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Catastrophic debris flow triggered by an extreme rainfall event in the Volcán village, January 2017. Cordillera Oriental of Argentina

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ABSTRACT

Slides, rockfalls, debris floods and debris flows are periodical events in the dry mountainous regions of Argentina, during times of torrential rainfalls. In the Grande River basin, Jujuy Province, these processes take place almost every summer. Extreme rainfall on January10, 2017 caused the seasonal acceleration of large-scale and slow-moving landslides in the Los Filtros River basin. These slides broke down into a disaggregated mass, triggering a debris flow which transformed progressively downstream into a debris flood, producing widespread damage along a narrow valley (named Quebrada de Humahuaca), with the Volcán village withstanding the worst of the disaster. The event caused four fatalities and great economic losses, mainly destroying infrastructure and buildings. In order to document this catastrophic event and to explore its causes, a morphometric analysis of the Los Filtros river basin, tributary of the western margin of the Grande River and located on the Cordillera Oriental area, was carried out. The drainage network was derived from digital elevation models. In addition, some landslides were mapped using high-resolution satellite data acquired before and after the event. Of a total landslide area of 2.39 km^2, 0.60 km^2 was considered as active and 0.089 km^2 as new

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sliding area (from 2015 to 2017) associated to the large-scale and slow-moving landslides. The geological characteristics of the study basin are very favourable conditioning factors in landslide generation. Precambrian- age low grade metaclastics shatter in the frost climate of the higher mountains and poorly consolidated Quaternary deposits along the sides of the gully erode readily and become source material for landslide that damage or bury roads, railroads, and houses. Finally, this study aims to increase knowledge of all the above-mentioned events in order to provide several methods of analysis for landslide prevention and control.

Keywords: Debris floods and debris flows, basin morphometry, Slow-moving landslides, Jujuy, Argentina

1. Introduction

Landslides sometimes occur on mountain slopes triggered by heavy rains changing into debris flows and then moving into mountain rivers, in a complex process. As was pointed by Hungr et al. (2013) shallow slides may begin with slow pre-failure deformation and cracking of surficial soil on a steep hillside. Then, landslide mass accelerates, disintegrates, enlarges through entrainment and becomes a flow like debris avalanche that enters a drainage channel, entrains water and more saturated soil and turns into a debris flow. When slope diminishes, the flow drops the coarsest fractions continuing as a sediment-laden flood. These authors proposed to apply the simple traditional term “debris flow” to the whole scenario. Additionally, these floods usually occur in mountain river basins draining less than 1000 km^2 (Gaume and Borga, 2008; Lumbroso and Gaume, 2012).

Debris floods and debris flows that take place in almost all the tributary valleys of the Grande River are the main hazardous processes that affect this portion of the Cordillera Oriental foothills of the Jujuy province in northwestern Argentina, inducing serious consequences on the erosion and sedimentation activity along the Quebrada de Humahuaca (Cencetti et al., 2001) where numerous human settlements are located (Fig. 1a, b). This is due to the special morphometric, geographical and geological configuration of river basins in the Cordillera Oriental of Argentina that is extremely favourable for the generation of debris floods and flows. Moreover, a great amount of loose debris, consequence of slope processes such as slides and rock falls, is available due to the geological characteristics of the outcropping lithology and structures. Debris flows/floods pose a serious threat to the socio-economic and physical environment of this region. In Table 1 are listed some of the most catastrophic events responsible for most deaths and damages to roads and villages that have occurred in northwestern Andes of Argentina.

Morphometric characteristics of a river basin area unit are basic tools to estimate and predict its behaviour under conditions of heavy rainfalls, and to compute the potential hazard of debris flows/floods to downstream settlements and infrastructure. For this reason, morphometric analyses were used for river basin characterization from different areas of the world in several previous researches, such as Topaloglu (2002), Moussa (2003), Sreedevi et al. (2004, 2013), Srinivasa Vittala et al. (2004), Mesa (2006), Esper Angillieri (2007, 2008, 2012), Esper Angillieri and Perucca (2014a,b) and Perucca and Esper Angillieri (2011), among others.

The focus of this work is to describe and analyse the destructive event that occurred in the Volcán village on January 2017, studying some geomorphological and hydrological aspects and identifying their effects during torrential rains in order to generate latest information of the basin for future river basin management.

2. Study area

The Volcán village, with 1731 inhabitants (2010), is located 41.9 km north of San Salvador de Jujuy city (capital town of the Jujuy province), Argentina. In this area operates since the 1970s, a cement production plant that is the main supplier of cement of the region and southern Bolivia. (Fig. 1a-c)

The Los Filtros River, which crosses the Volcán village, is a tributary of the northern margin of the Grande River that flows to the south in a narrow mountain valley trending N-S (Fig. 1d). This valley, named Quebrada de Humahuaca, follows the line of a strategic route connecting Argentina to Chile and Bolivia (National Route 9). There are almost 17 villages along the Grande River valley, which is characterized by a variable discharge due to extreme climatic variability, both in space and time. Mean daily discharge is between 16.4 and 24.75 m^3/s, with a maximum of 74.56 m^3/s in February and a minimum of 4.83 m^3/s in October. The historical maximum discharge was 358m^3/s and the minimum was 3m^3/s (Paoli et al., 2011).

The annual average temperature in the region is approximately 14°C; July is the coldest month, with an average temperature of 5.2°C, and the hottest month is December, with temperatures averaging 19°C (Buitrago, 1999).

Tropical humid air masses of Atlantic origin transported by the South American Summer Monsoon influence regional climate of NW Argentina. It is characterized by the large seasonality with most of the total annual precipitation falling in austral summer, from December to April (Bianchi and Yañez, 1992; Garreaud and Aceituno, 2007), with an average yearly rainfall of more than 400 mm. The total annual rainfall registered in the Volcán locality, from 1934 to 1996, oscillates from 123 to 719 mm, with an average of 391.31 mm, while the maximum monthly average rainfall is recorded in January with values close to 115 mm (Fig. 1e). The largest amount of rainfall measured in one month was 271 mm, in February 1971 (Data from INTA EEA SALTA © Copyright 2002).

On January 10, 2017, between 8 a.m. and 10 a.m. (local time), a very torrential rainfall of 170 mm (according to Engineer Sadir - Water Resources Director, verbal communication) affected the Los Filtros River basin.

Numerous slides were generated on the slopes of the headwaters of this drainage basin, initiating a flow where the main stream discharged quickly with a high sediment transport. At

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9:20 a.m. (local time), the debris flow/flood descended downstream from west to east, breaking the defenses and crossing the National route to the Volcán village. Citizens considered this event as the most catastrophic one to occur in 40 years, causing 4 fatalities, more than a thousand evacuees and great economic losses along the National Route N° 9 (Figs. 2 a-d and 3a-c). As the locals explained, the most affected area was the closest to the San Martin Street, located in the north of the village and with a W-E orientation, where the mud reached the houses' roofs, burying trees and light poles (Figs. 2c, d and 3c, d). Blocks and mud rushed through the village burying roads, vehicles and houses and destroying or damaging most of the local streets and shops (Figs. 3d-f).

The material deposited with a variable width of about 300 to 500 m and an average thickness of 1.5 m, became very fine in the front of the flow, acquiring a viscous behaviour and decreasing its speed. The deposits height reached up to 2 m according to the splash marks and material deposited. The muddy nature of the mass made it difficult to remove the material during the cleaning of the streets. In addition, the debris flow/flood reached the channel of the Grande River, partially obstructing it (Figs. 3g, h).

2.2 Geological setting

The Los Filtros River is located in the Cordillera Oriental geological province, consisting of large folds (Mon and Salfity, 1995), with Precambrian-age rocks of low metamorphic grade cropping out in the cores of the anticlines, beneath folded sedimentary strata of Cambrian, Ordovician, and Cretaceous age. Over these units, there is an extensive Quaternary cover generated by gravity processes acting in the upper part of the slopes together with debris flows and alluvial deposits in the valley bottom (Chayle and Aguero, 1987). Precambrian phyllites constitutes the bedrock geology of the upper portion of the Los Filtros River basin. These rocks overlay the cretaceous sandstones by a reverse fault that strikes NNW and dips to the west, with probable Quaternary tectonic activity. This regional fault system has an east-vergence, trending N-S to NNE. In the lower basin, mainly Quaternary alluvial deposits are exposed (Fig. 4a-e).

The vegetation cover in the basin is characterized by shrub steppe vegetation that is plentiful as well as cacti, mainly cardones (*Echinopsis atacamensis*), dwarf forests and bromeliad cushions. Above 3400 m asl, dominant vegetation consists in shrub steppe, grassland steppe, queñoa (*Polylepis tarapacana*) forests and in the wet areas and spring sources, pastures called vegas (Frigoni Prado, 2014).

Therefore, the soil can undergo intense superficial erosion during high intensity rainfall events.

3. Materials and methods

The analysis of the event was carried out through the compilation of local newspaper reports and field investigation. Furthermore, Los Filtros river basin delineation and the morphometric characterization through topographical data and satellite imagery were made. Post-disaster Spot images provided by CONAE (Comisión Nacional de Actividades Espaciales, Argentina) © CNES 2017, Distribution Spot Image SA were compared with pre-disaster images, in order to explore the overall scenario of the event. Previous small slides related to large-scale and slow-moving landslides were detected by using a semi-automatic analysis of the variations in the spectral signature of the land surface and resample with ESRI's ArcGis 10.3. Large-scale and slow-moving landslides were identified using high-resolution satellite imagery from Google Earth™, which was georeferenced to a geographical coordinate system (WGS84) within a geographical information system (GIS). The basin was delineated based on the water divide line concept and was on-screen digitalized using the same GIS technology. The main channel length (Mcl) and length (L) were calculated according to Schumm (1956).

The Elevations, Slope, Topographic wetness index and the Sediment transport capacity Index were obtained using a digital elevation model provided by ALOS/PALSAR

ALPSRP268846700 (ASF DAAC, 2015) with 12.5 x 12.5 m spatial resolution. The slope analysis was performed in a GIS environment.

The morphometric parameters of the basin, which divided in basic parameters are area (A), perimeter (P), length (L), mean width (W), maximum and minimum heights (H, h) and main channel length (Mcl), were quantitative calculated using GIS. Besides, several derived and shape morphometric parameters were obtained using the equations in Table 2, like circularity index, elongation ratio, form factor, sinuosity index ratio, relief ratio and basin relief, among others. These relief properties in the morphometric analysis bring into consideration the influence of aspect and height over the river basin area.

The geologic map modified from Savi et al. (2016) was used to construct a representative longitudinal topographic profile with the distribution of the main knickpoints along the Los Filtros River with SAGA GIS, in order to show regional topographic features controlling the river.

4. Result and discussion

4.1. Catastrophic event of January 2017 and the Los Filtros River basin description

The Los Filtros River flows along the eastern flank of the Chañi Hill (elev. 4,139 m asl), passing the Volcán village (elev. 2,125 m asl), to its junction with the Grande River (elev. 2,075 m asl). The results of the morphometric analysis of this mountain river basin is given in

Table 2, where the circularity index, elongation ratio and form factor show a very elongated basin. Basin morphology (Table 2) may be used to differentiate between basins prone to floods, debris floods and debris flows (Jackson et al., 1987; Wilford et al., 2004). Thus, the debris flow catchments have Melton's ruggedness number >0.6. Basin constituted by fine-grained materials, such as the Los Filtros River, may, however, have a lower Melton Ratio and still be

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prone to debris flow, since these materials are easily mobilized and can then travel longer distances.

Small (<20 km^2), rugged and low-order basins produced small and steep fans dominated by debris flow processes implying different sediment-water mixtures (Pierson, 2005). Such is the case of the study area, a system of distribution of rainwater in a rather small reception river basin, with a main discharge channel that is excavated in a very narrow valley with almost vertical walls of up to 50 m of height. The Los Filtros upper river basin is located almost 4,000 m high, in a hyper arid environment that is only disrupted by very heavy rainfall during summer. Throughout the year, frequent mass removal processes take place, such as slides and large blocks falls from loose, fractured and weathered materials. When heavy rains occur, they can re-mobilize large amounts of debris carried by high-density flows in a main river collector.

According to the movement mechanism and the genesis and plasticity of the material, the flow that occurred in the upper sections of the Los Filtros River basin can be classified as a non-plastic debris flow, with the material deposited in a steep channel (Hungr et al., 2001). The flow mobilized a mixture of mud and medium blocks (mostly between 10 and 20 cm in diameter), with few blocks > 1 m in diameter. The rocky substratum of the area composed of sandstones, limestones, metamorphic rocks and colluvial deposits of the river basin, saturated by the intense precipitation, began to move downstream.

We made a brief description of debris deposits with thicknesses ranging from 0.5 to 1.5 m in three natural and artificial exposures located along the Los Filtros River, two weeks after the event. One outcrop is located upstream, near the national route 9, the second some meters downstream of the route and the third almost at the mouth of the debris flow, near the confluence with the Grande River. Debris flow deposits vary from west to east. Upstream, the deposit mainly consists of rocks with a grain size of 10–40 cm. The cobbles and boulders are angular-shaped and unsorted and their size decreases significantly downstream while the clay content increases. Blocks are clast-supported, with a very low content of a sandy-clayed matrix that increases the floatage of the clasts and lubricates them to enable their transport. Downstream, the thicknesses (up to 1.5 m) of a poorly sorted mass of coarse material was measured, resulting in approximately 70 % gravel and cobbles, 20 % sand and 10 % lime-clay. According to the plasticity of this material, the flow was classified as a debris flow. Further downstream, the fabric deposit is disorganized, with the larger clasts dispersed within a predominantly clayey matrix (matrix-supported) (Fig. 3f). These materials might have been deposited by an intermediate type of flow that corresponds to those with low viscosity and high density (Pierson, 2005). They belong, at least in part, to the so-called debris flood, where the slope decreases markedly, especially near the confluence of the Los Filtros River with the Grande River (Figures 3g, h). Deposits in this sector possess mainly pebbles and a greater percentage of an argillaceous matrix (~40%) that resemble lava flows, with longitudinal furrows and ridges in its frontal lobe (Figs. 3g, h).

Harrington (1946) reported that Volcán area debris/ mud flows advanced rhythmically making jumps of 5-10 m every few seconds at velocities of 10-15 km/h. The larger fragments were deposited near the apex of the fan and the finer materials in the border more near the horizontal outer area of the fan. On the other hand, Polanski (1966) also described in the El Volcán area rhythmically advancing debris flow events in the form of internal waves with a ~ 15 km/h speed over 15 km, with some rapid and short-lived fluid episodes, locally showing a considerable thickness of sediments. According to several witnesses of the event, the debris flow that occurred in January 2017 had the same characteristics to those observed by these authors, i.e the larger clasts upstream national route 9 and a muddy, fluid and rhythmic behavior downstream, clearly manifested in the preserved buildings covered by up to 2 m of mud and debris carried by the flow, but without signals of destruction (Fig. 3d).

Gradient variations can be seen along the longitudinal river profile, with a concave shape upstream, slightly concave in the middle channel, and a relatively straight profile (very low concavity) at the end of the stream (Fig. 4f). Local distortions in the longitudinal profile represented by knickpoints are mainly due to lithological contrasts between the Precambrian metamorphic rocks, the Mesozoic sedimentary strata and the unconsolidated Quaternary alluvial deposits. However, a structural control is not ruled out.

The elevation map of the Los Filtros River shows the distribution of altitudes in meters along the basin, revealing a steep gradient oriented W-E (Fig. 5a).

The sediment transport capacity index SL (the distance from where the flow is originated, along its path, to where it concentrates or deposits) of the basin ranges from 0 to 376.8 (Fig. 5b). The larger the SL, the more water accumulates at the bottom of the field, increasing erosion.

The Topographic wetness index (TWI) was used in order to describe the effect of topography on the location and size of saturated areas of runoff generation (Nefeslioglu et al., 2008; Akgun and Turk, 2010). The TWI values calculated for the basin vary between 2.65 and 19.23 with a mean value of 5.89 (Fig. 5c). This indicates the probable existence of saturated soil conditions during rain events and the sediment accumulation (Beven and Kirkby, 1979). A comparison between the obtained TWI (Fig. 5c) values and the landslide occurrence showed a coincidence in the saturation and/or accumulation of material areas (Fig. 5d). This may be the result of the availability of lithological units with a relatively high permeability and low surface runoff. This map shows similar results to the sediment transport capacity index SL.

The slopes map shows gentler slopes in the headwaters of the basin and a bedrock with typically high slope angles and steep morphology, mainly in the hillside, with maximum slopes of 60° and an average of 29° (Fig. 5e). This gives a good indication of the areas that correspond to bedrock. The low slopes area in the end of the Los Filtros basin is the consequence of a repeated sequence of debris flows.

Landsat 8 OLI images provided by CONAE taken on 3 January 2017 were employed, at a spatial resolution of 30 m, to extract Normalized Difference Vegetation Index (NDVI) (Deering et al., 1975). The vegetation density was determined by NDVI in order to observe its relationship with a landslide area. The obtained values were on the closed interval [−1, +1]. Values approaching to +1 indicate dense vegetation while the values computed close to –1 indicate the lack of vegetation or bare lands. In the basin area, NDVI values were computed between 0.0611 and 0.8061 (Fig. 5f). Considering their spatial distributions, we concluded that approximately 76% of the study area is covered by dense vegetation with values of NDVI ranging from 0.3 to 0.8, and a small portion of approximately 6% is covered by rock, coincident with the sliding basin area. Nevertheless, due to the seasonal flora and the lack of perennial species, the vegetation cover as contributing factor is relative, depending on the season (Fig. 5f).

4.2. Sediment Sources and Supply

In some small low-order basins, located in mountain environments, a dramatic response to large flows is expected. In high relief areas such as first- and second-order basins, debris slides are important geomorphic processes that can drastically change the drainage network system. These kinds of events can occur in all climatic regions and should be considered as potentially devastating natural hazards (Honer, 2010).

Phyllites and unconsolidated alluvial deposits are relevant to debris flow process in the basin, as these rocks range in competency from slate or phyllite to metamorphosed pebble conglomerates that degrade to fine sands. The resulting product constitutes a significant source of relatively fine-textured sediment, easily mobilized in the channel, and capable of long run out distances due to its texture. That is why the current geomorphic activity contributing to the torrent’s recharge with debris, is concentrated exclusively in the headwater.

In addition, the river basin is strongly affected by large-scale and slow moving landslides during intense rainfall periods. Several landslides were confirmed to be present before the 2017 event, based on pre-disaster images (Figure 6a-c). Nearly all of them showed signs of enlargement or remobilization during the catastrophic event according to the post-disaster images (Fig. 6a'-c'). From the 2.39 km^2 identified as landslides area, 0.60 km^2 were classified as active and 0.089 km^2 as new slope failure area (from 2015 to 2017), associated to large-scale and slow-moving landslides. In some sectors, the crown of an inactive landslide retreated 53 m and the width near the crown increased from 58 to 89 m (Fig. 6c-c'). Comparison between satellite images taken before and after January 10, 2017's event let the authors find its initiation site and the main sediment-supplying zone in the upstream basin. Besides, figure 6d-d'compares pre-disaster scenario in the downstream river basin, with post-disaster situation after the January 2017, resulting in the widespread destruction of the Volcán village. Material from a large-scale landslide located in the middle of the basin, with several small-scale slope failures near the toe (mainly coarse rock fall debris, and small debris slides) constituted an abundant supply of loose debris that, lubricated by the rainfall and/or because of the erosion at the base were removed and incorporated into the riverbed that result in a debris flow (Fig. 7a, b). We selected this large-scale landslide in order to exemplify the major source and sediment supply to the river basin (Fig. 7c). The landslide covers an area of 0.49 km^2 with slope height of 419 m (from 2352 to 2771 m asl), a width of 802 m and a length of 984 m. At the toe of the slope a large bulge suggests that the river was dammed in the past (Fig. 7c).

5. Conclusions

Heavy rains occurred on January 10, 2017 caused the acceleration of large-scale and slow-moving landslides that triggered a debris flow/flood in the Los Filtros river basin traversing the National 9 trunk road and damaging the Volcán village. This event was favoured by the topographic and geological characteristics (gradient, lithology, sediment capacity, lack of dense vegetation, etc.) of the river basin that conditioned landslide generation that triggered a debris flow/flood. The slopes of the Los Filtros river basin show large-scale and slow moving landslides during torrential rainfalls providing loose debris to the riverbed that result in debris flows.

Most of the pre-existing alluvial fans are settlement areas and for several generations, people have lived in these landforms. Almost every summer, the slope failures interrupt the National Route 9, one of the main routes between Argentina and Bolivia. As a result of the impossibility to predict such events the evacuation of the population may result difficult. One way to mitigate the effects of debris flood and debris flows would be to allow only crops in high-risk areas, to reduce the harm to the population in case of a destructive event. Thus, it is necessary to make detailed hazard zonation maps with an inventory of landslides, size, activity, among other aspects. These studies are essential for an adequate land-use planning in mountainous areas. Finally, it is necessary to increase the existing knowledge of such events to provide specific skills and technical solutions for floods and debris flows prevention and control.

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Figure captions

Figure 1. a) Location of the Jujuy province in Argentina; b) Main villages of the Quebrada de Humahuaca; c) Map of Jujuy and Salta Provinces showing, in red dots, main affected areas, detailed in Table 1; d) Los Filtros river basin, Volcán Village and National route 9 locations. Surrounded by a black outline, the 2017 debris flow affected area; e) Average monthly rainfall for the Volcán village area, data from INTA EEA SALTA©Copyright 2002.

Figure 2. Aerial oblique views; a) To the south, showing the cut of the National Route 9; b) To the south, showing damages on the route and in the northern sector of the town; c) To the north, showing damages in the cement factory, route and town and d) To the northwest, showing the affected area in the town and the debris flow entering into the Grande River channel.

Figure 3. a) Westward view of the Los Filtros River basin. In the foreground, we can see the deposits carried by the flow; b) View to the east, downstream of the Los Filtros River basin, towards the town of Volcán; c) Damage to houses located west of National Route 9, d) Damages in the houses located along the San Martín street. It is possible to appreciate the mark that reached the flow in the walls of the buildings, e) Housing devastated by the flow; f) Detail of the debris deposit. The average size of the blocks is approximately 20 cm; g) View to the south of the debris flood deposit partially obliterating the riverbed of the Grande River; h) Detail of the previous photograph. Yellow arrows indicate furrows and ridges formed in the front of the flow because of the greater fluidity there.

Figure 4. a) Geological map of the Los Filtros River basin area (modified from Savi et al., 2016); b) Precambrian phyllites outcrops; c) Paleozoic limestones; d) Mesozoic sandstones; e) Quaternary alluvial deposits and f) Longitudinal the Los Filtros River profile.

Figure 5. a) Digital Elevation Model; b) Sediment transport capacity index (SL); c) Topographic wetness index (TWI); d) NDVI; e) Slope map; f) TWI and post-disaster Spot image of the Los Filtros River basin (Includes information © CNES 2017, Distribution Spot Image S.A., France, all rights reserved).

Figure 6. Pre-disaster and post-disaster Spot image of the Los Filtros river basin showing significant changes of the drainage after January 10, 2017 (Includes information © CNES 2017, Distribution Spot Image S.A., France, all rights reserved). a) and a') northern high basin; b) and b') south high basin; c) and c') middle basin, in circle is shown, as an example, a reactivated

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small slide, associated to a large-scale landslide, where the crown has increased from 58 to 89 m; d) Volcán village and National route pre-disaster and d') post-disaster.

Figure 7. a) Pre-disaster and b) Post-disaster Google Earth image of the Los Filtros River medium basin showing the selected large-scale a slow-moving landslide; c) Schematic model of main sediment sources and supply in the basin associated to large-scale landslide (concept after Hasegawa et al., 2008).

Table 1. Most catastrophic events occurred in northwestern Andes of Argentina (mainly Jujuy and Salta provinces) in the last century

Table 2. Morphometric parameters of the Los Filtros River basin.

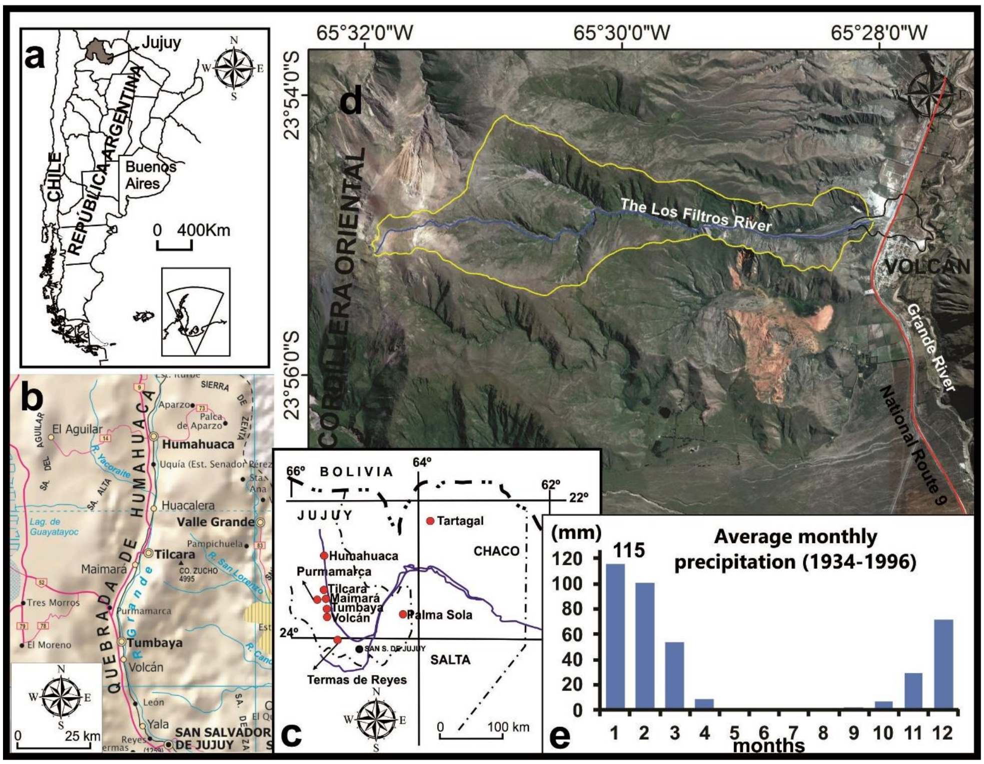

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Figure 1

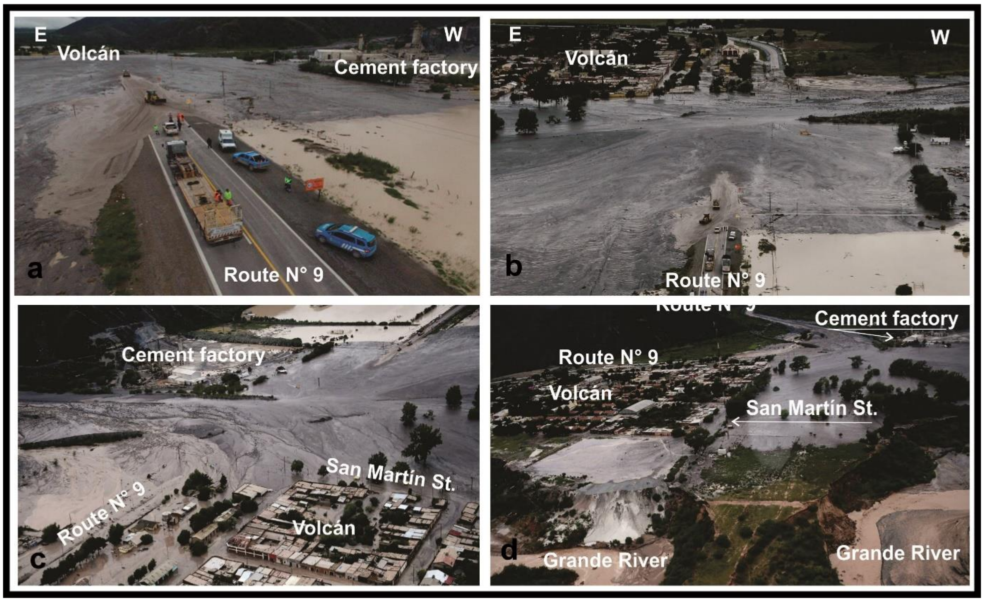

Figure 2

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1

2 Figure 3

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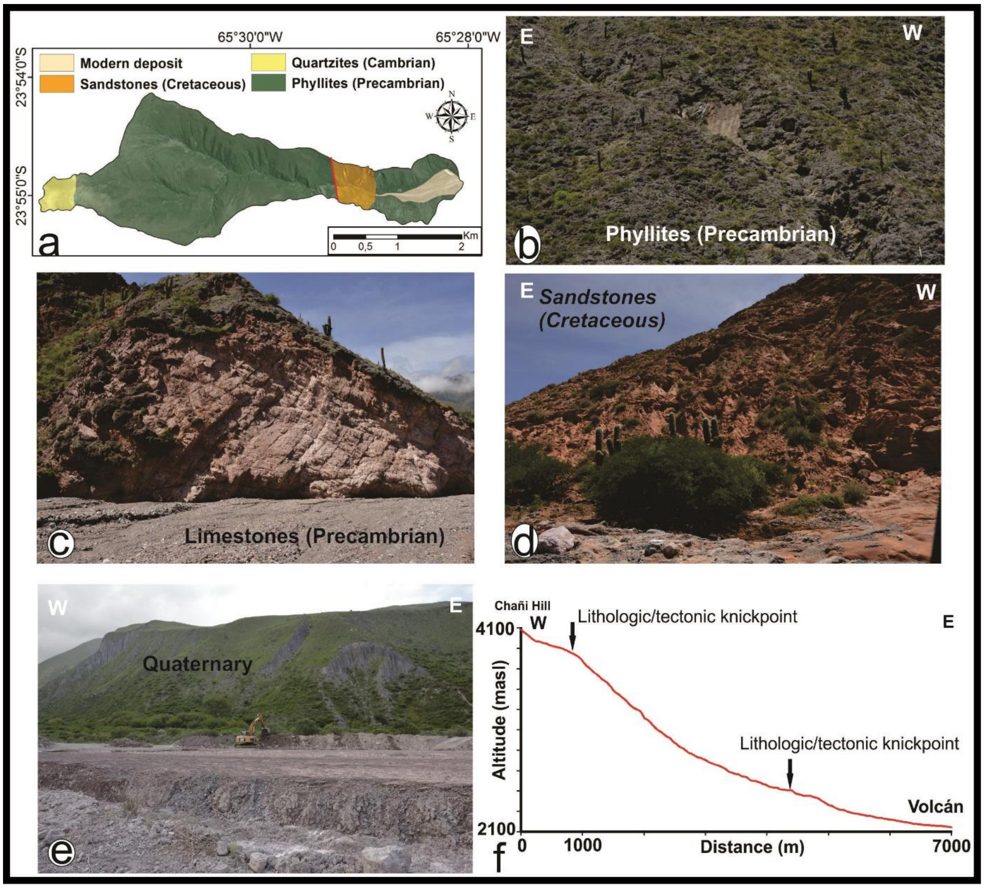

Figure 4

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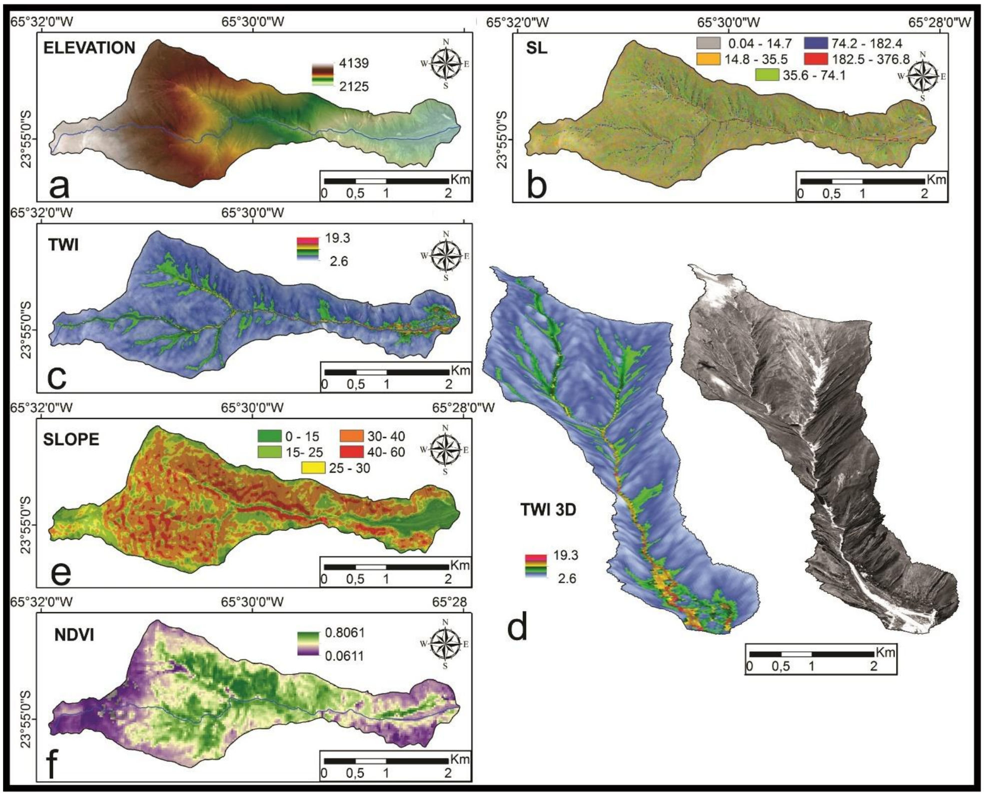

Figure 5

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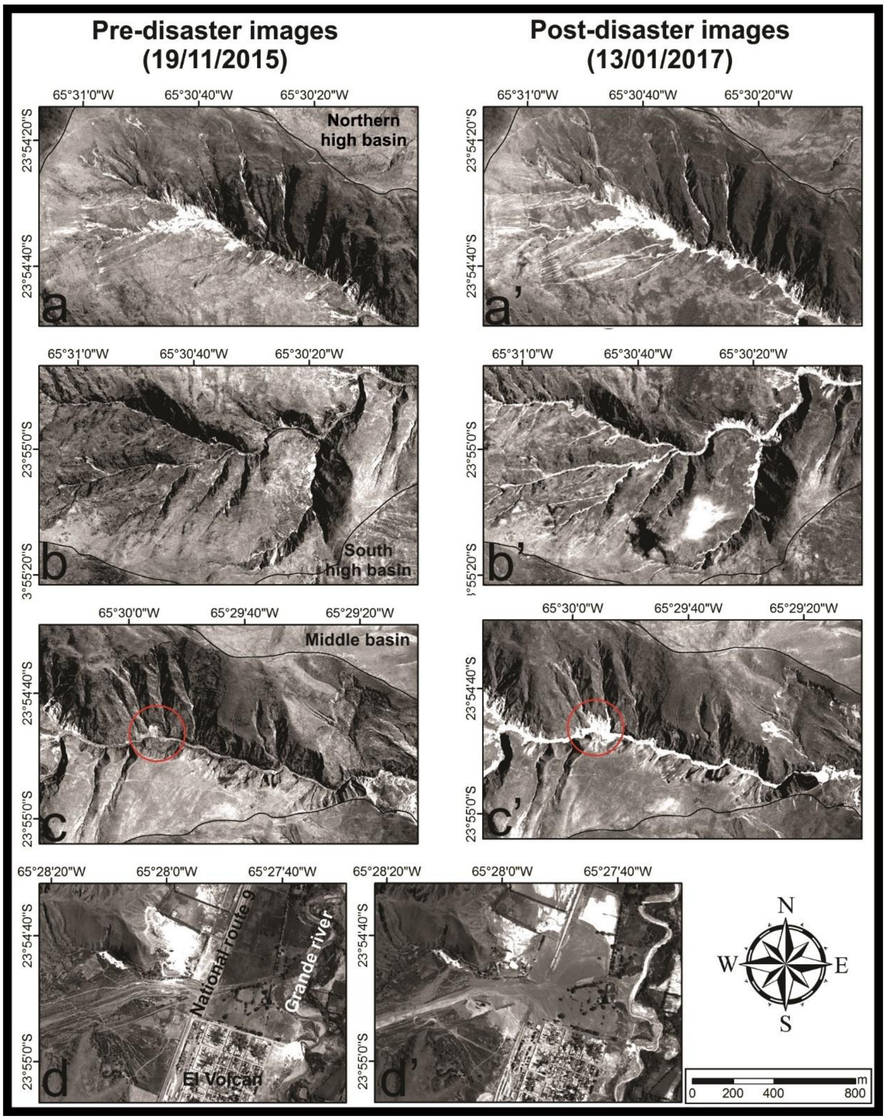

Figure 6

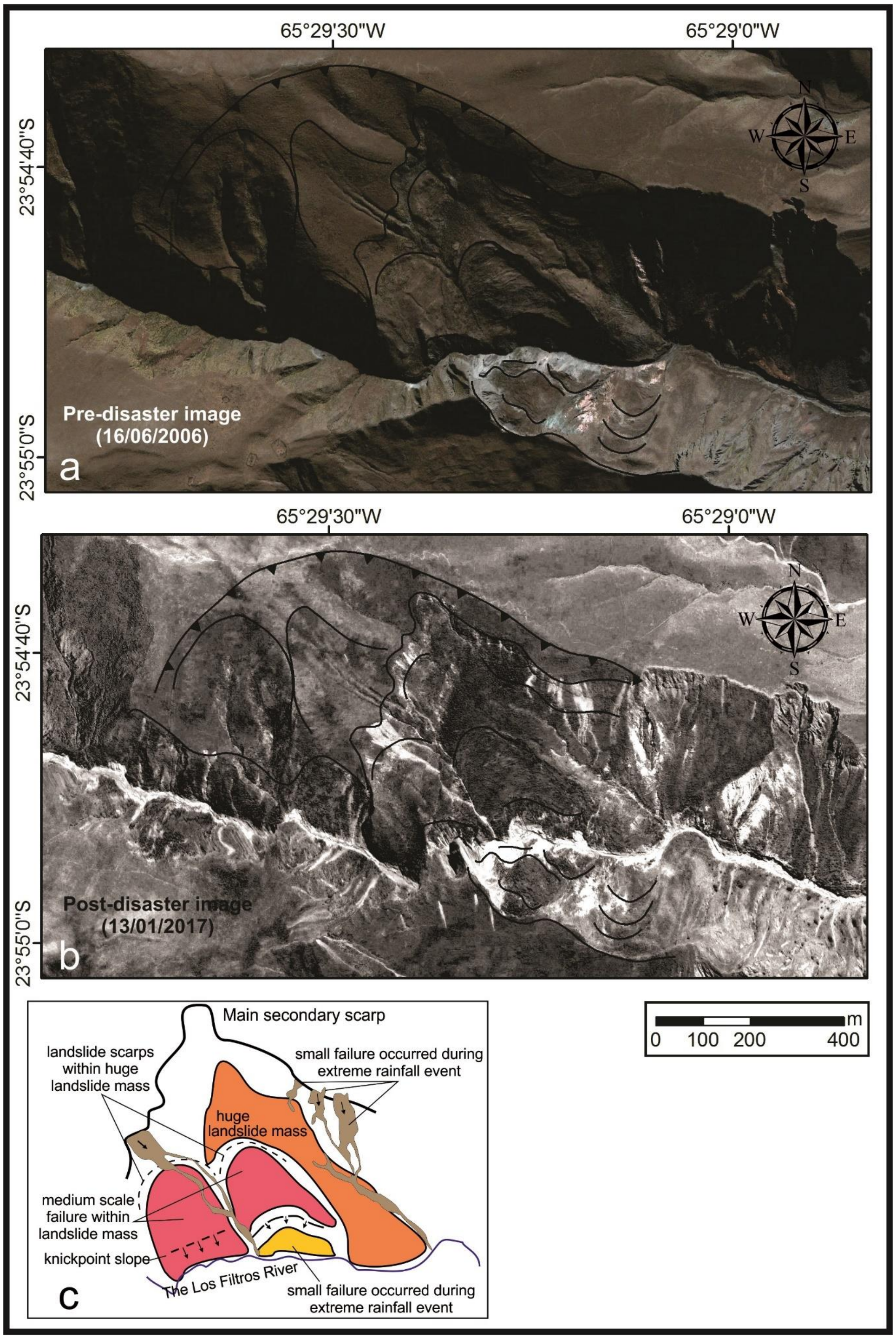
65°29'30"W
65°29'0"W
23°54'40"S
23°55'0"S
N
W
E
S
Pre-disaster image
(16/06/2006)
a
Post-disaster image
(13/01/2017)
b
Main secondary scarp
landslide scarps within huge landslide mass
small failure occurred during extreme rainfall event
huge landslide mass
medium scale failure within landslide mass
knickpoint slope
The Los Filtros River
small failure occurred during extreme rainfall event
c
m
0
100
200
400

Figure 7

Date	Region affected	Fatalities and damaged caused	Mechanisms involved	References
March 2, 1945	Quebrada de Humahuaca - Volcán village	The Grande River dammed forming a 2 km long lake that flooded the Volcán village. Town destruction. Loss of agricultural production. Isolation and food shortage.	Debris flood	Castro (2001)
February 18, 1969	Tumbaya village, Jujuy province	The event interrupted the road and rail communication. Damages to the cemetery and town.	Debris and mudflows	Castro (2013)
January 11, 1974	Tilcara, Humahuaca, Tumbaya and Maimará villages, Jujuy province	82 evacuated, 167 affected, 26 ha destroyed (most in Tilcara); Losses for farmers. Declaration of state of emergency throughout Provincial territory.	Debris flood	Castro (2013)
Summer, 1983	Tilcara village, Jujuy province	Two tourists lost their lives and the deposits dammed the Grande River valley, forming a lake.	Debris flood	Cencetti et al. (2004) Marcato et al. (2009)
February 2, 1984	Purmamarca, Tilcara; Tumbaya and Humahuaca villages, Jujuy province	Interruption of communications (the rail service remais interrupted for two months). 13 fatalities. Purmamarca station buried by the mud. Destruction of homes, 150 evacuated. Loss of crops, 100Ha were affected by the destruction of irrigation channels.	Debris and mudflows	Castro (2013)
February 2, 1985	Volcán, Purmamarca, Maimará, Humahuaca villages, Jujuy province	More than 4 m of thick deposits covered a large area, resulting in the complete destruction of a railway bridge, the interruption of the National Route 9. Railroad tracks destroyed. Partial flooding of Humahuaca localities (more than 200 houses affected, more than 50 evacuated). In Maimará there is an 80% loss of crops.	Debris flow	Cencetti et al. (2004) Marcato et al. (2009) Castro (2013)
April 4, 2001	Palma Sola town, Jujuy province	Severe damage to the irrigation infrastructure, land, people and buildings.	Debris flood	González Díaz and González (2002)
April 4, 2006	Tartagal city, Salta Province	The event destroyed or severely damaged bridges and roads along the course of the Tartagal River, which caused the city of Tartagal to be practically isolated.	Debris flood	Latrubesse and Brea (2009)
March 7, 2007	Purmamarca, Jujuy province	The design capacity of bridges was drastically reduced by the obstruction caused by the uprooted trees.	Debris flow	González et al. (2009)
March 25, 2007	Purmamarca, Jujuy province	The event devastated everything existing along its way to Purmamarca.	Debris flow	González et al. (2009)
February 9, 2009	Tartagal city, Salta province	The event dragged a large, unusual amount of sediment and trees. The collapse of a railway bridge caused the blockage of the riverbed, flooding the city. 3 dead, 600 evacuated and 10,000 injured	Debris flood	Brea et al. (2013)
January 12, 2010	Comedero River, Termas de Reyes, Jujuy province	Devastated everything existing along its way, causing 87 injured and severe material damage.	Mud flow	González et al. (2012)
December 11, 2012	Volcán village, Jujuy province	Affected the Volcán village, damaging the National Route 9 and several buildings.	Debris flow/flood	El Tribuno Newspaper (2012)
January 10, 2017	Volcán village, Jujuy province	The event raced down the Los Filtros river basin until it finally arrived at the Volcán village leading to great destruction. 4 deaths	Debris flow/flood	The present research

Table 1

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The Los Filtros river basin						
A [km^2]	**P [km]**	**L [m]**	**H [m asl]**		**h [m asl]**	
6.91	16.30	6605.67	4139		2125	
Circularity index	**Elongation ratio**	**Form factor ratio**	**Sinuosity index**	**Melton ratio**	**Mean Width**	**Basin rel**
$Rc = 4\pi A/P^2$	$Re = \sqrt{(4A/\pi)}/L$	$Ff = A/L^2$	S = Lcp/L	Wm=A/L	Hr = H − h	Rr = Hr/L
Miller (1953)	Schumm (1956)	Horton (1932)	Schumm (1977)		Hadley and Schumm (1961)	Schumm (1956)
0.33	0.45	0.16	1.15	1046.18	2014	0.30

Table 2