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A semi-quantitative risk assessment of debris flow in northernmost Patagonia, Argentina

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ABSTRACT

Debris flows cause human losses and material damages in many countries around the world. The associated risk often remains unknown because of uncertainties and the lack of data. This paper presents a semi-quantitative risk assessment of debris flow based on a Risk Matrix Approach to overcome that limitation. Three risk levels were defined through hazard and vulnerability analysis. Hazard scenarios were modeled in Flow path assessment of gravitational hazards at a regional scale (Flow-R). Vulnerability was analyzed and defined according to the physical characteristics of the elements-at-risk. The Huaraco and Huinganco basins, in the north of Patagonia, were selected for detailed analysis based on the frequency and consequences of the debris flows that occurred from the 19th to the 21st centuries, which had recurrence intervals between 30 and 56 years. A detailed study of the 8 February 2013 episode revealed extremely high flow velocities and peak discharges that carried huge boulders and produced extensive damage. The risk assessment determined that under present conditions 38 people might be severely affected by landslides in the high magnitude scenario, with losses up to 5.2 million USD due to the destruction of roads, bridges, and buildings by debris.

Keywords: Andacollo, Huinganco, debris flow, Risk Matrix Approach, Flow-R.

RESUMEN

Evaluación semicuantitativa de riesgo de flujo de detritos en el extremo norte de la Patagonia Argentina.
Los flujos de detritos causan pérdidas humanas y daños materiales en muchos países alrededor del mundo. El riesgo asociado a menudo permanece desconocido debido a las incertidumbres y la falta de datos. Este estudio presenta una evaluación semicuantitativa de riesgo de flujo de detritos basada en un Enfoque de Matriz de Riesgo para superar esa limitación. Se definieron tres niveles de riesgo a través del análisis de amenazas y vulnerabilidad. Los escenarios de amenaza se modelaron en *Flow path assessment of gravitational hazards at a regional scale* (Flow-R). Se analizó la vulnerabilidad y se la definió en función de las características físicas de los elementos en riesgo. Las cuencas de Huaraco y Huinganco, en el norte de la Patagonia, se seleccionaron para un análisis detallado con base en la frecuencia y consecuencias de los flujos de detritos ocurridos entre los siglos XIX y XXI, que presentaron intervalos de recurrencia entre 30 y 56 años. Un estudio detallado del episodio del 8 de febrero de 2013 reveló velocidades de flujo y picos de descarga extremadamente altos, que arrastraron enormes rocas y produjeron daños significativos. La evaluación de riesgos determinó que, en las condiciones actuales, 38 personas podrían verse gravemente afectadas por futuros deslizamientos en el escenario de alta magnitud, con pérdidas de hasta 5.2 millones de dólares, debido a la destrucción de carreteras, puentes y edificios por los detritos.

Palabras clave: Andacollo, Huinganco, flujo de detritos, Enfoque de Matriz de Riesgo, Flow-R.

INTRODUCTION

Some of the most devastating landslides have been associated with debris flows (Jakob and Holm 2012), which cause great socio-economic losses and casualties in human settlements located close to mountain regions around the world. A poor understanding of debris flow dynamics, frequency, and magnitude increases the associated risk, especially in view of the positive trend in urban population expected for the next decades (United Nations 2019) and the growing proximity of urban centers to natural hazard-prone areas.

Several methods ranging from quantitative to qualitative approaches have been developed to study the risk of natural hazards, such as debris flows (van Westen 2018). As fully numerical estimations are not always possible to apply due to information unavailability or a high degree of uncertainty, semi-quantitative Risk Matrix Approaches (RMA) can be applied instead (van Westen and Greiving 2017). This approach has been used in debris flow studies around the world, e.g., by Arksey and VanDine (2008) in Canada, Chou and Lee (2014) in Taiwan, Blahut et al. (2014) in Italy, and Frey et al. (2016) in Peru, among others. Those studies revealed a high research potential in the RMA field, which allows the development of a wide spectrum of approaching strategies and different scales of analysis.

Landslides and particularly debris flows are a common feature along the Argentine-Chilean Andes range, which runs from north to south over 3700 km. Such distance and the harsh environmental and topographic characteristics (with altitudes reaching almost 7000 m a.s.l.) make it very difficult to establish and maintain a monitoring network. Even under such complex conditions, several studies have been published about debris flows that occurred close to inhabited areas. In Jujuy province, north of Argentina, Gonzalez et al. (2008, 2009) studied the debris flows events occurred in March 2007 in the Chalala and Coquena basins supported by fieldwork information and satellite images; Savi et al. (2016) analyzed the surface processes and climate conditions linked to debris flows in Del Medio fan through dating techniques; and Esper Angillieri et al. (2020) presented a spatial and temporal analysis of debris flow occurrence in three adjacent basins of Quebrada de Humahuaca using topographical data, satellite imagery, as well as report- and fieldwork-derived information. In Salta province, Jaime et al. (2007) performed debris flow simulations in the Iruya river using FLO-2D models; Gonzalez and Sánchez (2012) characterized the 2011-debris flow episode in the Las Rosas river based on remote sensing and fieldwork data; and Fernandez (2017) analyzed the susceptibility to landslides, including debris flows, in the Argentine Puna through computational modeling. In Tucumán province, Fernández (2009) studied the different types, characteristics, and distribution of 279 landslides —including debris flows— using aerial and satellite images and field controls in a GIS environment.

In the Argentine province of Catamarca, Esper Angillieri et al. (2017) made a joint analysis of debris flows and flash floods in El Rodeo village during an episode occurred in January 2014 through morphometric parameters; and Fernández et al. (2021) analyzed a debris flow occurred in 2014 in Ambato Range based on rainfall data, digital elevation models, and field campaigns. In San Juan province, Esper Angillieri (2014) evaluated debris flow susceptibility through GIS statistics; Lauro et al. (2017) analyzed a summer rainstorm associated with debris flows next to Agua Negra international crossing, based on meteorological data, satellite images, and fieldwork; and Esper Angillieri (2020) obtained susceptibility maps in a section of route N°150 applying statistical modeling techniques on satellite information.

In the province of Mendoza, Moreiras (2006) studied the frequency and temporal distribution of debris flows and rockfalls that occurred along the valley of the Mendoza river from 1952 to 2002. Susceptibility and risk assessments, case study analyses, and simulations of debris flows were made across Mendoza from east to west, using satellite images, maps, rainfall measurements, historical information, local resident surveys, fieldwork, models, and Geographic Information System (GIS) (Wick et al. 2010, Baumann et al. 2011, Mergili et al. 2012, Páez et al. 2013). Field campaigns and meteorological records were used by Sepúlveda et al. (2015) to evaluate the characteristics and consequences of rainfall-induced landslides —debris flows and avalanches, and rockfalls— that occurred in the central Andes of Chile and Argentina in 2013. Alvarez et al. (2019) analyzed debris flow susceptibility in the Aconcagua Provincial Park using a physical model and statistical methods; and Moreiras et al. (2021) studied debris flow occurrence in the semiarid central Andes under climate change scenarios considering local reports, satellite data, and weather stations.

On the contrary, debris flow research in northernmost Patagonia is limited to the study by Hurley et al. (2020) of debris flow deposits in the area of the Domuyo Volcanic System through fieldwork and remote sensing. Specifically, the threats of debris flow to the inhabitants of the Huaraco and Huinganco basins in Neuquén province were first addressed by Hoeffler (1946) and Paesa (1964). Debris flows were later mentioned in the land-use planning of Andacollo and Huinganco urban centers (Baumann and Boujon 2011). Other reports and interviews focused on different aspects of the debris flow episode of 8 February 2013, such as its geological and sedimentary characteristics (Garrido 2013), major consequences (Tejedo and Gomá 2016), and government actions (Groch 2019).

Considering the potential implications of debris flows on the human environment, research naturally leads to the field of risk analysis. Consequently, this paper aims at developing a risk assessment of debris flows using a modified version of the RMA (van Westen and Greiving 2017) that makes it possible to overcome the limited availability of quantitative data. Considering the frequency and consequences of debris-flows, the Huaraco and Huinganco basins in northernmost Patagonia were selected as a case study. This paper presents here a new semi-quantitative approach strongly based on fieldwork and remote sensing that allows estimating casualties and material damages at different risk levels. This is particularly relevant to many areas over the world where quantitative methods are extremely difficult or even impossible to apply and numerical approaches are required. Mountain-region communities would benefit from this approach, given the importance of defining risk in areas where people might be dependent of assets such as bridges, roads, and lifelines.

STUDY AREA

The analysis was carried out in the Huaraco and Huinganco basins (24.5 km² and 17.2 km², respectively) in the northern extreme of Patagonia, Argentina (Fig. 1). Specifically, the study area is placed on the southwestern slope of the Cordillera del Viento, with altitudes ranging from 1024 to 2892 m a.s.l.. It includes the towns of Andacollo and Huinganco which are two of the most important and dynamic urban centers in the region with 2754 and 1162 inhabitants, respectively (Dirección Provincial de Estadística y Censos 2020).

Lithological inhomogeneities and structural guidelines of the Huaraco and Huinganco basins favored the development of established paths, as a necessary factor for the periodical occurrence of debris flows (Rovere et al. 2004, Hungr et al. 2014). This setting combined with the geology, geomorphology, topography, earthquakes, and meteorology of the region, among others, controls the occurrence of debris flows (Corominas et al. 2013).

The geomorphological scheme in the study area was developed by exogenous and endogenous processes acting on several geological units that include rocks from the Carboniferous in the West at low altitudes (6.3 km²), the Permian in the center (14.8 km²), and the Triassic in the East at high altitudes (10.0 km²) (Rovere et al. 2004). The two latter periods —i.e., 54.4 % of the study area— represent the source areas for debris flows and are composed of ignimbrites, gaps, andesites, rhyolites, granite, and granodiorites (Coppolecchia et al. 2010). Finally, glacial and fluvial Quaternary deposits have spread in the basins (10.6 km²), mainly in the form of blocks, gravels, sands, ashes, and conglomerates (Coppolecchia et al. 2010).

Seismic hazard in the region is moderate with maximum ground accelerations of 0.15 g according to National Institute for Seismic Prevention (Instituto Nacional de Prevención Sísmica 2022). Seismicity might be associated with tectonism and/or volcanism, given that the area under study is close to the subduction region of the Nazca Plate beneath the South American Plate and to eleven active volcanoes/volcanic complexes in a radius of 150 km (Servicio Nacional de Geología y Minería 2020, Instituto Geográfico Nacional 2021).

The drainage network has developed on areas of structural weakness —i.e., regional lithological inhomogeneities and structural guidelines— to current conditions (Rovere et al. 2004). The main perennial rivers, Huaraco and Huinganco, present dendritic design and flow from the top of Cordillera del Viento to the Neuquén river (Fig. 1). The climate in the area is associated with the passage of air masses from the Pacific Ocean that cause orographic precipitation in the Andes. Snowfall is the dominating precipitation in the Cordillera del Viento from winter to mid-spring when snowmelt begins and contributes to recharging rivers and wetlands during the summer.

The main traditional economic activities in the study area are forestry, mining, livestock farming, and tourism (Rivas 2011). According to Conejeros Bilbao (2019), the impacts of these anthropic activities could combine with natural drivers (fluvial and wind erosion) to cause landslides, soil degradation, and desertification. Nowadays, the area is experiencing a positive trend in tourism throughout the year, though mainly in summer, largely because of its natural beauty and local festivities (Finessi and Groch 2018). For instance, 4000 tourists visited Huinganco in 2011 (Rivas 2011), which is 3.9 times that year's local population. Changes in population should be considered in future risk assessments as well as in mitigation and urban planning.

METHODOLOGY

This paper presents a risk assessment of debris flow in the Huaraco and Huinganco basins. The risk was estimated con-

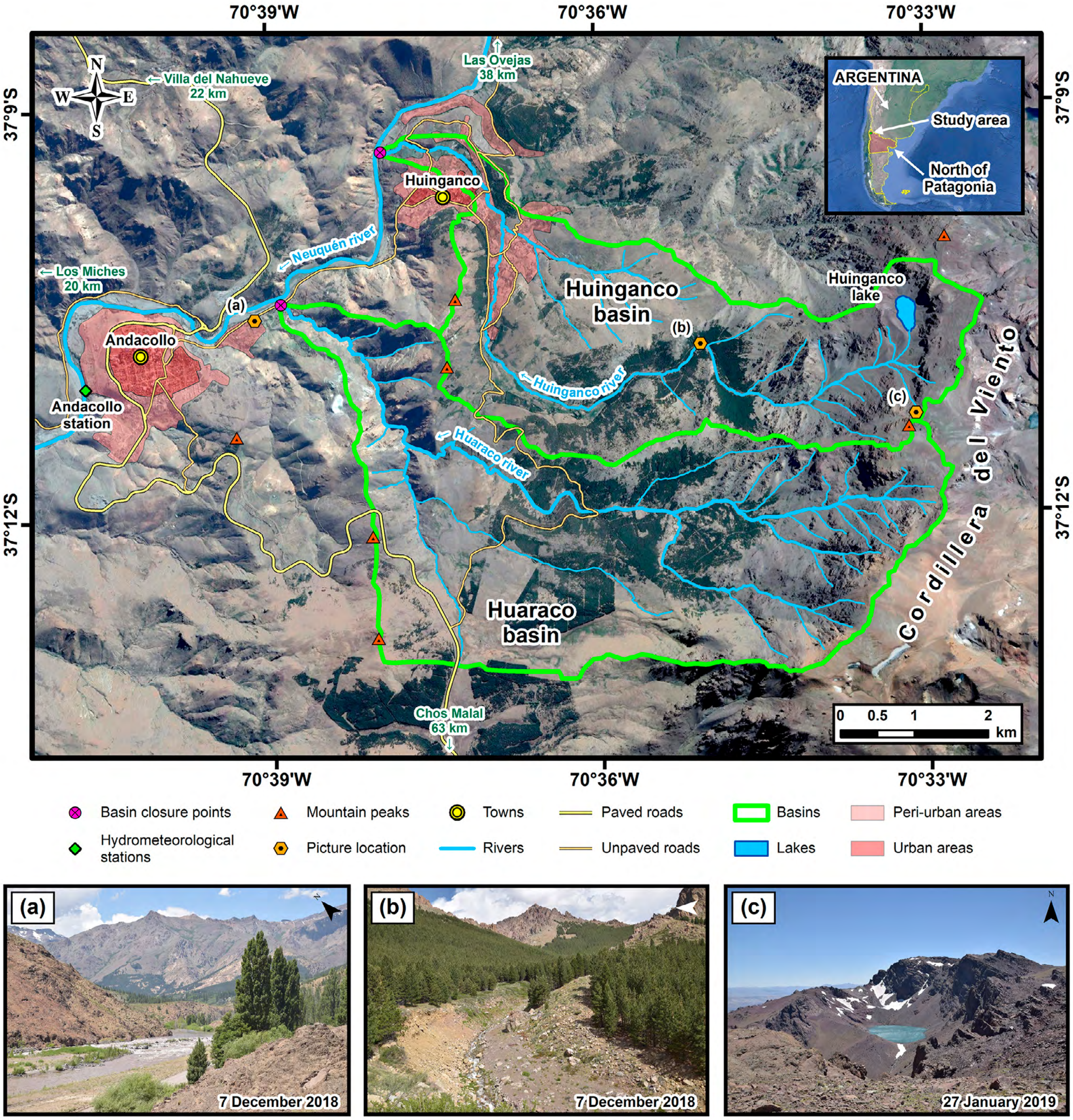


Figure 1. Location of the Huaraco and Huinganco basins and drainage networks: a) low altitude: deposits of the debris flow fan generated on 8 February 2013 at the confluence of the Huaraco and Neuquén rivers; b) medium altitude: curve section of the Huinganco river where erosion predominated during the episode; c) high altitude: cirque glacier and material dragged from the surroundings of Huinganco lake located near the top of Cordillera del Viento. Base satellite image: Google Earth Pro ©, dated 01 February 2017; urban and peri-urban area limits based on Rivas (2010).

sidering a semi-quantitative approach through a Risk Matrix Approach (RMA), using the modified version proposed by van Westen and Greiving (2017) and contained in Eq. (1):

$$Risk = H_{(I)} \times P_{(L/I)} \times V_{(Es/I)} \times A_{(Es)} \quad (1),$$

where: $H_{(I)}$ is the frequency of a specific hazard scenario of intensity *I*; $P_{(L/I)}$ is the locational or spatial probability of occurrence of a specific hazard scenario of intensity *I* impacting the elements-at-risk; $V_{(Es/I)}$ is the physical vulnerability, specified as the degree of damage to a specific element-at-risk E_s given the local intensity *I* caused due to the occurrence of a specific hazard scenario; and $A_{(Es)}$ is the quantification of the specific type of element-at-risk evaluated. Each component was obtained from the considerations detailed below. The procedure is displayed in the simplified flowchart of figure 2.

Hazard component

The analysis of hazards involved a literature review, the interpretation of the physical characteristics of the basins through existing cartography: geological (Rovere et al. 2004, Coppolecchia et al. 2010), geomorphological (Tchilinguirián 2010), and land use (Rivas 2010), with scales from 1:15000 to 1:250000, as well as fieldwork carried out between 2013 and 2020. The information collected allowed to establish the type of material associated with the debris flows and its origin. These data, along with satellite images and in-person interviews with local inhabitants provided the basic inputs for GIS processing in ArcGIS 10.1 and QGIS 3.8. The open and semi-structured interviews provided the dates, frequency, and magnitudes of debris flows. They also helped identifying the location of the starting points, triggering mechanisms, and affected areas, as well as the atmospheric conditions present during the episodes. This information made it possible to complement missing, scarce or with insufficient spatio-temporal resolution data, and allowed making reasonable assumptions such as the potential triggers of future episodes and modelling.

To gain insight into the characteristics of pre-existing valleys and the lake associated to debris flows, the longitudinal profiles and bed slopes of rivers and the lake in the Huaraco and Huinganco basins were mapped using Google Earth Pro

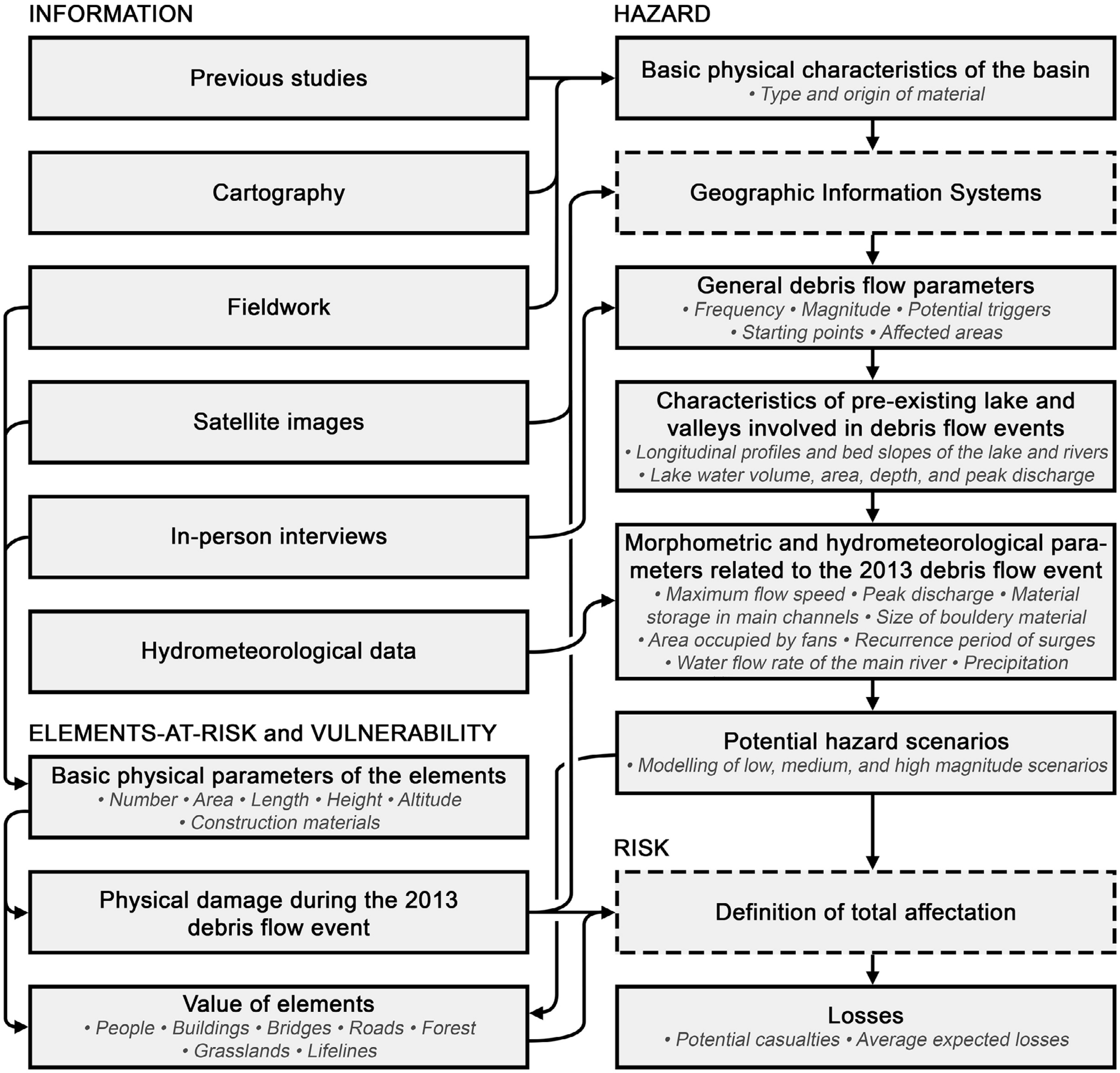


Figure 2. Simplified flowchart of the Risk Matrix Approach (RMA) used in this research.

images from 2006 to 2019 with ≈ 0.5 m spatial resolution (DigitalGlobe © and Airbus ©). Altitudinal levels were extracted from the Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM) with 1 arc-second spatial resolution (≈ 30 m), provided by the United States Geological Survey (USGS).

Considering that Huinganco lake (Fig. 1.c) might be a potential trigger for debris flows, the main characteristic parameters of the lake were determined. The peak discharge of the lake in case of total breach was estimated with Froehlich's model using the maximum water volume at the time of outburst and the depth of water above the breach invert at the time of failure (Froehlich 1995). The water volume was estimated considering the lake area, by means of the three empirical relationships proposed by Huggel et al. (2002), Loriaux and Casassa (2013), and Iribarren Anacona et al. (2014). The mean water depth was obtained from the width of the lake using the linear relationship proposed by Muñoz et al. (2020). These measurements were done indirectly because of limited budget.

The 8 February 2013 episode was analyzed to better understand debris flow´s physical characteristics and dynamics. Specifically, three morphometric parameters were measured in the field through cross-section profiles at different points of the main rivers. Maximum flow speeds (v) in super-elevated areas were obtained following Hungr et al. (1984) through Eq. (2):

$$v=((\Delta h \times r \times g \times k)/b)^{0.5} \quad (2),$$

where v is in m/s, Δh is the elevation difference between the two sides of the flow in m, r is the mean curvature radius in m, g is the gravity acceleration in m/s^2, k is a correction coefficient that was assumed to be 1, according to Gonzalez et al. (2009), and b is the surface width of the flow in m. Peak discharges (Q_p) were calculated as the product of the cross-sectional area at the boulder front of the debris flow and the velocity of the flow obtained from Eq. (2). The total material storage (Tms) in the main channels was estimated by calculating the probable accumulations under the cross-sectional profiles multiplied by the accumulation distance to the nearest profile. The potential maximum values of v and Q_p were obtained at points P1 and P2, while Tms was calculated from points P1 to P6, which represent different altitudinal levels (Fig. 4).

Other aspects related to the behavior of the debris flows and basins during the 8 February 2013 episode were also considered. The recurrence period of surges was carefully assessed by analyzing video recordings of the event, while the size of boulder material and the area occupied by debris flow fans were determined in fieldwork and from satellite images. The fluvial and atmospheric conditions during the episode were analyzed using hydrometeorological data of February 2013 obtained from Andacollo hydrometeorological station of the Interjurisdictional Authority of the Basins of the Limay, Neuquén, and Negro rivers (AIC, by its Spanish acronym) and the Real-time Environmental Applications and Display sYstem (READY) of the National Oceanic and Atmospheric Administration (NOAA). Andacollo station provided hourly precipitation and flow rates in the Neuquén river, while READY Global Data Assimilation System (GDAS) provided a 3-hourly and 1-degree spatial grid of cumulative precipitation at the top of Cordillera del Viento (Rolph et al. 2017).

Three hazard scenarios were modeled using Flow path assessment of gravitational hazards at a Regional scale (Flow-R) (Horton et al. 2013) to obtain the propagation extent considering different magnitudes of debris flows in the study area (also identified here as ‘hazard potential’). Flow-R is a spatially distributed empirical model developed under Matlab ®, that can be also useful to analyze natural hazards such as mudflows, floods, and snow avalanches. It has been already implemented successfully in mountain regions of Argentina for the analysis of debris flows by Baumann et al. (2011) and Fernandez (2017). For the analysis of debris flow propagation in this study, source areas and paths were determined from satellite images. Subsequently, flow spreading was simulated considering the parameters and criteria of each scenario, which had been selected from river-bed slopes, field data, and typical values for debris flows according to the academic literature (Table 1). Model scenarios were calibrated with the parameters of the best fit simulation of the debris flow of 8 February 2013 for the medium magnitude scenario (see ‘Hazard’ section in results). Values for the high and low hazard scenarios used in the spreading algorithms and energy calculations were those of the medium scenario ± 33.3 %. Values of the direction algorithm typically oscillate between 4 and 6 (Holmgren 1994), where 6 fitted the medium magnitude and 4 fitted the high magnitude. As flow divergence is reasonably expected to be smaller at a low magnitude scenario (Horton et al. 2013), an exponent of 8 was selected. Weights were set by default based on Gamma (2000). Travel angles were fixed at 2.5° for the three scenarios, similar to the 2–3° used by Sturzenegger et al. (2019) because the maximum simulated runout distance reached by the debris flows was the most realistic. Maximum velocities were set at 15 m/s for the medium scenario according to field measurements, while velocities of 10 m/s and 20 m/s were defined for the low and high magnitude scenarios, respectively, considering the typical debris flow velocities suggested by Arksey and VanDine (2008). Further details related to Flow-R parameters can be found in Horton et al. (2013). Models were supervised and manually

Table 1. Parameters and criteria used in the Flow-R analysis to model three hazard scenarios of debris flows in the Huaraco and Huinganco basins.

Parameters		Criteria	Values for each scenario magnitude		
			Low	Medium	High
Spreading algorithm	Direction algorithm	Holmgren (1994) exponent	8.0	6.0	4.0
	Persistence	Weights	Values based on Gamma (2000)		
Energy calculation	Friction loss function	Threshold of travel angle in degrees	2.5	2.5	2.5
	Energy limitation	Maximum velocity in m/s	10.0	15.0	20.0

adjusted with higher resolution satellite images, especially to overcome limited spatial resolution and correct vertical errors of the DEM over some underrepresented hills, possibly due to the occlusion of the radar signal in mountain sectors. The spatial recurrence of the hazard scenarios allowed generating a unique hazard map, with a three-level classification —from most to less frequent episodes. As a rule, high magnitude hazard was associated with low frequencies and high return periods, and vice-versa.

Elements-at-risk and vulnerability components

The areas within the modeled hazard limits were used to quantify the number of elements-at-risk. Seven elements were selected for this study as the most substantial ones: people, buildings, bridges, roads, forests, grasslands, and lifelines (water and gas pipes, and electricity wires). Vulnerability was considered from a physical point of view. Building occupation rates were estimated from field samples and then extrapolated to the total number of buildings to have an idea of the number of people living —permanently or temporarily— in the area. The number of people in the proximities of risk areas varies hourly, daily, and seasonally, so the number of people affected in the analysis is an estimate. Buildings were identified and built-up areas were then estimated from satellite images; the structural characteristics were examined in the field.

All the bridges in the study area were identified and morphometrically typified to establish their building materials and size parameters (length, height, and cross-sectional area under the deck). The surveys revealed that the low resistance to debris flows of bridges and buildings was independent from whether they were made of wood, steel, and/or concrete. Basic physical parameters for the main routes, forests, grasslands, and lifelines were calculated using satellite images and field observations. The improvements proposed here are mostly based on information about the location and observed resistance of the elements-at-risk damaged in the 2013 debris flow episode. Physical damages reported by locals were inventoried and analyzed using GIS. A first economic estimate was made using the unit value of elements-at-risk in vulnerable areas, to obtain the total price in each hazard magnitude scenario.

Risk estimation

Because of the lack of quantitative information from previous events, the risk was analyzed considering an average of expected losses through percentages of total affectation (i.e., a binary assignment of 0 or 100 % destruction) related to the vulnerable elements in the area. Those estimates take into account different intensities of debris flow over vulnerable elements for each scenario. A better gradation was simply not feasible with the information available. The values of affectation were determined by field observations, reported physical damages, and satellite imagery analysis from past events.

Finally, risk levels of debris flow events were calculated in a risk assessment matrix by multiplying the return periods by the consequence (or destructiveness) on exposed elements (Fig. 3), where yellow, blue, and red represent low, medium, and high risk, respectively. Potential casualties and average expected losses were estimated for each risk level.

RESULTS

Hazard

General characteristics of debris flows: The first-ever regional debris flow reconstruction in the southwestern slopes of Cordillera del Viento identified evidence of multiple events in four adjacent basins occurred since 1887 (Table 2). The recurrence periods estimated from debris flow records were 30 to 56 years, with an annual probability of occurrence between 0.033 and 0.017. Qualitative descriptions of sizes and volumes of debris flow fans were provided in the interviews, which contributed valuable information about past events. As a consequence, three event magnitudes were defined. The medium magnitude was assigned to the events of 1943 and 2013, and the low to the case of 1973/75. The high magnitude

Table 2. Records of dates, magnitudes, and triggering mechanisms of regional debris flows in the southwestern slopes of Cordillera del Viento. The rivers included in this analysis are in bold.

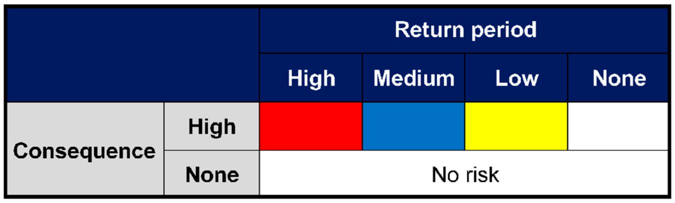
River / date	Winter 1887*	8 December 1943	1973/75*	8 February 2013
El Manzano river	N/A	Confirmed for 1943 and/or 1973/75[1]		Non-occurrence[2]
Huaraco river	N/A	N/A	Confirmed[3]	Confirmed[1, 2, 3, 4, 5]
Huinganco river	Confirmed[6, 7]	Confirmed[3, 6]	Confirmed[1, 3, 5]	Confirmed[1, 2, 3, 4, 5]
Rahueco river	N/A	Confirmed for 1943 and/or 1973/75[1]		Non-occurrence[3, 4]
Magnitude	N/A	Medium[3]	Low[3]	Medium[3]
Triggering mechanism	Rainfall[7]	Rainfall[6]	Rainfall[3]	Rainfall[2, 3, 4, 5]

* Note: Episode dates could not be determined precisely due to limited data availability.
Source of records: [1] Field observation; [2] Satellite images; [3] Interviews; [4] Garrido (2013); [5] Tejedo and Gomá (2016); [6] Hoeffler (1946); [7] Paesa (1964).

category was left for potential future events or past unknown events with a longer recurrence period. All the recorded debris flow episodes were simultaneous with rainfall events.

The material of debris flow episodes originates from ancient glacial and fluvial deposits and recent periglacial physical weathering. A predominance of rock outcrops, crested rocks, and needle ice, among others, was found above 1650 m a.s.l. during fieldwork performed in the higher sectors of both study basins in summer and winter. This altitude would roughly mark the limit of the cryosphere, allowing the yearly creation of material. The origin and paths of recorded debris flows in the Huaraco and Huinganco basins are shown in figure 4, where figures 4a, 4b, and 4c present different channel gradients. In the medium and lower sectors of the basins, fieldwork evidenced the prevalence of chemical weathering, specifically hydrolysis of granitic rocks at different degrees of evolution, in combination with erosion and contribution of natural and anthropic material from the riverbanks to debris flows. Particularly important is the role of trees as reducers of surface runoff and sediment and rock motion into debris flow channels (Fig. 4b). Those trees are 20 m high on average and are found up to 2050–2250 m a.s.l. —i.e., the timberline— (Fig. 4). Above that altitude, the lack of tree cover is noticeable and debris flow paths can be seen directly.

Figures 5a and 5b present the longitudinal profiles of the main channels and their altitudinal variations. Erosion, transit, and deposition zones were determined in each basin. Although the Huinganco and Huaraco rivers have similar lengths and average slopes (11.6 and 12.6 km, and 9.6° and 8.6°, respectively), the Huaraco is steeper. The average slopes of the Huaraco and Huinganco main channels are, respectively, 27.2° and 34.1° at the starting zones (Fig. 4a), 14.3° and 12.0° in erosion zones, 6.2° and 9.8° in transit zones (Fig. 4b), and 5.6° and 5.3° in accumulation zones (Fig. 4c). The greatest differences between the two basins were found in the transit and accumulation zones. The transit zone of the Huaraco river is considerably longer than Huinganco's (5.0 and 1.6 km), but the latter has a longer accumulation zone (2.9 and 7.5 km). In the higher altitude sectors, 124 starting points of debris flow were identified, most of them at the top of Cordillera del Viento and connected to debris supply zones. The starting points and longitudinal profiles presented in figures 5a and 5b reveal that debris contributions reach the transit zone of the main channels as low as 1603 and 1765 m a.s.l (in the Huaraco and Huinganco rivers, respectively). The average slope of these tributary channels is 30.1° and 27.4° for the Huaraco and Huinganco rivers, with peaks of 55.4° and 60.4°, respectively.



		Return period			
		High	Medium	Low	None
Consequence	High	🟥	🟦	🟨	⬜
	None	No risk			

Figure 3. Risk matrix considering different return periods and consequences of debris flows in the Huaraco and Huinganco basins. Risk levels: red, high; blue, medium; yellow, low; white, no risk.

Based on the analysis of the characteristics of the area, debris flow episodes could be triggered by rainfall, tsunamis, or a Glacial Lake Outburst Flood (GLOF). Rainfall —the most probable triggering mechanism— is particularly dangerous during spring and summer months when the freezing level is above 3000 m a.s.l. and there is a higher frequency of liquid precipitation at that altitude. Considering the current availability of susceptible material in the basins, new rainfalls might lead to new debris flow episodes. The second trigger, i.e., tsunamis, could only occur in Huinganco glacial lake (0.09 km²) (Fig. 1c) in case of a huge landslide from the headwall of the cirque glacier, possibly generated by recurring frost weathering and/or earthquakes. The possible "cascading effect" linked to tsunamis could provide a large water discharge to the main channel and drag existing materials downstream. Estimations of the available water volume in the lake range between 1.14

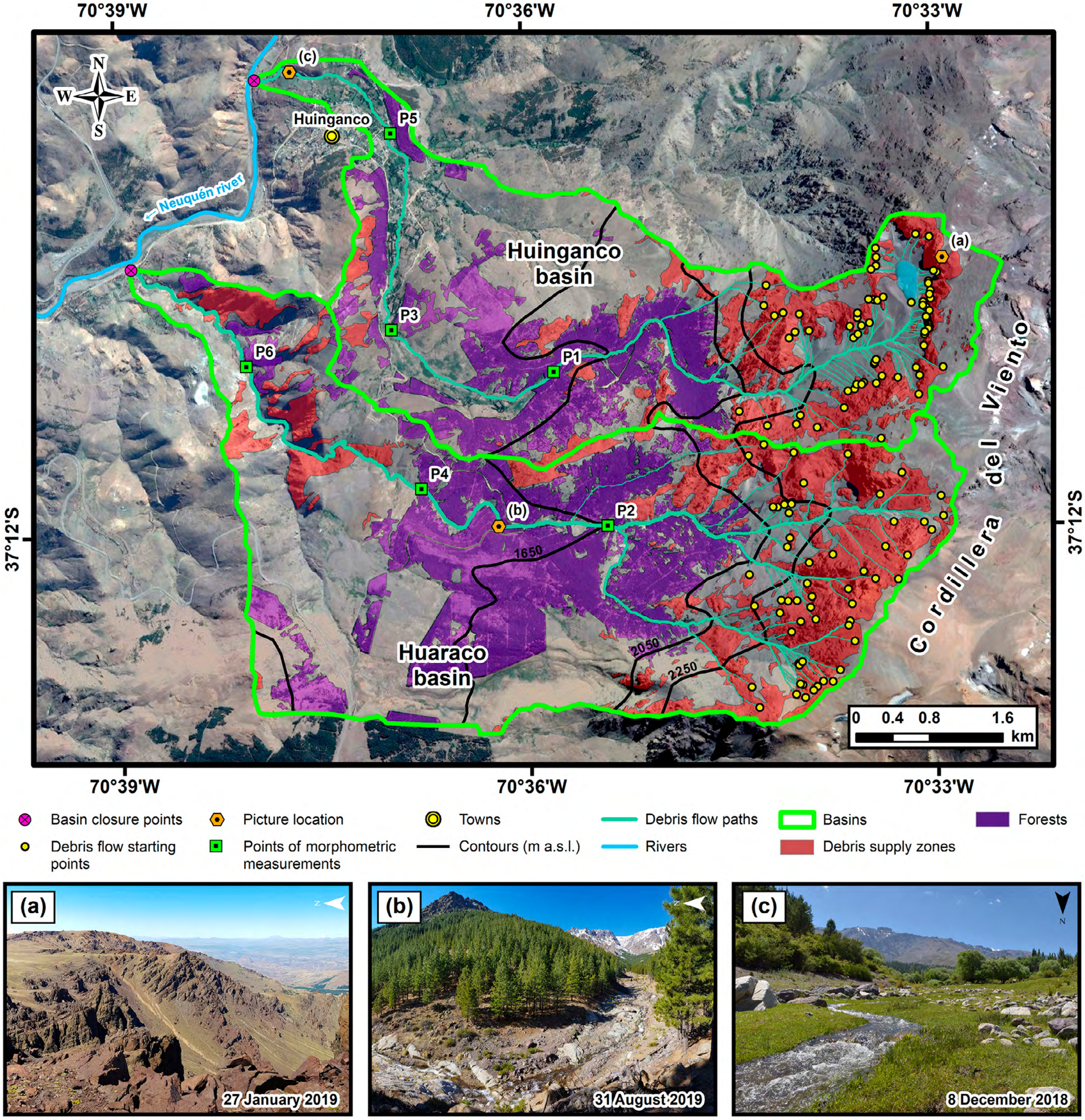


Figure 4. Origin and paths of debris flows in the Huaraco and Huinganco basins. Examples of channel gradients: a) starting zone at the top of Cordillera del Viento with several associated channels; b) transit zone in a medium-altitude sector where the channel passes through the forest and trees and basal-rock boots predominate; c) deposition zone in a low altitude area of the Huinganco river with small bed-slope gradients. Base satellite image: Google Earth Pro ©, dated 01 February 2017.

× 10^6 and 1.26 × 10^6 m^3, which are considered large enough to potentially mobilize those materials along the Huinganco river. Finally, an unprecedented but possible GLOF associated with Huinganco lake could also occur as a consequence of a potential sudden moraine rupture due to seismic activity. Although the moraine has seen a large number of earthquakes since its formation, the region exhibits cases of dam failure, e.g., Navarrete and Carri Lauquén lakes (Penna et al. 2008, Hermanns et al. 2011, Ramos 2017), in support of this hypothesis. A peak discharge of 815.7 m^3/s is estimated in the worst-case scenario.

The episode of 8 February 2013: The most recent debris

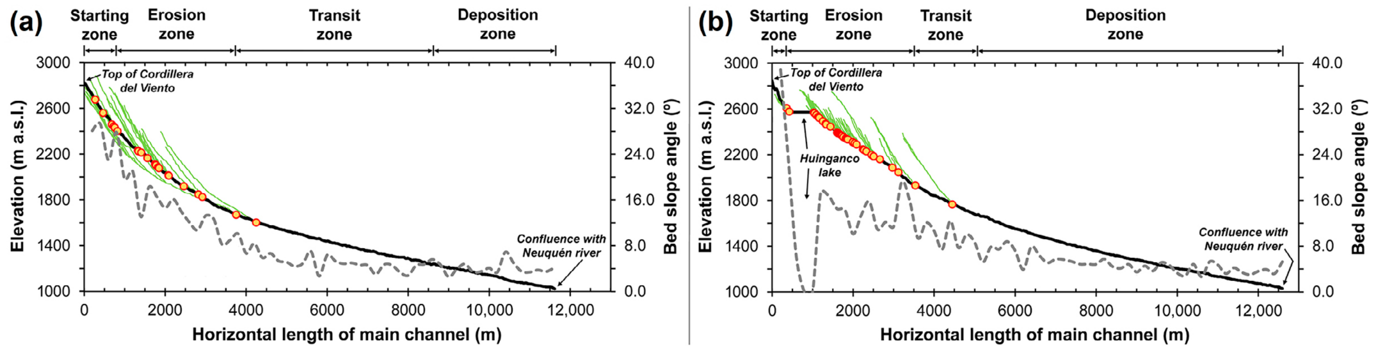


Figure 5. Longitudinal profiles (black line) and bed slopes (grey dashed line) of (a) the Huaraco and (b) Huinganco rivers. Tributary longitudinal profiles (green line), and points of debris contributions (yellow dot) at contact location with the main river.

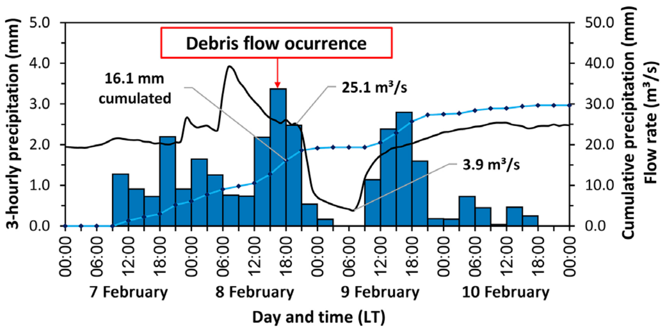


Figure 6. 3-hourly (blue bar) and cumulative (light blue line) precipitation at the top of Cordillera del Viento (37°10'54.32''S, 70°32'41.14''W, 2839 m a.s.l.) from READY and hourly flow rate records (black line) at the Neuquén river at Andacollo station (37º11'01.64''S, 77º40'41.35''W, 1012 m a.s.l.), between 7 and 10 February 2013.

flow episode impacted the Andacollo and Huinganco towns on 8 February 2013, triggered by rainfall in the Cordillera del Viento range. READY precipitation data indicate that rains started between 09:00 and 12:00 h local time (LT, i.e., UTC -3) of 7 February 2013 (Fig. 6). On the following day, two simultaneous debris flows developed in the Huaraco and Huinganco rivers (Table 2) between 15:00 and 18:00 h LT with 16.1 mm cumulative precipitation. According to multimedia material registered between 17:40 and 21:00 h LT in the lower sectors of the basins, the debris flows dragged sediments, rocks, and trees, destroying everything on their way. Locals reported a thunderstorm with hail, but the rain was only observed at top of the mountain range, not in urban areas. This information was confirmed with the records of Andacollo hydromete-orological station (i.e., 0.0 mm recorded). Although a similar amount of rain fell in the area on the following day, no new debris flows were registered, possibly because the basins had already unloaded most of the available material.

Field estimates showed that the debris flow in Huaraco was more rapid than the one in Huinganco, with speeds of 14.46 and 8.10 m/s, respectively. The peak discharge in Huaraco was estimated at 3.48 × 10^3 m³/s, almost three times the discharge in Huinganco —i.e., 1.29 × 10^3 m³/s. These debris flows can be classified as extremely rapid, following the classification proposed by Cruden and Varnes (1996). The characteristics of the longitudinal profiles and narrowness of the valleys would partially explain the high flow speeds and discharges in both basins. However, the Huaraco has a steeper flow path and a narrower valley than the Huinganco. During the episodes, ten 5-to-6m-high debris surges were recorded in a lapse of 12 minutes in the Huinganco basin (Garrido 2013). A second video of similar length, registered nine surges with an average recurrence of 78.3 s, with a minimum of 18.0 s and a maximum of 122.0 s. Based on these estimates and considering the duration of the events, hundreds of surges have probably occurred.

The characteristics of the Huinganco basin allowed a greater deposition of material at its riverbanks than at the riverbanks of the Huaraco basin. The total material stored in the main channels was approximately 9.62 × 10^5 and 7.81 × 10^5 m³ in Huinganco and Huaraco, respectively. This material remained available for future debris flows. In this line, optical images from before and after the 2013 event evidence a significant deepening and widening of the main channels in both basins. Measurements denoted maximum depths of 7.9 and 7.0 m and maximum widths of 64.3 and 98.6 m in the Huaraco and Huinganco debris flow paths, respectively. Deposit granulometry ranged from clay (Garrido 2013) to boulders of 10.5 m in diameter (as measured in the field). These results are similar to those reported by Hungr et al. (2001) for typical debris flows. The material accumulated along the main channels showed rough inverse grading, with the largest clasts close to the flow surface. Several landforms developed such as boulder trains, levees, lateral accumulation terraces, and debris flow fans. Some boulders were found on the riverbanks because they had been expelled during the episode impacting trees at heights of up to 2.5 m.

The debris flows of 8 February 2013 were classified as

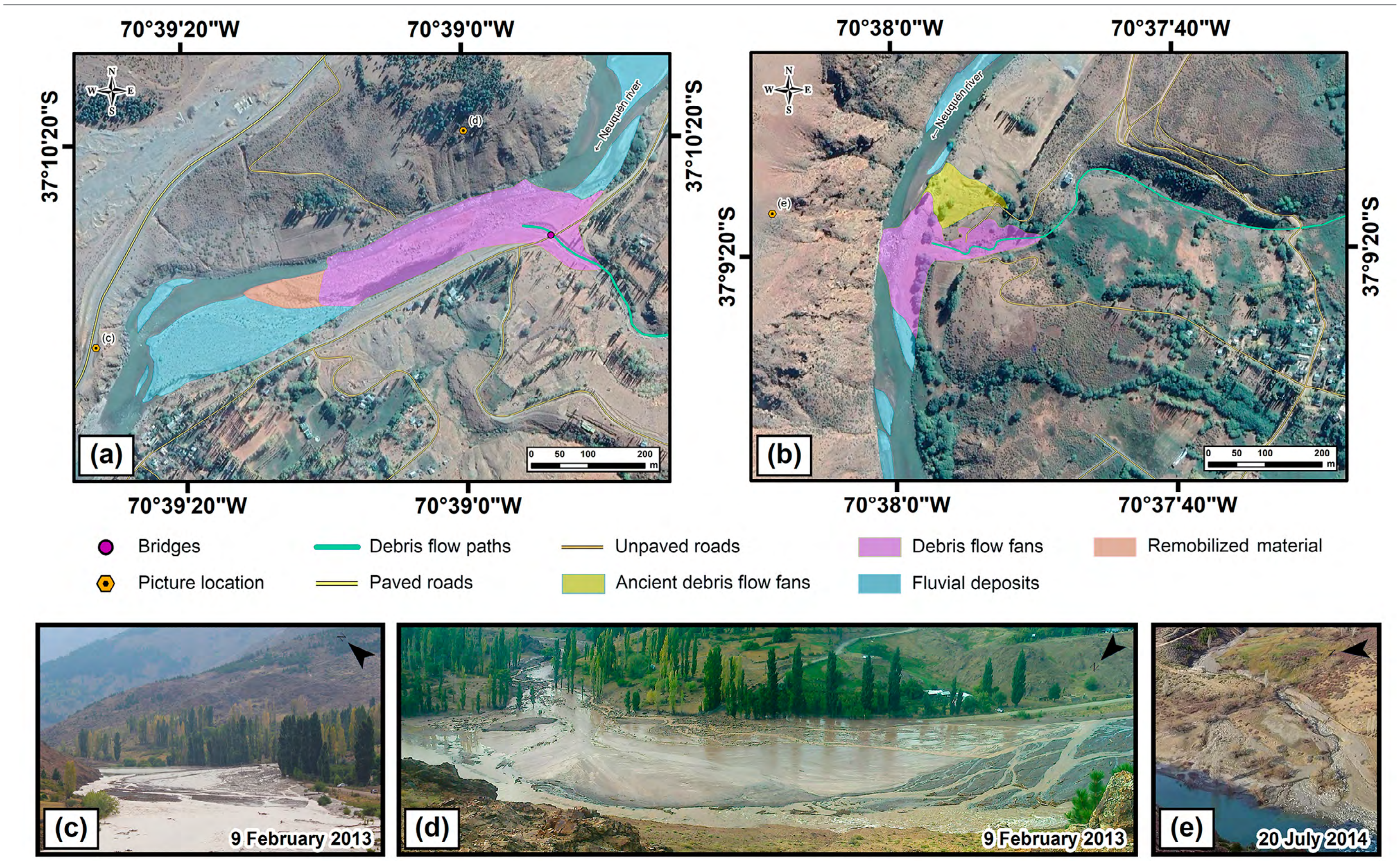


Figure 7. Maximum extent of debris-flow fans from the 8 February 2013 episode at (a) the Huaraco and (b) Huinganco basins. (c) and (d) Huaraco fan ≈ 13 hours after formation (photo credit: María A. Molinari and Marina Albornos, respectively), and (e) Huinganco fan (photo credit: Rodolfo M. Vallejos). Base satellite images: Google Earth Pro ©, dated 12 April 2019.

class 5 in Huaraco (4.8×10^4 m²) and class 4 in Huinganco (2.3×10^4 m²), following Jakob's (2005) size classification of debris flows in the bouldery inundated area of the fan. In both cases, the accumulation of material in the fan was large enough to intercept the flow of the Neuquén river and create natural dams (Fig. 7). Rocks belonging to the farthest geological unit with sizes up to two meters in diameter have been found in the fan of the Huaraco (Figs. 7a y 7c-d) and the Huinganco (Figs. 7b and 7e) basins, which proves the strong entrainment of material. Material corresponding to an ancient debris flow fan was found in the final section of the Huinganco river (Fig. 7b). Those deposits were classified as class 3 (8.7×10^3 m²) and were located in the 1943 and 1973/75 event paths, whose filling contributed to changing the debris flow path from North to South in the 2013 event, as was confirmed by local inhabitants. These deposits are believed to have been larger originally because they are partially overlaid by newer deposits.

Hydrometeorological data from Andacollo station (Fig. 1) denote a decrease in the flow rate of the Neuquén river from 25.1 m³/s at 20:00 h LT on 8 February to 3.9 m³/s at 07:00 h LT on the next day (Fig. 6). The 84.5 % drop in the flow rate would be justified by the formation of dams in the 3560.6 km² basin. The registered decrease in flow rate could have been caused by a partial closure, where the flow was maintained mostly by contributions from the Neuquén river (e.g., permeability, flow overpass, among others), or a total closure, where the flow persisted by contributions from small tributaries upstream of the station. Temporary lakes upstream of the Huaraco and Huinganco dams were 0.3 and 0.1 km² in area, respectively (Garrido 2013). The dams broke naturally eleven hours after formation in Huaraco and about thirty minutes in Huinganco. On the following days, the flow rate started increasing gradually to normal values, without clear daily oscillations. This would be directly associated with the formation of a natural lake upstream of Huaraco's dam, which attenuated the daily cycle of the river. The risk of flash floods in towns located downstream due to a sudden rupture of the remaining dam during maximum flow rates, forced the authorities to remove part of the material and rebuild the channel. The lack of planning in these works produced erosion problems in the southern riverbank during the subsequent winter, and material had to be mobilized again to its present position. Figure 8.a shows the maximum extent of the debris flow fan, where part of the material remains in the same place and only a small sector was mobilized anthropically.

Modeled magnitude scenarios: The hazard potential of

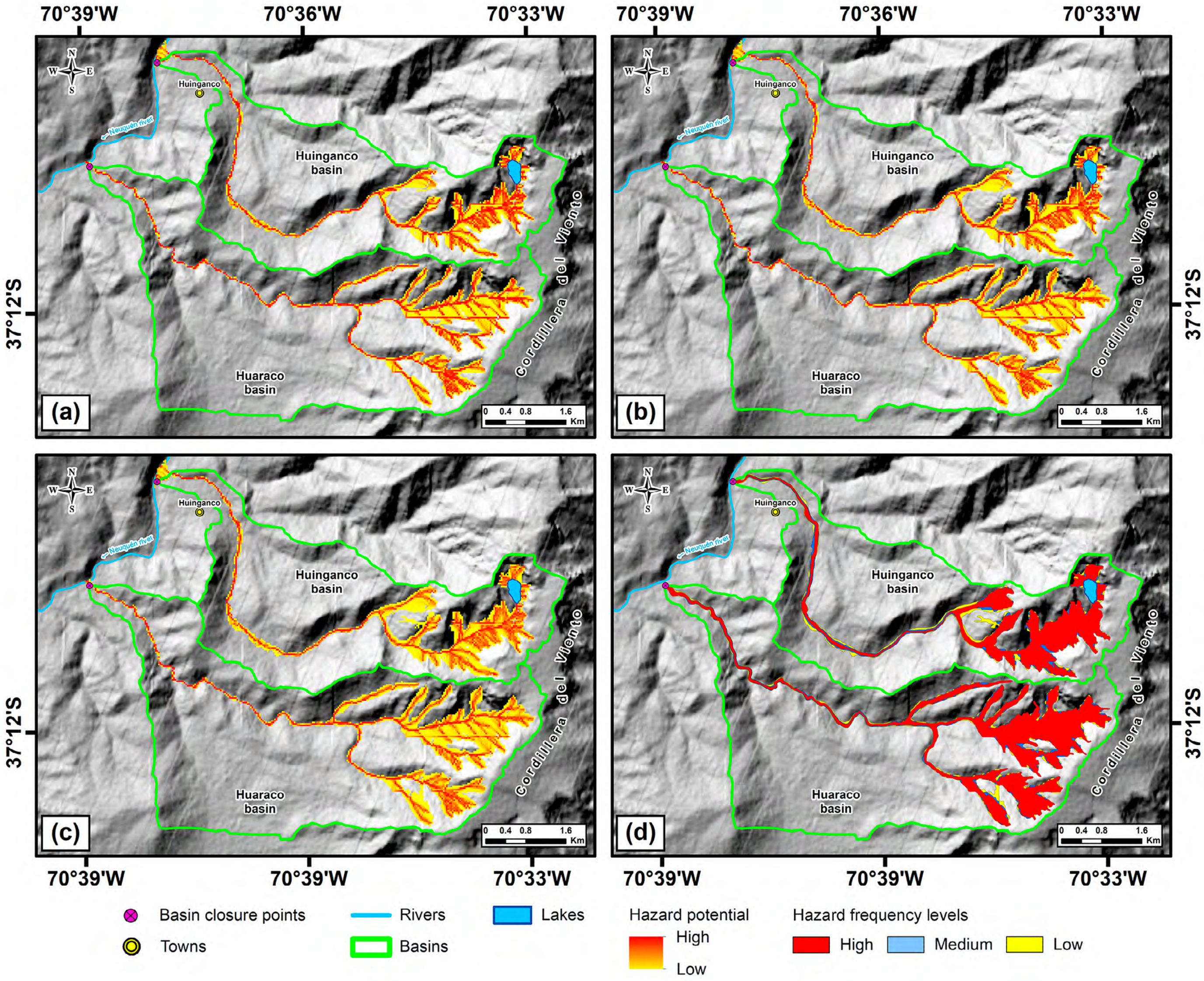


Figure 8. Hillshade map and debris flow hazard potential for scenarios of (a) low, (b) medium, and (c) high magnitudes and (d) resulting hazard frequency map in the Huaraco and Huinganco basins.

debris flows was modeled with Flow-R (Table 1, Fig. 8) for three magnitude scenarios considering the frequency of the events in the study area. These qualitative scenarios show the areas where material might activate, without the need for concurrence of all the channels in each event. In fact, there is no clear evidence of debris contributions from the lowest tributary channels of each basin during the 2013 episode. Regarding the propagation extent of the material, the greatest variations occurred in the high and medium altitude sectors of the basins, in opposition to the low sectors where the flow was more regular. The only exception is the location of the Huinganco debris flow fan; however, this particular variation was caused by the limited spatial resolution in the tri-dimensional representation.

In general terms, the potential of hazard in the medium scenario fitted the affected area of the 2013 debris flow episode (Fig. 8b). Based on this, the low and high scenarios might also be well represented (Figs. 8a and 8c, respectively). No significant differences were observed among the simulations of the three scenarios. This similarity could be due to the influence of flow channeling and to underrepresented lateral extent variations smaller than 30 m caused by DEM. Because of this limitation, results should only be analyzed on a regional scale.

Hazard modeling showed that 17.7 % of the basins at most can be affected by debris flows of different magnitudes (Fig. 8d). Calculated spatial occupation was 0.8, 1.3, and 7.3 km² in the low, medium, and high scenarios, respectively. Detailed higher resolution mapping and updated DEMs would allow determining the location of buffer zones to prevent the consequences of future episodes.

Elements-at-risk and vulnerability

The elements-at-risk and their vulnerability are important variables in the RMA of debris flows. The use of RMA in hazard-prone areas like the Huaraco and Huinganco basins increases the knowledge of the area and could help governments to make better decisions anticipating the occurrence of new episodes. Selected elements-at-risk for this study were people, buildings, forests, grasslands, and lifelines (Fig. 9).

In 2020, the towns of Andacollo and Huinganco had 3916 inhabitants in total (Dirección Provincial de Estadística y Censos 2020). Around 159 people are estimated to live in 59 buildings —i.e., 2.7 people per building on average— located at less than 100 m from the main channels of the Huaraco and Huinganco rivers. In general, buildings are made of bricks or wood and have two floors at most, no basement, and occasionally tree and/or wire fences (Fig. 9a). Some buildings close to the rivers are supported on columns to compensate for the steep slopes (Fig. 9b). Such type of construction is unstable if reached by the flow. The number of vulnerable people and buildings was assigned to each hazard scenario as follows: low magnitude, 11 people in 4 buildings; medium magnitude, 35 people in 13 buildings; and high magnitude, 65 people in 24 buildings, over areas of 290.0 m², 901.6 m², and 2076.1 m², respectively. All the people were considered to be in the buildings at the moment of event occurrence.

Ten access points, four bridges, six fords, and small sewers were counted in both basins (Fig. 9c). Three of the bridges have a beam design made of steel and wood and are supported by gabions (Figs. 9d-e). The fourth one is a simple 3-m-diameter steel tube covered with rocks and fixed with gabions (Fig. 9f). The areas under the decks (i.e., the cross-sectional areas) were measured during the fieldwork. The bridges at higher altitudes presented smaller areas than those in lower sectors, with 7.1 (Fig. 9f) and 37.4 m² (Fig. 9d), respectively, in the Huaraco river, and 29.3 and 48.9 m² (Fig. 9e), respectively, in the Huinganco river (a new higher bridge of 12.3 m² is currently under construction, Fig. 9g). The dimensions and location of the bridges were determined considering river discharges only, not including debris flow discharges. These designs reveal a poor understanding of debris flows in the area and a lack of hazard prevention planning. As a consequence, bridges are highly vulnerable under the three scenarios analyzed, which indicates they could be seriously affected in future debris flow events. In fact, the dysfunction and in some cases destruction of the land communication structures during the 2013 event left an area of approximately 23.6 km² isolated for 18 hours, including most of Huinganco town. Concrete bridges favored multiple blockages by material accumulation, with consequent development of dams and widening of upstream flow, which were subsequently filled and overpassed by subsequent surges.

Communication lines in the region are terrestrial only (Fig. 1), mostly unpaved single-way roads without traffic lanes, lateral fences, or pedestrian walkways (Fig. 9h). In general terms, they are fairly good during the year, but they become impassable because of snow in winter. Model simulations showed an affectation of 2.8, 3.9, and 5.3 km of road, under low, medium, and high hazard scenarios, respectively. Approximately 1.8 km of unpaved roads were affected in the 2013 episode, the cleaning and reconstruction of which took several days. Since no changes have been made to the design, these roads will be affected again in future events.

At present, 25.3 % of the basins is covered with forest (10.5 km²), which plays an important role in supplying material for debris flows given their proximity to the riversides (Figs. 9i and 9j). Forests, especially those located over debris flow terraces and slopes near main channels (Fig. 9k), could contribute trees to future debris flow episodes at altitudes from 2005 to 1435 m a.s.l in the Huinganco basin and from 1981 to 1406 m a.s.l. in the Huaraco basin. Estimated vulnerable areas in the low, medium, and high magnitude scenarios are 0.4, 0.5, and 0.7 km², respectively. The grasslands used for livestock farming (Figs. 9l and 9m) and agriculture could suffer negative impacts which would affect the livelihoods of local farmers. The estimated affectation area was about 0.1 km² in the three hazard scenarios.

Finally, water and gas pipes, and power lines could be compromised by debris flows in the Huaraco and Huinganco basins (Figs. 9n-o). So far, no lifeline countermeasures have been taken to face debris flows, except for the relocation of some utility poles farther from the channel path. Lifelines will be affected under the low, medium, and high scenarios as follows: 352.0, 626.3, and 931.7 m of water pipes; 394.3, 500.5, and 603.4 m of gas pipes, and 2265.4, 4049.5, and 4720.4 m of power lines, affecting medium (13.2 kV) and high (33.0 kV) voltage lines. Additionally, for each scenario damage was considered to two spherical gas valves. Subsequent studies are needed that would include a more detailed identification of the elements-at-risk.

A first estimate of the total price of the elements-at-risk was based on the average unit values and the different debris-flow magnitude scenarios (Table 3). Estimated prices in the high magnitude scenario reached about 6.4 million USD. In the medium and low magnitude scenarios costs were estimated at 3.9 and 2.3 million USD, respectively. The highest prices concentrated on buildings (high scenario) and roads (low and medium

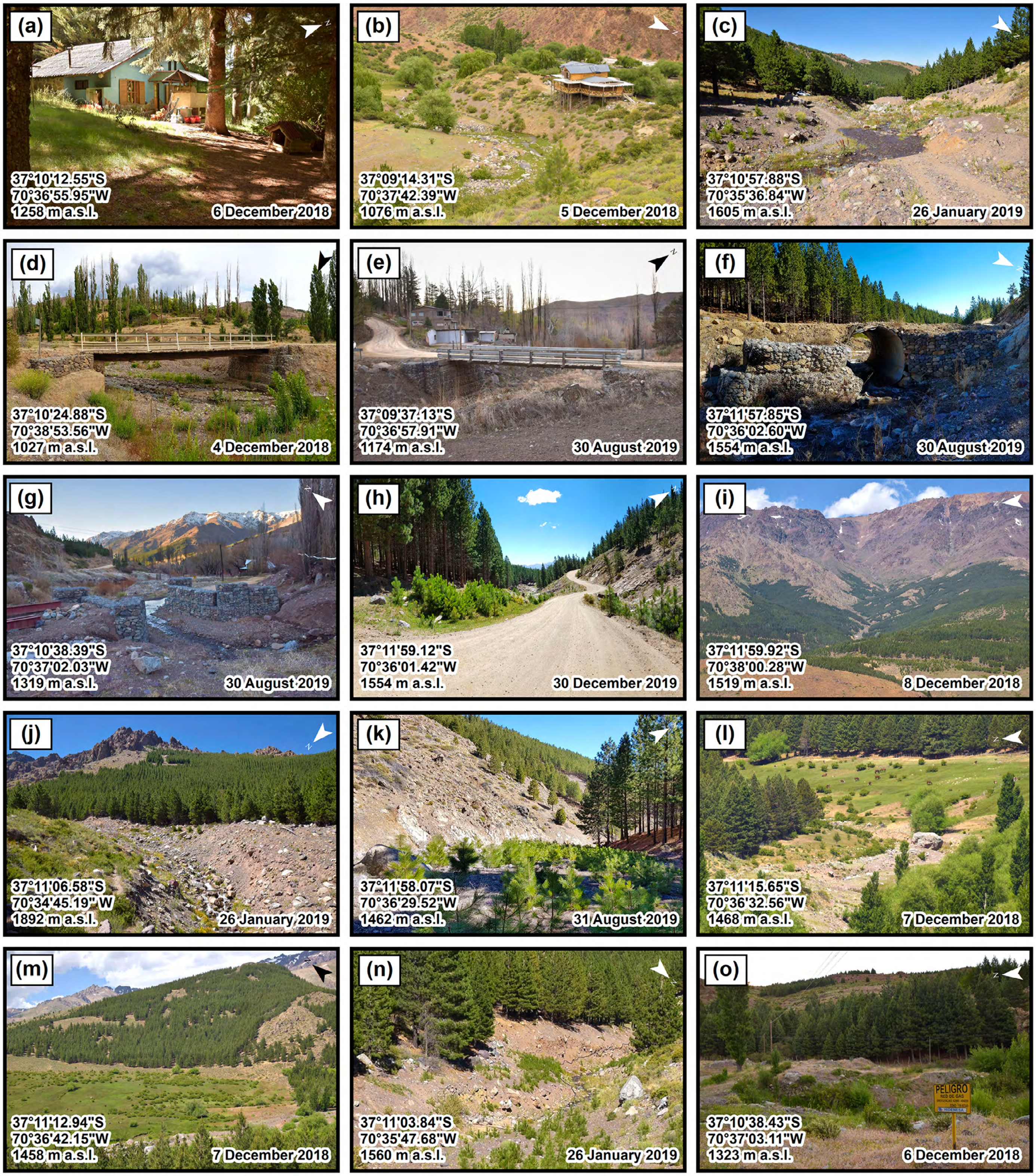


Figure 9. Elements-at-risk observed at the Huaraco and Huinganco basins: a-b) typical buildings at medium-low and low altitudes, respectively, in the Huinganco basin; c) ford in the medium-high basin of the Huinganco river used for tourism and forest maintenance; d-e) beam-design bridges in lower sectors of the Huaraco and Huinganco basins, respectively; f) simple steel tube bridge at medium-high altitude of the Huaraco basin; g) beam-design bridge under construction in the Huinganco river where the ford still remains; h) typical unpaved road in the Huaraco basin; i-j) forest in the Huaraco and Huinganco basins, respectively; k) natural revegetation of *Pinus* over a debris flow terrace in the Huaraco basin; l-m) grasslands in the Huinganco basin with typical livestock farming; n) water pipe on the left margin of the Huinganco river; o) underground and aerial crossing of gas pipes and electricity lines in a medium-low altitude sector of the Huinganco basin, respectively.

Table 3. Total price of elements-at-risk in different debris flow scenarios at the Huaraco and Huinganco basins. Values in USD as of December 2019.

Elements-at-risk		Average unit value	Total price by scenario magnitude			Observations
			Low	Medium	High	
Buildings[1]		1,200 per m^2	347,947	1,081,897	2,491,278	Costs in this region are 20 % higher than in the city of Neuquén, the biggest city in northern Patagonia.
Bridges[2]		80,000 per unit	320,000	320,000	320,000	-
Roads[2]		400,000 per km	1,124,420	1,552,809	2,111,310	Unpaved roads in mountain regions include one sewer every one kilometer.
Forests[3]		71,052 per km^2	27,523	32,867	46,646	Estimates consider the area of *Pinus* sp. and plant density above 700 per hectare in Neuquén and Río Negro provinces.
Grasslands[4]		6 per m^2	140,598	410,538	835,455	Estimate based on the average sale value of municipal property —not the market value of private property.
Lifelines	Water pipes[5]	6 per m	2,170	3,861	5,744	Estimate based on 75 mm diameter PVC pipes (most representative in the area).
	Gas pipes[5]	6 per m 63 mm Ø 12 per m 90 mm Ø 355 per valve	3,406	4,100	4,787	Estimates based on 63 and 90 mm diameter polyethylene pipes, plus two spherical valves for each scenario.
	Power lines[6]	125,000 per km 13.2 kV 150,000 per km 33.0 kV	288,075	511,081	605,261	Estimate based on specific affectation of 13.2 and 33.0 kV lines.
Total price per scenario			**2,254,138**	**3,913,053**	**6,420,481**	

Source of information for elements-at-risk: [1] Association of Architects of the Province of Neuquen; [2] Department of Road Systems, Province of Neuquén; [3] National Ministry of Agriculture, Farming, and Phishing, Argentina; [4] Department of Land Registry of Huinganco; [5] Department of Public Works of Huinganco; [6] Neuquén's Provincial Energy Entity.

scenarios), while the lowest were water and gas pipes.

The total price of elements-at-risk has to be considered in the years to come, especially after the experience of 2013 when social and economic activities were severely affected and it took months and even years to recover, if ever at all. Local inhabitants reported damage to more than 30 physical structures. However, this number could be higher because of the lack of systematic records and difficulties in recovering past information. According to available data, total damage to physical structures was 58 %, and partial damage, 42 %. Fortunately, no casualties were registered in any of the events (Table 2), probably because the debris flow occurred during daytime hours and was quickly noticed.

Risk

The information related to hazard, elements-at-risk, and vulnerability was used to determine the risk of debris flow at the Huaraco and Huinganco basins by means of a semi-quantitative approach based on average expected losses. Quantification was made by multiplying percentages of total affectation of the elements-at-risk, in order to replace the lack of vulnerability curves and the total prices of vulnerable elements (Table 3).

The percentage of total building damage was assumed at 25.0 % (i.e., 1 of 4 buildings, 85.4 m^2), 61.6 % (i.e., 8 of 13 buildings, 656.7 m^2), and 58.3 % (i.e., 14 of 24 buildings, 1251.5 m^2) for the low, medium, and high magnitude scenarios, respectively. These assumptions were based on building characteristics, resistance to previous events, and location with respect to modeled hazard limits. Considering the number of buildings at risk, 3, 22, and 38 people would be affected in the low, medium, and high magnitude scenarios, respectively. The population density in the study area is low, but the number of inhabitants is foreseen to increase in the next years, so the number of people affected by debris flow is likely to grow as well.

Damage to bridges, roads, and grasslands was estimated at 100.0 % in the three scenarios (i.e., four bridges, up to 5.3 km of roads, and 0.1 km^2 of grasslands), based on the lack of mitigation measures and the high potential of being covered with debris flows. However, values assumed for forest were 10.0 (i.e., 38,735.7 m^2), 15.0 (i.e., 69,385.4 m^2), and 20.0 % (i.e., 131,301.2 m^2) for low, medium, and high magnitude events, taking into consideration the natural resistance of trees to toppling and the high channelization of debris flows.

Regarding lifelines, a 100.0 % damage was assumed for water and gas pipes in the three scenarios, and 36.9 % (811.3 m), 64.4 % (2595.3 m), and 70.0 % (3266.2 m) for power lines,

Table 4. Average expected losses for elements-at-risk under debris flow magnitude scenarios in the Huaraco and Huinganco basins. Values in USD as of December 2019.

Elements-at-risk		Losses according to magnitude scenario		
		Low	Medium	High
Buildings		102,532	788,043	1,501,856
Bridges		320,000	320,000	320,000
Roads		1,124,420	1,552,809	2,111,310
Forests		2,752	4,930	9,329
Grasslands		140,598	410,538	835,455
Lifelines	Water pipes	2,170	3,861	5,744
	Gas pipes	3,406	4,100	4,787
	Power lines	106,306	329,312	423,492
Total losses per scenario		**1,802,184**	**3,413,594**	**5,211,973**

in the low, medium, and high magnitude scenarios, respectively, considering the location of utility poles. The planning of the electricity network, as that of all the other elements-at-risk, did not consider debris flow occurrence and impacted on the total price estimation.

Table 4 presents the resulting average losses for the different elements-at-risk. The high magnitude scenario represents the highest risk of debris flow in the Huaraco and Huinganco basins with an estimated loss of 5.2 million USD; while losses in the medium and low magnitude scenarios are estimated at 3.4 and 1.8 million USD, with a medium and low risk, respectively. The highest loss is due to road affectation in the three magnitude scenarios. Consequently, future mitigation measures should focus on roads, not only because of their monetary value but also because of the time of reconstruction and related societal impacts in terms of mobility and trade. The second highest losses are represented by buildings in the high and medium scenarios, and by bridges in the low scenario. In fact, measures should be taken on those elements in the near future, because they could be severely affected by events with medium and high return periods.

DISCUSSION

Risk assessments of debris flow usually require considerable amount of quantitative information (Corominas et al. 2014), which is not always possible to acquire in mountain regions in developing countries. Detailed landslide reconstructions are extremely difficult to perform in northern Patagonia because, unlike many developed countries, Argentina lacks a systematic data compilation strategy. The new semi-quantitative risk approach in northernmost Patagonia made it possible to overcome such limitation mainly through documentation analysis, post-event observations, satellite imagery, modeling, and decision making. Several extremely fast debris flows, the knowledge of which was scanty and limited to reports, were documented and assessed in the region for the very first time.

The RMA analysis included a 135-years-long debris flow data series (i.e., 1887–2022) for return period estimation, magnitude scenario establishment, and triggering mechanism determination, among others. In opposition to other approaches that require a huge number of data to assess risk (e.g., Quan Luna et al. 2013, Liu et al. 2018), the new risk matrix is less data-challenging and takes the best of both quantitative and qualitative methods, allowing risk estimations even in areas with low availability of information. Nevertheless, this type of assessment requires the contextualization of results, as some limitations can be still expected and require a different consideration. For example, a return period derived from four dates would seem inadequate when compared to other frequency-magnitude analyses (e.g., Gao et al. 2019), but in the new RMA the definition of scenarios is based on a qualitative consideration of return periods. It should be noted that debris flow records are not systematically compiled in northern Patagonia, unlike what has been usual in some European cities during the past century (e.g., Stoffel et al. 2005). Furthermore, debris flows are not as frequent and deadly as in Asian countries (Iylia Rosli et al. 2021, Prasad Sati 2022), but are equally important to local inhabitants, decision-makers, and scientists. The lack of knowledge of the debris flow episodes occurred before the end of the 19th century in the study area calls for dendrochronological studies to shed light on these events.

Rainfall was seen in the results to be the main triggering mechanism of debris flows on the southwestern slope of Cordillera del Viento. Rainfall would be rather linked to the South Pacific anticyclone than to El Niño - Southern Oscillation (ENSO) which has less influence in the region (Finessi and Groch 2018). In support of this, Groch et al. (2020) found weak and moderate correlations between meteorological and hydrographic variables and ENSO for the 2000–2014 period throughout northern Neuquén. The intense 1997 rainfall episodes that caused a debris flow in the Domuyo Volcanic System (70 km north of the study area) coincided with the very strong 1997–1998 El Niño (Hurley et al. 2020), meanwhile, the episodes of January and February 2013 coincided with an ENSO neutral phase. Noticeably, multiple rainfall-triggered debris flows took place during that 2013 summer in central Argentina and Chile, and were studied by Sepúlveda et al. (2015) and Lauro et al. (2017). The former paper examined the events from 12 January to 13 February that took place some 505 km north of the Huaraco and Huinganco basins (Sepúlveda et al. 2015). The latter addressed a single event occurred on 8 February 2013 at about 760 km northward from said basins (Lauro et al. 2017). Both papers attributed the landslides to summer convective storms. The coincidence in time of those debris flows and the one examined in this paper makes it possible to hypothesize that the latitudinal extension of atmospheric phenomena could be greater than previously thought. Further investigation is needed to link these episodes.

Another aspect linked to triggering mechanisms that requires attention is the possibility of an abrupt water discharge that could be generated from Huinganco lake after a tsunami and/or GLOF. These hypothetical triggering mechanisms were not included in the modeling of debris flows as they are beyond the purpose of this research. Nevertheless, results confirm that the expected peak discharge would be around 36.7 % less than the discharge measured in the 2013 debris flow. Thus, in the case of a lake outflow, like the one occurred in Ventisquero Negro (Worni et al. 2012), the water could produce a small to medium hazard scenario, spreading the available material over several kilometers. The areas affected by significant water and/or debris discharges might be defined through high-resolution DEM modelling (e.g., 12-m TanDEM-X), which allows an improvement in the calculation of losses near the channels.

CONCLUSIONS

The paper presents a new approach for the risk assessment of debris flows that might be applied in regions where fully numerical estimations are not feasible, as was shown for northernmost Patagonia, Argentina. Local basic information and fieldwork contributed key data for hazard modeling and vulnerability estimations and proved to be essential to study debris flows and estimate risk in terms of casualties and economic losses.

The analysis of historical and recent data revealed that the recurrence period of debris flows in the Huaraco and Huinganco area typically ranges from 30 to 56 years. Rainfall at the top of Cordillera del Viento is the trigger of these events, but other mechanisms are also likely to have place in future episodes. Considering the increased number of debris flows that can be reasonably foreseen to occur in the area in view of the global climate changes predicted for the 21st century and the current lack of prevention measures in local communities, future events will probably result in similar or even heavier damage than that caused by the event of 8 February 2013. It was during this episode when flow velocities reached 14.46 m/s, and peak discharges of up to 3.48×10^3 m^3/s transported large boulders and trees that remain available throughout the basins.

The elements-at-risk in the Huaraco and Huinganco basins reported multiple potential affectations for events with low, medium, and high magnitude modeled scenarios. In the worst-case scenario, with a spatial occupation of 7.3 km^2 (17.7 % of the basins), the price of vulnerable elements was estimated at about 6.4 million USD. As a priority, future works should focus on reducing zonal risk through community education and long-term commitments with local/regional agencies involved in risk and crisis emergencies. At present, it looks like debris flows in the area are not considered adequately.

The semi-quantitative approach determined that 3 to 38 people, as well as infrastructure, could be severely affected in low to high magnitude scenarios. For those scenarios, the average expected losses range from 1.8 to 5.2 million USD, mostly because of damage to roads, bridges, and buildings. Local and regional stakeholders should design and implement mitigation measures as soon as possible to reduce debris-flow-associated risk on people and elements.

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