FLUVIAL RESPONSES FOLLOWING VOLCANIC ERUPTIONS: THE BLANCO-ESTE RIVER, SOUTHERN CHILE

ANDRÉS IROUMÉ[1], VALERIA ZINGARETTI[1], DAMIÀ VERICAT[2], JOHNATHAN TENNY[3], MANEL LLENA[2] & RAMON J. BATALLA[2,4]
[1]Universidad Austral de Chile, Laboratory of Hydromorphology, Chile
[2]Fluvial Dynamics Research Group (RIUS), University of Lleida, Spain
[3]College of Forestry, Oregon State University, USA
[4]Catalan Institute for Water Research (ICRA), Spain

ABSTRACT

We examine the fluvial response of the River Blanco-Este (Chile) following the 1961 and 2015 eruptions of the Calbuco volcano. The river drains the north-eastern flanks of the Calbuco and was heavily affected by ash fall, pyroclastic flows and post-eruption channel reworking. The long-term morphological evolution of the river is analyzed along a 6.5 km-long segment using a sequence of remote aerial images. Since 2017, short-term fluvial responses are studied in two reaches representing the upstream and downstream parts of this segment, using multi-temporal high resolution topography and orthophotomaps obtained combining dGPS surveys and digital photogrammetry applied to photos acquired from drones, to monitor topographic changes in the channel topography and the area of exposed movable sediments, grain size and large wood deposits. Due to the lack of flow data we use photos from time-lapse cameras as a proxy to qualitatively characterize river flow. The active channel observed after the 1961 and 2015 eruptions has a similar pattern. According to the evolution of the channel morphology after the 1961 eruption, we hypothesize that the river reached a quasi-equilibrium condition in 2014, a situation severely modified by the 2015 eruption. Long-term (decadal) evolution of the river reflects the adjustment between sediment budget and channel morphology that progressively shifts from a braided pattern to a stable single-threat channel that illustrates the equilibrium between the water and sediments load, the grain-size and the gradient. The 2015 eruption increased sediment supply and modified channel morphology, a new braided configuration is observed. The annual to flood-based responses reflect the complexity of the geomorphic dynamics of the river: channel incision, development of single channel patterns and head cut erosion in the upper study reach, and continuous erosive-depositional changes of several meters thick, with evident incessant lateral migration and severe bank erosion in the downstream river reach.

Keywords: River Blanco-Este, channel morphologic evolution, volcanic eruptions, Chile.

1 INTRODUCTION

Natural disturbances such as volcanic eruptions, wildfires, landslides, debris flows, and floods can substantially modify hydrologic and geomorphic processes in watersheds by destroying or burying slope-stabilizing vegetation, by adding large volumes of sediments and large wood that can divert or dam stream channels, and by disrupting normal hydrologic pathways (interception, infiltration, and surface and subsurface runoff) [1]–[5]. The duration and severity of such disruptive effects vary with relief, climate, vegetation, and the degree and area of impact. Quantification of geomorphological changes and rates of landscape evolution is a matter of primary importance, as much in natural hazards studies [6] as in calibration of landscape evolution models [7]–[9]. It is thus important to study places where morphological changes are rapid enough to allow measurements to be made that reflect actual surface processes, while avoiding a large observation window which may smooth or even erase the short-term evolution [10].

WIT Transactions on Ecology and the Environment, Vol 234,
www.witpress.com, ISSN 1743-3541 (on-line)
doi:10.2495/RBM190031

Volcanic eruptions undoubtedly have the potential to inflict the largest impacts of all these disturbances in terms of scale and severity [5]. They can damage, destroy, or bury extensive areas of forest vegetation and cover the landscape with volcanic ash, filling river valleys, obliterating watersheds, disturbing drainage patterns and changing channel size, pattern and structure [5], [11]. Decay of tree roots compromises slope stability, dead trees contribute to large log jams on valley floors, and volcanic ash can wash off slopes for years following eruptions. Hydrologic, sedimentologic, and geomorphic responses to major explosive eruptions are dramatic, widespread, and persistent, and present enormous challenges to those entrusted with managing disturbance response. Volcanic eruptions have the potential to strongly alter river hydrology, as well as sediment and large wood dynamics, with consequences on human safety and infrastructures, and the environment [12]–[14].

Effects on the fluvial geomorphology and geologic and ecologic processes have been reported after eruptions in USA [15]–[17], Philippines [18], [19], Italy [20], Mexico [21], [22], New Zealand [23], Montserrat Island [24], and Perú [25]; i.e. Pierson and Major [5] presented a comprehensive analysis on the hydrogeomorphic effects of volcanic eruptions on drainage basins.

Very little was known in Chile on this issue until the Volcano Chaitén erupted in 2008; in fact, that eruption attracted researches worldwide whose works have enhanced the understanding of the short and medium-term effects of a volcanic eruption on adjacent river systems [11]–[14], [26]–[28]. Within this context, we have extended the research on the post-eruption fluvial responses studying the River Blanco-Este which drains the north-eastern flank of the Volcano Calbuco, following the last two eruptions in 1961 and 2015 to address the following research questions: a) To which extent the knowledge already acquired in river systems affected by the Chaitén volcano aids at better understanding of the fluvial response and recovery of the Blanco-Este? b) How do the intensity and type of volcanic disturbances (i.e. tephra fall, pyroclastic density currents (PDC) or dome collapses) control river morphology changes and subsequent recovery? c) Does the grain size of the sediments, for instance non cohesive sands in the Chaitén case and much coarser deposits in the Blanco-Este, control the evolution and recovery of the river channels? d) How does the sediments residence time in the drainage network inform on the rates of channel reworking and how does it in turn control the morphological evolution of the river? e) How different is the role of these controlling factors in distinct river systems and what is their relative weight on the evolution of the channel and its eventual recovery? and finally, f) How can river corridor management and the associated decision making processes be informed by the specific knowledge acquired?

Within this framework, here we present an initial study of: a) the long-term morphological evolution of the River Blanco-Este analysing sequences of remote images from 1961 to 2016 along a 6.5 km-long river segment, and b) the short-term fluvial responses in two reaches using HRT and orthophotomaps obtained combining dGPS surveys and digital photogrammetry applied to photos acquired from drones.

2 STUDY AREA

The study area corresponds to a 6.5 km-long channel segment of the River Blanco-Este (south Chile), that drains the north-eastern flanks of the Calbuco volcano and was heavily affected by ash fall, pyroclastic following the last two eruptions in 1961 and 2015. From the Calbuco crater at ≈1900 m a.s.l., the Blanco-Este flows for 13 km to join the River Hueñu-Hueñu and has an area of 39.6 km^2 at the confluence (see Fig. 1).

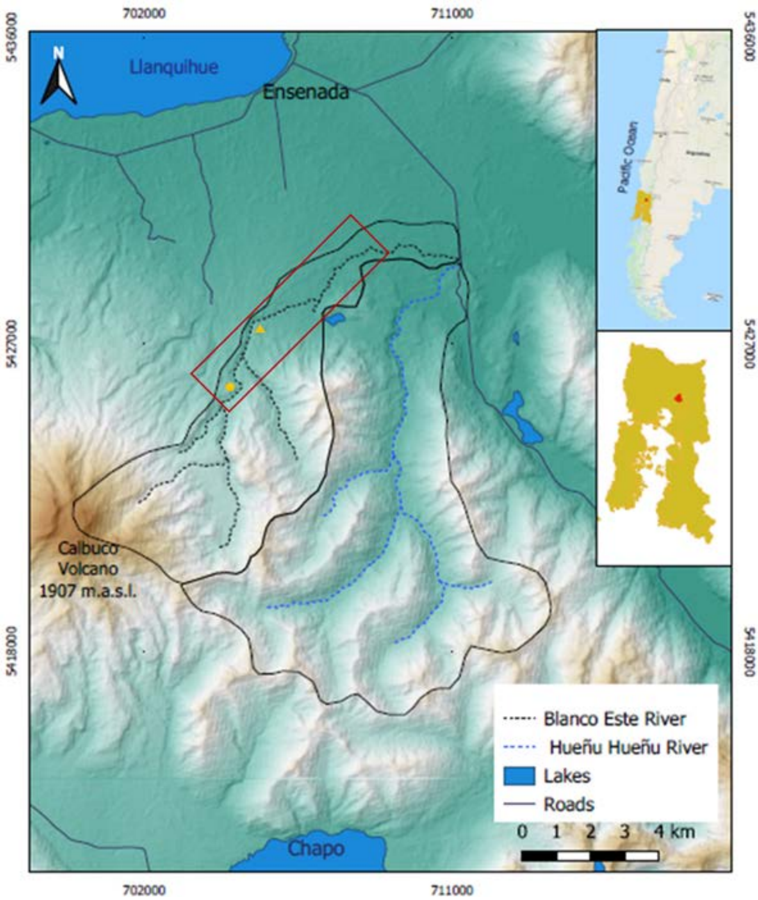

Figure 1: The study area, with the location of the River Blanco-Este draining the north-eastern flanks of the Volcano Calbuco. In a red rectangle, the 6.5 km-long channel segment. Yellow circle and triangle indicate the position of the upstream and downstream reaches.

The Calbuco is a stratovolcano localized in the Southern Andes (41°19’51”S, 72°36’46”W), which erupted on 22 April 2015 for the first time in 43 years, with very little warning. The Calbuco is one of the most active volcanoes in Chile and has a history of other twelve eruptions documented since the 18th century, occurring in 1792, 1893–1895, 1906–1907, 1911–1912, 1917, 1932, 1945,1961, 1972, with the 1893 and 2015 eruptions being the largest of this period [29], [30]. These events have included tephra fall, lahars, pyroclastic flows, and production of a dome and lava flows of basalt to basaltic-andesite composition. The 2015 event involved several phases during 22 and 23 April with the eruption column reaching a height of >15 km and delivering ca. 0.27 km^3 (dense rock equivalent) of basaltic-andesite tephra initially to the northeast and then east across Patagonia and ultimately circling the globe [30]. More than 40 cm of coarse-gravel tephra blanketed the terrain high on the cone and about 20 cm of tephra up to 2 cm diameter fell in the village of Ensenada. Pyroclastic flows were triggered by two processes: partial collapse of the eruption column and by the fall of hot, highly porous tephra (scoria, density ca. 1.5 g cm^{-3}) into the heads of steep drainages originating on the upper flanks of the cone. This immediately formed pyroclastic flows that raced down the steep, narrow channels. Where the tephra fell onto snow and ice fields, meltwater mixed with tephra and entrained alluvium to form cool lahars that moved rapidly down many channels radiating from the cone [29]–[31], as they have in other recent eruptions [32]. The northeast flank of Calbuco, where the Blanco-Este flows, received a higher proportion of hot flows than other areas around the cone. Fig. 1 shows the study segment together with the two reaches tackled in the analyses.

3 METHODS

The long-term morphological evolution of the 6.5 km-long study segment is analysed using a sequence of three aerial photos and remote sensing images from 1961 to 2016, a period that includes the last two eruptions (1961 and 2015). Historical photos and modern images are geo-rectified by comparing available LiDAR information and dGPS coordinates obtained at specific control points, in order to generate topographic models that will eventually aid at determining the long-term sediment budget of the river channel [33], [34].

In turn the short-term fluvial responses (months, years) are studied since 2017 in two reaches using HRT and orthophotomaps obtained combining Trimble® R5 PP/RTK dGPS surveys and digital photogrammetry applied to photos acquired from drones and analyses with Agisoft Photoscan Pro®. Multi-temporal HRT and orthophotomaps are used to study changes in channel topography and the area of exposed movable sediments, grain size and large wood deposits.

Due to the lack of flow data we use photos from time-lapse cameras as a proxy to qualitatively characterize river flow (i.e. no flow, low, medium and high flow).

4 RESULTS

4.1 Long term evolution

The long-term morphologic evolution of the River Blanco-Este was analyzed using a sequence of three remote images, one from 1961 (aero photo, Instituto Geográfico Militar, resolution 2.3 m) immediately after the 1961 eruption, and the others from 2014 (Bing, 5 m resolution) and 2016 (Google, 1–2.4 m resolution) just before and after the 2015 eruption, respectively. The first period 1961 to 2014 allows us to study how the river adjusted to the 1961 eruption, eventually reaching a *new equilibrium*. In terms of the second period, 2014–2015, we analyze how a single eruption abruptly altered channel's morphology and the overall valley floor configuration. After the 1961 eruption the mean active channel width in the study segment was 213 m, and by 2014 the channel had adjusted its morphology (i.e. single-threat meandering pattern) and showing a mean width of 78 m, altogether pointing to a *quasi-equilibrium* condition. The 2015 eruption severely modified this condition conveying the channel in the 6.5 km-long study segment to a mean width of 204 m and to a morphology almost identical to the one observed after the 1961 eruption (Fig. 2).

4.2 Short term evolution

In terms of the short-term effects of the 2015 eruption, field observations verify the extensive impact of this natural disturbance on the current morphology of the River Blanco-Este channel that the aerial images already displayed (Fig. 3).

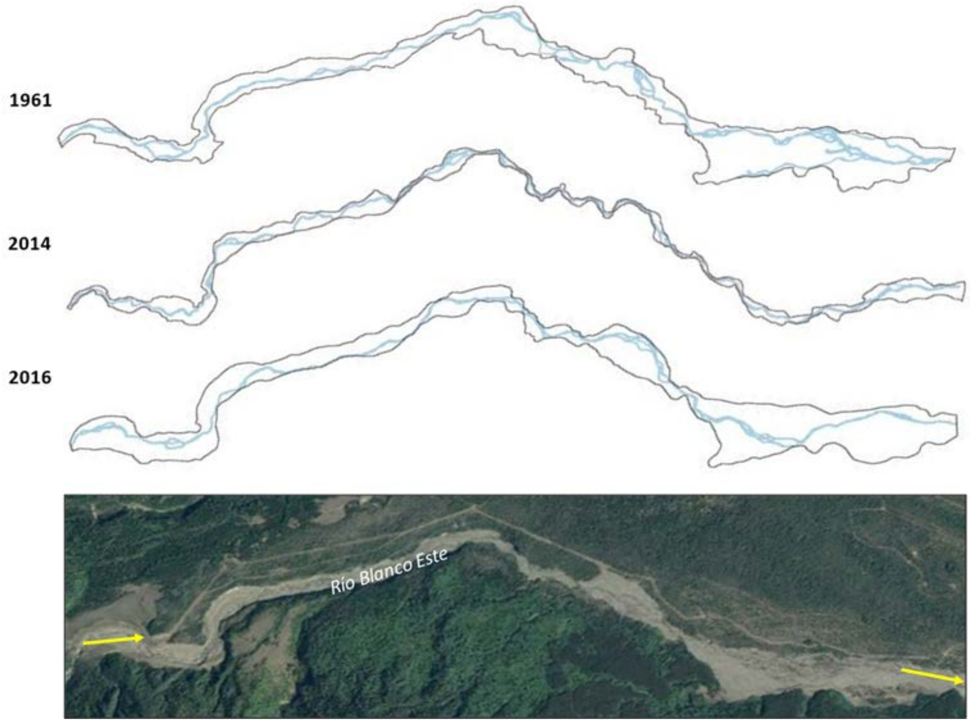

Figure 2: From above to below, the active channel and water limits (black and blue lines, respectively) for year 1961, 2014 and 2016, and a 2016 image (Google®, 2 June 2016) of the study segment. Yellow arrows indicate flow direction.

Figure 3: The downstream study reach of the Blanco-Este before (left, DigitalGlobe®) and after (right, Google®) the 2015 eruption.

The upstream study reach of the River Blanco-Este valley displays channel incision, development of single channel patterns and head cut erosion. On the other hand, the downstream study reach shows massive accumulations of sediments that fill the valley floor offering a complex braided morphology, a multi-threat highly unstable pattern, with shifting channels and numerous bars that change their position on a flood basis. Sedimentation (of up to >3 m) appears to be the dominant processes in this valley reach, with erosion concentrating in the channel margins (Fig. 4). Both reaches are being quasi-permanently re-shaped by flush-floods that typically occur in the area (Fig. 5).

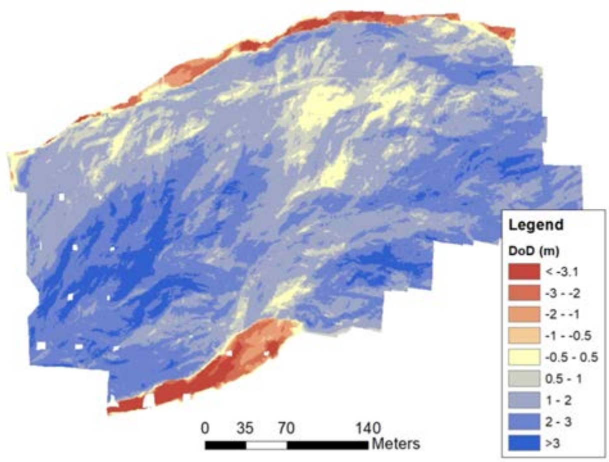

Figure 4: Raw difference of DEMs (DoD) between 11 April 2017 and 1 August 2017 on the downstream, study reach of the Blanco-Este (same spot as in Fig. 3). The colours displayed represent net change in elevation, expressed in meters. Negative values represent erosion (nearly entirely bank erosion in this case), while positive values represent deposition. The figure was produced using structure from motion photogrammetry processed in Agisoft Photoscan Pro® and GCD 6 for ArcGIS®. This DoD has not been classified to separate out vegetation or water and it has not been yet adjusted to account for uncertainty (i.e. minimum level of detection threshold of 0.5 m).

Figure 5: A view of flood dynamics in the downstream study reach of the Blanco-Este. Above from left to right, conditions at 16:00 on 18–20 July 2017. Below from left to right, conditions at 16:00 on 16–18 August 2017. Camera looking downstream.

Surface sediments are extremely poorly sorted, with large boulders, cobbles and gravels embedded in a sand matrix, conforming highly loose deposits easily mobilize by competent flows (Fig. 5), especially during austral winter and snowmelt related floods. Altogether, observations point out that the river is at the initial stages of a long-term readjustment process of the sediment budget after the perturbation. Downstream, at the confluence with the Hueñu-Hueñu, the Blanco-Este presents a rather stable gravel-bed morphology that leads us to hypothesize that the sediment wave affecting the valley after the eruption has not reached yet the lowermost segment of the river.

5 FINAL REMARKS

Based on evidences, we state that the river needed four decades to reach a more or less stable condition (or *quasi-equilibrium* condition) after the 1961 eruption, hence we hypothesize that the river system will require at least 40–50 years to reach again a stable morphological configuration. Nowadays, up-to-dated field and remote-sensing techniques allow tracking the short-term evolution of the new river channel and its responses through time, an approach that was not possible in the previous eruption period. So far, the river depicts extraordinary morphosedimentary activity following flood events, a fact that indicate that the alteration caused to valley floor was an intense and long-lasting phenomenon. Altogether, the Blanco-Este provides a worldwide opportunity to observe the medium to long long-term evolution of a fluvial landscape profoundly affected by the internal forces of the Earth further modified by the current hydroclimatic activity.

ACKNOWLEDGEMENTS

This research is developed within the Project FONDECYT 1170413 funded by the Chilean "Comisión Nacional de Investigación Científica y Tecnológica". Damià Vericat is currently a Serra Húnter Fellow at the University of Lleida.

REFERENCES

[1] Iverson, R.M., The physics of debris flows. *Reviews of Geophysics*, **35**(3), pp. 245–296, 1997.

[2] Moody, J.A. & Martin D.A., Initial hydrologic and geomorphic response following a wildfire in the Colorado Front Range. *Earth Surface Processes and Landforms*, **26**, pp. 1049–1070, 2001.

[3] Legleiter, C.J., Lawrence, R.L., Fonstad, M.A., Marcus, W.A. & Aspinall, R., Fluvial response a decade after wildfire in the northern Yellowstone ecosystem: A spatially explicit analysis. *Geomorphology*, **54**, pp. 119–136, 2003.

[4] Brummer, C.J. & Montgomery, D.R., Influence of coarse lag formation on the mechanics of sediment pulse dispersion in a mountain stream, Squire Creek, North Cascades, Washington, United States. *Water Resources Research*, **42**, W07412, 2006. DOI: 10.1029/2005WR004776.

[5] Pierson, T.C. & Major, J.J., Hydrogeomorphic effects of explosive volcanic eruptions on drainage basins. *Annual Review of Earth and Planetary Sciences*, **42**(1), pp. 469–507, 2014.

[6] Pasuto, A. & Soldati, M., An integrated approach for hazard assessment and mitigation of debris flows in the Italian Dolomites. *Geomorphology*, **61**(1–2), pp. 59–70, 2004.

[7] Hancock, G.R., Willgoose, G.R. & Evans, K.G., Testing of the SIBERIA landscape evolution model using the Tin Camp Creek, Northern Territory, Australia, field catchment. *Earth Surface Processes and Landforms*, **27**(2), pp. 125–143, 2002.

[8] Bogaart, P.W., Tucker, G.E. & deVries, J.J., Channel network morphology and sediment dynamics under alternating periglacial and temperate regimes: a numerical simulation study. *Geomorphology*, **54**(3), pp. 257–277, 2003.

[9] García-Castellanos, D., Vergés, J., Gaspar-Escribano, J. & Cloetingh, S., Interplay between tectonics, climate, and fluvial transport during the Cenozoic evolution of the Ebro basin (NE Iberia). *J. Geophysical Research*, **108**(B7), pp. 2347–2364, 2003.

[10] Garcin, M., Poisson, B. & Pouget, R., High rates of geomorphological processes in a tropical area: The Remparts River case study (Réunion Island, Indian Ocean). *Geomorphology*, **67**(3–4), pp. 335–350, 2005.

[11] Swanson, F.J., Jones, J.A., Crisafulli, C.M. & Lara, A., Effects of volcanic and hydrologic processes on forest vegetation: Chaitén Volcano, Chile. *Andean Geology*, **40**(2), pp. 359–391, 2013.

[12] Ulloa, H., Iroumé, A., Mao, L., Andreoli, A., Diez, S. & Lara, L.E., Use of remote imagery to analyse changes in morphology and longitudinal large wood distribution in the Blanco River after the 2008 Chaitén volcanic eruption, Southern Chile. *Geografiska Annaler: Series A, Physical Geography*, **97**(3), pp. 523–541, 2015. DOI: 10.1111/geoa.12091.

[13] Major, J.J. et al., Extraordinary sediment delivery and rapid geomorphic response following the 2008–2009 eruption of Chaitén Volcano, Chile. *Water Resources Research*, **52**(7), pp. 5075–5094, 2016. DOI: 10.1002/2015WR018250.

[14] Mohr, C.H., Korup, O., Ulloa, H. & Iroumé, A., Pyroclastic eruption boosts organic carbon fluxes into Patagonian fjords. *Global Biogeochemical Cycles*, **31**, pp. 1626–1638, 2017.

[15] Major, J.J., Post-eruption hydrology and sediment transport in volcanic river systems. *Water Resources Impact*, **5**(3), pp. 10–15, 2003.

[16] Dale, V.H., Swanson, F.J. & Crisafulli, C.M., *Ecological Responses to the 1980 Eruption of Mount St. Helens*, Springer-Verlag: New York, 2005.

[17] Major, J.J., Crisafulli, C.M., Frenzen, P. & Bishop, J., After the disaster: The hydrogeomorphic, ecological, and biological responses to the 1980 eruption of Mount St. Helens, Washington. *Volcanoes to Vineyards: Geologic Field Trips through the Dynamic Landscape of the Pacific Northwest: Geological Society of America Field Guide*, vol. 15, J.E. O'Connor, R.J. Dorsey & I.P. Madin (eds), pp. 111–134, 2009. DOI: 10.1130/2009.fld015(06).

[18] Hayes, S.K., Montgomery, D.R. & Newhall, C.G., Fluvial sediment transport and deposition following the 1991 eruption of Mount Pinatubo. *Geomorphology,* **45**, pp. 211–224, 2002.

[19] Gran, K.B. & Montgomery, D.R., Spatial and temporal patterns in fluvial recovery following volcanic eruptions: Channel response to basin-wide sediment loading at Mount Pinatubo, Philippines. *Geological Society of America Bulletin*, **117**(1–2), pp. 195–211, 2005.

[20] Branca, S., Geological and geomorphological evolution of the Etna volcano NE flank and relationships between lava flow invasions and erosional processes in the Alcantara Valley (Italy). *Geomorphology*, **53**(3–4), pp. 247–261, 2003.

[21] Inbar, M., Reyes, A. & Graniel, J.H., Morphological changes and erosion processes following the 1982 eruption of El Chichón volcano, Chiapas, Mexico. *Géomorphologie: Relief, Processus, Environnement*, **7**(3), pp. 175–183, 2001.

[22] Tanarro, L.M., Andrés, N., Zamorano, J.J., Palacios, D. & Renschler, C.S., Geomorphological evolution of a fluvial channel after primary lahar deposition: Huiloac Gorge, Popocatépetl volcano (Mexico). *Geomorphology*, **122**(1–2), pp. 178–190, 2010.

[23] Manville, V. & Wilson, C.J.N., The 26.5 ka Oruanui eruption, New Zealand: A review of the roles of volcanism and climate in the post-eruptive sedimentary response. *New Zealand Journal of Geology and Geophysics*, **47**(3), pp. 525–547, 2004.
[24] Cole, P.D. et al., Deposits from dome-collapse and fountain-collapse pyroclastic flows at Soufrière Hills Volcano, Montserrat, in The Eruption of the Soufrière Hills Volcano, Montserrat From 1995 to 1999. *Geological Society London Memoirs*, **21**, pp. 231–262, 2002.
[25] Harpel, C.J., de Silva, S. & Salas, G., The 2 ka eruption of Misti volcano, southern Peru: The most recent Plinian eruption of Arequipa's iconic volcano. *Geological Society of America Special Papers*, **484**, pp. 1–72, 2011.
[26] Umazano, A.M., Melchor, R.N., Bedatou, E., Bellosi, E.S. & Krause, J.M., Fluvial response to sudden input of pyroclastic sediments during the 2008–2009 eruption of the Chaitén Volcano (Chile): The role of logjams. *Journal of South American Earth Sciences*, **54**, pp. 140–157, 2014.
[27] Ulloa, H. et al., Massive biomass flushing despite modest channel response in the Rayas River following the 2008 eruption of Chaitén volcano, Chile. *Geomorphology,* **250**, pp. 397–406, 2015. DOI: 10.1016/j.geomorph.2015.09.019.
[28] Ulloa, H. et al., Spatial analysis of the impacts of the Chaitén volcano eruption (Chile) in three fluvial systems. *Journal of South American Earth Sciences*, **69**, pp. 213–225, 2016.
[29] Mella, M. et al., Productos volcánicos, impactos y respuesta a la emergencia del ciclo eruptivo abril–mayo (2015) del volcán Calbuco. *Actas XVI Congreso Geológico Chileno*, pp. 98–101, 2015.
[30] Romero, J.E. et al., Eruption dynamics of the 22–23 April 2015 Calbuco Volcano (Southern Chile): Analyses of tephra fall deposits. *Journal of Volcanology and Geothermal Research*, **317**, pp. 15–29, 2016. DOI: 10.1016/j.jvolgeores.2016.02.027.
[31] Russell, A., Dussaillant, A., Meier, C., Rivera, A., Gonzalez, C. & Harrison, D., Controls on rapid post eruption fluvial system response, Calbuco, Chile. *Geophysical Research Abstracts, European Geophysical Union General Assembly*, **20**, EGU2018-9887, 2018.
[32] Moreno, H., Naranjo, J.A. & Clavero, J., Generación de lahares calientes en el Volcán Calbuco, Andes del Sur de Chile (41,3°S). *Actas XI Congreso Geológico Chileno*, pp. 513–516, 2006.
[33] Wheaton, J.M., Brasington, J., Darby, S.E. & Sear, D.A., Accounting for uncertainty in DEMs from repeat topographic surveys: improved sediment budgets. *Earth Surface Processes and Landforms*, **35**(2), pp. 136–156, 2010.
[34] Batalla, R.J., Iroumé, A., Hernández, M., Llena, M., Mazzorana, B. & Vericat, D., Recent geomorphological evolution of a natural river channel in a Mediterranean Chilean basin. *Geomorphology*, **303**, pp. 322–337, 2018. DOI: 10.1016/j.geomorph.2017.12.006.