

VOLCANICA Article in Press

This is an uncorrected proof, meaning that this manuscript has not been copyedited or formatted according to Volcanica's styles and standards. In turn, this means that article content, including text, may still change prior to final publication. Although articles in press do not have all bibliographic details available yet, they can be cited using the year of online publication and the DOI, as follows: author(s)(year), article title, Volcanica, DOI.

Sale, R. B., Córdoba, G. A. and Caselli, A. T. (2026) "Numerical simulations of lahars triggered by phreatic explosions at Copahue Volcano and their relationship with the crater lake water volume", <i>Volcanica</i> , 9(2). doi: 10.30909/vol/ysfo5683.
--

article in press

Numerical simulations of lahars triggered by phreatic explosions at Copahue Volcano and their relationship with the crater lake water volume

Rafael B. Sale^{*1,2}, Gustavo A. Córdoba³, and Alberto T. Caselli^{1,2}

¹ Universidad Nacional de Río Negro. Instituto de Investigación en Paleobiología y Geología, Av. Roca 1242, 8332, General Roca, Río Negro, Argentina

² Consejo Nacional de Investigaciones Científicas y Tecnológicas (CONICET). Instituto de Investigación en Paleobiología y Geología. Av. Roca 1242, 8332, General Roca, Río Negro, Argentina

³ Faculty of Civil Engineering, Universidad del Nariño, Pasto, Colombia

* rbsale@unrn.edu.ar [corresponding author]

¹ ORCID (RBS): 0009-0005-9536-0619

² ORCID (GAC): 0000-0002-1104-0249

³ ORCID (ATC): 0000-0002-0457-1607

Keywords: Copahue volcano; Lahar; Numerical simulation; TITAN2F software; Water storage capacity; Geographic Information System (GIS)

Abstract

Copahue volcano is a stratovolcano located on the border between Argentina and Chile, whose active crater hosts a lake that represents a potential source for lahar formation. Lahars are two-phase flows of water and volcanic debris that can reach high velocities, obliterate infrastructure, and critically impact the economy, public health, and threaten the lives of individuals in both nearby and distant communities. This study focuses on the numerical modeling of lahar scenarios at Copahue volcano, using the volume of the crater lake as a critical input, estimated from the ALOS World 3D - 30m Digital Surface Model (AW3D30) within a QGIS environment. Lahar scenarios were simulated using TITAN2F software, incorporating different volumetric solid concentrations, facilitating an evaluation of flow behavior, its extent, and the potential impacts on surrounding areas.

Resumen

El volcán Copahue es un estratovolcán ubicado en la frontera entre Argentina y Chile, cuyo cráter activo alberga un lago que representa una fuente potencial para la formación de lahares. Los lahares son flujos bifásicos de agua y escombros volcánicos que pueden alcanzar altas velocidades, destruir infraestructuras e impactar gravemente la economía, la salud pública y amenazar la vida de las personas en las comunidades tanto cercanas como lejanas. Este estudio se centra en la modelización numérica de escenarios de lahares en el volcán Copahue, utilizando el volumen del lago cratérico como entrada crítica, estimado mediante el Modelo Digital de Superficie ALOS

World 3D - 30m (AW3D30) en un entorno QGIS. Los escenarios de lahares fueron simulados utilizando el software TITAN2F, incorporando diferentes concentraciones volumétricas de sólidos, lo que facilitó la evaluación del comportamiento del flujo, su extensión y los posibles impactos en las áreas circundantes.

1. Introduction

Lahars are biphasic flows of debris and water that travel down volcanic slopes, driven by gravity, and are distinct from normal stream flows (Smith and Fritz 1989). They are considered the second most significant volcanic hazard in terms of direct fatalities, surpassed only by pyroclastic flows (Tanguy et al. 1998; Brown et al. 2017; Thouret et al. 2020). Lahars have demonstrated the capacity to cause severe negative impacts on human life, infrastructure, and economic assets (Brown et al. 2015).

Typically, lahars can be differentiated based on their volumetric solid concentrations into hyperconcentrated flows and debris flows (Vallance 2000). Debris flows consist of a solid phase that constitutes at least 60 % by volume (>80 % by weight), fully mixed with water (Thouret et al. 2020). Hyperconcentrated flows, on the other hand, transport between 20 % and 60 % by volume of sediments (40 % and 80 % by weight) (Pierson and Scott 1985; Pierson 2005). Debris flow deposits are massive and very poorly to extremely poorly sorted (greater than 2 ϕ and typically exceeding 4 ϕ on the Wentworth scale), with grain-size distributions commonly bimodal (Vallance 2000; Vallance and Iverson 2015). Hyperconcentrated flow deposits, in contrast, have intermediate sorting coefficients (1–2 ϕ), are strongly bimodal, and commonly display weak stratification, characterized by horizontal beds and very low-angle cross bed-sets (Vallance 2000; Vallance and Iverson 2015; Kataoka et al. 2018; Procter et al. 2021).

Likewise, lahars can be distinguished as primary, which are directly related to an eruptive event, and secondary, which are not associated with any particular eruption (Vallance 2000). Their occurrence, whether primary or secondary, is conditioned by initial factors such as an adequate water source, abundant unconsolidated debris, steep slopes, and a triggering mechanism (Vallance 2000; Vallance and Iverson 2015). Lahars can be triggered by rainfall (Rodolfo and Arguden 1991; Lavigne et al. 2000; Paguican et al. 2009; De Bélizal et al. 2013; Capra et al. 2019), snowmelt caused by hydrothermal heating at the summit of the volcano or by the interaction of hot pyroclastic flows or lava flows with snow and ice (Pierson et al. 1990; Waythomas et al. 2013; Hemmings et al. 2016; Waythomas et al. 2023), landslides or debris avalanches (Vallance and Scott 1997; John et al. 2008), or by the release of water from a crater lake or a lake dammed by impermeable sediments (Umbal and Rodolfo 1996; Cronin et al. 1997; Pierson 2002; Manville et al. 2007; Manville and Cronin 2007; Schaefer et al. 2008; Procter et al. 2010; Procter et al. 2021).

Volcanic lakes, in particular, due to their ability to store large volumes of water, represent a significant risk of generating highly destructive water-rich mass flows (Neall 1976). Lahars of this nature can be triggered by the sudden expulsion of water contained in crater lakes during phreatic or phreatomagmatic eruptions (Nairn et al. 1979; Cronin et al. 1997; Nossin 2005; Kilgour et al. 2010; Rouwet et al. 2014) or by overflow caused by the instability of the lake's walls (Umbal and Rodolfo 1996; Pierson 2002; Manville et al. 2007; Manville and Cronin 2007).

The occurrence of the latter does not necessarily require a volcanic eruption or heavy rainfall, so its failure can happen without warning, months or years after the eruptive event (Vallance 2000), and even on sunny days (Rodolfo 2000; Daag 2003). The resulting flows can travel distances of tens of kilometers without diminishing their destructive power (Delmelle et al. 2015), with velocities that can reach up to 60 km/h (Daag 2003; Nossin 2005). An example of the disaster that can be caused by the rupture of a dammed lake is the Tangiwai event. In 1945, Mount Ruapehu erupted, producing lava and ash that formed a natural ice and tephra dam, causing the lake to rise six to eight meters above its previous level (Manville 2004; Eiby and Latter 2018; Brett 2018). In 1953 (eight years later), the dam collapsed without any eruption involved, generating a lahar that destroyed a bridge located 35 km downstream, resulting in the derailment of a train in which 151 passengers perished (Cronin et al. 1997; Delmelle et al. 2015; Eiby and Latter 2018). In recent times, the most volumetrically significant lake-breakout event occurred at Mount Ruapehu in 2007 (Procter et al. 2021), when a breach measuring 6.5 m by 40 m developed on March 18th of that year in Crater Lake, liberating 1.3×10^6 m³ of water in less than 90 minutes and generating the largest lahar in 100 years (Manville and Cronin 2007; Procter et al. 2010). Successful implementation of an early warning system ensured that the lahar caused no fatalities and only minimal property damage (Manville and Cronin 2007).

On the other hand, eruptions associated with relatively small crater lakes can empty their contents in seconds or minutes, generating extremely high water discharges, on the order of 10^4 to 10^5 m³/s (Delmelle et al. 2015). Mount Kelud in Indonesia has caused the death of more than 15000 people due to lahars over the past 450 years as a result of such events (Delmelle et al. 2015). The 1919 eruption lasted less than an hour, releasing 38×10^6 m³ of water, which mixed with eruption products and loose debris in the ravines, forming lahars with speeds of approximately 60 km/h. This resulted in 5100 deaths in less than forty-five minutes and the destruction of 104 villages, either partially or completely (Nossin 2005).

In this context, Copahue volcano, located on the border between Argentina and Chile in the Southern Andes (Figure 1), has experienced multiple volcanic crises over the past three decades, primarily affecting the tourist towns of Copahue and Caviahue, situated 7 km and 9 km from the vent, respectively. This volcano is considered

one of the most important in Argentina and poses a very high relative risk to the country due to both its hazard and the proximity of the mentioned towns (Elissondo et al. 2016; García et al. 2018). With predominantly phreatic and phreatomagmatic eruptive activity, it stands out in the region due to its easternmost crater, the only one of its nine craters that remains active and which also hosts a hyperacidic and hot lake (Delpino and Bermúdez 1994; Varekamp et al. 2001, Naranjo and Polanco 2004; Agosto 2011; Caselli et al. 2016a). Although considerable research has been carried out on the geochemistry and temperature variations of the crater lake (Varekamp et al. 2001; Caselli et al. 2005; Gammons et al. 2005; Caselli et al. 2006; Varekamp et al. 2009; Agosto 2011; Ayres 2012; Farnfield et al. 2012; Agosto et al. 2013; Jay et al. 2013; Tamburello et al. 2015; Agosto et al. 2017; Candela-Becerra et al. 2020; Suárez-Herrera et al. 2021; Llano et al. 2023), it has not yet been addressed as a critical water source for lahar generation.

The phreatomagmatic eruptions of Copahue volcano in the 1990s and in 2000 demonstrated its capacity to expel the crater lake (Varekamp et al. 2016). According to Caselli et al. (2016a), significant primary lahars formed by the mixture of solid fragments with the lake's hot water were observed during the main explosions recorded in 1992 and 1995, reaching distances of 5 to 6 km from the crater. A particularly notable event occurred on September 12, 1995, when one of these lahars extended up to 8 km along the Agrio River.

This study focuses on the numerical modeling of lahar scenarios at Copahue volcano, using the total volume of the crater lake as a critical input, estimated from the ALOS World 3D - 30m Digital Surface Model (AW3D30) (available at https://www.eorc.jaxa.jp/ALOS/en/dataset/aw3d30/aw3d30_e.htm), within a QGIS environment. Lahar scenarios were simulated using TITAN2F software, with varying volumetric solid concentrations, evaluating the flow behavior, its extent, and the potential impacts on surrounding areas.

TITAN2F (Córdoba et al. 2015; Córdoba et al. 2018), was developed to model gravity-driven flows. This software is based on a depth-averaged model for a shallow, incompressible, two-phase flow, where the Darcy-Weisbach law governs the liquid phase and Coulomb's law governs the solid phase. It employs a framework similar to that developed by Pitman and Le (2005) but establishes a complete set of model equations for both the granular and fluid phases (Córdoba et al. 2015; Córdoba et al. 2018). In addition to displaying the affected areas, it can track the spatiotemporal evolution of various flow parameters along its trajectory, such as flow height, velocity, solid concentration, and dynamic pressure at each point on the computational grid (Córdoba et al. 2015; Córdoba et al. 2018). The following input parameters are required: 1) the initial location and total volume of the debris pile collapsing due to gravity; 2) the volumetric solid concentration; 3) the initial velocity; 4) a Digital

122 Elevation Model (DEM); and 5) the simulation time. Constraints and parameters for the simulations were derived
123 from the characteristics of historical lahars observed on the eastern flank of Copahue volcano.

124 **2. Geological background**

125 **2.1 Copahue volcano**

126 Copahue volcano (37°45'S, 71°10.2'W, 2997 m.a.s.l.) is an active stratovolcano of basaltic-andesitic composition
127 (Delpino and Bermúdez 1993; Caselli et al. 2009), located in the Southern Volcanic Zone (SVZ) of the Andes
128 (Varekamp et al. 2001), on the border between Argentina and Chile (Figure 1). Its summit includes nine craters
129 aligned along an N60°E orientation (Naranjo and Polanco 2004). Of these, only the easternmost crater remains
130 active (Caselli et al. 2016a). This crater is characterized by a circular morphology with a diameter of 500 m
131 (Naranjo and Polanco 2004) and steep walls controlled by fractures (Delpino and Bermúdez 1994; Bonali et al.
132 2016).

133 Inside, it hosts a hyperacidic and hot lake (Delpino and Bermúdez 1994; Varekamp et al. 2001; Naranjo and
134 Polanco 2004; Agosto 2011; Caselli et al. 2016a; Agosto and Vélez 2017), which is continuously supplied by
135 high-temperature acidic fluids from the volcanic-hydrothermal system within the volcanic edifice, as well as by
136 meteorological waters such as precipitation and the melting of the glacier covering the summit (Agosto 2011).
137 The presence of sulfur on its surface, as well as in the material emitted during eruptive events, is particularly
138 abundant (Agosto and Vélez 2017). The temperature of the lake ranges from 20° C to 54° C (Caselli et al. 2005),
139 while the average annual ambient temperature is -2° C (Agosto 2011). However, in 2004, values of 0° C and 13°
140 C were recorded (August and May 2004, respectively) during an atypical period of behavior for the crater lake
141 (Agosto 2011).

142 Over the last 275 years, 11 low-magnitude phreatic and phreatomagmatic eruptive cycles have been reported:
143 1750, 1759, 1867, 1937, 1944, 1960, 1961, 1992, 1993, 1994, and 1995 (Delpino and Bermúdez 1993; Delpino
144 and Bermúdez 1994; Bermúdez and Delpino 1995; Naranjo and Polanco 2004 and references therein; Caselli et
145 al. 2016a and references therein), along with two low-magnitude phreatomagmatic to magmatic events in 2000
146 (Varekamp et al. 2001; Delpino and Bermúdez 2002; Naranjo and Polanco 2004) and in 2012 (Petrinovic et al.
147 2014a; Caselli et al. 2016b). Since the 1990s, more detailed and systematic geological studies on Copahue's
148 eruptions have been conducted, providing a much stronger foundation for the analysis of its volcanic events. The
149 eruption that occurred during the winter of 1992 triggered lahars due to the contact of snow with pyroclastic
150 material and hot water from the crater (Delpino and Bermúdez 1993). These flows affected the Agrio basin in

151 Argentina and the Lomín basin in Chile, reaching distances of up to 4 km and 3.5 km, respectively. By 1993,
152 sharp fluctuations in the lake level were observed, along with the generation of new lahars during the eruptive
153 events of 1994 and 1995, with maximum reaches of up to 8 km along the Agrio River channel (Bermúdez and
154 Delpino 1995). The 2000 eruption was marked by a drastic change in the eruptive style, characterized by the
155 disappearance of the crater lake, shifting from phreatic and phreatomagmatic eruptions to typically Strombolian
156 eruptions (Delpino and Bermúdez 2002). According to these authors, during phreatic and phreatomagmatic
157 eruptions, the fallout of hot tephra onto snow triggered a flood in the headwaters of the Dulce basin and lahars in
158 the upper course of the Agrio River. In the former, the water level increased 1 m above its normal level,
159 damaging the water supply system to the Caviahue town, while in the latter, the lahars reached heights of up to
160 3.5 m, carrying large blocks and depositing gravels and sands along the margins and central channel.
161 Downstream, the lahar transformed into a flood that widened the Agrio River channel at the Caviahue bridge.
162 After the eruption, by the end of 2000, the crater lake began to re-establish itself (Agusto 2011), stabilizing
163 completely between 2002 and 2003 (Varekamp et al. 2009). By July 2004, approximately 80 % of the lake's
164 surface was frozen (Agusto 2011; Agusto et al. 2012), and between 2005 and 2010, according to Caselli et al.
165 (2016b), there were no significant changes in the temperature or volume of the lake. On December 1, 2011, a
166 gradual increase in gas emission rates from the crater lake was recorded, intensifying in 2012, which nearly
167 completely obscured the lake's surface (Caselli et al. 2016b). On July 17, 2012, a phreatic explosion expelled
168 water and mud from the bottom of the crater lake to a height of 10 meters, forming a cock's tail jet, while two
169 days later, a phreatomagmatic eruption emitted pyroclastic material, with blocks up to 20 cm in diameter
170 observed near the crater, most of which showed signs of liquid sulfur presence (Caselli et al. 2016b). The ejection
171 of liquid sulfur was also a distinctive feature of the 1992 and 2000 eruptions (Delpino and Bermúdez 1993;
172 Bermúdez and Delpino 1995; Varekamp et al. 2001; Caselli et al. 2016b). In the following months, a significant
173 decrease in the water level of the crater lake (approximately 20 m) was reported, along with the appearance of
174 yellow sulfur spherules floating on the lake's surface for several days, later depositing on the shore (Caselli et al.
175 2016b). On December 22, 2012, eruptive activity began, initially sustained by a series of phreatic explosions.
176 This activity continued until the complete disappearance of the crater lake, and it is possible that sulfur particles
177 and sediments from the crater's bottom were also ejected, giving the plume a yellow hue. Ash emissions, ballistic
178 projections, and pyroclastic flows were the most significant phenomena associated with this eruptive event. Since
179 then, Copahue volcano has maintained relatively constant activity with persistent emissions of vapor, gases, and
180 ash.

181 2.2 Lahar deposit and previous simulations

182 At Copahue volcano, lahar deposits from the 1992–95 eruptions (**Figure 2**) are primarily found in the Agrio
183 basin, extending up to 6.26 km along the main channel. In the Lomín basin, they extend for 3.5 km and are
184 mainly concentrated at the base of the volcanic cone, where the slope changes abruptly, generating a fan-like
185 morphology. In the Las Mellizas basin, lahar deposits are more limited and observed in specific areas (**Figure**
186 **2B**). In the upper sectors of the Agrio and Lomín basins, and in the middle reach of the Agrio basin, the 1992–95
187 lahar deposits have been either eroded or buried by younger volcanic deposits (Báez et al. 2021). Similarly,
188 Balbis et al. (2016) observed that, during the 2007–2015 period, many of these outcrops disappeared or were
189 significantly reduced, particularly those occurring in flat areas. Therefore, they suggested that the original
190 deposits may have covered much larger areas and had a greater volume than those currently preserved.

191 The genesis and age of these deposits have been a subject of controversy. Petrinovic et al. (2014b) and Balbis et
192 al. (2016) interpreted them as pyroclastic density currents. Petrinovic et al. (2014b) proposed ages of AD 1963–
193 64 and AD 1976 based on radiocarbon dating of charred bushes found within the deposits. However, Balbis et al.
194 (2016) indicated that the obtained age may be slightly older due to incomplete charring of the wood, and
195 therefore they interpreted that the deposits were associated with a pyroclastic density current during the 2000
196 eruption. On the other hand, Báez et al. (2021) assigned them to the eruptions of 1992–95, based on remote
197 sensing analysis, and defined the deposit as corresponding to an "ice slurry" type lahar. Ice-slurry are defined as
198 mass flows composed of a mixture of snow, ice, rock particles, water, and air (Lube et al. 2009), whose most
199 common triggering mechanism is the rapid erosion and melting of ice and snow from glaciers by pyroclastic
200 density currents (Major and Newhall 1989; Lube et al. 2009), although ice slurries initiated by water and solid
201 material ballistically ejected from a crater lake have also been reported (Cronin et al. 1996; Kilgour et al. 2010).
202 For a more detailed discussion of the various interpretations and the conclusions reached, it is recommended to
203 consult the manuscripts of these authors.

204 The lahar deposit along the Agrio River is light gray, massive, and predominantly composed of sand and gravel
205 fragments (**Figure 2C**). Compositionally, the deposits consist of pyroclastic sulfur particles (20–35 %) and white
206 lithic fragments (20–40 %), accompanied by vitreous fragments (15–25 %), other volcanic lithic fragments (10–
207 20 %), and crystals (<5 %) (Báez, 2015). The grain size ranges mainly from gravel to sand, with less than 5%
208 silty matrix. The mean grain size ranging between 1.5ϕ and -1.5ϕ (Báez et al. 2021). Balbis et al. (2016)
209 distinguish two lithofacies: the upper facies is light gray, poorly sorted, composed of fine ash with a

predominance of lapilli, and the lower facies is grayish-white, laminated, with components ranging from extremely fine ash to medium ash. Lenses of the upper facies are intercalated in the lower deposits.

In low-slope areas, a maximum deposit thickness of 0.65 m was observed in the upper Agrio basin. Our field mapping only recorded an extension of up to 6.26 km in the middle Agrio basin, where the deposit thickness decreases significantly, reaching 0.1 m. The average thickness across the mapped area is 0.22 m, which is consistent with the 0.20 m thickness reported by Balbis et al. (2016).

Viotto (2020), Viotto et al. (2023), and Kaufman et al. (2023) used the LAHARZ model (Iverson et al. 1998) to simulate the planimetric extent of lahars in Copahue volcano, allowing for the evaluation of potential impacts on the surrounding region.

3. Methods and materials

3.1 Calibration of TITAN2F for modeling lahar deposits based on the Agrio basin

To assess the capability of the TITAN2F software in reconstructing the lahar deposits in the Agrio basin, it was necessary, first, to determine the volume of the lahar's solid content from the deposit. To achieve this, Landsat 4-5 Thematic Mapper (TM) Collection 2 Level 1 satellite images were first processed using QGIS software (<https://www.qgis.org/>). Two scenes were acquired from the United States Geological Survey (USGS) Earth Explorer website (<http://earthexplorer.usgs.gov/>), one from March 13, 1990 (Landsat Scene ID: LT42320861990072XXX08) and the other from February 26, 1999 (Landsat Scene ID: LT52320861999057COA00), representing the periods before and after the 1992 and 1995 eruptions, respectively. Combining bands 1, 4, and 7 from both images improved the visualization of the lahar deposit in the 1999 scene, ensuring accurate mapping of the flows generated during the referenced eruptions. The delineated area was adjusted with field data and multiplied by the average field-measured deposit thickness. Since the calibration of the solid volume is based on the preserved deposits rather than on the solid volume of the original flow, it represents only a minimum estimate of the solid content. Balbis et al. (2016) noted that many of these outcrops had been substantially reduced or had even disappeared between 2007 and 2015, suggesting that the original deposit may have had a much larger volume than the deposit currently preserved. Accordingly, we increased our estimate of the volume of the preserved deposit after erosion by a factor of two to account for the loss of solids associated with this process (Balbis et al. 2016). Although increasing the estimated volume by a factor of two is a simple assumption, we argue that the resulting volume remains within a reasonable order of magnitude. For example, Crandell (1971) estimated a volume of ~200 million cubic yards (~0.15 km³) for the “Electron

239 Mudflow”, a lahar deposit associated with a non-eruptive slope failure on the western flank of Mt. Rainier ~600
 240 years ago (Hoblitt et al. 1995). However, Scott et al. (1995) subsequently added a volume of post-depositional
 241 losses due to erosion and dewatering, resulting in a total estimated volume of 0.26 km³ for the original lahar
 242 deposits. This is equivalent to applying an increase factor of 1.7 (see Scott et al. 1995). Keeping the estimated
 243 volume of solids fixed, three scenarios with different water proportions were modeled, for volumetric
 244 concentrations of 45 %, 40 %, and 30 %, respectively (Tables 1-2). TITAN2F is capable of approximating the
 245 rheology of the fluid phase based solely on sediment concentration, since the rheology of the suspension is
 246 affected by both the interphase drag and the total fluid stress. The model includes both of these effects using
 247 physical and empirical approaches in evaluating the interaction forces between the solid and fluid phases (f_s and
 248 f_f in equations 3, 4 and 5 in Córdoba et al. 2018). Constitutive assumptions allow us to assess the interaction
 249 forces with a drag term and the total fluid stress. The effect of setting velocity, which in turn affects the rheology,
 250 uses a Richardson-Zaki approach, and the total fluid stress accounts both for the fluid pressure and the viscosity.
 251 The three simulated flows used an elliptical pile centered at the starting point Q1 (UTM coordinates
 252 310719E/5808024N) (Figure 3), representing the most proximal point in the basin near the crater lake, where
 253 lahars were reported during the 1992 and 1995 eruptions (Delpino and Bermúdez 1993; Bermúdez and Delpino
 254 1995). The major axis of the pile was oriented at 30° (counterclockwise from the geographic E-W axis at 0°),
 255 ensuring that the flow initiated parallel to the course of the Agrio River, assuming an initial velocity of zero for
 256 all scenarios. We use the predefined values incorporated into the TITAN2F code for bed friction and internal
 257 friction, set at 40° and 42°, respectively (Córdoba et al. 2018). In TITAN2F, friction coefficients are no longer
 258 required as input parameters, unlike in TITAN2D (e.g. Sheridan et al. 2005; Williams et al. 2008; Procter et al.
 259 2010; Procter et al. 2012; Mead and Magill 2017; Kataoka et al. 2021). The friction coefficients are not fixed
 260 during the spatiotemporal evolution of the simulated flow. Their values are automatically adjusted according to
 261 the evolution of the volumetric solid fraction within the computational grid and over time. Internal and basal
 262 friction are configured when the volumetric solid fraction tends to an assumed maximum packing concentration
 263 (65%) (Córdoba et al. 2018), both tend to correspond to the range of values used to model lahars with TITAN2D
 264 (see Sheridan et al. 2005; Williams et al. 2008). Conversely, when solid concentrations become too low, the
 265 water-phase laws become dominant over the friction-based solid phase (Córdoba et al. 2018).

266 The ALOS PALSAR Digital Elevation Model (DEM) (AP_26899_FBS_F6410_RT1), provided by the Alaska
 267 Satellite Facility with a spatial resolution of 12.5 m, acquired on February 11, 2011 (ASF DAAC 2015), and
 268 accessed on July 13, 2023, through <https://search.asf.alaska.edu/>, was used as the base for running the

simulations. The DEM was cropped to include the study area and then reprojected to the WGS 84/UTM Zone 19S coordinate reference system. Terrain voids were filled using the *r.fillnulls* RST algorithm from GRASS-GIS (<https://grass.osgeo.org/>).

The simulated flows were validated using the Jaccard index (R_j) (Table 3), which was calculated according to the equation (Charbonnier et al. 2018; Cruz-Vázquez et al. 2025):

$$R_j = \frac{TP}{TP+FN+FP} * 100 \quad (1)$$

Where TP is the area inundated by both the observed and simulated flows (true positive), FN is the area of the observed flow that the simulation failed to reproduce (false negative) and FP is the area inundated only by the simulated flow (false positive).

3.2 Simulation of hypothetical scenarios in the northeast area of Copahue volcano

To conduct the simulation of hypothetical scenarios in the northeast area of Copahue volcano, it was necessary to estimate the water volume of the crater lake. Once the water volume was estimated, this volume was fixed, and solid volumes was added in different proportions to generate the total volumes for modeling the mixture of water and debris.

First, to estimate the volume of the crater lake, we utilized the ALOS World 3D - 30m (AW3D30) Digital Surface Model (DSM), version 4.1, published in 2024 and available at https://www.eorc.jaxa.jp/ALOS/en/dataset/aw3d30/aw3d30_e.htm, with a horizontal resolution of 30 m. The AW3D30 DSM dataset, with 1 arcsec spacing, was generated based on the AW3D 5 m mesh (0.15 arcsec) DSM, developed by the Japan Aerospace Exploration Agency (JAXA) in collaboration with NTT DATA Corp. and the Remote Sensing Technology Center of Japan (RESTEC), using the archived data from the Panchromatic Remote-sensing Instrument for Stereo Mapping (PRISM) onboard the Advanced Land Observing Satellite (ALOS), acquired from 2006 to 2011 (Tadono et al. 2016). The AW3D30 dataset is open to the public free of charge.

Preliminary validation of AW3D30 DSM confirmed a 4.40 m (RMSE) of the height accuracy of the dataset, using 5121 independent check points distributed in the world (Tadono et al. 2016). It was also found that this DSM exhibits better vertical accuracy compared to both Shuttle Radar Topography Mission (SRTM) data and the Global Digital Elevation Model (GDEM) data (Santillan and Makinano-Santillan 2016). Furthermore, in open areas, AW3D30 DSM it can be comparable to TanDEM-X, visually and about the representation of terrain by contour lines (Grohmann 2018).

297 The AW3D30 DSM was reprojected to EPSG: 32719 - WGS 84/UTM Zone 19S and the *Clip Raster by Mask*
298 *Layer* algorithm in QGIS software (<https://www.qgis.org/>) was used to crop the raster, covering the crater region
299 to optimize computational efficiency. Contour lines with a 1 m interval were generated, with the 2752 m
300 elevation line demarcating the lake's maximum area. From the crater region, rasters at 10 m and 1 m resolutions
301 were derived from the original 30 m horizontal resolution using the *r.resamp.rst* RST algorithm in GRASS-GIS
302 (<https://grass.osgeo.org/>), applying the regularized spline with tension method. The 2752 m elevation contour line
303 was subsequently converted into a polygon and applied as a mask to the 30 m resolution AW3D30 DSM of the
304 crater region, as well as to the 10 m and 1 m rasters, effectively isolating the lake's maximum surface area as a
305 raster. The maximum surface area of the crater lake for the three obtained rasters was utilized as an input
306 parameter for the *Raster Surface Volume* algorithm in QGIS software (<https://www.qgis.org/>). This algorithm
307 directly provides the total volume, the covered area, and the total number of pixels analyzed based on a given
308 raster surface in relation to a specified base level. The selected base level corresponds to an elevation of 2752 m,
309 from which the volume below this threshold was calculated for all cases (**Table 4**).

310 For the simulation of hypothetical scenarios from different starting points, piles with varying geometries and
311 orientations, corresponding to the estimated water volume and volumetric solid concentrations of 30 % and 40 %
312 based on historical lahars at Copahue volcano, were considered (**Tables 5-6**). In this regard, TITAN2F provides
313 two predefined pile shapes: a cylindrical base and an elliptical base. The cylindrical pile acts as an initial wall, as
314 in the case of a collapsing wall of a lake, whereas the elliptical pile provides an approximation of a natural
315 hydrograph. The program automatically splits the flow according to the topography, as well as the velocity and
316 depth of the flow when it encounters a topographic barrier. The amount of material that splits depends on the
317 flow evolution in time which is a result of the modeling, instead of a predetermined volume or path (see Córdoba
318 et al. 2018).

319 The starting points P1 and P2 correspond to the UTM coordinates 310163E/5807913N and 310409E/5807586N,
320 located on the crater rim and in the Lomín basin, respectively, while the starting points P3 and P4 in the Agrio
321 basin correspond to the UTM coordinates 310424E/5807860N and 310719E/5808024N, respectively. For all
322 scenarios, the simulations were executed based on the ALOS PALSAR DEM which was used during the
323 calibration phase, as well as the initial velocity, bed friction, and internal friction values given above (see **Sub-**
324 **section 3.1**).

325 In the upper Agrio basin, at UTM coordinate 311618E/5808489N, where a slope change and historical lahar
326 deposits are observed, to the maximum extent reached by each simulated flow, points were selected along the

main channel of the Agrio River using tools provided by QGIS (<https://www.qgis.org/>). These points were defined at non-equidistant but consistently spaced intervals, with an average distance of every 17.35 m. From these points, velocity, depth, and dynamic pressure values were extracted for each initial pile based on its volume, geometry, and location within the basin. The average values of each parameter along the channel, as well as those for the final kilometer, are presented in **Table 6**.

4. Results

4.1 Calibration of TITAN2F for modeling lahar deposits based on the Agrio basin

At Copahue volcano, the Agrio basin contains the most extensive 1992-95 lahar deposits, extending up to 6.26 km along the main channel and remaining relatively well preserved, allowing for detailed analysis of their distribution and extent. Mapping of these deposits was performed using Landsat 4-5 Thematic Mapper (TM) Collection 2 Level 1 satellite imagery and field data to estimate their volume. This estimate was then combined with hypothetical water volumes, to calculate different total initial volumes of water and debris, which were used in simulations with TITAN2F to assess the best replicating results for the 1992-95 lahar deposits in the Agrio basin.

The determination of these volumes began with the delineation of the lahar deposit in the Agrio basin using remote sensing data in QGIS software. **Figures 2A-B** display Landsat scenes from March 13, 1990, and February 26, 1999, representing the periods before and after the 1992 and 1995 eruptions, respectively. The combination of bands 1, 4, and 7 in the images from both years enhanced the visibility of the lahar deposit in the 1999 image, ensuring that the mapping accurately reflected the flows generated by these eruptions (**Figure 2B**). Given that the 1992 lahar extended approximately 4 km in the Agrio basin (Delpino and Bermúdez 1993) and the 1995 flow had the greatest reach, surpassing the previous deposits (Bermúdez and Delpino 1995), it is inferred that the lahar mapped in the February 26, 1999 Landsat image corresponds to the 1995 event.

Once the area affected by the lahar was delineated from satellite images, it was adjusted with field data, resulting in an affected area of 1,146,473 m² ($\sim 1.15 \times 10^6$ m²). By multiplying this area by the average field-measured thickness of 0.22 m, a minimum solid volume of 252,224 m³ ($\sim 2.52 \times 10^5$ m³) was obtained. Since the solid volume estimated from the preserved lahar deposit represents a minimum volume and is likely not fully representative of the solid content of the original flow, its value was increased by a factor of two. From this adjusted volume, three scenarios were generated considering different water proportions. When the solid volume

represented 30 % of the total volume, the combined volume was $\sim 1.68 \times 10^6 \text{ m}^3$, while for 40 % and 45 %, the total volume resulted in $\sim 1.26 \times 10^6 \text{ m}^3$ and $\sim 1.12 \times 10^6 \text{ m}^3$, respectively (**Table 1**).

Figure 3 shows the results of the three simulated flows. In all cases, TITAN2F accurately replicates the trajectory of the lahars generated during the evaluated period (**Figure 3B-D**). **Figure 4A** details the initial configuration, represented by an elliptical pile oriented parallel to the Agrio River's course in its upper section. **Figure 4B** illustrates how the simulations replicate the super-elevation at the first bend of the river at 100 seconds into the simulation. **Figure 4C** shows the overflow of the lahar into a sub-basin in the upper reaches of the Agrio River replicated at the 150-second mark of the simulation. Between 300 and 760 seconds, flow bifurcations within the Agrio sub-basin are accurately reproduced, followed by its realignment to the main channel downstream (**Figures 4D-F**). It can also be observed that as the initial volume increases, the models tend to extend laterally the area covered by the flows (**Figures 3B-D**). In **Figure 5**, the areas where none of the three simulated flows reached (i.e., false negatives) are shown in red. The simulations were validated against the historical deposit in terms of area using the Jaccard index. The R_j values obtained using Equation 1 for the simulated flows were 41 %, 39 %, and 27 % for initial volumes of $\sim 1.12 \times 10^6 \text{ m}^3$, $\sim 1.26 \times 10^6 \text{ m}^3$, and $\sim 1.68 \times 10^6 \text{ m}^3$ respectively (**Figure 5; Table 3**).

Regarding the flow reach, the analysis shows that when the initial total volume is $\sim 1.12 \times 10^6 \text{ m}^3$, the flow travels 6.97 km along the Agrio River. On the other hand, when the initial total volume is $\sim 1.26 \times 10^6 \text{ m}^3$ and $\sim 1.68 \times 10^6 \text{ m}^3$, the distances reached are 7.44 km and 11.73 km, respectively, highlighting that a larger initial volume increases the travel distance of the simulated lahars (**Table 2**). **Figure 6** illustrates the simulated lahar extents and compares them with the limits of the 1995 lahar deposit mapped in the field, as well as the 8 km limit along the Agrio River reported by [Bermúdez and Delpino \(1995\)](#).

The average depths of the simulated flows were 2.66 m, 2.77 m and 2.70 m for initial volumes of $\sim 1.68 \times 10^6 \text{ m}^3$, $\sim 1.26 \times 10^6 \text{ m}^3$, and $\sim 1.12 \times 10^6 \text{ m}^3$, respectively (**Table 2**). These values are considerably larger than the observed thickness of the original lahar deposit in the field, which was estimated to be an average of 0.22 m.

The lahar with the greatest reach corresponds to an initial total volume of $\sim 1.68 \times 10^6 \text{ m}^3$ and a solid volumetric concentration of 30 %. This flow reaches less than 0.3 km from the bridge to the town of Caviahue and only 1.4 km from flowing into Lake Caviahue (**Figure 6**). Non-equidistant points, consistently spaced with an average distance of $\sim 16.50 \text{ m}$ between them, were defined to extract key parameters. From these points, values for velocity, depth, and dynamic pressure were obtained, and the average values for each parameter were calculated.

384 The average flow depth, velocity, and dynamic pressure over the final kilometer of the Agrio River channel are
385 2.24 m, 3.27 m/s, and 9.61 kPa, respectively (Table 2).

386 4.2 Simulation of hypothetical scenarios in the northeast area of Copahue volcano

387 The calculation of the crater lake volume required the generation of three rasters with resolutions of 30 m, 10 m,
388 and 1 m from the AW3D30 DSM, representing the maximum crater lake surface area derived from the contour
389 line at an elevation of 2752 m. The minimum elevations were 2718 m for the original resolution (30 m) and
390 2714.76 m and 2714.31 m for the reinterpolated resolutions of 10 m and 1 m, indicating decreases of 3.24 m and
391 3.69 m, respectively. Conversely, the maximum elevations decrease to 2751 m in the 30 m raster, while they
392 increase to 2753.11 m and 2755.39 m in the reinterpolated rasters at 10 m and 1 m, respectively.

393 The volume of the crater lake at Copahue volcano was calculated using the *Raster Surface Volume* algorithm in
394 QGIS. For the 30 m raster, a base level of 2751 m was established, corresponding to the maximum elevation for
395 this case. This resulted in an area of 69948 m², with 90 pixels counted and a calculated volume of 1625908 m³.
396 For the 10 m and 1 m rasters, the elevation of 2752 m was used as the base level, as the heights resulting from the
397 reinterpolation were greater. The corresponding areas were 73100 m² and 74646 m², with 727 and 74651 pixels
398 counted, resulting in volumes of 1719183 m³ and 1723449 m³, respectively. Considering that the area of the
399 contour line at 2752 m is 74690 m², the absolute and relative errors for the areas computed by the *Raster Surface*
400 *Volume* algorithm for the three rasters, 30 m, 10 m, and 1 m, were 4742 m² and 6 %, 1590 m² and 2 %, and 44 m²
401 and 0.1 %, respectively. All results are summarized in Table 4.

402 The volume of a water body is intrinsically linked to its area and depth. In this study, we utilized the volume
403 calculated from a raster reinterpolated to a resolution of 1 m, as this approach provides a more accurate
404 representation of the lake's maximum surface area. The rationale behind using a higher resolution raster lies in its
405 ability to minimize errors in the computed areas, particularly when applying algorithms such as the surface area
406 volume function in QGIS. Our findings indicated a relative error of only 0.1 % when compared to the area
407 delineated by the 2752 m contour line. Similarly, the relative error in the minimum elevation was 0.14 % when
408 compared to the minimum elevation derived from the original 30 m resolution raster (Table 4).

409 The estimated water volume was $\sim 1.72 \times 10^6$ m³ for the crater lake of Copahue volcano. Since ALOS/PRISM is
410 an optical sensor, it is not possible to determine whether the elevation difference between the 2752 m contour line
411 and the lowest point within the crater (~ 30 m) corresponds to the lake bottom or to the water surface; therefore,
412 the calculated volume may be underestimated. For example, Naranjo and Polanco (2004) reported that, before the
413 2000 eruption, the acidic lake that developed in the crater of Copahue volcano had a volume between 3 to $4.5 \times$

10⁶ m³. Given this limitation, the water volume was increased by a factor of two, and volumetric solid concentrations of 30 % and 40 % were subsequently added, resulting in two total volumes to model: $\sim 4.91 \times 10^6$ m³ and $\sim 5.73 \times 10^6$ m³, respectively (Tables 5-6). We emphasize that Copahue volcano has demonstrated the ability to generate lahars when the mixture of hot water and sediments from the crater lake combines with snow from the flanks (Delpino and Bermúdez 1993; Caselli et al. 2016a). Although phreatic eruptions do not necessarily mobilize all the available water for such flows (Lube et al. 2009), in our model we assume that the entire water volume is available for lahar generation, under the premise that any fraction not exceeding the crater rim would be compensated by the additional water supplied by snow and ice entrained along the volcano's slopes.

4.2.1 Scenarios with $\sim 4.91 \times 10^6$ m³ volume and 30 % volumetric solid concentration

Five initial piles were defined with a total initial volume of $\sim 4.91 \times 10^6$ m³ for simulations (Tables 5-6). The first three piles, characterized by cylindrical geometries, were located at various points of interest to qualitatively evaluate the trajectory, reach, and areas affected by the simulated flows in relation to historical lahar deposits. Figure 7 show the selected locations: P1, P2 and P3 corresponding to crater lake rim, Lomín basin, and Agrio basin, respectively. The remaining two piles were positioned within the Agrio basin and consisted of elliptical geometries: one located at P3 (coinciding with the third cylindrical pile) and the other at P4 (the same location, Q1, used during the calibration phase).

The first pile (P1), is depicted in Figure 8 in violet, representing the pre-collapse phase due to gravity. As the simulation progresses, a significant portion of the pile's volume begins displacing a large amount of material toward the crater interior.

The second pile (P2), show that the simulated flow predominantly extends along the main channel of the Lomín basin, funneling 75.84 % of the total volume toward the lower part of the basin (Figure 9). The trajectory and affected area in the steepest region of the Lomín basin are consistent with the historical lahar deposit. Upon reaching the slope break zone at the base of the volcano, the simulated flow expands into an alluvial fan, extending up to 5.45 km from the pile's starting point, covering a broad section of the valley (Table 5). Figure 9 shows that 24.16 % of the simulated flow diverting toward the Agrio basin, reaching a maximum of 5 km along its main channel, with overflow observed up to 0.60 km into the Agrio sub-basin. Conversely, no flow was recorded toward the Las Mellizas basin.

The simulated flows from the cylindrical and elliptical piles at P3 in the Agrio basin, exhibit similar behavior in terms of covered area and trajectory (Figure 10). The flow primarily channels through the Agrio basin, followed

by the Lomín River basin, with a small portion diverting toward the Las Mellizas basin, a pattern consistent with past lahar events at Copahue. When the pile geometry is cylindrical, 72.54 % of the total volume is directed toward the Agrio basin, 26.55 % toward the Lomín basin, and 0.91 % toward the Mellizas basin. In contrast, when the pile geometry is elliptical, 69.58 % of the total volume flows toward the Agrio basin, 28.83 % toward the Lomín basin, and 1.21 % toward the Mellizas basin, with 0.38 % entering the crater.

The travel distances of the simulated flows are 7.27 km and 8 km in the Agrio River and 4.69 km and 4.91 km in the Lomín River channel for elliptical and cylindrical initial piles, respectively (Table 5). In the Las Mellizas basin, both simulations reproduce the trajectory and reach of historical deposits, although some portions of the deposit area are not covered by the simulated flows. It is noteworthy that when the pile has an elliptical geometry, the simulated flow covers shorter distances and part of the simulated flow shifts toward the crater interior (Figure 10A). This behavior does not occur with the cylindrical pile, where the flow remains outside the crater throughout the simulation, influencing its reach (Figure 10B).

For the pile located within the Agrio basin at UTM coordinate 310719E/5808024N (P4) (Figure 11), 85.05 % of the simulated flow primarily diverges toward the Agrio River basin, reaching 7.45 km, while 1.48 % is distributed toward the Las Mellizas basin. Additionally, 13.47 % of the simulated flow is directed toward the Lomín River basin, covering a smaller area compared to historical lahar deposit, with a reach of 4.04 km (Table 5).

For all three simulated flows originating from piles at P3 and P4 in the Agrio River basin, the trajectories generally align with historical flows (Figures 10 and 11). Super-elevation is observed at the first curve, with overflow into the Agrio sub-basin in its upper course, followed by realignment downstream, as previously described in (see Figures 3 and 4). However, more extensive flow branches into the Agrio sub-basin are evident (Figure 12). Likewise, the simulated flows reached ~0.35 km and deviated toward the Dulce basin, which is hydrologically disconnected from the crater lake. The pattern of the simulated flow is consistent with distribution of the 1995 lahar deposits (Figure 12).

Additionally, at a distance of 3.88 km, the simulated flows divert toward the Jara sub-basin of the Agrio basin and reached a maximum distance of ~0.40 km (Figure 12).

4.2.2 Scenario with $\sim 5.73 \times 10^6 \text{ m}^3$ volume and 40 % volumetric solid concentration

The cylindrical pile located at the starting point P2 within the Lomín basin exhibits a flow predominantly confined along the main course. The trajectory and the affected area in the steepest regions are consistent with the distribution pattern of historical lahar deposit, similar to the scenario with an initial total volume of $\sim 4.91 \times 10^6$ m³. However, upon reaching the break in slope at the foot of the volcano, the simulated flow expands into an alluvial fan, extending up to 7.21 km from the starting point of the pile, widely occupying the valley section. A portion of the flow is directed toward the Agrio basin, reaching a maximum of 6.72 km along its main channel (Table 5). No flow was recorded toward the Mellizas basin.

Regarding the piles located in the Agrio basin, two geometric forms were defined: one cylindrical and one elliptical, situated at starting points P3 and P4, respectively. The cylindrical pile exhibits flow paths reaching up to 3.17 km and 1.83 km along the main courses of the Agrio and Lomín Rivers, respectively. In contrast, the flow simulated with the elliptical pile covers maximum distances of 4.79 km (Agrio River) and 2.78 km (Lomín River) (Table 5). Both piles replicate the trajectories of historical deposits, although they exhibit significant differences in their behavior and the extent of the generated flows. The simulation of cylindrical pile has shorter reaches and shows super-elevation at the first curve without spilling into the Agrio sub-basin, limiting its extension into adjacent areas. Additionally, this pile results in reduced volume within the Mellizas basin, with a portion of the flow entering the crater. On the other hand, the simulated flow by the elliptical pile diverts a larger volume of the flow toward the Mellizas basin.

4.2.3 Flow simulation parameters in the Agrio basin: depth, velocity and dynamic pressure

Average values for velocity, depth, and dynamic pressure along the main channel of the Agrio River were extracted, with particular focus on the results from the final kilometer of each simulated flow (Table 6). Calculations were performed for initial volumes of $\sim 4.91 \times 10^6$ m³ and 5.73×10^6 m³, considering solid volumetric concentrations of 30 % and 40 %, respectively.

When the starting point (P2) is located in the Lomín basin, the average depth are 5.39 m and 5.10 m, with average velocities of 7.76 m/s and 7.17 m/s and average dynamic pressures of 1182.56 kPa and 5577.04 kPa, corresponding to volumetric concentrations of 30 % and 40 %, respectively.

On the other hand, when the starting points (P3) are located in the Agrio basin, depth values range from a maximum of 12.31 m to a minimum of 7.47 m, while velocities vary between 21.58 m/s and 10.77 m/s for concentrations of 40 % and 30 %, respectively. The average dynamic pressures vary between 50135.30 kPa and

498 49813.87 kPa for solid volumetric concentrations of 40 %. For concentrations of 30 %, average values increase
499 for elliptical piles, reaching a maximum of 21433.00 kPa.

500 In the final kilometer of the Agrio River stretch, when the starting point is in the Lomín basin, the average values
501 obtained for flow depth, velocity, and dynamic pressure were 2.71 m and 2.59 m, 4.45 m/s and 2.87 m/s, and
502 19.80 kPa and 7.77 kPa, respectively, for solid volumetric concentrations of 30 % and 40 %.

503 When the starting points (P3 and P4) are located in the Agrio basin, average minimum and maximum values for a
504 40 % solid volumetric concentration were recorded as 6.43 m and 10.85 m for depth, 11.02 m/s and 17.06 m/s for
505 velocity, and 7212.22 kPa and 12462.64 kPa for dynamic pressure, respectively. Regarding the volumetric solid
506 concentration of 30 %, the average values for the last kilometer of the Agrio River stretch vary between a
507 minimum and maximum of 4.08 m and 4.39 m for flow depth, 4.17 m/s to 4.60 m/s for velocity, and 13.28 kPa to
508 16.26 kPa for dynamic pressure, respectively.

509 **5. Discussion**

510 **5.1 Calibration of TITAN2F for modeling lahar deposits based on the Agrio River basin**

511 Three scenarios were modeled with total volumes of $\sim 1.12 \times 10^6 \text{ m}^3$, $\sim 1.26 \times 10^6 \text{ m}^3$ and $\sim 1.68 \times 10^6 \text{ m}^3$, with
512 solid volume concentrations of 45 %, 40 %, and 30 %, respectively. The simulated flow that best fits the covered
513 area corresponds to a solid volume fraction of 45 %, with a Jaccard index (R_j) of 41 %. **(Figure 5; Table 3)**. The
514 low R_j value is most likely attributable to the tendency of the simulated flows to exhibit greater lateral expansion
515 of the affected area (Cruz-Vázquez et al. 2025). The relative error of the simulated extent to field-mapped deposit
516 is 11.34 % 18.85 % and 87.38 % for solid volume fractions of 45 % 40 % and 30 %, respectively.

517 The calibration suggests that the 1995 lahar had a volumetric solid concentration of around 45 %, within the
518 range of hyperconcentrated flows. Actually, the lahar deposits exhibit intermediate sorting coefficient ranging
519 from 1.5ϕ to -1.5ϕ (Báez et al. 2021) and display parallel and cross-stratification with lenses of the massive
520 facies in areas with gentle slopes (Balbis et al. 2016). Although Balbis et al. (2016) do not specify whether the
521 cross-stratification is of low-angle, which is one of characteristic features of hyperconcentrated flow deposits
522 (Vallance 2000; Vallance and Iverson 2015; Kataoka et al. 2018), they described diffuse lamination in the
523 deposits, probably suggesting weak stratification developed in hyperconcentrated flow. Such faint or crude
524 stratification distinguishes hyperconcentrated flow deposits from deposits derived from normal streamflow (Scott
525 et al. 1995; Kataoka et al. 2018; Procter et al. 2021). On the other hand, it is important to highlight the limitations

of the modeling in this study. [Delpino and Bermúdez \(1993\)](#) describe that during the 1992 eruption, when sediment and hot water from the crater lake mixed with snow, the resulting lahars consisted of a mixture of ice, snow, and solid material fragments, while the final stages of the lahar was predominantly composed of ice. Although there are no detailed descriptions of the lahars generated in 1995, they can be attributed to the same mechanism, since they occurred in winter and were triggered by the expulsion of sediment and hot water from the crater lake ([Bermúdez and Delpino 1995](#); [Caselli et al. 2016a](#)). Lahars composed of a mixture of snow, ice, rock particles, water, and air (ice-slurry lahars), such as those described at Copahue volcano, have also been reported at other volcanoes covered by snow and ice (e.g. [Gardner et al. 1994](#); [Branney and Gilbert 1995](#); [Cronin et al. 1996](#); [Lube et al. 2009](#); [Kilgour et al. 2010](#); [Waythomas et al. 2013](#)). The deposits of these flows, upon losing their ice and air components, deflate to a small fraction of their original thickness, thereby removing evidence of their unusual origin ([Smellie 2022](#)). For example, the ice-rich lahar deposits generated during the August and October 1991 eruptions of Hudson Volcano (Chile), by February–March 1992, most of these ice blocks had melted, and the deposit had compacted sufficiently to be walked on ([Branney and Gilbert 1995](#)). Similarly, [Graettinger et al. \(2010\)](#) described ice-slurry lahar deposits generated by a small phreatic eruption through the crater lake at Mt. Ruapehu in 2007. Thawing of the frozen deposits resulted in a reduction of approximately 90% of their original thickness within one month after the initial deposition. After snow and ice melt of the lahar deposits, they (composed of non-meltable material) were subject to erosion, which played an important role in further reducing their original thickness ([Graettinger et al. 2010](#)). In this context, estimating the solid fraction volume of the deposit based on simple average values of area and thickness constitutes a significant source of uncertainty ([Gardner et al. 1994](#); [Waythomas et al. 2013](#)), with the average thickness being the most influential parameter ([Gardner et al. 1994](#)). Furthermore, as our approach considers only the non-meltable solid volume for calibration, it is likely that the flow involved a lower volumetric content of rock fragments, owing to the significant presence of snow and ice in the original deposit (e.g. [Lube et al. 2009](#); [Kilgour et al. 2010](#); [Waythomas et al. 2013](#)).

Another important aspect to consider is that, in TITAN2F, the total mass of the flow is fixed, and erosion-deposition are neglected ([Córdoba et al. 2018](#)), which constitutes a potential source of error in the simulation results ([Mead and Magill 2017](#)). In addition, entrained snow and ice particles would have significantly affected the rheology and flow behavior of the original lahar; therefore, it is important to emphasize that the TITAN2F code is designed for two-phase mixtures of water and sediment and may not accurately reproduce the rheology of more complex flows involving three or more phases (e.g. water, rock fragment, ice, and air).

The average depths of the simulated flows ranged from 2.66 m to 2.77 m, while in the field, an average deposit thickness of 0.22 m was estimated, a result similar to the 0.20 m described by Balbis et al. (2016). Báez et al. (2021) and Kaufman et al. (2023) observed deposits up to 0.65 m thick in the upper basin and between 0.55 and 0.95 m thick in the middle and lower sections, respectively. The higher average depths of the simulated flows compared to the average deposit thickness measured in the field are likely due to the flow modeled by TITAN2F represents the mixture of water and sediment in each computational grid cell, rather than the deposited sediment. Delpino and Bermúdez (1993) reported flow depths for the 1992 lahar ranging between 0.5 m and 1 m, whereas no descriptions are available for the flow depths of the 1995 lahar event. Williams et al. (2008) report an overestimation of simulated flow depths compared to observed flow depths, which they attribute to the DEM used for the simulations, while Córdoba et al. (2018) attribute it to the geometry of the initial pile. It should also be noted that the thickness of lahar deposit is subject to erosion due to prevailing regional conditions (Petrinovic et al. 2014b; Balbis et al. 2016), and thus differs from the thickness at the time of deposition. The fact that the models generated with TITAN2F do not fully cover the area of the lahar deposits could indicate that the deposited material influences the flow trajectory, representing the behavior of the lahar under post-event topographic conditions (e.g. Stevens et al. 2003).

Finally, the lahar with the greatest reach occurs with an initial total volume of $\sim 1.68 \times 10^6 \text{ m}^3$ and a solid volumetric concentration of 30 %. It reaches a distance of 11.73 km, being 0.3 km away from reaching the bridge to the town of Caviahue and 1.4 km from flowing into Lake Caviahue (Figure 6). The average values of flow depth, velocity, and dynamic pressure, calculated along the last kilometer of the Agrio River channel, are 2.24 m, 3.27 m/s, and 9.61 kPa, respectively. It is inferred that as the flow volume increases, it is expected to travel greater distances, which is consistent with the findings of Viotto et al. (2023), who established that flow volume of 10^6 m^3 would be needed to reach Caviahue.

5.2 Hypothetical scenario simulations on the northeast flank of Copahue volcano

This study selected the ALOS World 3D - 30m (AW3D30) Digital Surface Model (DSM), due to its extensive global coverage and open-access datasets, which provided the necessary digital elevation data for calculating the lake's volume. The original 30 m raster presents a relatively high error compared with the reinterpolated 10 m and 1 m rasters in terms of area, reflecting the greater ability of higher-resolution rasters to represent finer topographic details. This may be due to the fact that, while reinterpolation does not increase the level of detail of the original DEM (Grohmann and Steiner 2008) and improve data accuracy, it can provide a way to better

585 represent and identify topographic and hydrological features (Her et al. 2015 and references therein). While the
586 reinterpolation causes a reduction in the minimum elevation and an increase in maximum elevations, the volume
587 calculated with the 1 m raster allows for a more accurate estimation of the lake volume, as the maximum level is
588 determined by the fixed value derived from the 2752 m contour line.

589 It is important to note that the water volume of the crater lake, was estimated based on the terrain configuration of
590 2006-2011 (Tadono et al. 2016), prior to the 2012 eruption. Therefore, this value does not reflect the current state
591 of the lake, as the topography is likely to have been changed by the eruptive event.

592 Another important point to highlight is that the water volume obtained in this study may be underestimated
593 (Naranjo and Polanco 2004). ALOS/PRISM is an optical sensor, and therefore it is not possible to determine
594 whether the elevation difference between the 2752 m contour line and the lowest point within the crater (~30 m)
595 corresponds to the lake bottom or the water surface. Consequently, this uncertainty should be considered in future
596 studies. The volume obtained from the DSM was $\sim 1.72 \times 10^6 \text{ m}^3$, whereas Naranjo and Polanco (2004) reported
597 that the volume of the crater lake before to the 2000 eruption ranging between 3 to $4.5 \times 10^6 \text{ m}^3$. Thus, by
598 increasing the DSM-derived volume by a factor of two, it yields a maximum value of $3.44 \times 10^6 \text{ m}^3$, which was
599 used to model the hypothetical scenarios. Likewise, we emphasize that the model assumes all the water is
600 available for the simulation of hypothetical scenarios. This approach was adopted because lahars at Copahue are
601 generated by the interaction between the sediment–water mixture of the crater lake and the snow from the
602 volcano’s slopes. Therefore, we assumed that the fraction of water not overflowing the crater rim would likely be
603 compensated by additional water supplied by snow and ice entrained along the volcano’s flanks (Lube et al. 2009;
604 Kilgour et al. 2010).

605 To model potential lahars on Copahue volcano, four starting points were defined, each located to analyze how the
606 volume of simulated material is distributed across the different basins (Figures 7-11). The first point was
607 established at the crater rim (Figure 8). During the simulation, it was observed that a large portion of the material
608 volume tended to move inward towards the crater. This simulated tendency of material to retract inward suggests
609 that the amount of material entering the crater reduces the available mass, altering the flow dynamics, primarily
610 affecting the maximum reach of the simulated flow. This could explain the shorter reach of the simulated flows
611 when the pile is elliptical at P3, as when the simulation begins, part of the volume enters the crater, while when
612 the pile is cylindrical, it does not enter, and thus, the flow is directed toward the respective basins of Copahue
613 volcano (Figures 10A-B; Table 5).

614 According to historical records, the Agrio basin confined the lahars with the greatest reach, followed by the
615 Lomín basin, and to a lesser extent, the Las Mellizas basin. The piles, with volumes of $\sim 4.91 \times 10^6 \text{ m}^3$, generally
616 follow the trajectories and areas affected by historical flows. The maximum reach of the simulated lahars in the
617 Agrio basin extends up to 8 km, similar to the travel distance reported for the 1995 lahar (Bermúdez and Delpino
618 1995). In the Lomín River channel, the travel distance of the simulated flows is up to 5.46 km and is greater than
619 the reported value (3.5 km).

620 Lahar models with an initial total volume of $\sim 5.73 \times 10^6 \text{ m}^3$ show similar distributions to those with an initial
621 total volume of approximately $\sim 4.91 \times 10^6 \text{ m}^3$. The most notable feature is that all models with higher solid
622 concentrations exhibit a shorter flow reach than those with a lower volumetric concentration of solids. However,
623 the simulated pile with a starting point in the Lomín basin (P2) shows a greater reach of 7.21 km along its main
624 channel when the pile originates within this basin.

625 Flows associated with Copahue volcano display a distinct tendency to follow well-defined trajectories, as
626 observed in both historical events and modeled analyses. Figure 13 presents satellite images from Landsat 4-5
627 Thematic Mapper (TM) Collection 2, from March 13, 1990 (Landsat Scene Identifier:
628 LT42320861990072XXX08) and February 26, 1999 (Landsat Scene Identifier: LT52320861999057COA00),
629 both in a composition of bands 6, 1, and 3, highlighting the lahar path with yellowish tones. Figure 13A-B shows
630 the pattern of a possible flow associated with an unknown eruptive event prior to the 1992 eruption, while Figure
631 13C-D illustrates the lahar attributed to the 1995 eruptive event. Both show similar flow paths in the upper
632 section of the Lomín basin and in the upper and middle sections of the Agrio basin. Numerical models suggest
633 that when originating from the sector most proximal to the crater, the flows are widely distributed across the
634 Agrio, Lomín, and Las Mellizas basins, causing a redistribution of volumes in various areas (see Sub-section
635 4.2.1). It is common to observe the migration of flows into sub-basins in the upper Agrio basin due to phenomena
636 of super-elevation or overflow. This behavior even includes deviations towards the Dulce basin, despite lacking a
637 direct hydrological connection to the crater lake.

638 Considering the simulated flow with the greatest reach across the Agrio basin (8.00 km), average values of 7.47
639 m in depth, 10.77 m/s in velocity, and 8298.79 kPa of dynamic pressure are recorded along the Agrio River. For
640 the final kilometer of the river, average values of 4.25 m in depth, 4.17 m/s in velocity, and 13.28 kPa of dynamic
641 pressure are observed.

642 6. Conclusions

643 This study focuses on lahar modeling, emphasizing the critical role of the crater lake, from which hypothetical
644 scenarios were simulated using the TITAN2F software, considering solid volumetric concentrations of 30 % and
645 40 %, resulting in two total volumes to be modeled: $\sim 4.91 \times 10^6 \text{ m}^3$ and $\sim 5.73 \times 10^6 \text{ m}^3$, respectively.

646 The results show that the Agrio and Lomín basins, act as the main receptors of lahars. In the Las Mellizas basin,
647 flows are more limited and do not exhibit the same magnitude as those found in the Agrio and Lomín basins.
648 Historical lahars, as well as numerical models tend to follow river valleys, influenced by the terrain's relief, slope,
649 and the presence of natural obstacles. The models predict a maximum reach of up to 8 km over the Agrio basin
650 when the initial volume is $\sim 4.91 \times 10^6 \text{ m}^3$ with a solid volumetric concentration of 30 %. This scenario results in
651 dynamic pressures and average velocities of 13.28 kPa and 4.17 m/s, respectively, calculated in the last kilometer
652 of the Agrio River. The average dynamic pressure in the last kilometer is low, due to a decrease in flow velocity
653 as the topography becomes smoother.

654 In the Agrio basin, simulated lahars are observed to migrate into sub-basins due to super-elevation or overflow
655 phenomena. This behavior even includes deviations towards the Dulce basin, despite the absence of a direct
656 hydrological connection to the crater lake, reaching a maximum distance of $\sim 0.35 \text{ km}$ in that direction. This is
657 consistent with observations from past lahar events. Furthermore, at a distance of 3.88 km along the main channel
658 of the Agrio River, the simulated flow is predicted to divert into the Jara sub-basin of the Agrio basin with a
659 maximum reach of $\sim 0.40 \text{ km}$.

660 Before simulating hypothetical scenarios, a calibration process was conducted to assess the reliability of the
661 TITAN2F software. The flow simulations showed good agreement with the path of the historical lahar deposits in
662 the Agrio basin, suggesting that the developed models may be effective in predicting future events. However, the
663 complex rheology of flows composed of a mixture of water and sediment that entrain snow and ice along their
664 flow path represents an important limitation of the numerical code, which was developed for two-phase flow
665 simulations, assumes a fixed total flow mass, and neglects erosion and deposition.

666 The numerical modeling techniques to forecast lahars underscore the importance of integrating different data
667 sources and methodologies to address complex issues related to volcanic risk management. In particular, the
668 temporal analysis of satellite images is especially useful for identifying the extent and distribution of past lahar
669 deposits, as well as for determining the flow trajectories. This is particularly relevant, as a volcanic environment
670 can hinder the preservation of deposits, potentially underestimating the original area of the lahars in the field
671 years after, which consequently influences the volume calculation.

672 The integration of open-access satellite datasets, such as the ALOS World 3D Digital Surface Model (AW3D30)
673 with open-source GIS tools like QGIS and GRASS-GIS, is crucial for estimating volumes in volcanic lakes, such
674 as the crater lake of Copahue volcano. This study demonstrated that reinterpolating the AW3D30 DSM to higher
675 resolutions improves volume estimation by isolating the lake's maximum surface. However, the data used here
676 does not represent the current configuration of the crater, and therefore the calculated volume is likely
677 underestimated. Also the scenarios evaluated in this study do not consider other lahar-triggering mechanisms, nor
678 do they include additional water sources, such as intense rainfall, which could increase the total volume of the
679 simulated flows.

680 **Author contributions**

681 **Rafael B. Sale:** conceptualization, methodology, data analysis and interpretation, fieldwork, GIS and mapping,
682 simulations using numerical code TITAN2F, writing - original draft. **Gustavo A. Córdoba:** supervision,
683 TITAN2F training for Author. **Alberto T. Caselli:** supervision, fieldwork. All authors contributed to and
684 reviewed the final manuscript.

685 **Acknowledgements**

686 This work has been supported by the projects PIP743. The authors sincerely thank the two anonymous reviewers
687 and the Editor, Prof. Kyoko Kataoka, for their constructive comments, which greatly improved the manuscript.

688 **Data availability**

689 All data are available upon request from the corresponding author.

690 **References**

- 691 Agosto, M. R. (2011). “Estudio geoquímico de los fluidos volcánicos e hidrotermales del Complejo Volcánico
692 Copahue-Caviabue y su aplicación para tareas de seguimiento”. PhD thesis, page 294. Facultad de Ciencias
693 Exactas y Naturales. Universidad de Buenos Aires.
- 694 Agosto, M., A. Caselli, F. Tassi, M. do Santos Afonso, and O. Vaselli (2012). “Seguimiento geoquímico de las
695 aguas ácidas del sistema Volcán Copahue-Río Agrio: posible aplicación para la identificación de precursores
696 eruptivos”. *Revista De La Asociación Geológica Argentina* 69(4), pages 481—495. Retrieved from
697 <https://revista.geologica.org.ar/raga/article/view/500>

698 Augusto, M., F. Tassi, A. Caselli, O. Vaselli, D. Rouwet, B. Capaccioni, and G. Chiodini (2013). “Thermal and
699 chemical changes in the crater lake of Copahue volcano (Argentina) prior to the December 2012
700 phreatomagmatic eruption”. *IAVCEI General Assembly 2013, Kagoshima Japan*, page 1019.

701 Augusto, M., and M. L. Vélez (2017). “Avances en el conocimiento del sistema volcánico-hidrotermal del
702 Copahue: a 100 años del trabajo pionero de Don Pablo Groeber”. *Revista De La Asociación Geológica Argentina*
703 74(1), pages 109-124. Retrieved from <https://revista.geologica.org.ar/raga/article/view/269>

704 Augusto, M. R., A. Caselli, R. Daga, J. Varekamp, A. Trinelli, M. Dos Santos Afonso, M. L. Vélez, P. Euillades,
705 and S. Ribeiro Guevara (2017). “The crater lake of Copahue volcano (Argentina): geochemical and thermal
706 changes between 1995 and 2015”. *Geological Society, London, Special Publications* 437, pages 107-130.
707 <https://doi.org/10.1144/sp437.16>

708 ASF DAAC (2015). “ALOS PALSAR_Radiometric_Terrain_Corrected_hi_res; Includes Material ©JAXA/METI
709 2007”. Accessed through <https://search.asf.alaska.edu/> on 13 July 2023. DOI: 10.5067/Z97HFCNKR6VA

710 Ayres, G. (2012). “Behaviour of rare earth elements during water-rock interaction and alteration processes in
711 volcanic lake systems”. Master thesis, page 108. Utrecht University.

712 Báez, A. (2015). “Estudio de los depósitos post-glaciares del volcán Copahue: análisis de la peligrosidad”.
713 Trabajo final de grado. Universidad Nacional de Río Negro.

714 Báez, A. D., W. Báez, A. T. Caselli, R. Daga, and C. A. Sommer (2021). “A reinterpretation of pyroclastic
715 density current deposits at Copahue volcano, Andean Southern Volcanic Zone, Argentina-Chile”. *Journal of*
716 *South American Earth Sciences* 111, article 103479. <https://doi.org/10.1016/j.jsames.2021.103479>

717 Balbis, C., I. A. Petrinovic, and S. Guzmán (2016). “A contribution to the hazards assessment at Copahue
718 volcano (Argentina-Chile) by facies analysis of a recent pyroclastic density current deposit”. *Journal of*
719 *Volcanology and Geothermal Research* 327, pages 288-298. <http://dx.doi.org/10.1016/j.jvolgeores.2016.08.009>

720 Bermúdez, A. and D. Delpino (1995). “Mapa de los peligros potenciales en el área del Volcán Copahue Sector
721 Argentino”. Serie Mapas de Riesgo Geológico. Servicio Geológico Neuquino, Neuquén.

722 Bonali, F. L., C. Corazzato, F. Bellotti, and G. Groppelli (2016). “Active Tectonics and Its Interactions with
723 Copahue Volcano”. In: *Tassi, F., Vaselli, O., Caselli, A. (eds) Copahue Volcano. Active Volcanoes of the World*.
724 Springer, Berlin, Heidelberg, pages 23-45. https://doi.org/10.1007/978-3-662-48005-2_2

725 Branney, M. J. and J. S. Gilbert (1995). "Ice-melt collapse pits and associated features in the 1991 lahar deposits
726 of Volcán Hudson, Chile: criteria to distinguish eruption-induced glacier melt". *Bulletin of Volcanology* 57, pages
727 293-302. <https://doi.org/10.1007/BF00301289>

728 Brett, A. (2018). "Lahar Meets Locomotive: New Zealand's Tangiwai Railway Disaster of Christmas Eve 1953".
729 *Environment & Society Portal, Arcadia* 31. Rachel Carson Center for Environment and Society.
730 doi.org/10.5282/rcc/8476.

731 Brown, S. K., M. R. Auken, and R. S. J. Sparks (2015). "Populations around Holocene volcanoes and
732 development of a Population Exposure Index". In S. C. Loughlin, S. Sparks, S. K. Brown, S. F. Jenkins, & C. Vye-
733 Brown (Eds.), *Global Volcanic Hazards and Risk*. Cambridge: Cambridge University Press, pages 223-232.
734 <https://doi.org/10.1017/CBO9781316276273.006>

735 Brown, S. K., S. F. Jenkins, R. S. J. Sparks, H. Odbert, and M. R. Auken (2017). "Volcanic fatalities database:
736 analysis of volcanic threat with distance and victim classification". *Journal of Applied Volcanology* 6, article 15.
737 <https://doi.org/10.1186/s13617-017-0067-4>

738 Calhoun, N. C. and J. J. Clague (2018). "Distinguishing between debris flows and hyperconcentrated flows: an
739 example from the eastern Swiss Alps". *Earth Surface Processes and Landforms* 43(6), pages 1280-1294.
740 <https://doi.org/10.1002/esp.4313>

741 Candela-Becerra, L. J., G. Toyos, C. A. Suárez-Herrera, S. Castro-Godoy, and M. Agosto (2020). "Thermal
742 evolution of the Crater Lake of Copahue Volcano with ASTER during the last quiescence period between 2000
743 and 2012 eruptions". *Journal of Volcanology and Geothermal Research* 392, article 106752.
744 <https://doi.org/10.1016/j.jvolgeores.2019.106752>

745 Capra, L., J. C. Gavilanes-Ruiz, N. Varley, and L. Borselli (2019). "Origin, Behaviour and Hazard of Rain-
746 Triggered Lahars at Volcán de Colima". In: Varley, N., Connor, C., Komorowski, J.C. (eds) *Volcán de Colima.*
747 *Active Volcanoes of the World*. Springer, Berlin, Heidelberg, pages 141-157. [https://doi.org/10.1007/978-3-642-](https://doi.org/10.1007/978-3-642-25911-1_2)
748 [25911-1_2](https://doi.org/10.1007/978-3-642-25911-1_2)

749 Caselli, A. T., M. Agosto, and A. Fazio (2005). "Cambios térmicos y geoquímicos del lago cratérico del volcán
750 Copahue (Neuquén): posibles variaciones cíclicas del sistema volcánico". In *XVI Congreso Geológico Argentino,*
751 *La Plata, Argentina*, pages 332-336.

752 Caselli, A. T., C. Dapeña, M. Agosto, and A. Delgado Huertas (2006). “Geothermal Copahue volcano system,
753 Argentina. New stable isotope and geochemical data”. In *Proceedings of the Vth South American Symposium on*
754 *Isotope Geology, Uruguay*, pages 332-336.

755 Caselli, A. T., M. L. Velez, M. R. Agosto, C. L. Bengoa, P. A. Euillades, and J. Ibañez (2009). “Copahue volcano
756 (Argentina): a relationship between ground deformation, seismic activity and geochemical changes”. In: *Bean*
757 *CJ, Braiden AK, Lockmer I, Martini F, O’Brien GS (eds) The volume project. Volcanoes: understanding*
758 *subsurface mass movement*. Jaycee Printing, Dublin, pages 309–318.

759 Caselli, A. T., M. L. Velez, M. Agosto, C. Liccioli, and O. Vaselli (2016a). “Prehistoric to Historic Volcanic
760 Activity at Copahue Volcano”. In: *Tassi, F., Vaselli, O., Caselli, A. (eds) Copahue Volcano. Active Volcanoes of*
761 *the World*. Springer, Berlin, Heidelberg, pages 49–59. https://doi.org/10.1007/978-3-662-48005-2_3

762 Caselli, A., M. Agosto, M. L. Velez, P. Forte, C. Bengoa, R. Daga, J. M. Albite, and B. Capaccioni (2016b). “The
763 2012 Eruption”. In: *Tassi, F., Vaselli, O., Caselli, A. (eds) Copahue Volcano. Active Volcanoes of the World*.
764 Springer, Berlin, Heidelberg, pages 61-77. https://doi.org/10.1007/978-3-662-48005-2_4

765 Charbonnier, S. J., C. B. Connor, L. J. Connor, M. F. Sheridan, J. P. Oliva-Hernández, and J. A. Richardson
766 (2018). “Modeling the October 2005 lahars at Panabaj (Guatemala)”. *Bulletin of Volcanology* 80, article 4.
767 <https://doi.org/10.1007/s00445-017-1169-x>

768 Córdoba, G., G. Villarosa, M. F. Sheridan, J. G. Viramonte, D. Beigt, and G. Salmuni (2015). “Secondary lahar
769 hazard assessment for Villa la Angostura, Argentina, using Two-Phase-Titan modelling code during 2011 Cordón
770 Caulle eruption”. *Natural Hazards Earth System Sciences* 15(4), pages 757–766. [https://doi.org/10.5194/nhess-](https://doi.org/10.5194/nhess-15-757-2015)
771 [15-757-2015](https://doi.org/10.5194/nhess-15-757-2015)

772 Córdoba, G. A., M. F. Sheridan, and B. Pitman (2018). “Titan2F code for lahar hazard assessment: derivation,
773 validation and verification”. *Boletín de la Sociedad Geológica Mexicana* 70(3), pages 611-631.
774 <http://dx.doi.org/10.18268/BSGM2018v70n3a3>

775 Crandell, D. R. (1971). “Postglacial Lahars From Mount Rainier Volcano, Washington”. *U.S. Geological Survey*
776 *Professional Paper* 677, page 75.

777 Cronin, S. J., V. E. Neall, J. A. Lecointre, and A. S. Palmer (1996). “Unusual “snow slurry” lahars from Ruapehu
778 volcano, New Zealand, September 1995”. *Geology* 24(12), pages 1107-1110. [https://doi.org/10.1130/0091-](https://doi.org/10.1130/0091-7613(1996)024<1107:USSLFR>2.3.CO;2)
779 [7613\(1996\)024<1107:USSLFR>2.3.CO;2](https://doi.org/10.1130/0091-7613(1996)024<1107:USSLFR>2.3.CO;2)

780 Cronin, S. J., K. A. Hodgson, V. E. Neall, A. S. Palmer, and J. A. Lecoindre (1997). “1995 Ruapehu lahars in
 781 relation to the late Holocene lahars of Whangaehu River, New Zealand”. *New Zealand Journal of Geology and*
 782 *Geophysics* 40(4), pages 507-520. <https://doi.org/10.1080/00288306.1997.9514780>

783 Cruz-Vázquez, O., L. Capra, L. Borselli, and G. Norini (2025). “Inter-eruptive lahars at El Chichón Volcano
 784 (Mexico): Susceptibility analysis and numerical modelling”. *Earth Surface Processes and Landforms* 50(5),
 785 article e70070. <https://doi.org/10.1002/esp.70070>

786 Daag, A. S. (2003). “Modelling the erosion of the pyroclastic flow deposits and the occurrences of Lahars at Mt.
 787 Pinatubo, Philippines”. PhD thesis, page 238. Research external, graduation external, Utrecht University,
 788 International Institute for Geo-Information Science and Earth Observation - ITC. International Institute for Geo-
 789 Information Science and Earth Observation.

790 De Bélizal, E., F. Lavigne, D. S. Hadmoko, J.-P. Degeai, G. A. Dipayana, B. W. Mutaqin, M. A. Marfai, M.
 791 Coquet, B. Le Mauff, A.-K. Robin, C. Vidal, N. Cholik, and N. Aisyah (2013). “Rain-triggered lahars following
 792 the 2010 eruption of Merapi volcano, Indonesia: A major risk”. *Journal of Volcanology and Geothermal*
 793 *Research* 261, pages 330-347. <http://dx.doi.org/10.1016/j.jvolgeores.2013.01.010>

794 Delmelle, P., R. W. Henley, and A. Bernard (2015). “Volcano-related lakes”. In *The encyclopedia of volcanoes* .
 795 Academic Press, pages 851-864 <http://dx.doi.org/10.1016/B978-0-12-385938-9.00048-1>

796 Delpino, D. and A. Bermúdez (1993). “La actividad del volcán Copahue durante 1992. Erupción con emisiones
 797 de azufre piroclástico, Provincia de Neuquen, Argentina”. In *Proceedings of XII Congreso Geológico Argentino*,
 798 pages 292-301.

799 Delpino, D. and A. Bermúdez (1994). “Volcanismo post-glacial en el volcan Copahue (37° 45’S) sector
 800 argentino. Peligros potenciales asociados”. *VII Congreso Geológico Chileno, Puerto Varas, Chile* 1, pages 260–
 801 264.

802 Delpino, D. and A. Bermúdez (2002). “La erupción del volcán Copahue del año 2000. Impacto social y al medio
 803 natural. Provincia del Neuquén. Argentina”. *XV Congreso Geológico Argentino*, pages 365-370.

804 Eiby, G. A. and J. H. Latter (2018). “Volcanoes: A historical account and tribute to George Eiby and John
 805 Latter”. *Lower Hutt, N.Z.: GNS Science. Geoscience Society of New Zealand Miscellaneous Publication 149*;
 806 *GNS Science Miscellaneous Series* 115, page 224. DOI: 10.21420/G2NS8Z.

807 Elissondo, M., C. Fariás, and E. Collini (2016). “Volcanic Risk Assessment in Argentina”. *Cities on Volcanoes 9*,
808 *Puerto Varas, Chile*, actas: S1.4.

809 Farnfield, H. R., A. L. Marcilla, and N. I. Ward (2012). “Arsenic speciation and trace element analysis of the
810 volcanic río Agrio and the geothermal waters of Copahue, Argentina”. *Science of the Total Environment* 433,
811 pages 371-378. <https://doi.org/10.1016/j.scitotenv.2012.05.098>

812 Gammons, C. H., S. A. Wood, F. Pedrozo, J. C. Varekamp, B. J. Nelson, C. L. Shope, and G. Baffico (2005).
813 “Hydrogeochemistry and rare earth element behavior in a volcanically acidified watershed in Patagonia,
814 Argentina”. *Chemical Geology*, 222(3-4), pages 249-267. <https://doi.org/10.1016/j.chemgeo.2005.06.002>

815 García, S., P. Sruoga, and M. Elissondo (2018). “Programa de Evaluación de Amenazas Volcánicas del
816 SEGEMAR, Argentina”. *Foro Internacional: Los volcanes y su impacto*, pages 174-178.

817 Gardner, C. A., C. A. Neal, R. B. Waitt, and R. J. Janda (1994). “Proximal pyroclastic deposits from the 1989–
818 1990 eruption of Redoubt Volcano, Alaska—Stratigraphy, distribution, and physical characteristics”. *Journal of*
819 *Volcanology and Geothermal Research* 62(1-4), pages 213-250. [https://doi.org/10.1016/0377-0273\(94\)90035-3](https://doi.org/10.1016/0377-0273(94)90035-3)

820 Graetinger, A. H., V. Manville, and R. M. Briggs (2010). “Depositional record of historic lahars in the upper
821 Whangaehu Valley, Mt. Ruapehu, New Zealand: implications for trigger mechanisms, flow dynamics and lahar
822 hazards”. *Bulletin of Volcanology* 72, pages 279-296. <https://doi.org/10.1007/s00445-009-0318-2>

823 Grohmann, C. H. and S. S. Steiner (2008). “SRTM resample with short distance-low nugget kriging”.
824 *International Journal of Geographical Information Science* 22(8), pages 895-906.
825 <https://doi.org/10.1080/13658810701730152>

826 Grohmann, C. H. (2018). “Evaluation of TanDEM-X DEMs on selected Brazilian sites: Comparison with SRTM,
827 ASTER GDEM and ALOS AW3D30”. *Remote Sensing of Environment* 212, pages 121-133.
828 <https://doi.org/10.1016/j.rse.2018.04.043>

829 Hemmings, B., F. Whitaker, J. Gottsman, and M. C. Hawes (2016). “Non-eruptive ice melt driven by internal
830 heat at glaciated stratovolcanoes”. *Journal of Volcanology and Geothermal Research* 327, pages 385-397.
831 <http://dx.doi.org/10.1016/j.jvolgeores.2016.09.004>

832 Her, Y., C. D. Heatwole, and M. S. Kang (2015). “Interpolating SRTM elevation data to higher resolution to
 833 improve hydrologic analysis”. *Journal of the American Water Resources Association* 51(4), pages 1072-1087.
 834 <https://doi.org/10.1111/jawr.12287>

835 Hoblitt, R., J. S. Walder, C. L. Driedger, K. M. Scott, P. T. Pringle, and J. Vallance (1995). “Volcano hazards
 836 from Mount Rainier, Washington”. *U.S. Geological Survey Open-File Report 95-273*, page 10.
 837 <https://doi.org/10.3133/ofr95273>.

838 Iverson, R. M., S. P. Schilling, and J. W. Vallance (1998). “Objective delineation of lahar-inundation hazard
 839 zones”. *Geological Society of America Bulletin* 110(8), pages 972-984. [https://doi.org/10.1130/0016-
 840 7606\(1998\)110<0972:ODOLIH>2.3.CO;2](https://doi.org/10.1130/0016-7606(1998)110<0972:ODOLIH>2.3.CO;2)

841 Jay, J. A., M. Welch, M. E. Pritchard, P. J. Mares, M. E. Mnich, A. K. Melkonian, F. Aguilera, J. A. Naranjo, M.
 842 Sunagua, and J. Clavero (2013). “Volcanic hotspots of the central and southern Andes as seen from space by
 843 ASTER and MODVOLC between the years 2000 and 2010”. *Geological Society, London, Special Publications*
 844 380, pages 161-185. <https://doi.org/10.1144/SP380.1>

845 John, D. A., T. W. Sisson, G. N. Breit, R. O. Rye, and J. W. Vallance (2008). “Characteristics, extent and origin
 846 of hydrothermal alteration at Mount Rainier Volcano, Cascades Arc, USA: Implications for debris-flow hazards
 847 and mineral deposits”. *Journal of Volcanology and Geothermal Research* 175(3), pages 289-314.
 848 <https://doi.org/10.1016/j.jvolgeores.2008.04.004>

849 Kataoka, K. S., T. Matsumoto, T. Saito, K. Kawashima, Y. Nagahashi, T. Iyobe, A. Sasaki, and K. Suzuki
 850 (2018). “Lahar characteristics as a function of triggering mechanism at a seasonally snow-clad volcano:
 851 contrasting lahars following the 2014 phreatic eruption of Ontake Volcano, Japan”. *Earth, Planets and Space* 70,
 852 article 113. <https://doi.org/10.1186/s40623-018-0873-x>

853 Kataoka, K. S., K. Tsunematsu, T. Matsumoto, A. Urabe, and K. Kawashima. (2021). “Crisis hazard assessment
 854 for snow-related lahars from an unforeseen new vent eruption: the 2018 eruption of Kusatsu-Shirane volcano,
 855 Japan”. *Earth, Planets and Space* 73(1), article 220. <https://doi.org/10.1186/s40623-021-01522-0>

856 Kaufman, J. F., M. Elissondo, P. Sruoga, and M. G. Yamin (2023). “Peligrosidad del volcán Copahue. Provincia
 857 del Neuquén, República Argentina”. *Serie de Contribuciones Técnicas Peligrosidad Geológica N° 24*. Buenos
 858 Aires, Servicio Geológico Minero Argentino. Instituto de Geología y Recursos Minerales, page 51. Retrieved
 859 from <https://repositorio.segemar.gov.ar/handle/308849217/4308>

860 Kilgour, G., V. Manville, F. Della Pasqua, A. Graettinger, K. A. Hodgson, and G. E. Jolly (2010). “The 25
 861 September 2007 eruption of Mount Ruapehu, New Zealand: directed ballistics, surtseyan jets, and ice-slurry
 862 lahars”. *Journal of Volcanology and Geothermal Research* 191(1-2), pages 1-14.
 863 <https://doi.org/10.1016/j.jvolgeores.2009.10.015>

864 Lavigne, F., J. C. Thouret, B. Voight, H. Suwa, and A. Sumaryono (2000). “Lahars at Merapi volcano, Central
 865 Java: an overview”. *Journal of volcanology and geothermal research* 100(1-4), pages 423-456.
 866 [https://doi.org/10.1016/S0377-0273\(00\)00150-5](https://doi.org/10.1016/S0377-0273(00)00150-5)

867 Llano, J., S. Calabrese, M. C. Lamberti, L. Li Vigni, F. Brugnone, D. Sierra, S. García, F. Carbajal, L. Brusca, W.
 868 D’Alessandro, and M. Agosto (2023). “Hydrogeochemistry of trace and rare earth elements in the Cavihue-
 869 Copahue Volcanic Complex”. *Chemical Geology*, 634 page 121602.
 870 <https://doi.org/10.1016/j.chemgeo.2023.121602>

871 Lube, G., S. J. Cronin, and J. N. Procter (2009). “Explaining the extreme mobility of volcanic ice-slurry flows,
 872 Ruapehu volcano, New Zealand”. *Geology* 37(1), pages 15-18. <https://doi.org/10.1130/G25352A.1>

873 Major, J. J. and C. G. Newhall (1989). “Snow and ice perturbation during historical volcanic eruptions and the
 874 formation of lahars and floods”. *Bulletin of volcanology* 52(1), pages 1-27. <https://doi.org/10.1007/BF00641384>

875 Manville, V. (2004). “Palaeohydraulic Analysis of the 1953 Tangiwai Lahar; New Zealand's Worst Volcanic
 876 Disaster”. *Acta vulcanologica* 16, pages 137-152.

877 Manville, V., K. A. Hodgson, and I. A. Nairn (2007). “A review of break-out floods from volcanogenic lakes in
 878 New Zealand”. *New Zealand Journal of Geology and Geophysics* 50(2), pages 131-150.
 879 <https://doi.org/10.1080/00288300709509826>

880 Manville, V. and S. J. Cronin (2007). “Breakout lahar from New Zealand's crater lake”. *Eos, Transactions*
 881 *American Geophysical Union* 88(43), pages 441-442. <https://doi.org/10.1029/2007EO430001>

882 Mead, S. R. and C. R. Magill (2017). “Probabilistic hazard modelling of rain-triggered lahars”. *Journal of*
 883 *Applied Volcanology* 6(1), article 8. <https://doi.org/10.1186/s13617-017-0060-y>

884 Nairn, I. A., C. P. Wood, and C. A. Y. Hewson (1979). “Phreatic eruptions of Ruapehu: April 1975”. *New*
 885 *Zealand Journal of Geology and Geophysics* 22(2), pages 155–170.
 886 <https://doi.org/10.1080/00288306.1979.10424215>

887 Naranjo, J. A. and E. Polanco (2004). "The 2000 AD eruption of Copahue volcano, southern Andes". *Revista*
888 *geológica de Chile* 31(2), pages 279-292. <http://dx.doi.org/10.4067/S0716-02082004000200007>

889 Nossin, J. J. (2005). "Volcanic Hazards in Southeast Asia". In *The physical geography of Southeast Asia*. Oxford
890 University Press, pages 250-274. <https://doi.org/10.1093/oso/9780199248025.003.0027>

891 Neall, V. E. (1976). "Lahars as major geological hazards". *Bulletin of the International Association of*
892 *Engineering Geology* 13, pages 233–240. <https://doi.org/10.1007/BF02634799>

893 Paguican, E. M. R., A. M. F. Lagmay, K. S. Rodolfo, R. S. Rodolfo, A. M. P. Tengonciang, M. R. Lopus, E. G.
894 Baliatan, and E. C. Obille Jr (2009). "Extreme rainfall-induced lahars and dike breaching, 30 November 2006,
895 Mayon Volcano, Philippines". *Bulletin of volcanology* 71, pages 845-857. [https://doi.org/10.1007/s00445-009-](https://doi.org/10.1007/s00445-009-0268-8)
896 0268-8

897 Petrinovic, I., G. Villarosa, L. D'Elía, S. Guzman, G. Páez, V. Outes, C. Manzoni, A. Delménico, C. Balbis, R.
898 Carniel, and I. Hernando (2014a). "La erupción del 22 de diciembre de 2012 del volcán Copahue, Neuquén,
899 Argentina: Caracterización del ciclo eruptivo y sus productos". *Revista De La Asociación Geológica Argentina*
900 71(2), pages 161-173. Retrieved from <https://revista.geologica.org.ar/raga/article/view/418>

901 Petrinovic, I. A., L. D'Elia, G. Páez, C. Balbis, S. Guzmán, G. Villarosa, and R. Carniel (2014b). "Depósito de
902 corriente piroclástica reciente (1963-64 AD? - 1976 AD?) del volcán Copahue (I): evidencias geológicas de
903 campo y edad radiocarbónica". *Revista De La Asociación Geológica Argentina* 71(1), pages 139-142. Retrieved
904 from <https://revista.geologica.org.ar/raga/article/view/442>

905 Pierson, T. C. and K. M. Scott (1985). "Downstream dilution of a lahar: transition from debris flow to
906 hyperconcentrated streamflow". *Water resources research* 21(10), pages 1511-1524.
907 <https://doi.org/10.1029/WR021i010p01511>

908 Pierson, T. C., R. J. Janda, J. C. Thouret, and C. A. Borrero (1990). "Perturbation and melting of snow and ice by
909 the 13 November 1985 eruption of Nevado del Ruiz, Colombia, and consequent mobilization, flow and
910 deposition of lahars". *Journal of Volcanology and Geothermal Research* 41(1-4), pages 17-66.
911 [https://doi.org/10.1016/0377-0273\(90\)90082-Q](https://doi.org/10.1016/0377-0273(90)90082-Q)

912 Pierson, T. C. (2002). "Evaluation of Lahar Mitigation Proposals at Mt. Ruapehu". *DOC Science Internal Series*
913 63. Department of Conservation, Wellington, page 18.

- Pierson T. C. (2005). “Hyperconcentrated flow – transitional process between water flow and debris flow”. In: Jakob, M., Hungr, O. (Eds.), *Debris-Flow Hazards and Related Phenomena*. Springer, Berlin, Heidelberg, pages 159-202. https://doi.org/10.1007/3-540-27129-5_8
- Pitman, E. B. and L. Le (2005). “A two-fluid model for avalanche and debris flows”. *Philosophical transactions. Series A, Mathematical, physical, and engineering sciences* 363(1832), pages 1573-1601. <https://doi.org/10.1098/rsta.2005.1596>
- Procter, J., S. J. Cronin, I. C. Fuller, G. Lube, and V. Manville (2010). “Quantifying the geomorphic impacts of a lake-breakout lahar, Mount Ruapehu, New Zealand”. *Geology* 38(1), pages 67-70. <https://doi.org/10.1130/G30129.1>
- Procter, J. N., S. J. Cronin, and M. F. Sheridan (2012). “Evaluation of Titan2D modelling forecasts for the 2007 Crater Lake break-out lahar, Mt. Ruapehu, New Zealand”. *Geomorphology* 136(1), pages 95-105. doi:10.1016/j.geomorph.2011.05.001
- Procter, J., A. Zernack, S. Mead, M. Morgan, and S. Cronin (2021). “A review of lahars; past deposits, historic events and present-day simulations from Mt. Ruapehu and Mt. Taranaki, New Zealand”. *New Zealand Journal of Geology and Geophysics* 64(2–3), pages 479–503. <https://doi.org/10.1080/00288306.2020.1824999>
- Rodolfo, K. S. and A. T. Arguden (1991). “Rain-lahar generation and sediment-delivery systems at Mayon Volcano, Philippines”. In: *Sedimentation in volcanic settings (Fisher RV, Smith GA, eds)*. Society of Economic Paleontologists and Mineralogists, Special Publication 45, pages 71–88.
- Rodolfo, K. S. (2000). “The hazards from lahars and jökulhlaups”. In: Sigurdsson, H. (Ed.), *Encyclopedia of Volcanoes*. Academic Press, pages 973–995.
- Rouwet, D., F. Tassi, R. Mora-Amador, L. Sandri, and V. Chiarini (2014). “Past, present and future of volcanic lake monitoring”. *Journal of volcanology and geothermal research* 272, pages 78-97. <http://dx.doi.org/10.1016/j.jvolgeores.2013.12.009>
- Santillan, J. R. and M. Makinano-Santillan (2016). “Vertical accuracy assessment of 30-M resolution ALOS, ASTER, and SRTM global DEMs over Northeastern Mindanao, Philippines”. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences* 41, pages 149-156. <https://doi.org/10.5194/isprs-archives-XLI-B4-149-2016>

941 Schaefer, J. R., W. E. Scott, W. C. Evans, J. Jorgenson, R. G. McGimsey, and B. Wang (2008). “The 2005
 942 catastrophic acid crater lake drainage, lahar, and acidic aerosol formation at Mount Chiginagak volcano, Alaska,
 943 USA: field observations and preliminary water and vegetation chemistry results”. *Geochemistry, Geophysics,*
 944 *Geosystems* 9(7). <https://doi.org/10.1029/2007GC001900>

945 Scott, K. M., J. W. Vallance, and P. T. Pringle (1995). “Sedimentology, Behavior, and Hazards of Debris Flows
 946 at Mount Rainier, Washington”. *U.S. Geological Survey Professional Paper* 1547, page 56.
 947 <https://doi.org/10.3133/pp1547>

948 Sheridan, M. F., A. J. Stinton, A. Patra, E. B. Pitman, A. Bauer, C. C. Nichita (2005). “Evaluating Titan2D mass-
 949 flow model using the 1963 Little Tahoma Peak avalanches, Mount Rainier, Washington.” *Journal of Volcanology*
 950 *and Geothermal Research* 139(1–2), pages 89–102. <https://doi.org/10.1016/j.jvolgeores.2004.06.011>

951 Smellie J. L. (2022). “Sedimentation associated with glaciovolcanism: a review”. *Geological Society, London,*
 952 *Special Publications* 520, pages 121-163. <https://doi.org/10.1144/SP520-2021-135>

953 Smith, G. A. and W. J. Fritz (1989). “Volcanic influences on terrestrial sedimentation”. *Geology* 17(4), pages
 954 375–376.

955 Stevens, N. F., V. Manville, and D. W. Heron (2003). “The sensitivity of a volcanic flow model to digital
 956 elevation model accuracy: experiments with digitised map contours and interferometric SAR at Ruapehu and
 957 Taranaki volcanoes, New Zealand”. *Journal of Volcanology and Geothermal Research* 119(1-4), pages 89-105.
 958 [https://doi.org/10.1016/S0377-0273\(02\)00307-4](https://doi.org/10.1016/S0377-0273(02)00307-4)

959 Suárez-Herrera, C. A., G. Toyos, L. J. Candela-Becerra, and M. Agosto (2021). “Analysis of thermal anomalies
 960 at Copahue Volcano between October 2011 and the December 2012 eruption with MODIS”. *Journal of South*
 961 *American Earth Sciences* 110, article 103310. <https://doi.org/10.1016/j.jsames.2021.103310>

962 Tadono, T., H. Nagai, H. Ishida, F. Oda, S. Naito, K. Minakawa, and H. Iwamoto (2016). “Generation of the 30
 963 M-mesh global digital surface model by ALOS PRISM”. *The international archives of the photogrammetry,*
 964 *remote sensing and spatial information sciences* 41, pages 157-162. [https://doi.org/10.5194/isprs-archives-XLI-](https://doi.org/10.5194/isprs-archives-XLI-B4-157-2016)
 965 [B4-157-2016](https://doi.org/10.5194/isprs-archives-XLI-B4-157-2016)

966 Tamburello, G., M. Agosto, A. Caselli, F. Tassi, O. Vaselli, S. Calabrese, D. Rouwet, B. Capaccioni, R. Di
 967 Napoli, C. Cardellini, G. Chiodini, M. Bitetto, L. Brusca, S. Bellomo, and A. Aiuppa (2015). “Intense magmatic

968 degassing through the lake of Copahue volcano, 2013–2014”. *Journal of Geophysical Research: Solid Earth*,
 969 120(9), pages 6071–6084. <https://doi.org/10.1002/2015JB012160>

970 Tanguy, J.-C., C. Ribière, A. Scarth, and W. S. Tjetjep (1998). “Victims from volcanic eruptions: a revised
 971 database”. *Bulletin of volcanology* 60, pages 137–144. <https://doi.org/10.1007/s004450050222>

972 Thouret, J.-C., S. Antoine, C. Magill, and C. Ollier (2020). “Lahars and debris flows: Characteristics and
 973 impacts”. *Earth-Science Reviews* 201, page 103003. <https://doi.org/10.1016/j.earscirev.2019.103003>

974 Umbal, J. V. and K. S. Rodolfo (1996). “The 1991 lahars of southwestern Mount Pinatubo and evolution of the
 975 lahar-dammed Mapanuepe Lake”. In: *Newhall, C.G., Punongbayan, R.S. (Eds.), Fire and mud: eruptions and*
 976 *lahars of Mount Pinatubo, Philippines*. University of Washington Press, Seattle, pages 951–970.

977 Vallance, J. W. and K. M. Scott (1997). “The Osceola Mudflow from Mount Rainier: Sedimentology and hazard
 978 implications of a huge clay-rich debris flow”. *Geological Society of America Bulletin* 109(2), pages 143–163.
 979 [https://doi.org/10.1130/0016-7606\(1997\)109<0143:TOMFMR>2.3.CO;2](https://doi.org/10.1130/0016-7606(1997)109<0143:TOMFMR>2.3.CO;2)

980 Vallance, J. W. (2000). “Lahars”. In: *Sigurdsson, H. (Ed.), Encyclopedia of Volcanoes*. Academic Press, pages
 981 601–616.

982 Vallance, J. W. and R. M. Iverson (2015). “Lahars and Their Deposits”. In: *Sigurdsson, H., Ed., The*
 983 *Encyclopedia of Volcanoes (Second Edition)*. Academic Press, pages 649–664. [https://doi.org/10.1016/B978-0-](https://doi.org/10.1016/B978-0-12-385938-9.00037-7)
 984 [12-385938-9.00037-7](https://doi.org/10.1016/B978-0-12-385938-9.00037-7)

985 Varekamp, J. C., A. P. Ouimette, S. W. Herman, A. Bermúdez, and D. Delpino (2001). “Hydrothermal element
 986 fluxes from Copahue, Argentina: a “beehive” volcano in turmoil”. *Geology* 29(11), pages 1059–1062.
 987 [https://doi.org/10.1130/0091-7613\(2001\)029<1059:HEFFCA>2.0.CO;2](https://doi.org/10.1130/0091-7613(2001)029<1059:HEFFCA>2.0.CO;2)

988 Varekamp, J. C., A. P. Ouimette, S. W. Herman, K. S. Flynn, A. Bermudez, and D. Delpino (2009). “Naturally
 989 acid waters from Copahue volcano, Argentina”. *Applied Geochemistry* 24(2), pages 208–220.
 990 <https://doi.org/10.1016/j.apgeochem.2008.11.018>

991 Varekamp, J. C., J. E. Zareski, L. M. Camfield, E. Todd (2016). “Copahue Volcano and Its Regional Magmatic
 992 Setting”. In: *Tassi, F., Vaselli, O., Caselli, A. (eds) Copahue Volcano. Active Volcanoes of the World*. Springer,
 993 Berlin, Heidelberg, pages 81–117. https://doi.org/10.1007/978-3-662-48005-2_5

994 Viotto, S. A. (2020). “Topografía digital y modelado de lahares en el Volcán Copahue, Argentina-Chile”. Master
 995 thesis, page 79. Universidad Nacional de Córdoba. Retrieved from <http://hdl.handle.net/11086/15384>

996 Viotto, S., G. Toyos, and B. Bookhagen (2023). “An assessment of the effects of DEM quality and spatial
 997 resolution on a model for mapping lahar inundation areas at volcán Copahue (Argentina & Chile)”. *Journal of*
 998 *South American Earth Sciences* 121, article 104138. <https://doi.org/10.1016/j.jsames.2022.104138>

999 Waythomas, C. F., T. C. Pierson, J. J. Major, and W. E. Scott (2013). “Voluminous ice-rich and water-rich lahars
 1000 generated during the 2009 eruption of Redoubt Volcano, Alaska”. *Journal of Volcanology and Geothermal*
 1001 *Research* 259, pages 389-413. <https://doi.org/10.1016/j.jvolgeores.2012.05.012>

1002 Waythomas, C. F., B. R. Edwards, T. P. Miller, and R. G. McGimsey (2023). “Lava-ice interactions during
 1003 historical eruptions of Veniaminof Volcano, Alaska and the potential for meltwater floods and lahars”. *Natural*
 1004 *Hazards* 115, pages 73-106. <https://doi.org/10.1007/s11069-022-05523-4>

1005 Williams, R., A. J. Stinton, and M. F. Sheridan (2008). “Evaluation of the Titan2D two-phase flow model using
 1006 an actual event: Case study of the 2005 Vazcún Valley Lahar”. *Journal of Volcanology and Geothermal*
 1007 *Research* 177(4), pages 760-766. <https://doi.org/10.1016/j.jvolgeores.2008.01.045>

1008

1009 **FIGURE 1.** Location map of major settlements near the active crater lake of Copahue volcano,
 1010 highlighting the main access routes and the drainage network of the study area.

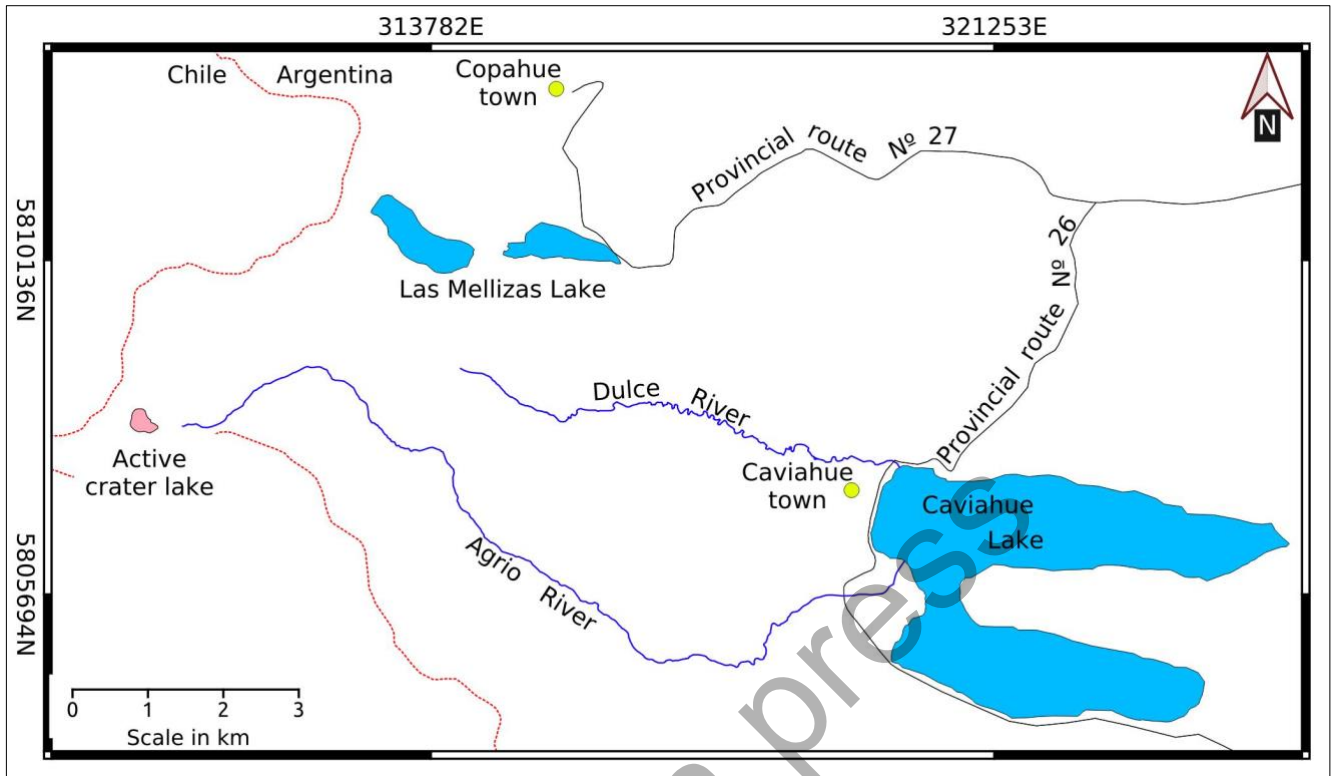
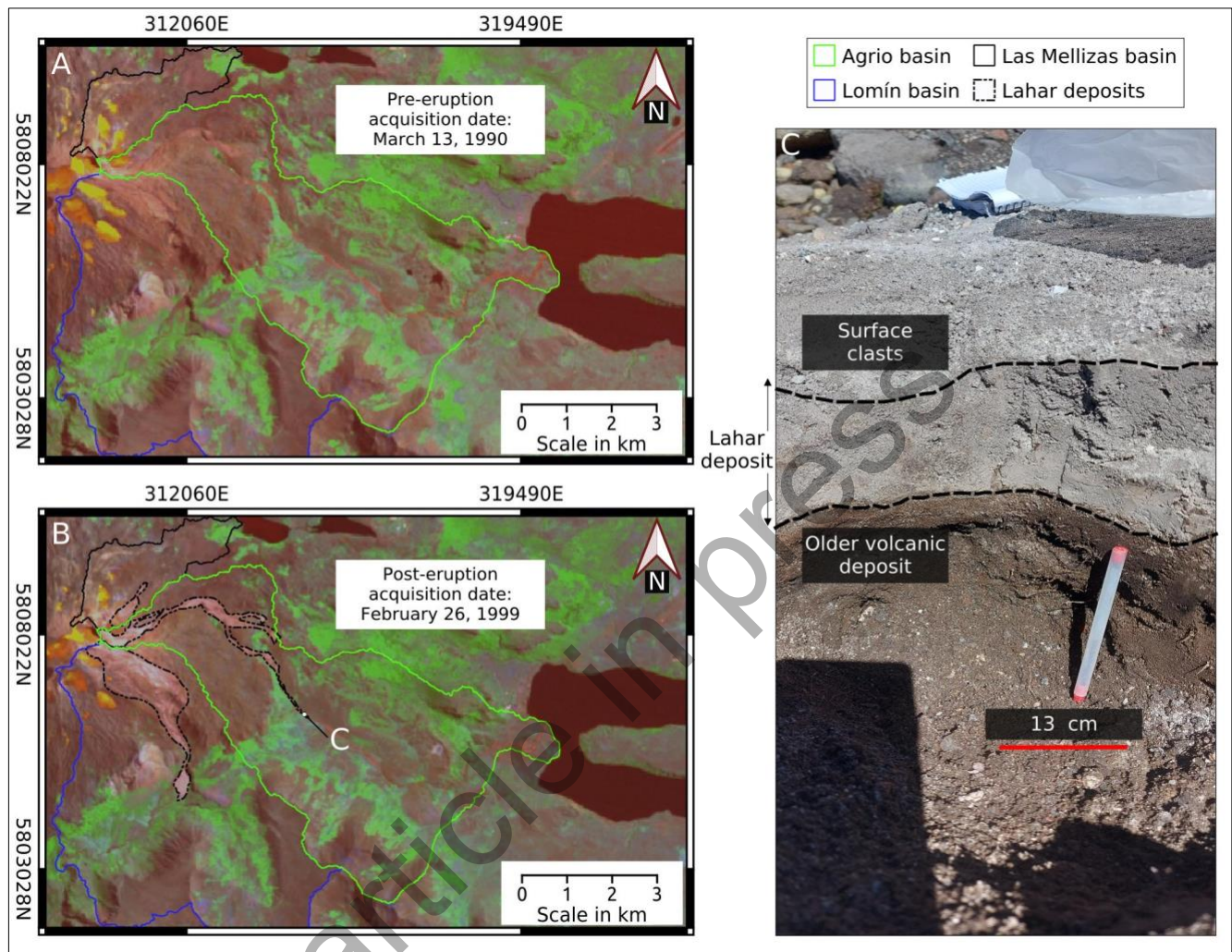


Figure 2. The changes in the landscape before and after the 1992 and 1995 eruptions **A)** Landsat 4 TM Collection 2 Level-1 image acquired on March 13, 1990 (bands 1-4-7 in RGB composition), prior to the 1992 eruption. **B)** Landsat 5 image acquired on February 26, 1999 (bands 1-4-7 in RGB composition), showing a lahar-plausibly associated with the 1995 eruption. In black dotted lines indicate the lahar

1024 deposits corresponding to the Agrio, Lomín, and Las Mellizas basins. **C)** Photograph of the light-gray
 1025 lahar deposit.



1026
 1027 **Figure 3.** Distribution of the 1995 lahar along the Agrio River basin **A)** Landsat 4-5 TM satellite image
 1028 (February 26, 1999) (bands 6-1-3 in RGB composition), highlighting the lahar deposit (yellow), the
 1029 Agrio River basin (green outline), the Agrio River (blue line), its tributaries (blue dashed lines), the
 1030 Agrio sub-basin (violet outline), and the mapped lahar (black dashed line). **B-D)** Results of modeling
 1031 with initial volumes of $\sim 1.12 \times 10^6 \text{ m}^3$, $\sim 1.26 \times 10^6 \text{ m}^3$ and $\sim 1.68 \times 10^6 \text{ m}^3$, respectively, with the starting
 1032 point at Q1 (UTM coordinates 310719E/5808024N).

1033
1034
1035
1036
1037
1038
1039
1040
1041
1042
1043
1044
1045
1046
1047
1048
1049
1050
1051
1052
1053

article in press

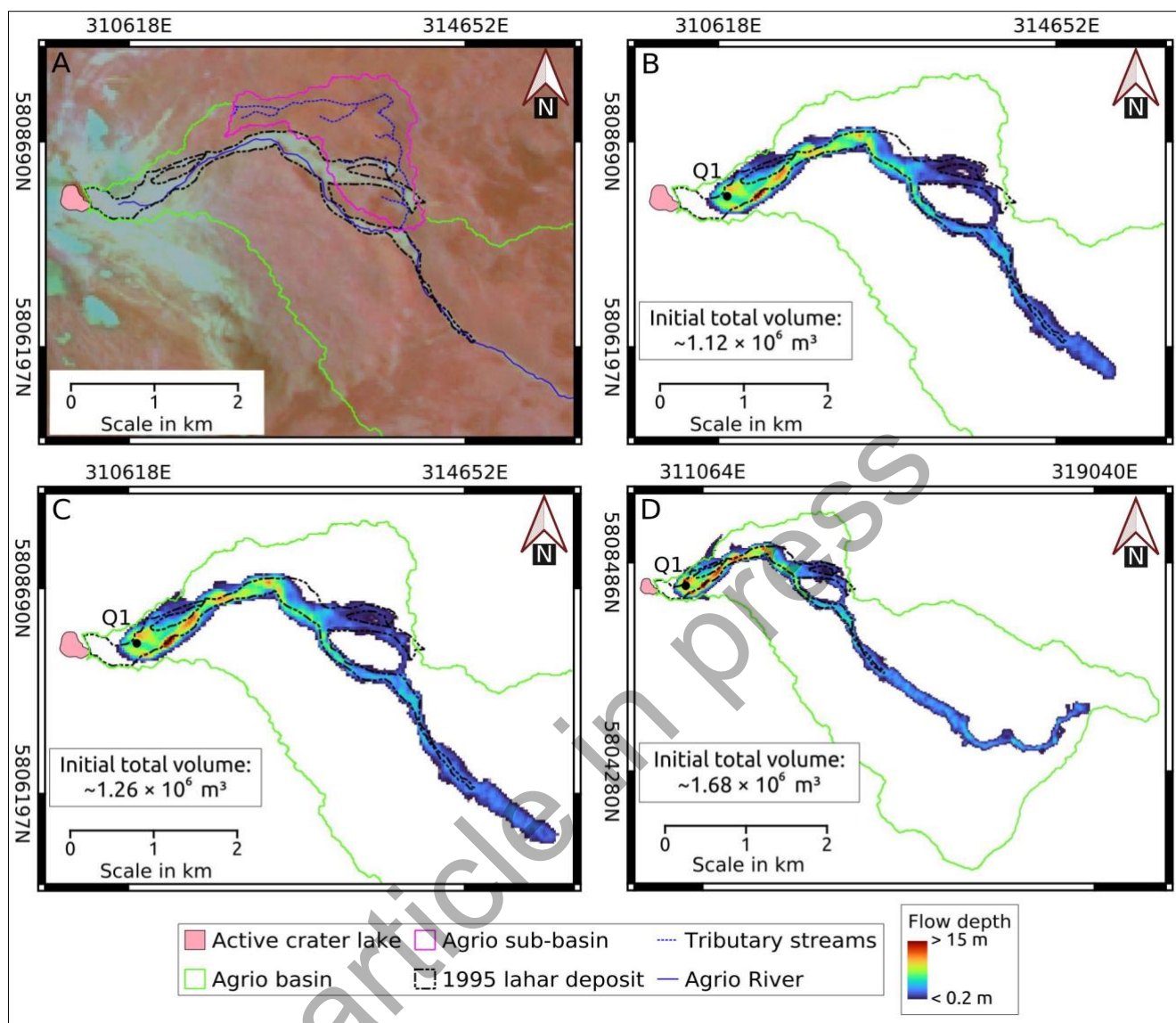
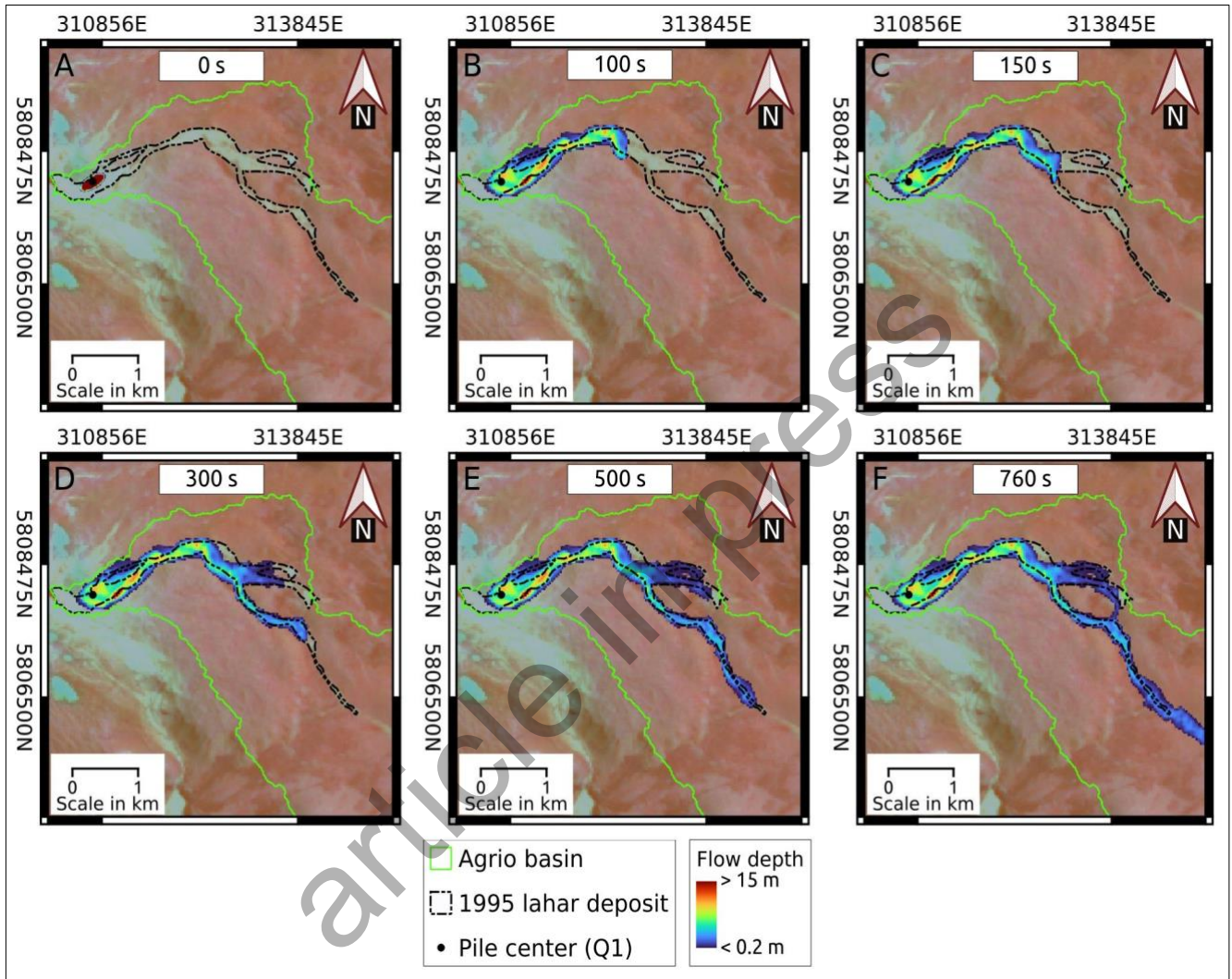


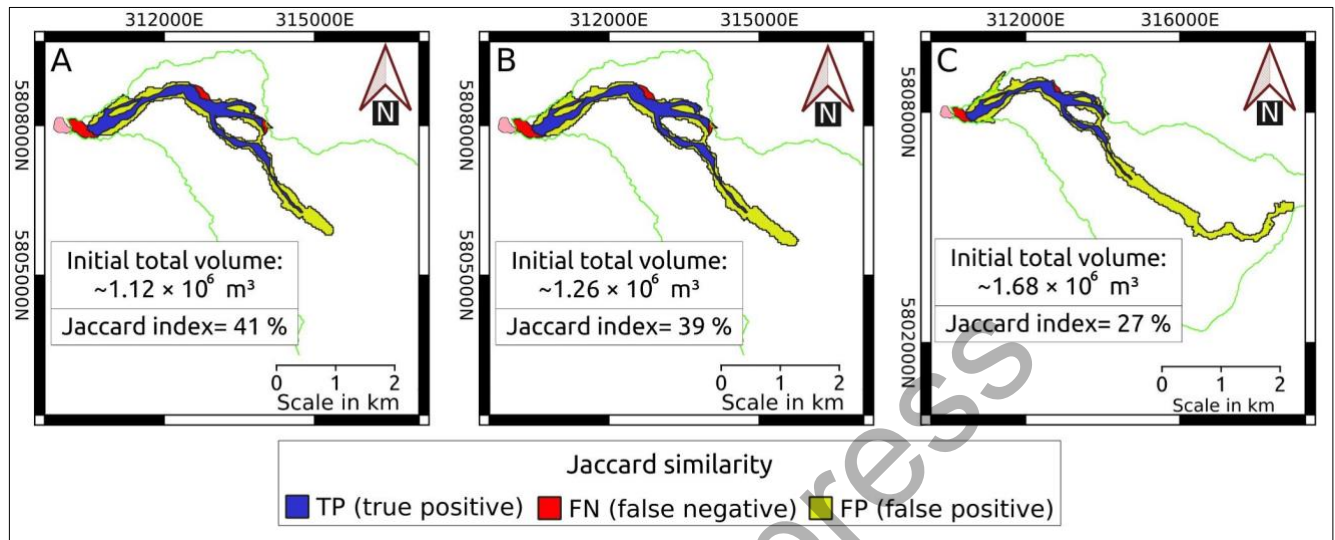
Figure 4. Comparison between the 1995 lahar, mapped with black dashed lines,

1061 and the trajectory and area covered by the simulated flow from a starting point at Q1. **A-F)** Detail of
 1062 the simulated flow for the 0–760 s time interval. The figure corresponds to the simulation with a total
 1063 volume of $\sim 1.12 \times 10^6 \text{ m}^3$.

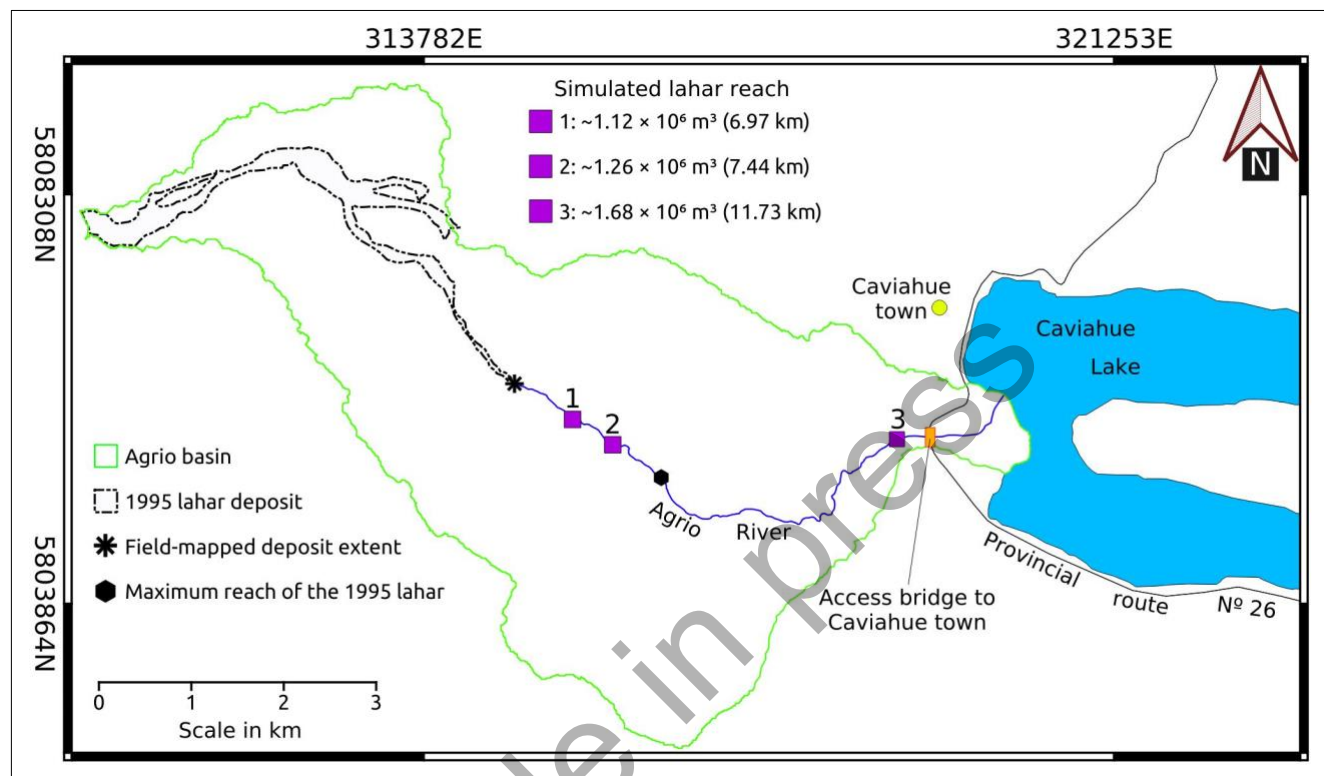


1064
 1065
 1066
 1067
 1068

1069 **Figure 5.** Jaccard index for each simulated flow during the calibration phase. Blue denotes true
 1070 positives (TP), red false negatives (FN), and yellow false positives (FP). Note in red (i.e., false negatives)
 1071 the areas not reached by any of the three simulated flows.



1085 **Figure 6.** Maximum reaches simulated for the three modeled volumes, denoted as 1, 2, and 3, in
 1086 relation to the maximum distance traveled by the lahar: 8 km as reported by [Bermúdez and Delpino](#)
 1087 ([1995](#)) and the 6.26 km corresponding to the field-mapped deposit extent.



1088
 1089
 1090
 1091
 1092
 1093
 1094
 1095 **Figure 7.** Map showing the starting points of the initial piles (P1, P2, P3, and P4) simulated in this
 1096 study, along with the main basins affected by lahars during the 1992 and 1995 eruptions.
 1097

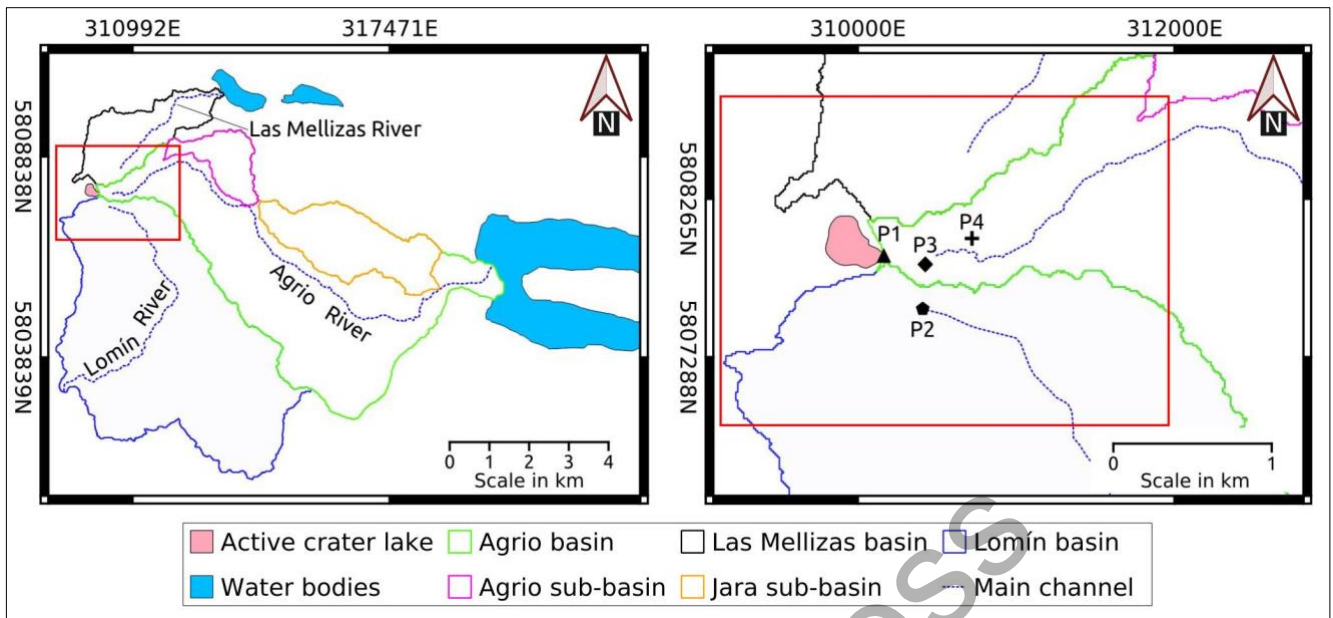


Figure 8. Simulation result with a cylindrical geometry. **A)** The initial pile (in violet), located at the lake rim, represents the phase prior to the collapse due to gravity. **B)** As the simulation progresses, a significant portion of the pile's volume begins to displace a large amount of material toward the interior of the crater.

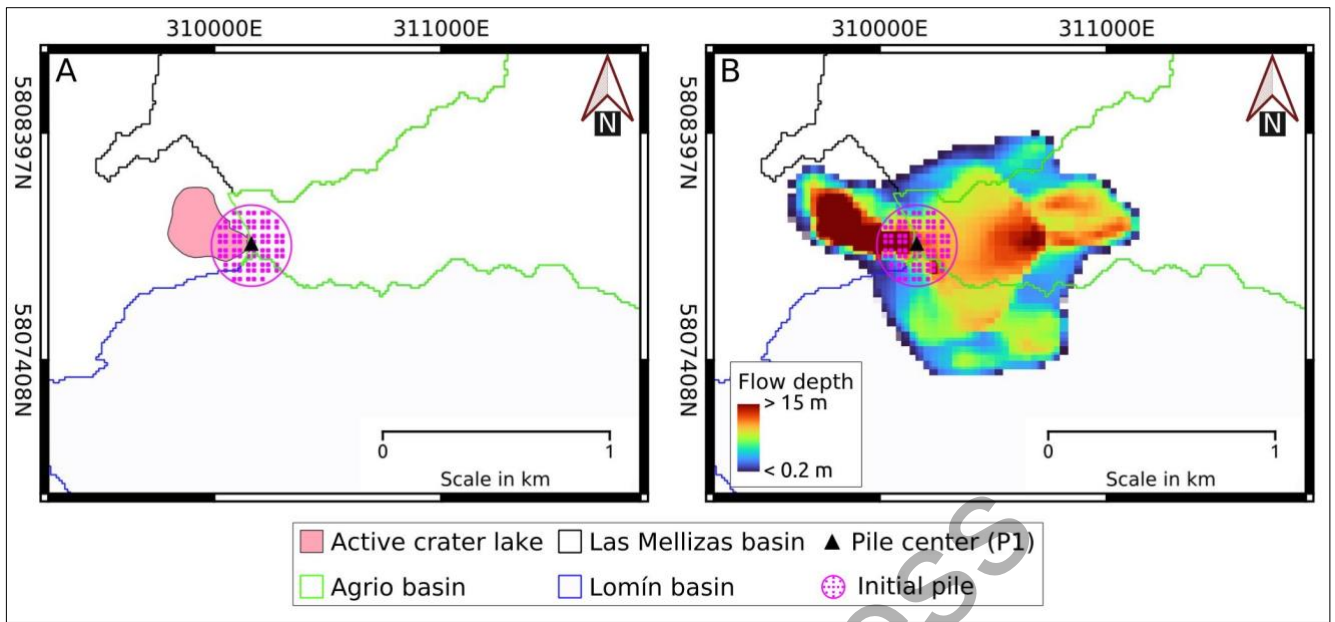


Figure 9. Representation of pile with a solid volumetric concentration of 30 % and an initial total volume of $\sim 4.91 \times 10^6 \text{ m}^3$. The figure shows the cylindrical initial pile located in the Lomín basin at P2.

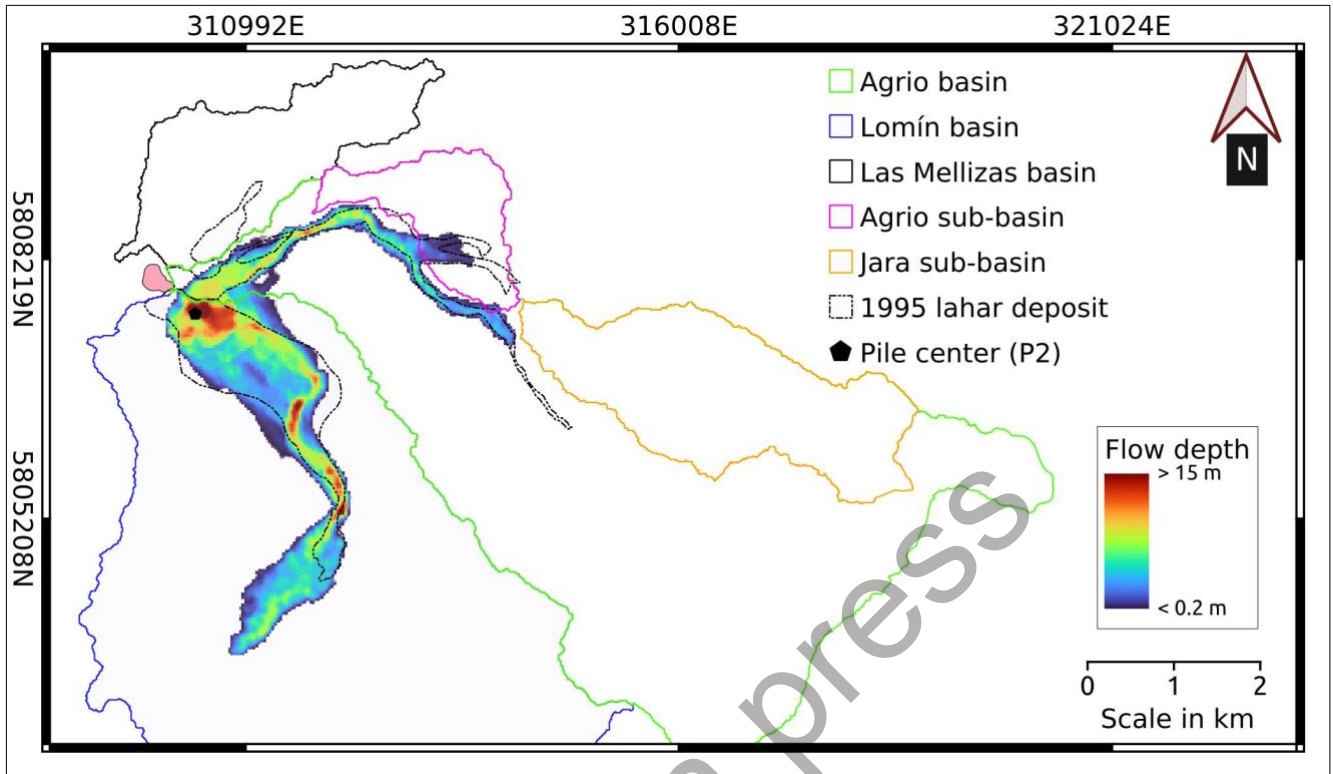


Figure 10. Representation of pile P3 with a solid volumetric concentration of 30 % and an initial total volume of $\sim 4.91 \times 10^6 \text{ m}^3$. **A)** and **B)** correspond to the elliptical and cylindrical initial piles located in the Agrio basin, respectively.

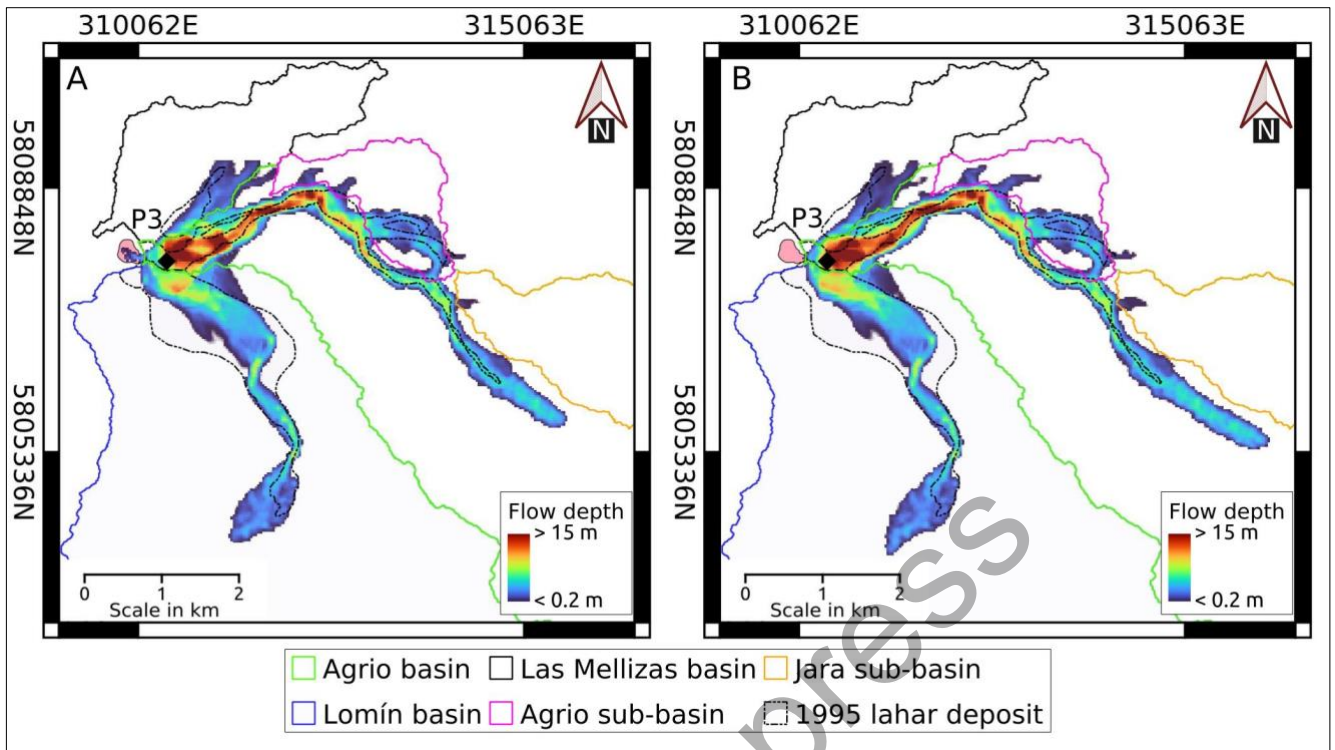


Figure 11. Representation of pile with a solid volumetric concentration of 30 % and an initial total volume of $\sim 4.91 \times 10^6 \text{ m}^3$. The figure shows the elliptical initial pile located in the Agrio basin at P4.

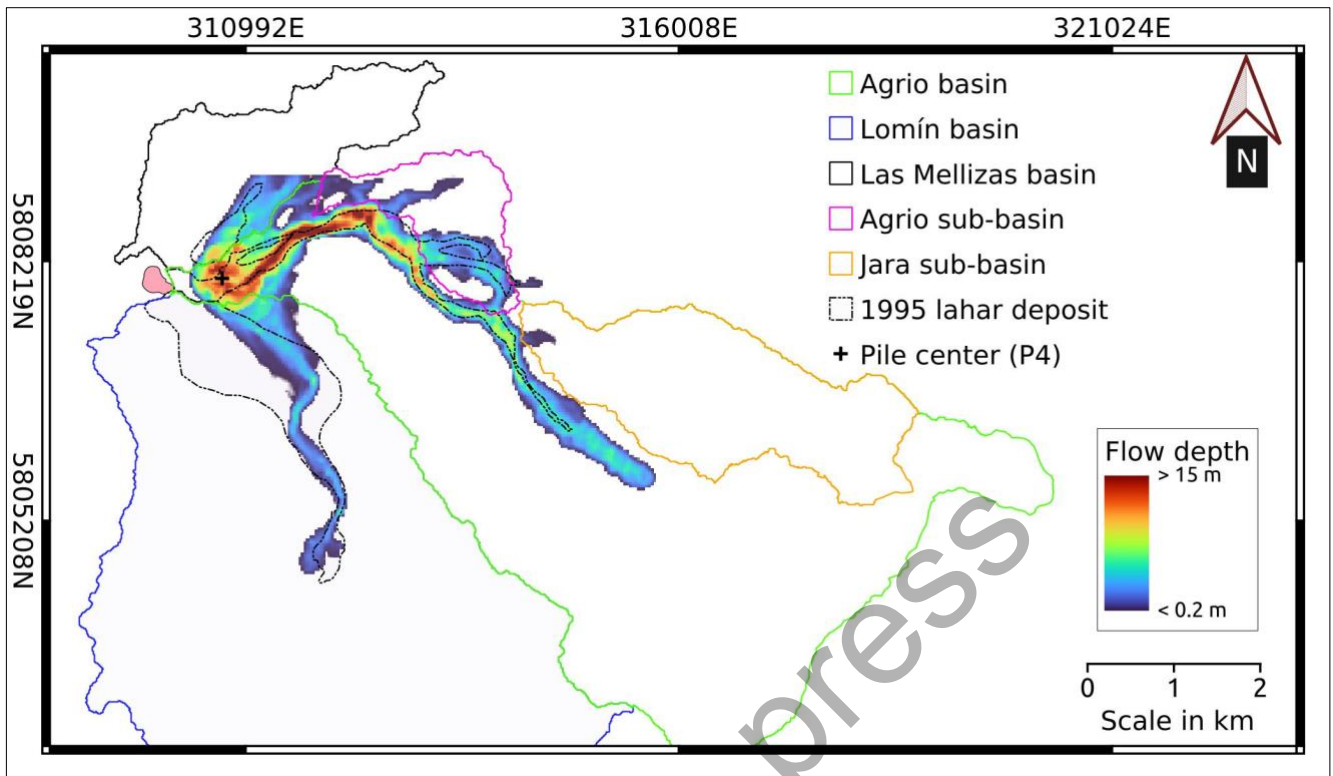


Figure 12. Flow extensions across different areas for simulated flows originating from piles in the Agrio basin, with an initial volume of $4.91 \times 10^6 \text{ m}^3$. The simulated flows develop more extensive branches into the Agrio sub-basin, while other branches diverge toward the Dulce basin and the Jara sub-basin.

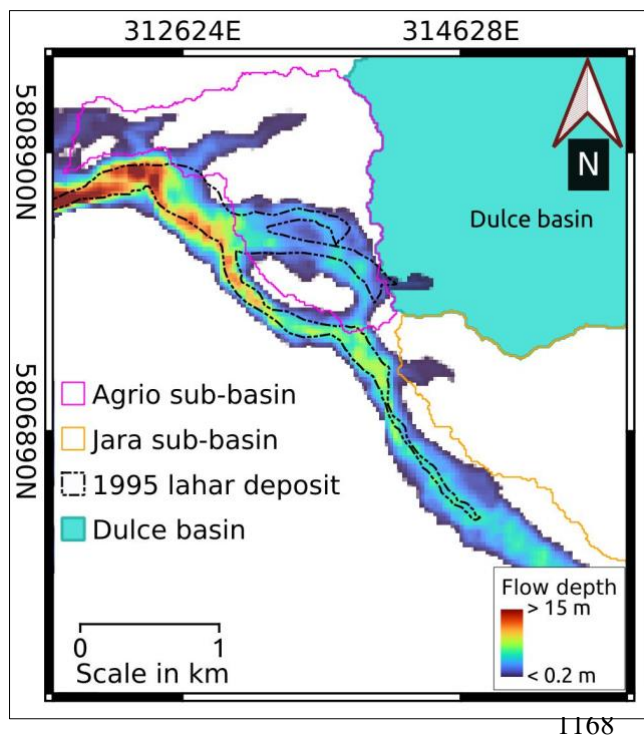
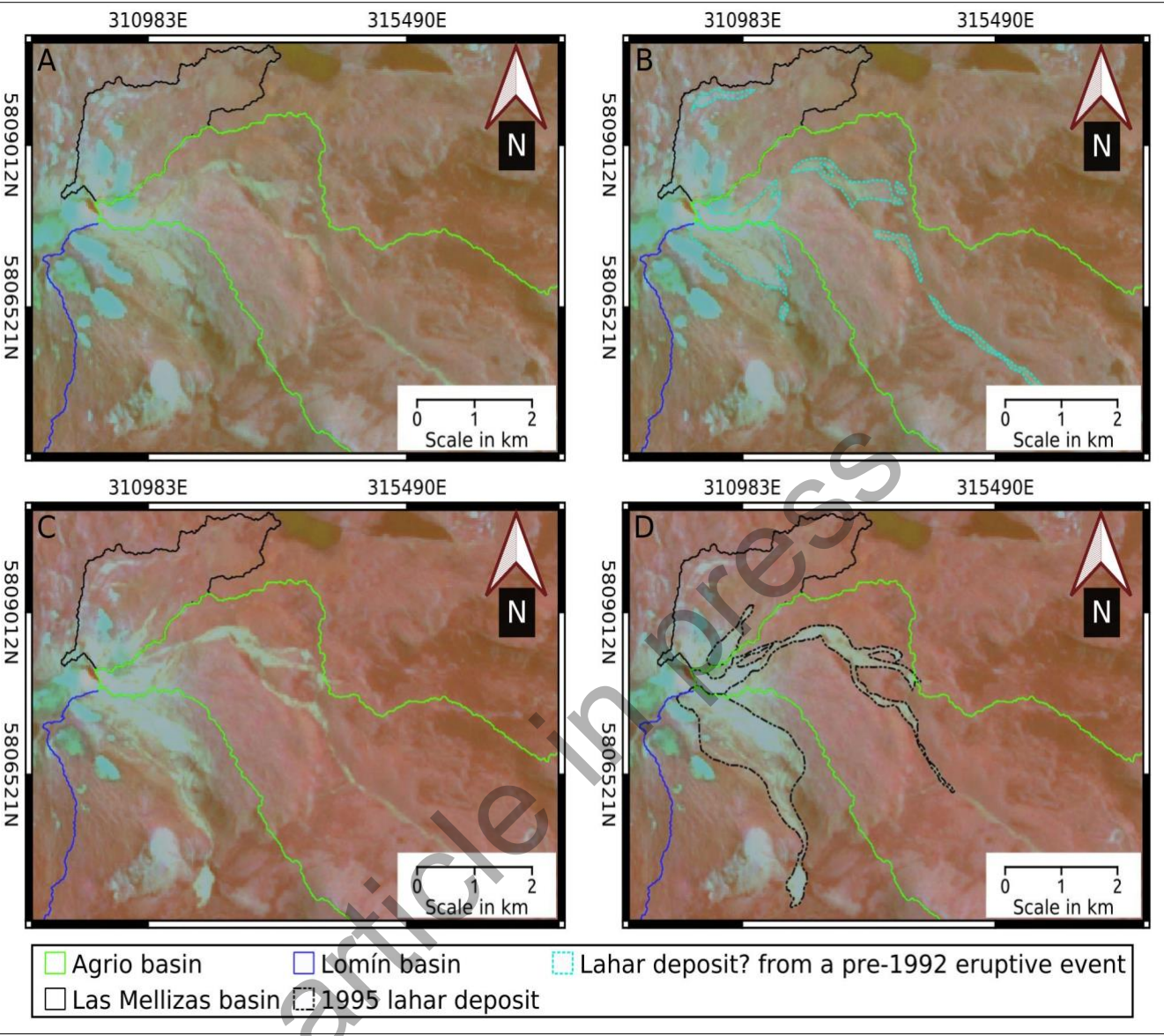


Figure 13. Landsat 4-5 Thematic Mapper (TM) Collection 2 satellite images from March 13, 1990, and February 26, 1999 (bands 6-1-3 in RGB composition), highlighting the lahar deposit in yellowish tones. **A)** and **B)** display the pattern of a possible flow associated with an unknown eruptive event prior to

the 1992 eruption. **C)** and **D)** illustrate the flow attributed to the 1995 eruptive event, showing that both follow similar pathways.

article in press



1197

1198

1199

1200

1201 Table 1. Lahar volumes and volumetric solid concentrations for the calibration phase.

Solid volume (m ³)	Volumetric solid concentration (%)	Water volume (m ³)	Total volume (m ³)
~5.04 x 10 ⁵	30	~1.18 x 10 ⁶	~1.68 x 10 ⁶
	40	~7.56 x 10 ⁵	~1.26 x 10 ⁶
	45	~6.16 x 10 ⁵	~1.12 x 10 ⁶

Table 2. Results of numerical simulations for the calibration phase.

Total volume (m ³)	Travel distance (km)	Average values of the simulated lahars			
		Flow depth (m)	Flow depth* (m)	Flow velocity* (m/s)	Dynamic pressure* (kPa)
~1.68 x 10 ⁶	11.73	2.66	2.24	3.27	9.61
~1.26 x 10 ⁶	7.44	2.77	-	-	-
~1.12 x 10 ⁶	6.97	2.70	-	-	-

*Average value along the last 1 km of the Agrio River.

Table 3. Jaccard index (Rj) for each simulated total volume.

Total volume (m ³)	Volumetric solid concentration (%)	True positive (TP) (m ²)	False negative (FN) (m ²)	False positive (FP) (m ²)	Jaccard index (Rj) (%)
~1.68 x 10 ⁶	30	1.00 x 10 ⁶	1.45 x 10 ⁵	2.58 x 10 ⁶	27
~1.26 x 10 ⁶	40	9.72 x 10 ⁵	1.73 x 10 ⁵	1.34 x 10 ⁶	39
~1.12 x 10 ⁶	45	9.55 x 10 ⁵	1.90 x 10 ⁵	1.16 x 10 ⁶	41

article in press

1228 Table 4. Comparison of lake surface raster properties using the original and reinterpolated resolutions
 1229 of the DSM AW3D30. DSM source:
 1230 https://www.eorc.jaxa.jp/ALOS/en/dataset/aw3d30/aw3d30_e.htm).

Resolution	Original	Reinterpolated	
	30 m	10 m	1 m
Maximum elevation of the lake's surface raster (m)	2751	2753.11	2755.39
Minimum elevation of the lake's surface raster (m)	2718	2714.76	2714.31
Elevation difference of the lake's surface raster (m)	33	38.35	41.08
Lake's base level (m)	2752		
Number of pixels counted calculated with raster "Surface Volume Algorithm"	90	727	74651
Area calculated with raster "Surface Volume Algorithm" (m ²)	69948	73100	74646
Volume calculated with raster "Surface Volume Algorithm" (m ³)	1625908	1719183	1723449
Maximum contour line area at 2752 m (m ²)	74690		
Absolute error in area m ²	4742	1590	43
Relative error in area %	6	2	0.1

1231

1232

1233 Table 5. Travel distances of simulated lahars for each simulated total volume, initial pile locations, and
 1234 initial pile geometries.

Total volume (m ³)	Volumetric solid concentration (%)	Starting point - Pile geometry*	Travel distance (km)	
			Agrio River	Lomín River
~4.91 x 10 ⁶	30	P1 - C	-	-
		P2 - C	5.00	5.45
		P3 - C	8.00	4.91
		P3 - E	7.27	4.69
		P4 - E	7.45	4.04
~5.73 x 10 ⁶	40	P2 - C	6.72	7.21
		P3 - C	3.17	1.83
		P4 - E	4.79	2.78

1235 *C: cylindrical, E: elliptical.

1236

1237

1238

1239

1240

1241

1242

1243

1244 Table 6. Key simulated flow parameters in the Agrio River for different total volumes, starting points,
1245 and initial pile geometries.

Total volume (m ³)	Starting point - Pile geometry*	Average value along the Agrio River			Average value along the last 1 km of the Agrio River		
		Flow depth (m)	Flow velocity (m/s)	Dynamic pressure (kPa)	Flow depth (m)	Flow velocity (m/s)	Dynamic pressure (kPa)
~4.91 x 10 ⁶	P1 - C	-	-	-	-	-	-
	P2 - C	5.39	7.76	1182.56	2.71	4.45	19.80
	P3 - C	7.47	10.77	8298.79	4.25	4.17	13.28
	P3 - E	7.59	10.87	11824.13	4.08	4.23	13.84
	P4 - E	7.91	12.01	21433.00	4.39	4.60	16.26
~5.73 x 10 ⁶	P2 - C	5.10	7.17	5577.04	2.59	2.87	7.77
	P3 - C	12.31	21.58	49813.87	10.85	17.06	12462.64
	P4 - E	10.29	17.10	50135.30	6.43	11.02	7212.22

1246 *C: cylindrical, E: elliptical.