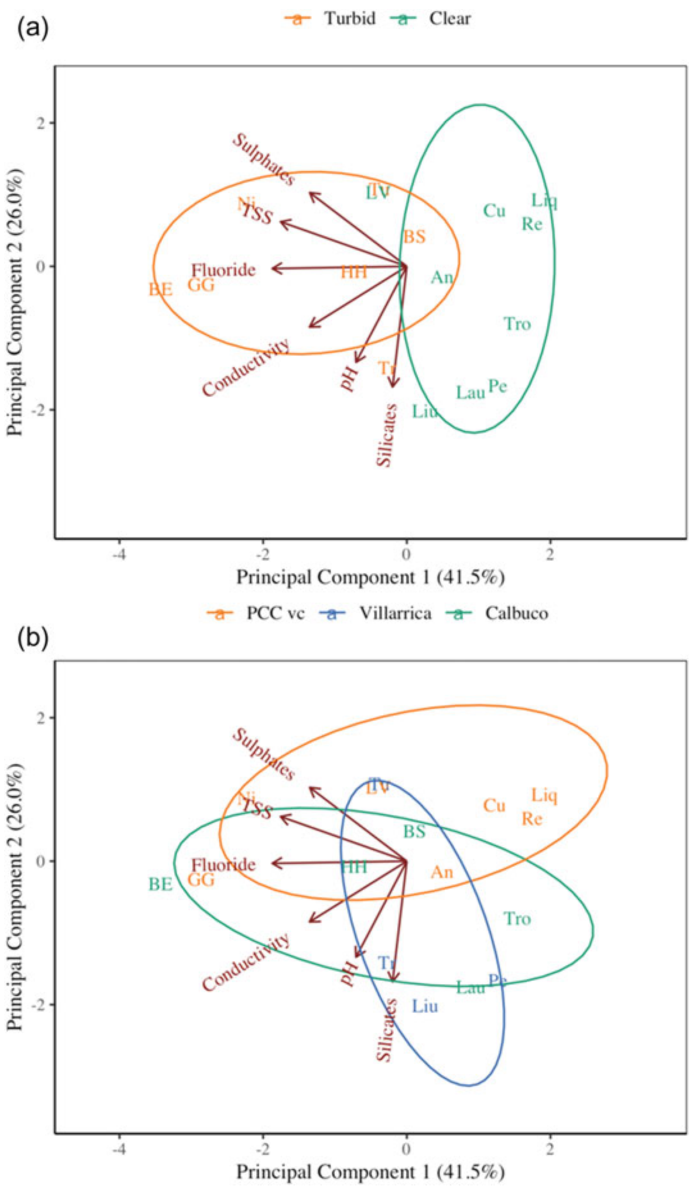

Fig. 5.3 Bi-plot ordination for the first two principal components of the PCA. In the upper plot **a** sites are separated according to river category, while in the lower plot **b** rivers are differentiated according to the volcanic emission centres (river abbreviations as in Fig. 5.1). The ellipses represent the reclassification of the scores with a 90% confidence level

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