Agricultural and Forestry Sciences
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June 29, 2020

Dear Editor Dr. Daniele Giordan

In this iteration, we submit our responses to all the comments from the three reviewers where we indicate the changes in the main document, a version with the changes, and a version with the changes accepted in pdf format.

With all the best,

Dr. Marcelo Somos-Valenzuela

Dear Editor Dr. Daniele Giordan and Dr. Martin Mergili

Thank you for your comments, we addressed them in our resubmitted version of this paper. In this document, we put the point-by-point responses to your comments.

With all the best,

Dr. Marcelo Somos-Valenzuela

Comments R1: Dr. Martin Mergili

General Comments R1 (GCR1):

GCR1_1: Even though the paper is mostly written in an understandable way, there are various language issues which require substantial polishing (if possible, by a native speaker).

Response to GCR1_1:

We agree with your comment and had sent the paper for review to a professional Spanish-English translator. In the revised version you can see several corrections from Dr. Helen Lowry a native English speaker that provides this service.

GCR1_2: Title: the title sounds nice, but does it really describe the main content of the paper? I have the feeling that the paper is not so much about the conditions that potentially enabled the mud flow disaster, but rather on the propagation of the mud flow.

Response to GCR1_2:

We change the tittle to "The mudflow disaster at Villa Santa Lucía in Chilean Patagonia: understandings and insights derived from numerical simulation and post event field surveys" as it was suggested by the third reviewer (see **Response to GCR3_1**)

GCR1_3: Abstract: in my opinion, it could be condensed and a little bit more focused, but this is an issue of preference. The general statements at the beginning are maybe too long, given that the paper mainly describes a case study.

Response to GCR1_3:

We agree with the reviewer and modified the first paragraph from:

"The evaluation of potential mass wasting in mountain areas is a very complex process because there is not enough information to quantify the probability and magnitude of these events. Identifying the whole chain of events is not a straightforward task, and the impacts of mass wasting processes depend on the conditions downstream of the origin. Additionally, climate change is playing an essential role in the occurrence and distribution. Mean temperatures are continuously rising to produce long term instabilities, particularly on steep slopes. Extreme precipitations events are more recurrent as well as heat waves that can melt snow and glaciers, increasing the water available to unstabilized slopes"

To this:

"The evaluation of potential mass wasting in mountain areas is a very complex process because there is not enough information to quantify the probability and magnitude of these events. Identifying the whole chain of events is not a straightforward task, and the impacts of mass wasting processes depend on the conditions downstream of the origin."

GCR1_4: Introduction: the same as for the abstract. It starts with “Climate change”, and the first tree paragraphs deal with change-landslide relations. Even though this is certainly an important topic, it is not the subject of the paper when looking at the methods, results, discussion and conclusions. If the authors would like to stay with the focus on climate change, this aspect has to be more strongly included in the main content of the paper. Otherwise, the introduction should be restructured and reformulated, shortening the part on climate change and coming more quickly to the core topic of the paper.

Response to GCR1_4:

We agree with the reviewer and took out all the paragraphs that may misleads the focus of the paper, which is not a climate change study and we rearrange the introduction.

Now the introduction reads:

“Introduction

Landslides processes are particularly dangerous in areas close to human settlements. They can affect nearby villages, directly destroying houses and taking human lives (Gariano and Guzzetti, 2016) or indirectly affecting the connectivity of remote areas (Winter et al., 2016). The impacts of landslides are a function of the size of the event but also of the conditions downstream. For example, glaciar lakes susceptible to overflow, as well as unstable valleys that, given the right soil matrix and water content, can mobilize and produce mudflows (Carey et al., 2011; Haeberli et al., 2013). Areas where glaciers are receding worsen this situation because they expose unstable hillslopes that can collapse as well as potentially create glacier lakes. Currently, baseline information availability still critical in austral zones of South America, especially in Northern Patagonia, with a low population density that has not encouraged rigorous evaluation. Moreover, in recent years landslides events have increased due to anthropic and climatic effects (Aldunce and González, 2009). Parallelly, northern Patagonia shows an increase in the population (INE, 2018) increasing the risk. Therefore, a better understanding of landslide dynamics like the chain of events type like mudflows is urgent.

In our contribution, we will evaluate the generation of a cascade of events associated with the Villa Santa Lucia mudflow in Northern Patagonia. In this study, we will evaluate the mechanisms that enable a landslide of 7x106 m3 to evolve to the catastrophic mudflow that destroy Villa Santa Lucía in Chilean Patagonia, resulting in 22 people dead. The landslide, which may have been triggered by hydrometeorological conditions and destabilization of the wall around the receding Yelcho glacier, led to the generation of a hyper-concentrated flow at the head of the Burritos River that traveled around ten kilometers and affected 50% of the urban area of Villa Santa Lucia on December 16, 2017. The first observations indicated that the event was possible because of the presence of a glacier lake. However, field results do not allow to support this hypothesis in the area. Therefore, this study, which seeks to understand the conditions that enabled the event without the presence of a glacier lake, will have a two-fold application. First, it will allow us to understand the mechanisms of the chain of events leading to the 2017 mudflow in Villa Santa Lucia, and second, and probably most important, update the criteria for mapping risks associated with mudflows in Chilean Patagonia.”

Specific comments RC1 (SCR1)

SCR1_1: L36: Please mention already here the region (southern Chile), many readers might not know the Yelcho mountain range.

Response to SCR1_1: We added (southern Chile) in the place indicated

SCR1_2: L47 (and in general): r-avaflow -> r.avaflow

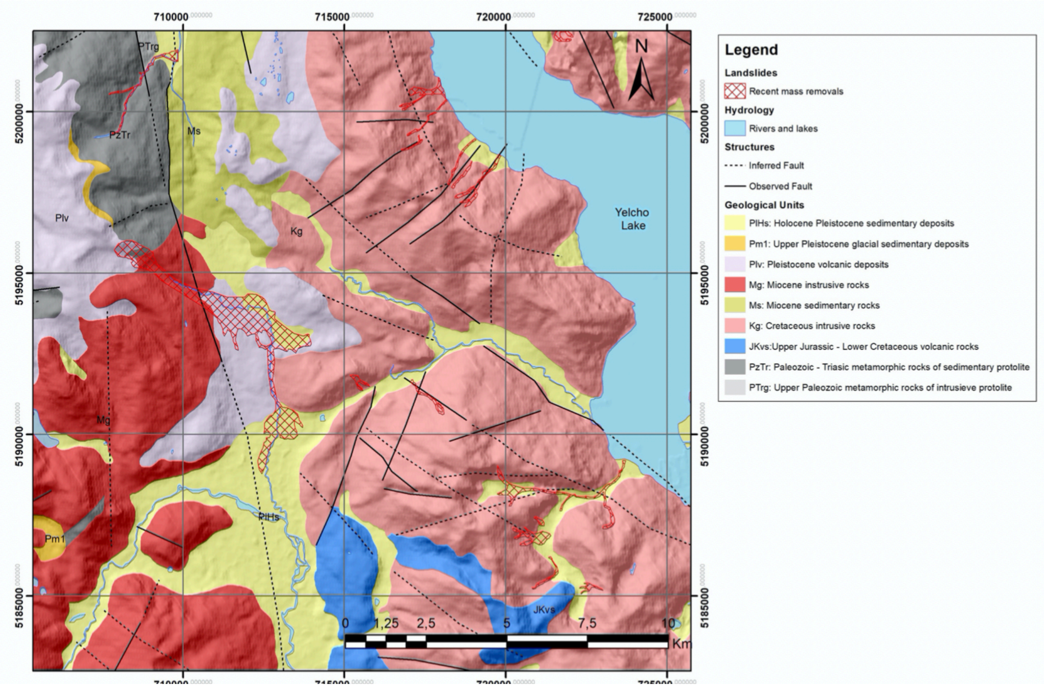
Response to SCR1_2: We corrected the name of the software in several places.

SCR1_3: L49-50: You cannot determine the total water content from simulations and soil tests – you can just estimate it. Further, the precision given in the volume number (also in some other places) is too high, considering the uncertainties. In this case, 2.8 million m³ would be sufficient.
Response to SCR1_3: we changed from 2,789,500 to 2.8 million as suggested.

SCR1_4: L113: "… alluvial and river processes …": aren't alluvial processes also river processes?
Response to SCR1_4: Yes, they are. We deleted "alluvial" to avoid redundancy.

SCR1_5: L124 NO -> NW
Response to SCR1_5: Corrected

SCR1_6: Figure 2: Nice figure, but there are some hispanicisms is the legend … "Leyend" -> "legend"; "Hidrology" -> "Hydrology"; further, in the map itself the lake polygon should be deselected before exporting the map.
Response to SCR1_6: We fixed the figure



SCR1_7: L136: What would be the average annual rainfall in this area?
Response to SCR1_7: The average annual rainfall is
The original text read "According to the information provided by the "Dirección General de Aguas" (DGA), at the time of the event, the total annual rainfall was 3,650 mm, and in the 30 hours prior to the event the rainfall reached 124.8 mm, with a maximum intensity of 10.6 mm/hr at 16:00 hours on December 15, 2017."

Now it reads: "According to the information provided by the "General Water Directorate" (DGA in Spanish), the annual average rainfall in this area is 3,420 mm. At the time of the event, the total annual rainfall was 3,650 mm, and in the 30 hours prior to the event the rainfall reached 124.8 mm, with a maximum intensity of 10.6 mm/h at 16:00 hours on December 15, 2017."

SCR1_8: L156: A new section about the description of the event should start here.

Response to SCR1_8: We added a new section “Description of the event”

SCR1_9: L157: I would expect a little bit more information on the landslide-glacier interaction. Was there some glacier ice entrained, which was included in the flow downstream? This can be an important issue, even though it is not always straightforward to analyze its importance (see e.g.: *Mergili, M., Jaboyedoff, M., Pullarello, J., Pudasaini, S.P. (2020): Back-calculation of the 2017 Piz Cengalo-Bondo landslide cascade with r.avaflow. Natural Hazards and Earth System Sciences 20: 505-520. doi:10.5194/nhess-20-505-2020*)

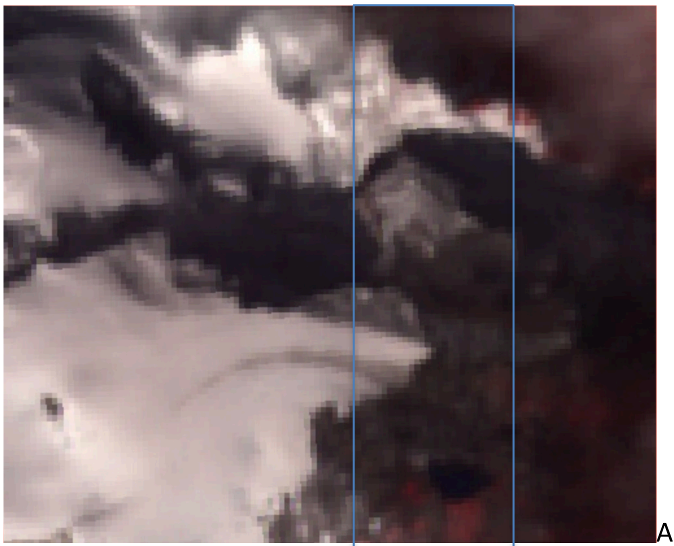
Response to SCR1_9: Yes, this is an issue that we discuss, and as the reviewer mentioned, it is not a straightforward one. We did not quantified this, not have knowledge that somebody else did. However, we looked into satellite imagery to understand this interaction or to guess the importance of the ice entrainment. In the figure below, we put three images from the landslide area. The first image is an Aster image from 2010, the second is a Sentinel-2 image from 2017 before the event, and the third is a sentinel-2 image after the event.

When we compare Figures a and b, we can see that the glacier terminal shrunk about 250 meters from 2010 to 2017, exposing the walls in the north side. However, when we compare Figures b and c, we can see that the landslide moved away from the glacier terminal. The shape of the glacier terminal was not modified. The only option that we have left is that the end of the glacier is covered by debris. This is plausible; however, the volume remains unknown. Also, there is no indication of a glacier lake, as it was indicated in earlier studies. We can not ignore the fact that there was glacier entrainment, there is clear evidence in the field that there was. However, given the little information related to the volume of ice involved in this process, we seek to demonstrate using numerical modeling that the water available in the river banks and valley downstream was enough or nearly enough to generate a mudflow. We are aware though that there were other sources of water involved

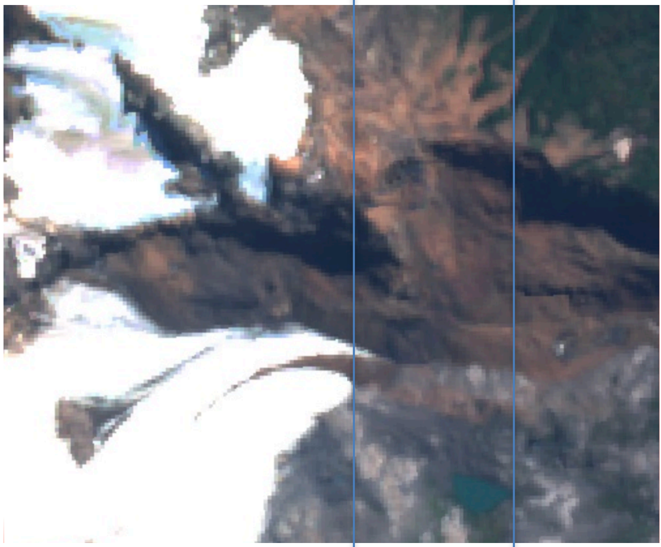
We added extra information in the description of the event:

“2.4 Description of the event

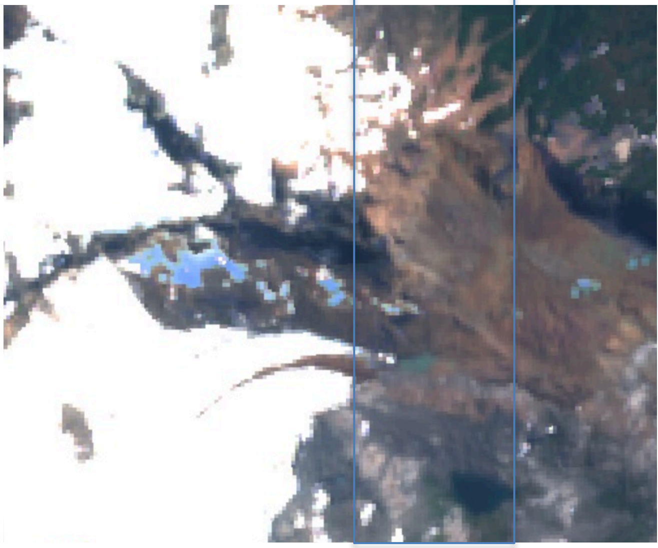
On December 16, 2017, a 7 million cubic meter volcanic rock slide detached (Figure 3, point 1), falling next to the Yelcho glacier toe that sits on an intrusive formation that has a drop of about 80 meters. The glacier shows a retreat during the last decade. Sernageomin (2018c) indicated that there might have been a small lake and water available on top of the intrusive formation, but there is no conclusive information. Satellite images before the events do not indicate a lake above the intrusive unit. Also, there were indications that ice contributed to the mudflow. Remote sensing data do not show that the landslide felt on top of the glacier unless detritus had covered the glacier, although we can see ice on top of the flank that collapsed. However, we do not have data to prove or disregard the covered ice on the intrusive and how much water it contributed to the mix. Two million cubic meters of the material stayed above the intrusive, and five million cubic meters of material continued downstream, sliding on the intrusive unit at a slope of more than 70 degrees. At this point, the mudflow reaches the Burrito River with high topographic differences. The flow continued along with the drainage network at high speed (Figure 1 and Figure 3, point 2), adding a significant amount of sediment into the mudflow. The sediments are mainly associated with glaciolacustrine deposits (easy to mobilize) and ancient alluvials present in the valley and on the river walls.”



Aster image, austral summer 2010



Sentinel S2 Austral summer before the event



Sentinel 2 after the event

SCR1_10: L175: Maybe add some brief information (1 sentence) about damages and casualties, readers might be interested in that. As the term “disaster” is included in the title of the paper, there should be at least some information on the socio-economic component.

Response to SCR1_10: After the dot we adeed “The mudflow destroyed of 50% of Villa Santa Lucía, killind 22 people and blocking two out of three access to the village Route 7 and Route 235”.

SCR1_11: Figs. 4-8: They are very informative, but I recommend to put them together into one full-page figure with 7 panes or so.

Response to SCR1_11: We put them all together in Figure 4

Figure 4: a) Area of slope failure slid and deposit; b) Channeled flow at the foothills; c and d) Aerial photo of non-channeled flood deposited in an old wetland captured with an InspireII UAV; e and f) Aerial photo of the channel in the last section before entering Villa Santa Lucia (left) captured with an InspireII UAV. Picture of the channel facing downstream (right); h and i) Villa Santa Lucia after the mudflow (From Sernageomin (2018c)).

SCR1_12: L273: "Topography". Further I recommend to shift the section 3.2.3 farther up, as it rather concerns data acquisition. In the place where it is now, it disturbs the flow of reading from the models to the parameterization.

Response to SCR1_12:

We move this section up and merge it with the first section of the metholodogy "3.1 Fieldwork, Geotechnical sampling and **topography**". So we pasted the paragraph and put it at the end of the 3.1 section.

SCR1_13: Table 1: you may round the inundation area and the flow velocity at Villa Santa Lucía – the numbers indicate a precision which is probably not justified by the data.

Response to SCR1_13:

We rounded it to 21 m/s

SCR1_14: L289: How did you perform the calibration? Did you just use an iterative optimization procedure ("trial and error"), or did you use some automated, systematic procedure? Please explain! These things are explained a little bit in Section 4 (results), but they should already be explained in the methods section.

Response to SCR1_14:

Yes, we did a trial and error calibration.

We added this in the calibration section in the methodology

It reads: "For the calibration of the models we used a **trial and error aproach seeking** too match the following three pieces of data available from Sernagomin: (1) Flood area, which was mapped after the event using aerial imagery (SAF, 2017); (2) Flow heights estimated by Sernageomin in Villa Santa Lucía and at the beginning of the canyon; and (3) Flow velocities in the canyon curve and at the beginning of Villa Santa Lucia (Figure 11). See Table 1 for the values."

SCR1_15: 4.3.: The heading "Numerical modelling" is misleading as, in this section, just the modelling domain and the calibration procedure are briefly described. This is something I would rather expect in the methods section, as it is not a result. Further: did you also consider simulating the entire event (including the initial landslide?) This could be an interesting task for the future and, as such, could be mentioned in the discussion. There is now the multi-phase model of Pudasaini (*Pudasaini, S.P., Mergili, M. (2019): A Multi-Phase Mass Flow Model. JGR Earth Surface. doi: 10.1029/2019JF005204*), which could also serve for the simulation of the interaction between the landslide and the glacier.

Response to SCR1_15:

We agree with the reviewer, we move this paragraph to Numerical modeling in the methodology section.

Thank you for the reference, this is a great resource for our future work. We considered to model the event from the initial landslide. However, we decided to simplify our simulations using the information that was generated by SERNAGEOMIN which is the national institution that deals with natural disaster associated to landslides. They quantify the amount of solid that continues downstream from the intrusive formation right below the glacier tongue. Also, we wanted to compare the different models we used. We had Flo2D and that model does not handle avalanches. But certainly this is a great study case that we will continue exploring.

SCR1_16: Section 4.4/Table 4: Again, some Hispanicisms (Si->Yes).

Response to SCR1_16: Corrected, our apologies for this type of mistakes.

SCR1_17: Further, there is no information about entrainment. Did you allow entrainment and, if yes, which value did you set for the entrainment coefficient? The “environmental resistance coefficient” is the “ambient drag coefficient”, I think. Further, the Quasi Reynolds number and mobility number are 10^4.5 and 10^3. It is the logarithms which are given in the r.avaflow input.

Response to SCR1_17:

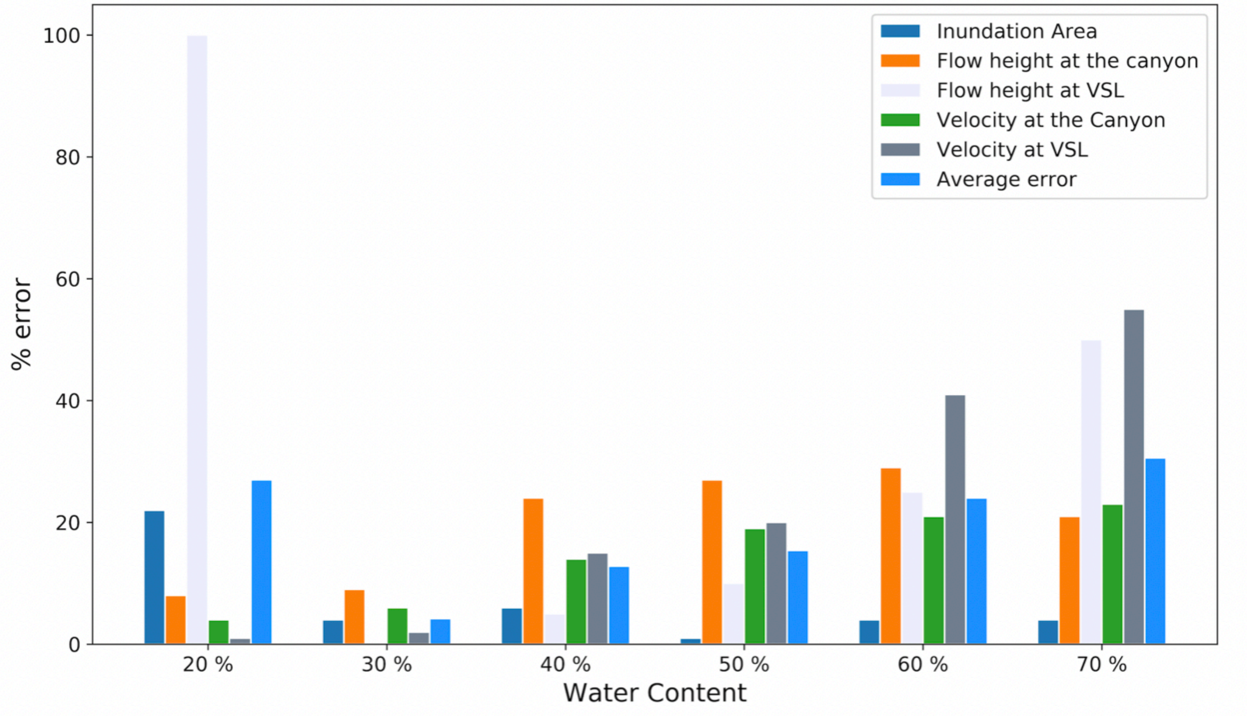
Yes, we did use entrainment and the entraiment coefficient is $10^{-5.75}$, the mobility number are indeed $10^{4.5}$ and 10^{3}. Our mistake was that we translated entrainment to Spanish and then back to English as “drag”. We corrected this in the document as well as the symbol and the base 10.

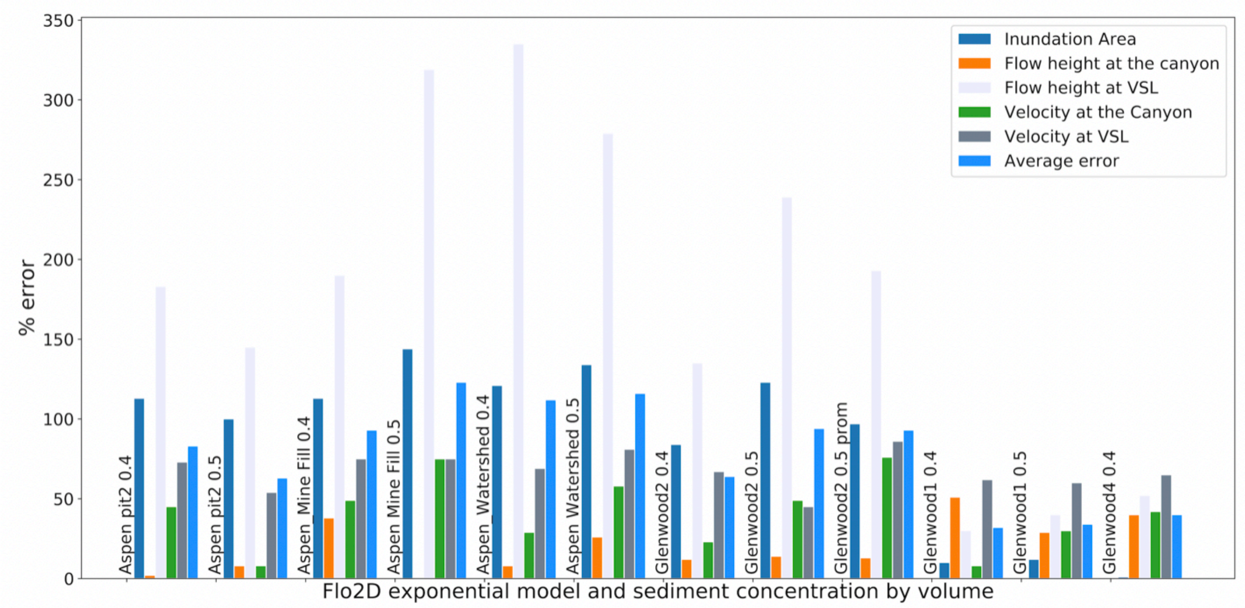
We modify Table 4, so now it look like this.

Solid density $[g/cm^3]$	2.400	Terminal Velocity	1
Liquid density $[g/cm^3]$	1.000	Contribution parameter S-L drag resistance	0.500
Virtual mass	0.500	Fluid friction coefficient	0.002
Hydrograph	No	Output writing time (s)	10
Diffusion control	Yes	Internal friction angle	24
Conservation of volume	Yes	Particle Reynolds number	1
Surface control	Yes	Exponent for drag	1
Viscous shear coefficient of the fluid	0	Quasi Reynolds Number	$10^{4.5}$
Solids concentration distribution with depth	0	Mobility Number	10^{3}

SCR1_18: Fig. 12 (and some other places): flow high -> flow height

Response to SCR1_18: We replaced Figures 12-16, now they are Figures 8-12, see also **Response to SCR1_20.**





SCR1_19: L341/342: Better: "… We varied the percentage of water between 20% and 70% …" – the formulation as it is now is misleading.

Response to SCR1_19:

We modified this sentence, thank you for the suggestion.

SCR1_20: Fig. 14, legend: revise the thresholds: e.g., to which class would a flow height of 49.95 m belong?

Response to SCR1_20:

We modified Figure12 (now figure 8):

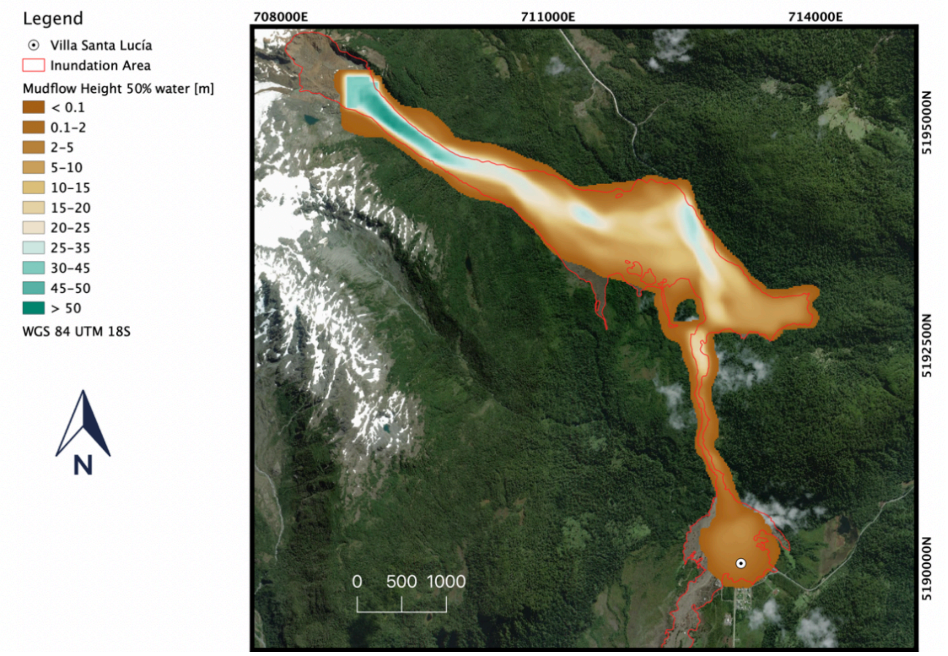


Figure 8: R.avaflow modeling results for a concentration by volume of 50% (Background © ESRI).

We modified Figure14 (now figure 10):

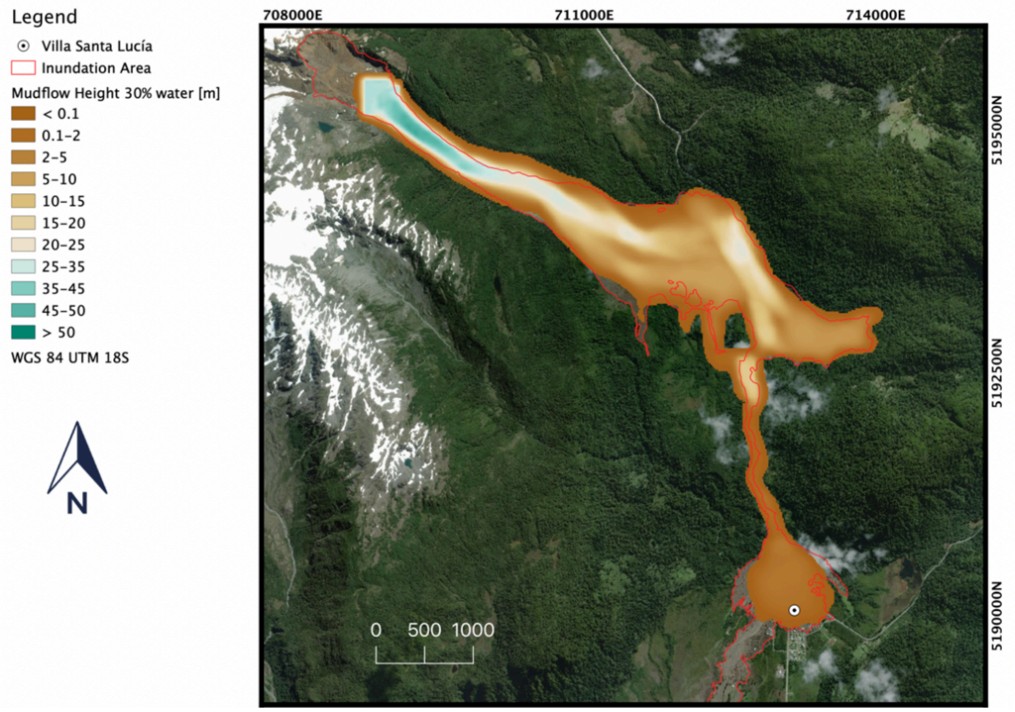


Figure 10: Best simulation results using the calibrated parameters for r.avaflow and 30% water content (Background © ESRI)

And we modified Figure 16 (now Figure 12)

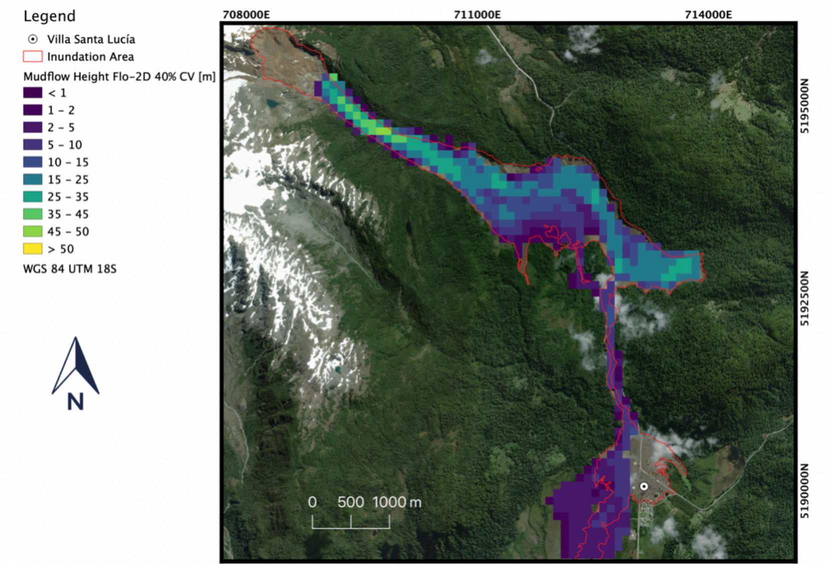


Figure 12: Result for Glenwood 1 using a 40% concentration of water by volume (Background © ESRI)

SCR1_20: Section 5.2.: You should also briefly mention the limitations of your calibration due to issues of equifinality (e.g. *Beven, K. (1996). 12 Equifinality and uncertainty in geomorphological modelling. In The Scientific Nature of Geomorphology: Proceedings of the 27th Binghamton Symposium in*

Geomorphology, Held 27–29 September 1996 (Vol. 27). John Wiley & Sons.), and the multi-dimensional parameter space (e.g. *Saltelli, A., & Annoni, P. (2010). How to avoid a perfunctory sensitivity analysis. Environmental Modelling & Software, 25(12), 1508-1517.*).

Response to SCR1_10:

Thank you for these excellent references that we did not have considered. They certainly open a new way of thinking on how to carry out calibration for these very complex processes.

So we added this paragraph in section 5.2

"For the calibration, we calculated the standard deviation from the modeling results and the parameters from Table 1. The parameter combination that results in less standard deviation is considered the best parameterization for the particular software used. Our procedure, as described in Saltelli and Annoni (2010), corresponds to a one-factor-at-a-time type of calibration where we change one parameter at a time manually, trying to match Table 1. The limitations of this procedure, according to Saltelli and Annoni (2010), are: Its efficiency is poor. The method does not capture the interaction of the factors because that would require the movement of more than one element at a time; therefore, the approach assumed that all the variables are independent, and the processes are linear, which is not usually the case. Another limitation of our calibration is the potential presence of equifinality. We did not test if different combinations of parameters would provide similar performance. We selected one best combination of parameters without checking the degrees of freedom that these variables may have had to replicate the observations (Beven, 1996)."

SCR1_21: L400: The water content leading to the empirically most adequate results was approx. 30%. Is this fraction also plausible from a physical point of view, and from the observations? Please briefly elaborate on this aspect more explicitly (some indirect information is given in the paragraph below).

Response to SCR1_22:

It is possible from the physical point of view and from our observations. We added in the section Source of water "Our analyses determined that in the area scoured, the soil has a porosity of 84.18%. Similar values were reported by Cuevas et al. (2013) in volcanic soils in the south of Chile. From our observations, we also notice the ground is saturated all the time. We did fieldwork after a couple of weeks of no rain, and the whole area around the river was saturated; indeed, our soil sample had a saturation of 97.4%. Therefore, using the results from r.avaflow, we estimated that a volume of 3.402.100 m^3 was scoured. Consequently, there was the potential of adding roughly 2.8 million m^3 of water and 600,000 m^3 of soils to the avalanche, which evolved to a mudflow due to the water added to the event."

Cuevas, J., Horn, R., Seguel, O. and Dörner, J.: Hydraulic conductivity variation in chilean volcanic soils due to wheeling and management, J. Soil Sci. Plant Nutr., 13(3), 756–766, doi:10.4067/S0718-95162013005000060, 2013.

SCR1_23: L404, 405: *Oh, you computed entrainment! This is good, but it is mentioned here for the first time (unless I overlooked it). You should appropriately address this important aspect also in the methods and the results sections.*

Response to SCR123:

*We apologize for the poor translation. You did not overlooked, the words use in our manuscrit were incorrect. In the methodology, it was mentioned that we considered the "drag of material" (line 256) now it reads "*The entraiment of material along the flow path was also considered." Then in line 262, we change "dragged heights" for "scoured heights" which refers to the basechanges file from r.avaflow. *Therefore in section 4.1 we mention this in the first paragraph*

And we include this topic in the discussion, see **Response to SCR1_22**

"4.1 R.Avaflow
To simplify the calibration, we divided the process into two. First, we set the sediment concentration by volume of the mudflow in 50% and change the entrainment coefficient, basal friction angle, ambient drag coefficient and fluid friction coefficient. For the description of the parameters in r.avaflow see Mergili et al. (2017). Table 4 shows the first set of parameters used."

In the result section we reporte the calibrated value for the entrainment coefficient as $10^{-5.75}$

SCR1_24: L409: *Now, the entrainment of glacier ice comes into play! You have to introduce this aspect already in the event description (see comment above).*
Response to SCR1_24:
We modified the description of the event. See **Response to SCR1_9** where we addressed this issue.

SCR1_25: L420: *FLO-2D is not a freely available software.*
Response to SCR1_25:
*We were refereeing just to r.avaflow, so we added sentence to make this point clear "*The combination of geotechnical tests and R.avaflow, which is a freely available computational software,…"

SCR1_26: *Conclusions, second paragraph: I would rather suggest to move this text to the discussion. The conclusions should rather focus on the key messages from your work (just extend what is written in the first paragraph).*
Response to SCR1_26*:*
We moved part of the second paragraph of the conclusion to the end of the discussion. The other part, we move it to the beginning of the conclusion section which now reads as follow:

"6 Conclusions
Given the complexity and the potential increase in the future of extreme event occurrence that can trigger landslides, we suggest that hazard studies should consider the structural conditions present in the area of influence of the mudflows. Soil characteristics ought to be included because they may be a crucial factor amplifying the impacts of local events triggered by hydroclimatic events. Such was the case of Villa Santa Lucia, where the water necessary to fluidize the mudflow mixture was in the soil in a volatile system that was easy to mobilize.
The combination of geotechnical tests and r.avaflow, which is a freely available computational software, to model mudflow are useful tools to characterize and reproduce mass wasting events, such as the mudflow occurred on December 2017 in Villa Santa Lucia in Chile. Our results present the possibility of open-source software implementation to represent mudflow events in the Patagonian Andes with a good performance. These types of studies will allow for the integration of better methodologies to enhance risk scenarios related to mudflow events in active subduction zones like the Andes."

Dear Editor Dr. Daniele Giordan and Dr. Haruyuki Hashimoto

Thank you for your comments, we addressed them in our resubmitted version of this paper. In this document, we put the point-by-point responses to your comments.

With all the best

Dr. Marcelo Somos-Valenzuela

Comment R2 (CR2) Dr. Haruyuki Hashimoto

CR2_1: Pages 2 to 20: There are various technical terms expressing 'sediment-related disaster', such as rockslide, landslide, avalanche, hyper-concentrated flow, hyperconcentrated sediment flow, mudflow, debris flow, debris and mud flow, detritus flow, avalanche flow, mass flow, two-phase flow, non-Newtonian flow, and water-sediment mixture. These similar technical terms make us confused. In order to avoid the confusion, the authors should unify these similar words and then describe the definition of each term.

Response to CR2_1:

Thank you for this comment. We appoligize for being sloopy in the used of the terminology and finally used "landslide" to refer to the collapse of the wall that started the event. And mudflow when we refer to the event when water was added.

For the other terms,

- Hyper-concentrated sediment flows, mudflows and non-Newtonian flow are terms used in the Flo2D description Therefore, we provided in the text the references to consult the meaning (O'Brien and Zhao, 2004).
- For debris flow and avalanche flow, mass flow, two-phase flow, and water-sediment mixture in the description of R.Avaflow, we included the refence (Mergili, M., Pudasaini, 2019)
- Mud flow, Detritus flow Water-sediment mixture are not longer part of the document

References:

FLO-2D: Reference Manual, Nutrioso, AZ., 2018.

Mergili, M., Pudasaini, S. P.: r.avaflow - The mass flow simulation tool. r.avaflow 2.0 Software 2014-2019, http://r.avaflow.org/software.php, 2019.

CR2_2: Pages 7 to 10: Slope of land along the flow trajectory is one of important factors for the mechanism of the landslide and debris flow. The more detailed information of the slope is needed. Therefore, the cross sectional profile of the land along the flow is helpful for the discussion. Using the figure of the cross sectional profile, the authors should discuss the landslide and debris flow event.

Response to CR2_2:

We added a slope profile in Figure 1, which now looks as follow

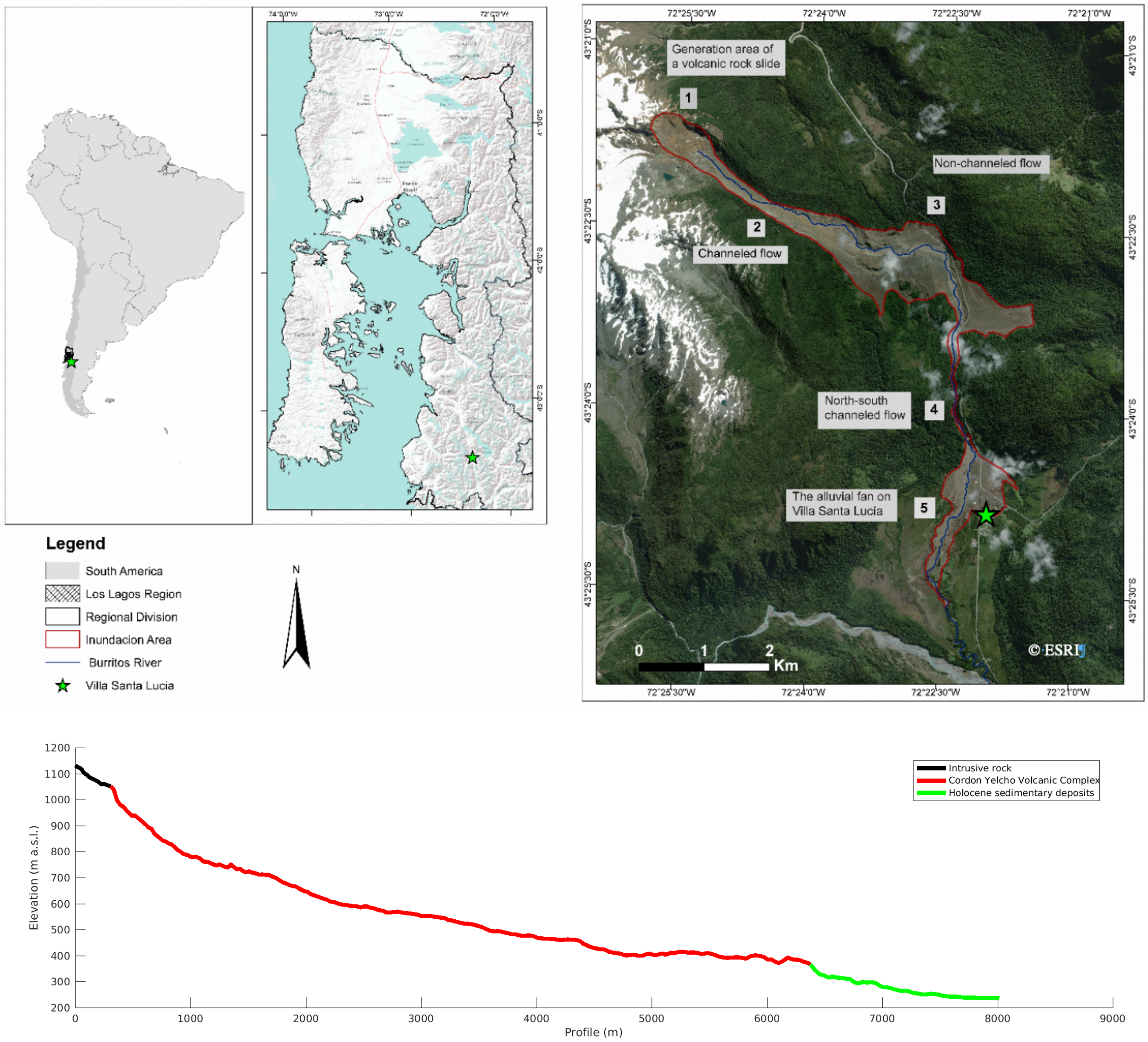


Figure 1: Top left: Study area and extension of the inundation (South America and Los Lagos Region layer from https://tapiquen-sig.jimdo.com,.Top right: Burritos River blue line layer from http://datos.cedeus.cl/, background © ESRI). Bottom: Elevation profile and geological formation along the mudflow path.

CR2_3: Pages 10 and 19 The budget of sediment and water during this event is important for understanding the process of the landslide and debris flow. A schematic figure of this budget is helpful for the discussion.

Response to CR2_3: We appreciate your observation. After reviewing in detail our manuscript, we noted that figure 13 needs to be explained correctly. Now, we inserted the following sentence in the results section of r.avaflow

“We varied the percentage of water between 20% and 70%. The error for the heights, speeds calculated in each model are in Figure 9. Therefore, we propose that a mudflow with a 30% water volume could reproduce best the VSL event (Figure 10).”

We renumber Figure 13 as Figure 9, according to the figure prioritization suggested by reviewers.

CR2_4: Line 217, Page 10 Sernageomin (2018 c) found flow velocity 20 m/s at the Burritos River canyon. The authors should explain the method of estimating the velocity.

Response to CR2_4:

Sernageomin (2018) used Equation 1 from Johnson (1970) that empirically estimated the flow's velocity in a curve.

$$V = \sqrt{\left(g * R * cos \propto * \frac{\Delta h}{\Delta x}\right)}$$

Equation 1

Where:

V= mean velocity (m/s)
g=gravity (m/s2)
R=curve radius (m)
α=channel slope (°)

The curves used for the calculationa re shown in the figure below:

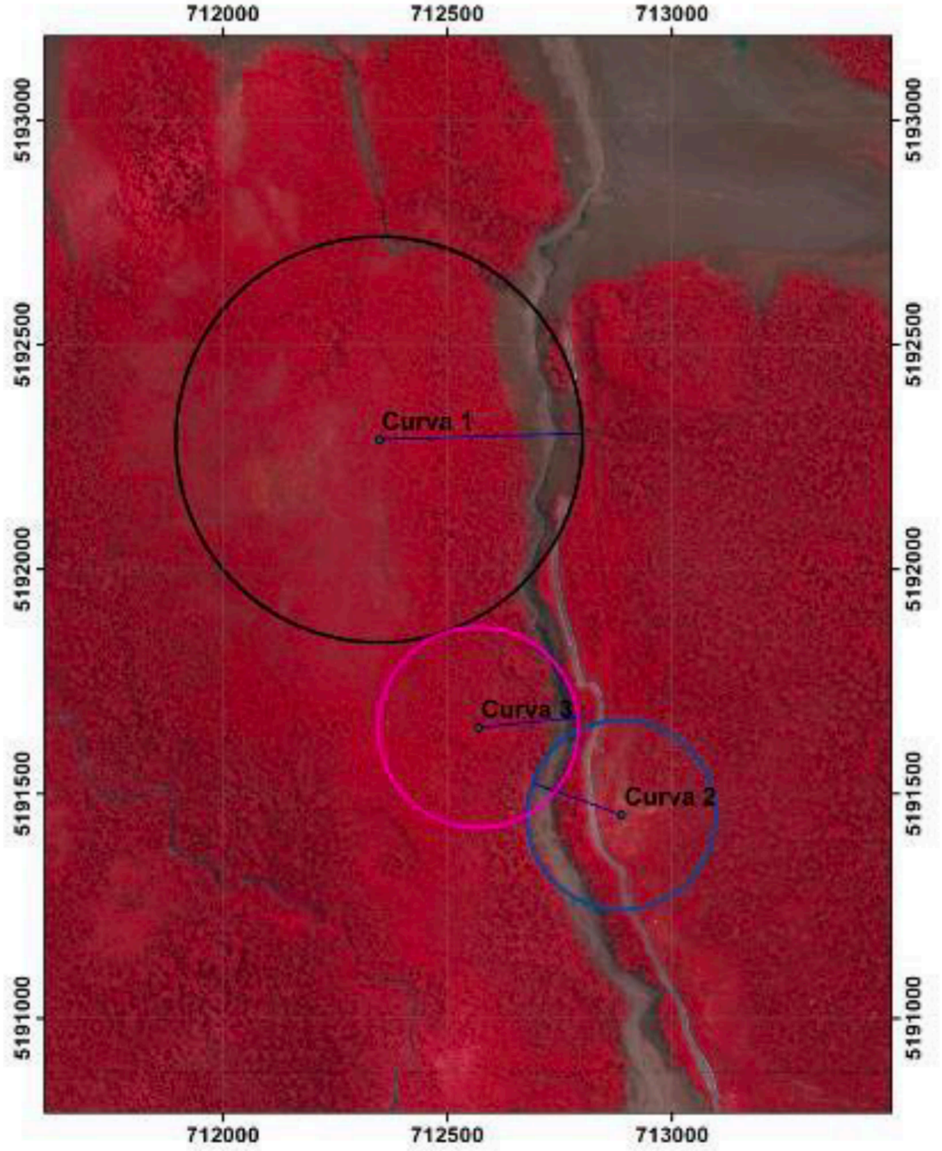


Figure: Curves used by Sernageomin (2018) to estimate the velocity of the flow in that section of the Burritos River.

Table: Summary of the result from Sernageomin (2018)

Curve		C1	C2	C3	
R		460	210	225	
$\propto$		2.121	1.626	10	
Camber	Δx	145	55	57.4	
	Δh	12	11	11	
$\frac{\Delta h}{\Delta x}$		0,08275862	0,2	0,19163763	
$cos \propto$		0,9993149	0,99959734	0,98480775	
V^2		372,820266	411,434266	416,141325	
V (m/s)		19,3085542	20,2838425	20,3995423	Average
V (Km/hr.)		69,5107952	73,0218329	73,4383522	71,9903268

References:

Sernageomin: Origen y efectos de la remoción en masa del 16.12.2017 que afectó la localidad de Villa Santa Lucía, comuna de Chaitén, Región de los Lagos, , 60, 2018.

Sernagoemin (2018) used: Johnson, A. M. (1970). Physical Processes in Geology: a Method for Interpretation of Natural Phenomena—Intrusions in Igneous Rocks, Fractures and Folds, Flow of Debris and Ice, Freeman, Cooper, and Co., San Francisco, California, 577 .

Since we did not do these calculations, we consider that we should not include them in our document and just cited the reference unless the editor thinks we should do so.

CR2_5: Line 331, pages 15 There are various factors in the basic equations describing the numerical simulation of the event, such as drag coefficient, basal friction angle, environmental resistant coefficient and fluid friction coefficient. Because the definition of these factors is not clear, it should be described in this paper.

Response to CR2_5:

We corrected the terms in the document that were poorly translated (see Response to SCR1_17) and we added the reference from r.avaflow. Therefore the descripton of the section where those terms were indicated reads as follow:

“To simplify the calibration, we divided the process into two. First, we set the sediment concentration by volume of the mudflow in 50% and change the entrainment coefficient, basal friction angle, ambient drag coefficient and fluid friction coefficient. For the description of the parameters in r.avaflow see Mergili et al. (2017).”

Mergili, M., Fischer, J. T., Krenn, J. and Pudasaini, S. P.: R.avaflow v1, an advanced open-source computational framework for the propagation and interaction of two-phase mass flows, Geosci. Model Dev., 10(2), 553–569, doi:10.5194/gmd-10-553-2017, 2017.

CR2_6: 'pressures', line 342, page 16 and line 357, page 17 Generally speaking, the word 'pressure' is not used for open-channel flow but for pipe flow. Therefore, this word is incorrect.

Response to CR2_6:

One of the outputs from r.avaflow is flow pressure (see Table 1 from Mergili, M., Fischer, J. T., Krenn, J. and Pudasaini, S. P.: R.avaflow v1, an advanced open-source computational framework for the propagation and interaction of two-phase mass flows, Geosci. Model Dev., 10(2), 553–569, doi:10.5194/gmd-10-553-2017, 2017.)

However, we did not use pressure for the validation of the model and incorrectly used it here. So we deleted the word "pressure" from line 342 and 357.

CR2_7: 'a mudflow with a volume of water of 30%', line 346, Page 17 Does this mean the mudflow with sediment concentration of 70 %.?

Response to CR2_7:

Yes, it means that the sediment concentration is 70%

Dear Editor Dr. Daniele Giordan and anonymous reviewer

Thank you for your comments, we addressed them in our resubmitted version of this paper. In this document, we put the point-by-point responses to your comments.

With all the best

Dr. Marcelo Somos-Valenzuela

Comments R3: Anonymous

General Comments R3 (GCR3):

GCR3_1:

The paper appears more as a technical paper describing and analyzing a case study than a research paper, and it should be presented as such, starting from the title. A possible suggestion would be for instance: The mudflow disaster at Villa Santa Lucía in Chilean Patagonia: understandings and insights derived from numerical simulation and post event field surveys

Response to GCR3_1:

We take you recommendation and now the title of the paper is "The mudflow disaster at Villa Santa Lucía in Chilean Patagonia: understandings and insights derived from numerical simulation and post event field surveys"

GCR3_2:

The topic and the contents of the paper are certainly of interest for the scientific community and deserve publication, but the paper should be shortened and should focus on its real core. Unfortunately, the paper is also written in an awkward English that does not help its understanding and clean reading. So the text requires substantial revision, possibly by a native speaker. I recommend a major revision, to be carried out also on the basis of the comments below.

Response to GCR3_2:

We appreciate that you considered that this works deserves to be published after the suggested correction are made. We sent this document for professional English translation and edition. Which you can check in the modified document. We also modified the summary and introduction following your suggestion and Reviewer 1's suggestions. Please see **Response to GCR1_3 and Response to GCR1_4**

Specific comments R3 (SCR3)

SCR3_1: Abtract - I would suggest to shorten the abstract and focus it on the main content of the paper, which is the interpretation of the catastrophic event and its causes based on field survey and numerical simulation. The reader expects to rapidly find in the abstract information regarding the main content of the paper, more than general comments on the treated issues. I have also reported some possible corrections to the English language, which are not intended, however, to be exhaustive because the entire paper requires substantial revision, possibly by a native speaker.

Response to SCR3_1:

Thank you for all the suggestion to the original document, we have included them and also sent the paper for English professional revision. We also shorthened the abstract please see **Response to GCR1_3 (response to general comment 3 from reviewer 1)**

SCR3_2: Introduction -The same shortening suggested for the abstract should be done with the introduction, that should expand the focus regarding the interpretation of the mudflow event and its causes through field surveys and simulation. For this purpose I would move lines 94-104 to the beginning of the introduction and then proceed with the other comments, substantially reduced.

Response to SCR3_2:

We added a short paragraph before the suggested place from Reviewer 3. We reduced the introduction from 947 to 345 words. Please see **Response to GCR1_4.**

SCR3_3: Methodology - The chapter should be restructured because it would be much better to have the content of the chapters 4.1 (Geotechnical results) and 4.2 (Soil Classification) presented all together in the chapter 3.1 (Fieldwork and Geotechnical sampling). This for two reasons: 1) the reader may have an idea of all the available geotechnical data collected in the field, finding them in the same place, without having to skip here and there in the paper 2) the reader would expect to find, within a chapter titled "results", the output of the calculations of the mathematical modelling, not the data deriving from field surveys and tests which concern more data acquisition than results of analysis or calculations.

Response to SCR3_3:

We partially agree with this coments. Chapter 4.1 and 4.2 are part of the results of our work so we think that for that reason they belong to the result section. However, it is true that the paper looked disorganized since it provided bits of the same information in different sections which gets confusing. So we accept the suggestion and moved the sections 4.1 and 4.2 from the results to the methodology limiting the results section to the results from the modeling work

SCR3_4: *The titles of the chapters (or sub-chapters) should be restructured too: there are three chapters titled the same way, that is "numerical modeling": 3.2 Numerical Modeling 3.2 Numerical Modeling 5.2 Numerical Modeling This is somewhat misleading and does not reflect an describe the real content of each of these sections.*

Response to SCR3_4:

Following the comment above (**SCR3_3**), we reduced the results section and eliminate the secion 4.2 Numerical modeling. We also renamed the section 5.2 to "Back-calculation of the mudflow"

SCR3_5: Conclusions. This is the best written part of the entire paper. It is simple, clear, straightforward. It declares what has been done, without any general digression. The entire paper should be restructured to adhere and to reflect what the authors write in their final conclusions, which should appear as the final synthesis of what has been written and developed before.

Response to SCR3_5:

We hope that after the modifications the entire document reads as it does the former conclusion section.

Extra comments:

We also included all the English suggestions from the nhess-2019-419-RC3-supplement into the revised document that is included in a separate file.

The mudflow disaster at Villa Santa Lucía in Chilean Patagonia: understandings and insights derived from numerical simulation and post-event field surveys

Marcelo A. Somos-Valenzuela[1,2], Joaquín E. Oyarzún-Ulloa[3], Ivo J. Fustos-Toribio[3*], Natalia Garrido-Urzua[4], Chen Ningsheng[5,6]

[1] Department of Forest Sciences, Faculty of Agriculture and Forest Sciences, Universidad de La Frontera, Av. Francisco Salazar 01145, Temuco, Chile, 4780000

[2] Butamallin Research Center for Global Change, Universidad de La Frontera, Av. Francisco Salazar 01145, Temuco, Chile, 4780000

[3] Department of Civil Engineering, Universidad de La Frontera, Av. Francisco Salazar 01145, Temuco, Chile, 4780000

[4] Servicio Nacional de Geologia y Mineria, Av. La Paz 406, Puerto Varas, Región de los Lagos, Chile, 5550000

[5] Institute of Mountain Hazards and Environment, Chinese Academy of Sciences, Chengdu 610041, China;

[6] University of Chinese Academy of Sciences, Beijing 100049, China;

Corresponding author: Ivo J. Fustos-Toribio (ivo.fustos@ufrontera.cl)

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Abstract. The evaluation of potential landslides in mountain areas is a very complex process. Currently, event understanding is limited due to information limitations. Identifying the whole chain of events is not a straightforward task, and the impacts of mass wasting processes depend on the conditions downstream of the origin. In this paper, we present an example that illustrates the complexities in the evaluation of the chain of events that may lead to a natural disaster. On December 16, 2017, a landslide occurred in the Yelcho mountain range (southern Chile). In that event, 7 million m^3 of rocks and soil fell on the Yelcho glacier depositing 2 million m^3 on the glacier terminal, and the rest continued downstream, triggering a mudflow that hit Villa Santa Lucia in Chilean Patagonia, killing 22 people. The complex event was anticipated in the region by the National Geological and Mining Survey (Sernageomin in Spanish). However, the effects of the terrain characteristics along the runout area were more significant than anticipated. In this work, we evaluate the conditions that enabled the mudflow that hit Villa Santa Lucia. We used the information generated by Sernageomin's professional after the mudflow. We carried out geotechnical tests to characterize the soil. We simulated the mudflow using two hydrodynamic softwares (r.avaflow and Flo-2D) that can handle the rheology of the water-soil mixture.

Our results indicate that the soil is classified as volcanic pumices. This type of soil can be susceptible to the collapse of the structure when subjected to shearing (molding), flowing as a viscous liquid. From the numerical modeling, we concluded that r.avaflow performs better than Flo2D. The mudflow was satisfactorily simulated using a water content of the mixture ranging from 30 to 40%, which would have required a source of about 3 million m^3 of water. Coupling the simulations and the soil tests that we performed, we estimated that in the area scoured by the mudflow, there were probably around 2,800,000 m^3 of water within the soil. Therefore, the conditions of the valley were crucial to enhancing the impacts of the landslide. This result is relevant because it highlights the importance of evaluating the complete chain of events to map hazards. We suggest that in future hazard mapping, geotechnical studies in combination with hydrodynamic simulation should be included, in particular, when human lives are at risk.

Keywords: Geological hazards, r.avaflow, mudflow modeling, Southern Andes mudflows

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1 Introduction

Landslides processes are particularly dangerous in areas close to human settlements. They can affect nearby villages, directly destroying houses and taking human lives (Gariano and Guzzetti, 2016) or indirectly affecting the connectivity of remote areas (Winter et al., 2016). The impacts of landslides are a function of the size of the event but also of the conditions downstream. For example, glaciar lakes susceptible to overflow, as well as unstable valleys that, given the right soil matrix and water content, can mobilize and produce mudflows (Carey et al., 2011; Haeberli et al., 2013). Areas where glaciers are receding worsen this situation because they expose unstable hillslopes that can collapse as well as potentially create glacier lakes. Currently, baseline information availability still critical in austral zones of South America, especially in Northern Patagonia, with a low population density that has not encouraged rigorous evaluation. Moreover, in recent years landslides events have increased due to anthropic and climatic effects (Aldunce and González, 2009). Parallelly, Northern Patagonia shows an increase in the population (INE, 2018) increasing the risk. Therefore, a better understanding of the mudflows chain of events triggered by landslides is urgent.

In our contribution, we will evaluate the generation of a cascade of events associated with the Villa Santa Lucia mudflow in Northern Patagonia. In this study, we will evaluate the mechanisms that enable a landslide of 7x10^6 m^3 to evolve to the catastrophic mudflow that destroy Villa Santa Lucía in Chilean Patagonia, resulting in 22 people dead. The landslide, which may have been triggered by hydrometeorological conditions and destabilization of the wall around the receding glacier in the Yelcho range, led to the generation of a mudflow at the head of the Burritos River that traveled around ten kilometers and affected 50% of the urban area of Villa Santa Lucia on December 16, 2017. The first observations indicated that the event was possible because of the presence of a glacier lake. However, field results do not allow to support this hypothesis in the area. Therefore, this study, which seeks to understand the conditions that enabled the event without the presence of a glacier lake, will have a two-fold application. First, it will allow us to understand the mechanisms of the chain of events leading to the 2017 mudflow in Villa Santa Lucia, and second, and probably most important, update the criteria for mapping risks associated with mudflows in Chilean Patagonia.

2 Study Area

2.1 Location

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In South America, permanent landslides monitoring is not suitable, generating uncertainty to risk decision-makers. Currently, the landslides have addressed from different points of view, always post-event [Fustos et al., 2017; García et al., 2018; Mergili et al., 2020]. In recent years progress was carried out in the implementation of satellite monitoring techniques [Fustos et al., 2017], numerical modelling [García et al., 2018; Fustos et al., 2020], geomechanical analysis [Sepulveda et al., 2016] and geomorphological studies [Lara et al., 2018] allowing an initial understanding in landslides susceptibility. However, landslides like mudflow/debris flow based on cascade of events still partially evaluated, constraining the quality of the interpretations [Sepulveda & Petley, 2015]. Herein, a large number of complex processes associated with extreme precipitation events that are not ... [10]

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Villa Santa Lucia is located in the valley of the Frio River, 75 kilometers south of Chaitén (closest town), along the Carretera Austral, in the Los Lagos Region, Chile. The landslide event started at the head of the Burritos river basin (43.413°S, 72.367°W) that runs to the west of Villa Santa Lucía (Figure 1). It begins on the eastern slope of the western side of the regional Andes in the Yelcho glacier.

This area was under tectonic modeling associated with the Liquiñe-Ofqui Fault System (LOFS), forming NS-trending valleys (Hervé et al., 2017). The geomorphological analysis shows glacier erosion in Frio River Valley and Yelcho Lake during the Pleistocene followed by sedimentary deposition of volcanic and river processes (Sernageomin, 2018). The climate of the area presents intense thermal variations, high summer temperatures and freezing temperatures in the winter. The rainfall reaches 3,000 mm annually, decreasing to the east (CECS, 2017).

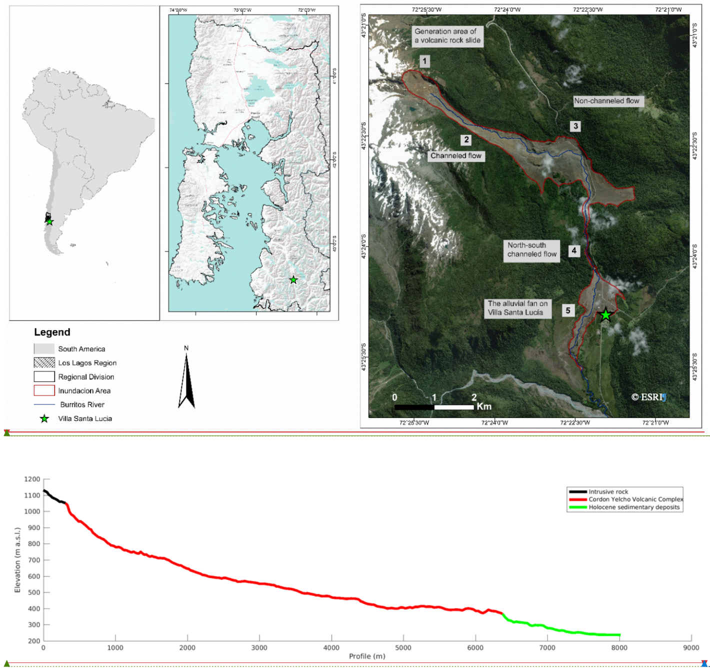

Figure 1: Top left: Study area and extension mudflow (South America and Los Lagos Region layer from https://tapiquen-sig.jimdo.com. Top right: Burritos River blue line layer from http://datos.cedeus.cl/ background © ESRI). Bottom: Elevation profile and geological formation along the mudflow path.

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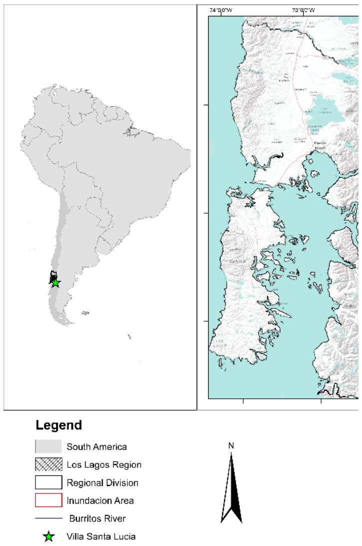

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2.2 Geological setting

The study area consists mainly of 9 geological units (Figure 2). The dominant geological unit corresponds to an intrusive rock (Cretaceous and Miocene age) composed of tonalites, granodiorites, granites, diorites, and others. Moreover, the basement material is an old metamorphic rock. This unit is composed of micaceous shales, amphibolite. Volcanic and volcanoclastic rocks represent, in part, the NW-SE volcanic arc, called the Cordon Yelcho Volcanic Complex (Sernageomin, 1995). Sedimentary rocks, mainly sandstone, shales, conglomerates are presented as intercalations. Recent sedimentary deposits are mainly associated with rivers, alluvial, colluvial, morainic and glaciolacustrine deposits (Aguilera et al., 2014) (Figure 2).

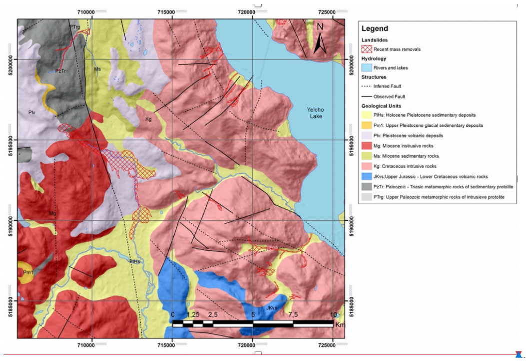

Figure 2: Geology of the study area (Modified from Sernageomin (1995))

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2.3 Event Background

The event in Villa Santa Lucía was triggered during a rainfall event front that passed over the area in a year where the entire Los Lagos Region. The event generated a significant record of rainfall surplus. Therefore, the hydrometeorological condition could constitute a condition of soil saturation that is favorable to natural hazards (Nguyen et al., 2018).

According to the information provided by the "General Water Directorate" (DGA in Spanish), the annual average rainfall in this area is 3,420 mm. At the time of the event, the total annual rainfall was 3,650 mm, and in the 30 hours prior to the event the rainfall reached 124.8 mm, with a maximum intensity of 10.6 mm/h at 16:00 hours on December 15, 2017. This hydrometeorological event exceeds 99% of the historical precipitation events in the area (CECS, 2017). The precipitation events in Villa Santa Lucía occurred after two weeks with maximum daily temperatures that

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Formatted: Do not check spelling or grammar exceeded 22°C on at least nine days between December 1 and 15, with December 2 and 5 being the hottest days with temperatures that exceeded 27°C. During December, before the event, the air temperature reached an average of 14.9°C (CECs, 2017). The Center for Scientific Studies (CECs in Spanish) determined through the data of a radiosonde located in Puerto Montt-El Tepual (41.44°S, 73.09°W) that the isothermal level on December 15 was 2,771 meters above sea level (m a.s.l.) for the Villa Santa Lucía coordinates. This implies that in the study area, there were only liquid precipitations in the days before the event, even in the glaciers of the Yelcho range, considering that the maximum heights of the peaks do not exceed 1,800 m a.s.l. approximately.

Previous studies shows that the surroundings of the Villa Santa Lucia presents a high and moderate risk of being affected by mass wasting processes, highlighting possible debris flows at the bottom of the valleys and active channels (Sernageomin, 2008). Areas that are not classified in high or moderate risk have low or no risk, which should be assessed at greater detail. High flood hazard would affect only the flood plain adjacent to Villa Santa Lucia, although some degree of risk in the town itself must be evaluated on a more detailed scale. This shows that the area of Villa Santa Lucía and its surroundings were and are prone to mass wasting phenomena. Although the town itself was not in risk, it was mentioned that more detailed studies are needed in the area.

2.4 Description of the event

On December 16, 2017, a 7 million cubic meter volcanic rock slide detached (Figure 3, point 1), falling next to the Yelcho glacier toe that sits on an intrusive formation that has a drop of about 80 meters. The glacier shows a retreat of at least 250 meters during the last decade. Sernageomin (2018c) indicated that there might have been a small lake and water available on top of the intrusive formation, but there is no conclusive information. Satellite images before the events do not indicate a lake above the intrusive unit. Also, there were indications that ice contributed to the mudflow. Remote sensing data do not show that the landslide felt on top of the glacier unless detritus had covered the glacier, although we could see ice on top of the flank that collapsed. However, we do not have data to prove or disregard the covered ice on the intrusive and how much water it contributed to the mix. Two million cubic meters of the landslide material stayed above the intrusive, and five million cubic meters of material continued downstream, sliding on the intrusive unit at a slope of more than 70 degrees. At this point, the mudflow reaches the Burrito River with high topographic differences. The flow continued along with the drainage network at high speed (Figure 1 and Figure 3, point 2), adding a significant amount of sediment into the mudflow. The sediments are mainly associated with glaciolacustrine deposits (easy to mobilize) and ancient alluvials present in the valley and on the river walls.

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Sernageomin (2018b) compile a series of reports; several studies are mentioned that help to understand the origin and explain the event as a whole. ... [36]

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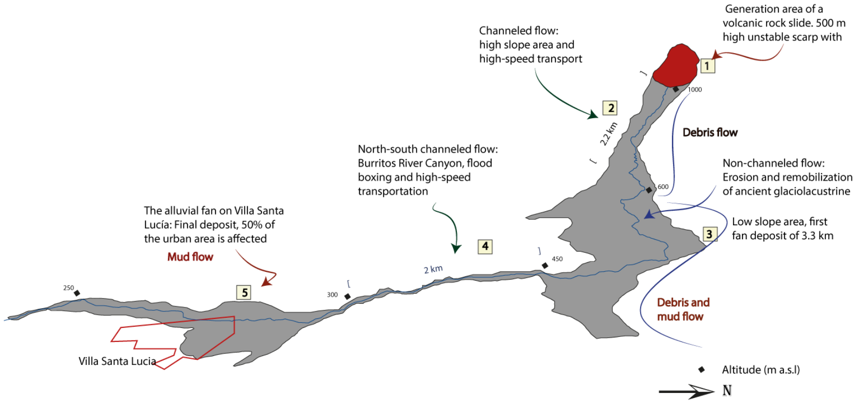

Figure 3: Flow trajectory scheme and details of the five key sections identified by Sernageomin and our fieldwork.

Additionally, the soil was almost saturated, which added water to the mix, transforming the landslide flow into a mudflow. Moreover, dense forest was present, which added a significant amount of biomass to the mix. Then the mudflow reached an area with low slopes at a distance of 8.6 km from its origin through the Burritos River to the east. In its trajectory, the mudflow crossed Route 7 (Carretera Austral) in a stretch estimated to be 2 km and filling an old wetland. In that sector, the flow was channeled in a canyon oriented north-south toward Villa Santa Lucia in a section of 1.5 km (Figures 1 and 3, point 4). Once the flood reached Villa Santa Lucia, it slowed down and deposited the sediment in a alluvial fan of 600 to 1,000 m with variable height between 1 up to 5 meters (Figure 1 and 3, point 5). The mudflow destroyed 50% of Villa Santa Lucía, killing 22 people and blocking two out of three accesses to the village (route 7 and route 235).

Through field observations, we identified five key sections that describe what happened in Villa Santa Lucía (Figures 1 and 3).

1. Generation area: It has a range of peaks between 1,000 to 1,400 m a.s.l., with the main escarpment of 900 m long and 520 m wide. The north wall has maximum slopes between 77 to 81° (Figures 3 and 4a). As a result of the chain processes, the material deposited acts as a dam creating two small lakes. The largest lake has a length of 180 m and an average width of 50 m (Sernageomin, 2018).
2. Channeled flow: This corresponds to the upper segment at the foothills, the flow is channeled and travels 2 km. The flow width was between 200 to 400 m wide. Using photo-interpretation of the digital elevation models (SAF,

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2017), and aerial photos, Sernageomin personnel (Sernageomin, 2018), estimated an approximate wave 20 m high (Figure 3 and 4 b).

3. Non-channeled flow: This section has a length of 2.3 km in a west to east direction until the Burritos River changes its orientation to a north-south direction. The elevation goes from 600 to 380 m a.s.l. The slopes decrease, slowing down the flow, which deposited sediments. The non-channeled flow width reaches 1.4 km. In this sector, the flow goes over the road (Carretera Austral) to the east in 1.3 km, affecting an old wetland (Figure 3 and 4c-d).

4. North-south channeled flow: The flow descends through the enclosed channel at the Burritos River canyon from 380 to 250 m a.s.l. on a 2 km long section (Figure 3 and 4e-f).

5. The alluvial fan on Villa Santa Lucía: Due to the loss in confinement, the flow expands with a radial distribution in a southeast-southwest direction of 600 to 1,000 m (Figure 3 and 4g-h)

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Figure 4: a) Area of slope failure slide and deposit; b) Channeled flow at the foothills; c and d) Aerial photo of non-channeled flood deposited in an old wetland captured with an InspireII UAV; e and f) photos of the channel in the last section before entering Villa Santa Lucia: left, captured with an InspireII UAV; right, picture of the channel facing downstream; h and i) Villa Santa Lucia after the mudflow (from Sernageomin (2018c)).

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As a result of the avalanche, the material deposited acts as a dam creating two small lakes. The largest lake has a length of 180 m and an average width of 50 m (Sernageomin, 2018c).¶

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Channeled flow: Corresponds to the upper segment at the foothills, the flow is channeled and traveled 2 km. The flow width was between 200 to 400 m wide. Using photo-interpretation of the digital elevation models (SAF, 2017) and aerial photos, Sernageomin personnel (Sernageomin, 2018c) estimated an approximate wave of 20 m height (Figure 3 and 5).¶

Channeled flow at the foothills.¶

Non-channeled flow: This section has a length of 2.3 km in a west to east direction until the Burritos river changes its orientation to a north-south direction. The elevation goes from 600 to 380 m a.s.l. The slopes decrease slowing down the flow, which deposited sediments. The ... [41]

In addition, Sernageomin (2018c) estimated the volume of material mobilized during the event using digital elevation models (DEM) created from photointerpretation of the orthomosaic provided by SAF (2017). Sernageomin (2018c) identified the release and the intrusive formation before the mudflow started. They compared digital elevation models before the event, Intermap and SRTM 30, with the DEM created by SAF (2017) estimated a volume of 7,200,000 m^3. Likewise, they estimated that approximately 2,200,000 m^3 of sediments were deposited in the upper part of the basin and that approximately 5,000,000 m^3 were the contribution to the flow.

The speed of the flow at the Burritos River canyon (Figure 4e-f) and at the beginning of Villa Santa Lucía when the flow opens (Figure 4g-h) is approximately 20 m s^{-1} (Sernageomin, 2018)

3 Methodology

3.1 Fieldwork, Topography and Soil Characteristics

A fieldwork campaign was carried out in January 2019 to map in high resolution the area using an unmanned aerial vehicle (UAV). We used aerial photogrammetry to produce a high-resolution DEM for some parts of the study area. Aerial photogrammetry creates 3D models from 2D images, obtaining geometric characteristics of the objects they represent. We used a UAV Inspire II with a Zenmuse X4 camera to capture aerial photos (Figure 5). We did not have differential GPS at the moment of this survey to take control points to correct the DEM generated. Therefore, we just used this DEM to corroborate that the DEMs with lower resolution and freely available were able to capture specific features such as canyons or small changes in slopes that could affect the hydrodynamic simulation and the path of the flood. We also generated a high-resolution mosaic to observe details of the mudflow deposition to improve the delimitation of affected area. We used the software Agisoft PhotoScan Professional 1.4 desktop to process the images. The software performs the restitution of images by spatial coincidence among the elements represented in each image.

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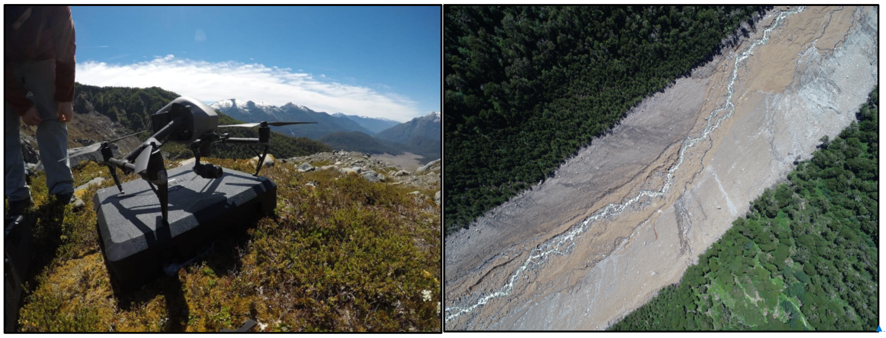

Figure 5: UAV mapping survey

In the study area, we have two freely available DEMs: the Shuttle Radar Topography Mission DEM (SRTM) of 30 meters resolution and the ALOS-PALSAR DEM of 12.5 meters spatial resolution. Alganci et al. (2018) and Caglar et al. (2018) compare these two DEM and other global products concluding that ALOS-PALSAR has fewer errors. Therefore, we used it for numerical simulation. We resampled the resolution of ALOS PALSAR to 30 meters to speed up the simulations.

3.1.1 Geotechnical Sampling

It was not possible to carry out the extraction of unaltered geotechnical samples from the upper part, mainly due to the 5 kilometers of steep terrain, including a section that needed to be climbed to transport the material by foot. However, we extracted soil samples in the middle-low part of the first section of the flow (Figure 6). The geotechnical soil sample represents the material added to the mudflow during the event. Therefore, the soil properties become relevant to reproduce the mudflow flow of Villa Santa Lucía.

The tests performed to determine the geotechnical properties of the primary materials were: direct shear test, unconfined compression, density, and soil classification following the American Society of Testing Materials ASTM D3080 (ASTM, 2017a). The parameters obtained in each laboratory test will serve as constraints for the numerical modeling of the mudflow of Villa Santa Lucía.

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The tests performed to determine the geotechnical properties of the primary materials were: direct shear test, unconfined compression, density, and soil classification. The parameters obtained in each laboratory test will serve as constrains for the numerical modeling of the hyper-concentrated flow of Villa Santa Lucía.¶
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Figure 6: Extraction of an undisturbed soil sample

For the soil moisture, a wet portion of the soil was extracted and allowed to dry in an oven at 60°C for two days. Following, we estimated mass soil water content (by weight) using the relation 1.96 g_{water}/g_{solid}

Then, a fraction of the soil sample was covered with paraffin to seal all pores and thus determine its density through the submerged weight difference. The wet soil density was 1.24 grams per cm^3, and the dry soil's apparent density was 0.419 grams per cm^3 — the specific weight Gs=2.65 gr. Therefore, the void ratio was 5.324. Using these values, it turned out that the soil porosity was 84.18%, and the water saturation of the soil sample 97.4%; therefore, 81.95% of the total unaltered soil volume corresponded to water.

Then a direct shear test was performed in three probes. Each probe was loaded with 2, 4, and 8 kg, respectively, allowing them to consolidate for 24 hours. We recorded the deformations versus time in the first sample to determine the speed for the direct shear test using the square root scale method (Table 1).

Table 1: Direct shear test results

Square root scale method	
t_{90} [min]	1.44
Conversion factor from t_{90} to t_{50} [min]	0.34
Total time estimated [mm]	16.70
Displacement estimated [mm]	10.00
Displacement rate obtained [mm/min]	0.599
Displacement rate to use [mm/min]	0.5

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Finally, we estimated a cohesion value of 22.5 kPa and an internal friction angle of 23.8°.

3.1.2 Soil Classification

In order to carry out the classification of the soil, we used two tests. First, we determined the soil granulometry using the American Society of Testing Materials ASTM D2487 (ASTM, 2017a), and then we determined soil consistency limits (liquid and plastic) using the American Society of Testing Materials ASTM D4318-17e1 (ASTM, 2017b). For the granulometry, Table 2 shows what percentages pass through the different sieve sizes. We omitted the larger sieves since 100% of the material passed through them.

Table 2: Percentage that passes through sieves

Sieve size	Percentage that passes
Sieves 4.75 mm	100
Sieves 2.0 mm	99
Sieves 0.425 mm	96
Sieves 0.075 mm	73

Finally, the liquid and plastic limits of the soil are 50% and 27%, respectively. According to the USCS classification, the soil corresponds to a CH, an inorganic clay of high plasticity, whereas for the AASHTO classification, it is considered to be clay.

3.2 Numerical Modeling

The modeling of the mudflow was carried out using two pieces of software: r.avaflow and Flo-2D, which we describe below. According to the antecedents of the event, the landslide fell on the intrusive formation. A fraction of the material stayed deposited between the glacier and the intrusive formation. The difference (about five million cubic meters of sediment) continued downstream, initiating the scouring process and mudflow that led to the Santa Lucia event. Therefore, the domain of the models starts at the base of the intrusive formation with an initial volume of 5,000,000 cubic meters.

3.2.1 R Avaflow

R.avaflow is an open-source model that offers a practical, innovative and unified solution to simulate granular and debris flows produced in high mountains around the world. The model can handle rapid mass flows, including

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avalanches and two-phase flows (Mergili, M., Pudasaini, 2019). R.avaflow calculates the propagation of mass flows from one or more given release areas on a defined baseline topography until (I) all material has been stopped and deposited; (II) all the material has left the area of interest; or (III) the maximum simulation time has been reached. R.avaflow is developed in two formats for its environment and operation, r.avaflow expert and r.avaflow professional. The latter is an autonomous version with reduced functionalities. It operates through a graphical user interface (GUI). ~~In this study,~~ we used the professional version (Mergili et al., 2017). This model represents a complete open-source computational framework based on a geographic information system (GIS) that offers a two-phase flow model. The entraiment of material along the flow path was also considered. These characteristics facilitate the simulation of complex mass flows, as well as chained processes and interactions.

For the propagation of the flow, we used the Pudasaini model (Pudasaini, 2012), which is a two-phase mass flow model. Solids and fluids materials can be dragged from the bottom and incorporated into the flow. The r.avaflow output consists mostly of raster maps of solid and fluid flow heights, velocities, pressures, kinetic energies and scoured heights.

3.2.2 Flo2D

Flo-2D is a two-dimensional finite differences model (FLO-2D, 2018; O'Brien and Zhao, 2004) that simulate non-Newtonian flow. The model creates simulations in complex topographies, urbanized areas and floodplains, allowing fluid exchange between the channels and the floodplain. It can model water flows, hyper-concentrated sediment flows and mudflows (FLO-2D, 2018; O'Brien and Zhao, 2004). The input data required are a digital topography of the land, the geometry of the channel, estimated values of the channel roughness and the flood plain, liquids and solids inputs, precipitation and rheological properties of the water-sediment mixture. The software calculates the surface flow in eight directions, considering the conservation of the mass. It uses a variable time step by increasing and decreasing the scheme that incorporates efficient numerical stability criteria (FLO-2D, 2018). The rheological model used in FLO-2D is based on the work of (Julien and Lan, 2007; O'Brien et al., 1993; O'Brien and Julien, 1988), which describes the dynamic viscosity and the shear stress of the mixture as an exponential function of the sediment content (FLO-2D, 2018).

3.2.3 Model calibration

For the calibration of the models we used a trial and error aproach seeking too match the following three pieces of data availablse from Sernagomin: (1) Inundated area, which was mapped after the event using aerial imagery (SAF,

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2017); (2) Flow heights estimated by Sernageomin in Villa Santa Lucía and at the beginning of the canyon; and (3) Flow velocities in the canyon curve and at the beginning of Villa Santa Lucia (Figure 7). See Table 3 for the values.

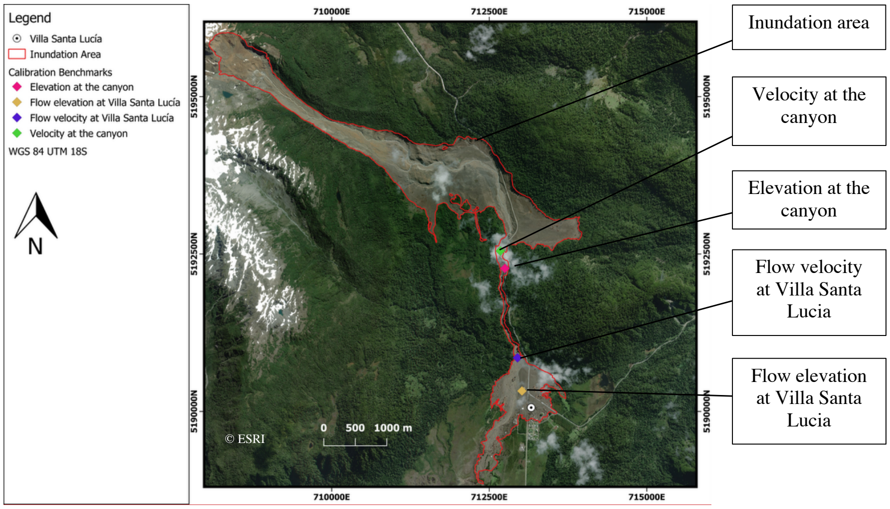

Figure 7: Location of the parameter estimation for the calibration of the models (Background © ESRI)

Table 3: Parameter for the calibration

Parameters	Magnitude	Units
Inundation area	4,926,533	m^2
Elevation at the canyon	20	m
Flow elevation at Villa Santa Lucia	2	m
Velocity at the canyon	20	$m\,s^{-1}$
Flow velocity at Villa Santa Lucia	21	$m\,s^{-1}$

To define the model that best adjusts to the Sernageomin's estimations, we calculated the standard deviation from the modeling results and the parameters from Table 3. The parameterization of the model with less standard deviation is considered the best parameterization for the particular software used.

4 Results

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4.1 R.Avaflow

To simplify the calibration, we divided the process into two. First, we set the sediment concentration by volume of the mudflow in 50% and change the entrainment coefficient, basal friction angle, ambient drag coefficient and fluid friction coefficient. For the description of the parameters in r.avaflow see Mergili et al. (2017). Table 4 shows the first set of parameters used.

Table 4: Initial parameters for the r.avaflow simulations

Solid density $[g/cm^3]$	2.400	Terminal Velocity	1
Liquid density $[g/cm^3]$	1.000	Contribution parameter S-L drag resistance	0.500
Virtual mass	0.500	Fluid friction coefficient	0.002
Hydrograph	No	Output writing time (s)	10
Diffusion control	Yes	Internal friction angle	24
Conservation of volume	Yes	Particle Reynolds number	1
Surface control	Yes	Exponent for drag	1
Viscous shear coefficient of the fluid	0	Quasi Reynolds Number	$10^{4.5}$
Solids concentration distribution with depth	0	Mobility Number	10^3

The best set of parameters is $10^{-5.75}$, 2, 0.022 and. 0.0005 for the entrainment coefficient, basal friction angle, ambient drag coefficient and fluid friction coefficient, respectively, and the corresponding map result is in Figure 8.

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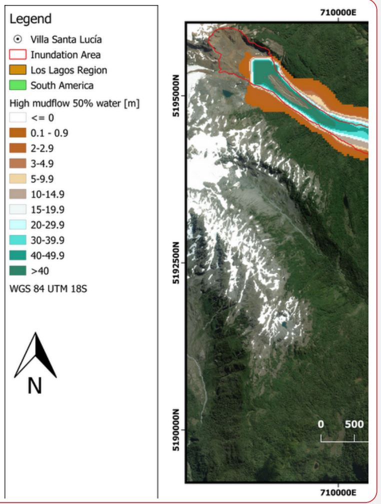

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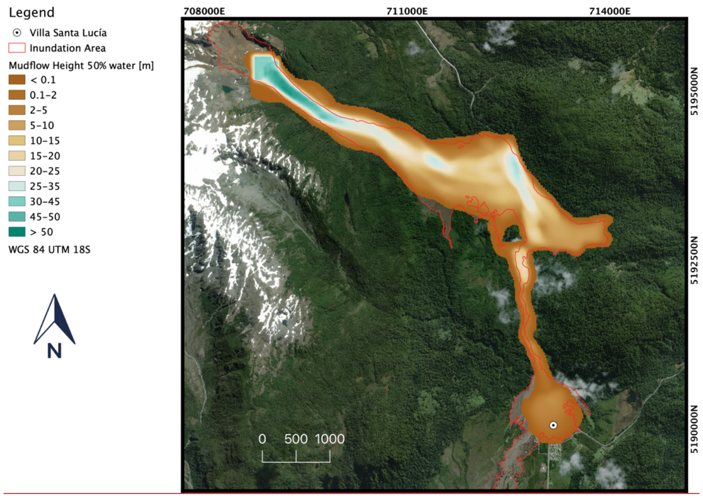

Figure 8: r avaflow model results for a concentration by volume of 50% (Background © ESRI).

Figure 8 shows good agreement with what was reported by (Sernageomin, 2018). However, the mixture is still largely fluidized, and it does not follow the edges of the inundation. For this reason, we performed simulations with the same input parameters but a varying percentage of initial water. We varied the percentage of water between 20% and 70% The error for the heights, speeds calculated in each model are in Figure 9. Therefore, we propose that a mudflow with a 30% water volume could reproduce best the VSL event (Figure 10).

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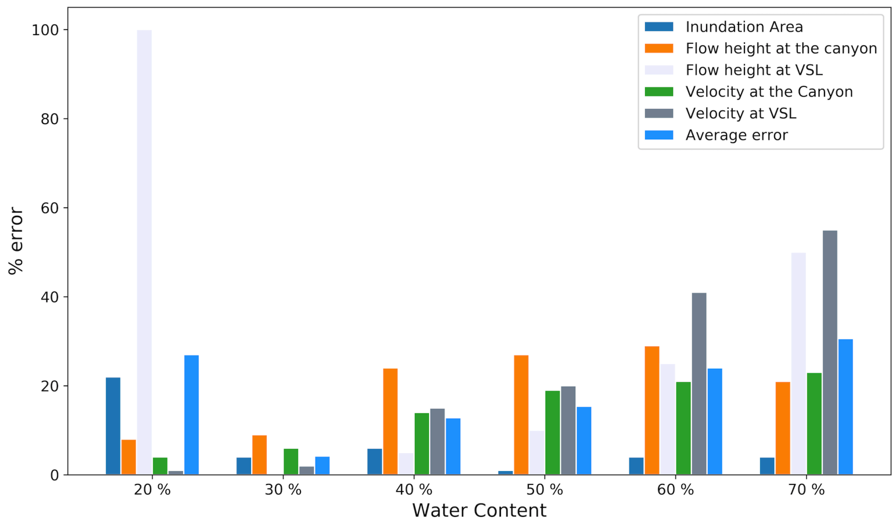
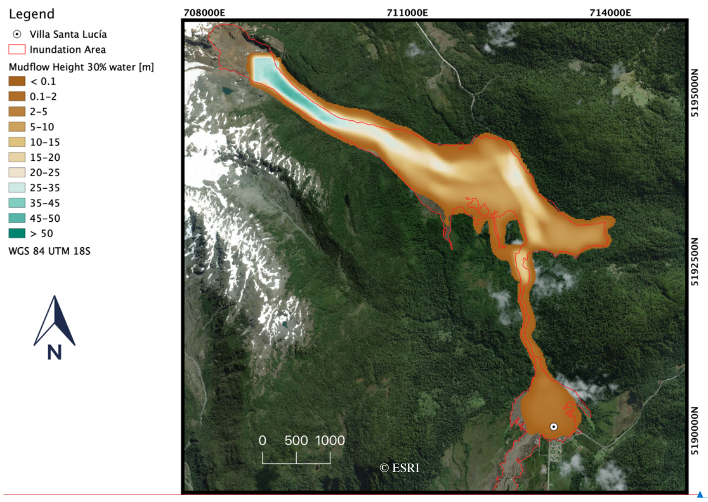
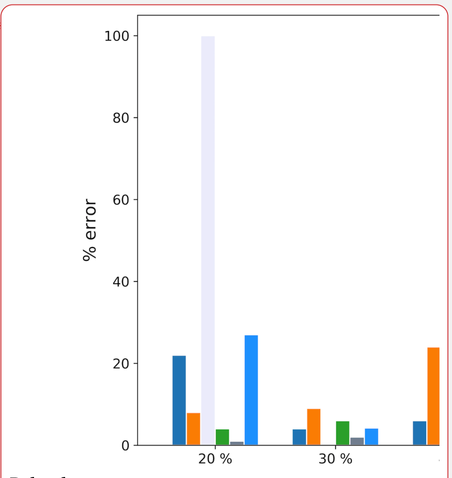


Figure 9: Error obtained with different water content and the best set of parameters obtained in the first calibration.





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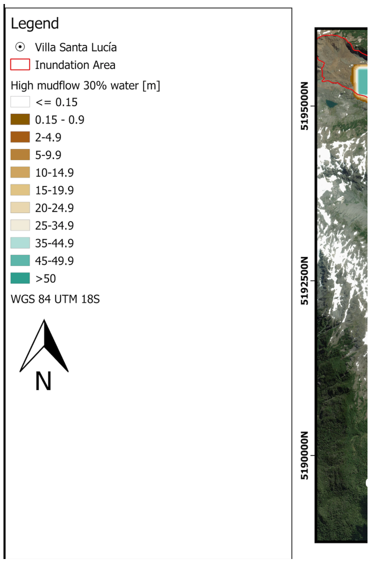

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Figure 10: Simulation results using the calibrated parameters for ravaflow and 30% water content (Background © ESRI)

4.2 Flo2d

The main results from Flo-2D for the mudflow flow in Villa Santa Lucía are presented below. For the laminar resistance k, we used the default number 3000. The influence of the value of *K* does not affect simulations significantly compared to other parameters related to flow resistance (Hsu et al., 2010). The specific gravity of sediments Gs is equal to 2.65 g cm^{-3}. For the sediment concentration by volume, we used values between 40% to 50%, which correspond to mudflow flows. The error for the heights, speeds calculated in each model are in Figure 11. Figure 12 shows the extension of the best model using Flo2D.

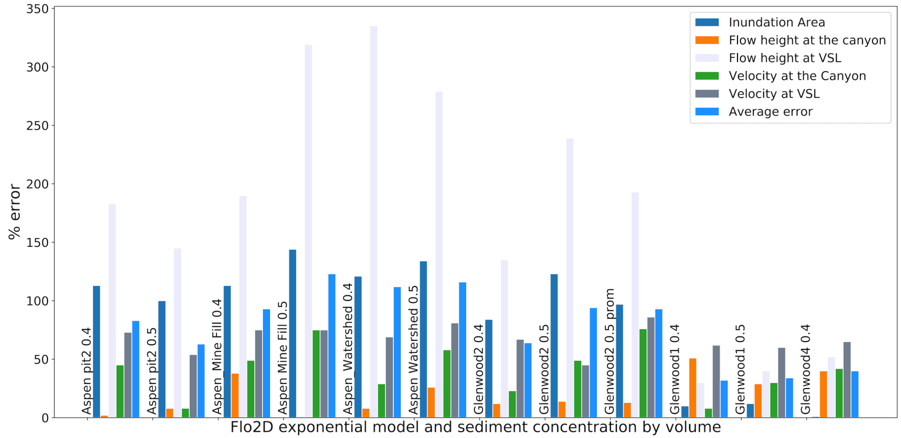

Figure 11: Sensitivity analysis for different dynamic viscosity and shear stress models (FLO-2D, 2018)

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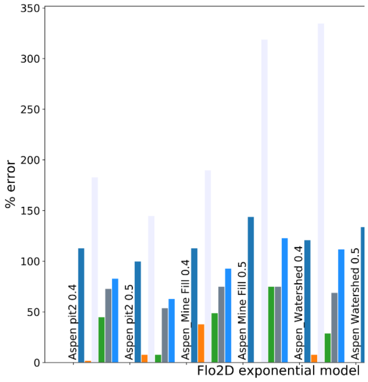

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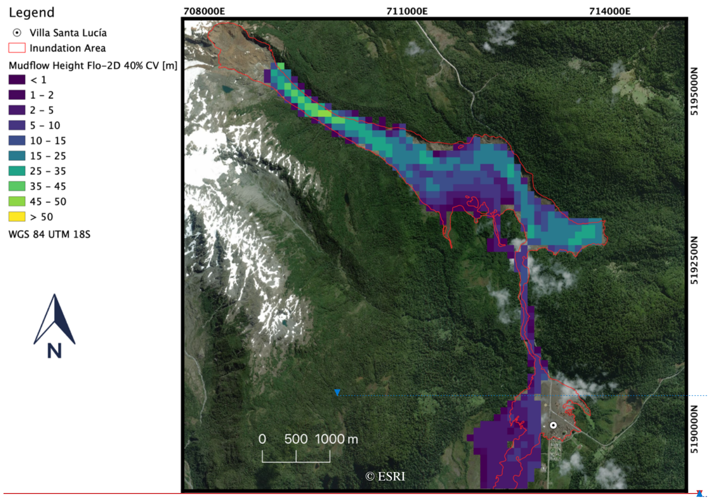

Figure 12: Result for Glenwood 1 using a 40% concentration of water by volume (Background © ESRI)

5 Discussion

5.1 Geotechnical sample

Our geotechnical data shows that soil correspond to clay with high plasticity (CH). The soil has an internal friction angle of 23.8 ° and a cohesion value of 22.5 kPa, characteristic of a consolidated clay. However, the soil extracted had various types of soils and minerals in its composition, which made this a rare soil not described or classified by USCS. For the granulometry, 72% of the soil passed through sieve No. 200. Mainly sand and volcanic soils did not pass sieve No 200. Similar results were founded by Gonzalez-Pulgar (2012) in volcanic soils that have an internal soil friction angle of 25° and a cohesion value of 2.9 kPa. Moreover, our results were consistent with their high soil water content, greater than 150%, and a very low dry density of solids with values between 0.4 and 0.7 kg cm^{-3}. The values obtained by (Gonzalez-Pulgar, 2012) are comparable to the results of this study.

The results of the dry density and natural moisture determination tests help to ascertain the natural state of the unaltered soil sample obtained in the mudflow zone of Villa Santa Lucía. Additionally, these tests help to calculate intrinsic soil parameters, such as the relative density of solid particles (2.65 g cm^{-3}), the void ratio, the degree of saturation and porosity. The humidity estimated under ASTM D2216-19 (ASTM, 2019) showed a value of 195.85% and a dry soil density of 48.1 kPa. The soil saturation was 97.4%. Therefore, 81.58% of the soil volume was water.

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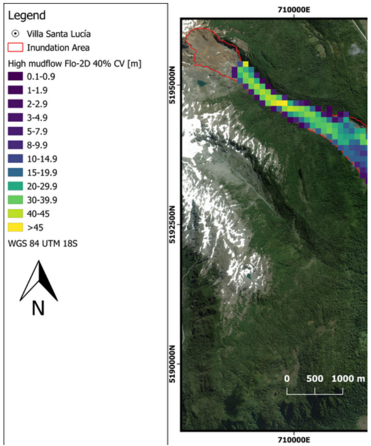

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The previous result is relevant because the liquid and plastic limits are 50 and 27%, respectively. These parameters indicate if the soil has a more liquid or plastic behavior, given the moisture content. Also, incorporating the moisture of the soil sample of 195.85%, the liquidity index was determined at a value of 7. When the liquid index is higher than one, and the soil is subjected to cutting, it has a viscous liquid behavior. Such soils can be susceptible to the collapse of the soil structure. As long as they are not altered, they can be relatively stable, but if these soils are subjected to shearing (molding), and the soil structure collapses, then they can easily flow like a viscous liquid (Holtz and Kovacs, 1981). These results show that the area downstream of the collapsed wall was prone to producing a mudflow due to the high water content and the perturbation produced by the mudflow mobilized the soil bed producing the mudflow flow that affected Villa Santa Lucía.

5.2 Back-calculation of the mudflow

The modeling in the r.avaflow software successfully reproduced the budflow flow of Villa Santa Lucía. The model was able to reproduce the area affected, reference heights and speeds during the back calculations. Moreover, our results were highly consistent with in-situ measurements two days later of the event (Sernageomin, 2018). We ran three hundred simulations to calibrate the model. We determined that the general ambient drag coefficient is the most sensitive of all since even a change of a decimal in the coefficient changed the viscosity of the flow, reducing or exaggerating the runout. The sensitivity analysis showed that r.avaflow is also sensitive to changes in the basal friction angle. These strongly condition the rheology of the flow, determining the height and speeds. The results obtained in the modeling in the FLO-2D software were diverse. We could not achieve the same level of r.avaflow's results. The inundation area was the most sensitive result in the concentration of sediments by volume and the rheology model (Figure 11). The best combination of parameters was the Glenwood 1 rheology model and a 40 % concentration sediment, which has an error of 32%. We concluded that we could reproduce the mudflow satisfactorily using r.avaflow with water content in the mixture ranging from 30 to 40 % (Figure 11).

For the calibration, we calculated the standard deviation from the modeling results and the parameters from Table 3. The parameter combination that results in less standard deviation is considered the best parameterization for the particular software used. Our procedure, as described in Saltelli and Annoni (2010), corresponds to a one-factor-at-a-time type of calibration where we changed one parameter at a time manually, trying to match Table 3. The limitations of this procedure, according to Saltelli and Annoni (2010), are: Its efficiency is poor. The method does not capture the interaction of the factors because that would require the movement of more than one element at a time. Therefore, the

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approach assumed that all the variables are independent, and the processes are linear, which is not usually the case. Another limitation of our calibration is the potential presence of equifinality. We did not test if different combinations of parameters would provide similar performance. We selected one best combination of parameters without checking the degrees of freedom that these variables may have had to replicate the observations (Beven, 1996).

5.3 Source of water

From the observation and information provided by Sernageomin, our soil samples analyses and numerical simulation, we found that the primary source of water was in the soil. Our analyses determined that in the area scoured, the soil has a porosity of 84.18%. Similar values were reported by Cuevas et al. (2013) in volcanic soils in the south of Chile. From our observations, we also notice the ground is saturated all the time. We did fieldwork after a couple of weeks of no rain, and the whole area around the river was saturated; indeed, our soil sample had a saturation of 97.4%. Therefore, using the results from r.avaflow, we estimated that a volume of 3.402.100 m^3 was scoured. Consequently, there was the potential of adding roughly 2.8 million m^3 of water and 600,000 m^3 of soils, which evolved to a mudflow due to the water added to the event. Additionally, extra water was added, not quantified in this study, from the ice pieces detached from the glacier and carried by the landslide first and the mudflow later.

Our results highlight the importance of considering the potential chain of events in risk analysis and hazard mapping. In the practice of predicting a mudflow hazard, we seek areas where evident water sources are available such as glacial lakes. However, in this work, we showed that it is possible to have the catastrophic event that hit Villa Santa Lucia only with the water within the soil in the valleys downstream of the landslide. Additionally, the soil has a particular volcanic origin, and it is highly fluidizable under low lateral effort. This result is relevant for the Patagonia region because, in order to update the hazard maps, we need to consider not only the primary events but also the potential reactions from the downstream elements of the chain of events, which as in this case, may not be evident prior to the event.

What actually triggered the landslide event is not clear and not part of this research. We focused on what conditions in the valley enabled the landslide to evolve into a mudflow and traveled all the way to Villa Santa Lucia. We have no information to guess how much water was available at the glacier terminal so we wanted to understand if this event was possible without a lake or large water reservoir at the glacier. Our results show that in fact the water available around the Burritos River was sufficient to transform the avalanche into a mudflow. Our numerical models and geotechnical work show that the mudflow event was possible due to pre-existing water in the saturated soil.

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Geotechnical evidence demonstrates a high plasticity soil (CH) with a low internal friction angle associated with volcanic soils of the Holocene age. Hence, weak soils are prone to mass wasting events due to their geomechanical properties.

6 Conclusions

Given the complexity and the potential increase in the future of extreme event occurrence that can trigger landslides, we suggest that hazard studies should consider the structural conditions present in the area of influence of the mudflows. Soil characteristics ought to be included because they may be a crucial factor amplifying the impacts of local events triggered by hydroclimatic events. Such was the case of Villa Santa Lucia, where the water necessary to fluidize the mudflow mixture was in the soil in a volatile system that was easy to mobilize.

The combination of geotechnical tests and r.avaflow, which is a freely available computational software, to model mudflow are useful tools to characterize and reproduce mass wasting events, such as the mudflow occurred on December 2017 in Villa Santa Lucia in Chile. Our results present the possibility of open-source software implementation to represent mudflow events in the Patagonian Andes with a good performance. These types of studies will allow for the integration of better methodologies to enhance risk scenarios related to mudflow events in active subduction zones like the Andes.

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