Recent catastrophic debris flows in Chile: Geological hazard, climatic relationships and human response

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Abstract

Debris flows are an important type of geological hazard in Chile, affecting cities, towns and rural areas throughout the country despite the variation in climate regimes. In this summary paper, recent debris flows in the cities of Antofagasta and Santiago, in northern and central Chile, and in a rural area near Lake Ranco in central-southern Chile in 1991, 1993 and 2004, respectively, are reviewed. Triggering factors for flow occurrence are identified and different approaches to debris flow hazard assessment and the effects of debris flows on people and the environment are discussed. Furthermore, the relationships between debris flow occurrence and climatic anomalies such as El Niño episodes are analysed. A clear pattern of debris flow generation associated with El Niño events is found for Antofagasta and Santiago. The risk related to debris flows in Chile is of increasing importance because of the continuous expansion of cities to hazardous areas such as alluvial fans. The results show that hazard assessment based on several factors is essential for the implementation of proper prevention and mitigation measures for future debris flow events in the country.

1. Introduction

Debris flows are one of the most common types of geological hazards in Chile. The geographical and geological configuration of the country, located along the convergent boundary between the Nazca and Pacific plates, and the related orogeny of the Andes, is favourable for the generation of all types of landslides. The usual location of cities and towns in valleys and alluvial fans at the foothills of mountain ranges has implied that many cities and villages, as well as inhabited rural areas, are in hazard zones. The main hazards are debris and mud flows that are generated in the nearby mountains and reach the plains along the drainage system.

Flows are a type of landslide that consists of a spatially continuous movement of a saturated mass of earth materials, such as debris and mud, mainly controlled by gravity and whose movement mechanics resembles that of a viscous liquid (Cruden and Varnes, 1996). A debris flow is a very rapid to extremely rapid flow of saturated debris in a steep channel, such as a gully or a ravine (Hungr et al., 2001). When the material is plastic, usually associated with a higher amount of fine particles, the flow is termed a mudflow (Hungr et al., 2001). Flows are usually triggered by heavy rainfall on loose soil deposits or by landsliding on slopes. They commonly pose a hazard, particularly due to their great velocity (several tens of km/h), long run-out distance (several km) and their capacity to transport large and heavy items such as trees and rock blocks several metres in dimension, implying significant destructive power (Sepúlveda, 2000).

In Chile, debris flows are usually triggered by heavy rainfall, although the amounts of precipitation required to initiate the flows are very variable according to the climatic regime. Climates in Chile vary from dry tropical in the north to tundra in the extreme south (Magellan's Strait region). In the north (about 18–26°S), precipitation of less than 2 mm/yr typifies extremely dry conditions and characterizes the world's driest desert, the Atacama. After a transition zone with a steppe climate, the central part of Chile (32–38°S), and the most populated region of the country, has a warm temperate, Mediterranean-like climate, with precipitation that varies from 300 to around 1000 mm/yr, increasing to the south. In the central-southern part of Chile, including the Araucania and the Lakes

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District regions (38–42°S), the climate can be classified as rainy temperate, where the annual rainfall is around 1000–2000 mm/yr. South of 42°S, in the Patagonia, the climate is colder and less rainy in the continent, although heavy rainfall of up to 4000 mm/yr can be registered in the coastal islands (Dirección Meteorológica de Chile, 2005).

Over the last 20 years, cities and towns located all along the country have suffered debris flows associated with heavy rains. In this review paper, three recent cases of debris flows with an important impact on society are compared. They have been triggered in parts of the country with different geographical and climatic characteristics. The flows of 1991 in the coastal city of Antofagasta, northern Chile and the event of 1993 in the capital city of Santiago, central Chile (Fig. 1), are reviewed, and new data on flows that affected a rural area on the shores of Lake Ranco, central-southern Chile, in 2004, are presented.

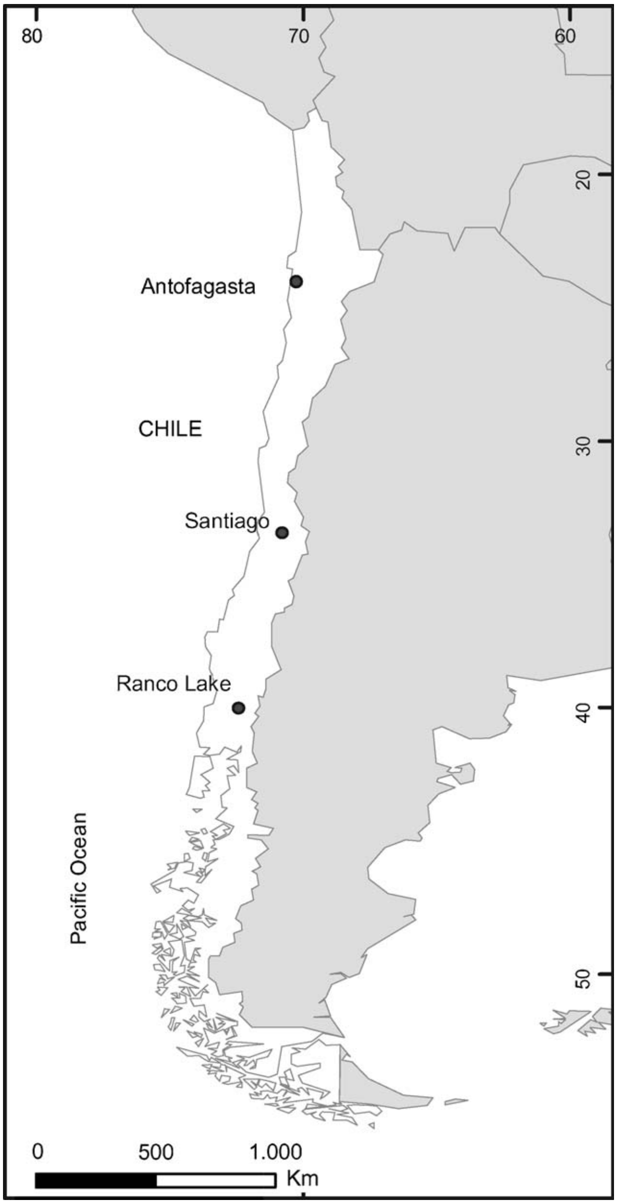

Fig. 1. Map of Chile showing the three studied locations affected by debris flows.

The three events were triggered by heavy rainfall on hilly terrain, and caused fatalities and important economic losses in damage of housing and infrastructure. In this paper, the geological and physical characteristics of the flows are reviewed and discussed from the perspective of hazard assessment. New insights into relationships of the flow occurrence with climatic events such as El Niño are presented. Finally, the social impact of the flows and the response and attitude of the society to them are also discussed.

2. The 1991 Event in Antofagasta, Northern Chile

2.1. Geomorphological and geological context

The city of Antofagasta (23.5°S, Fig. 2) is situated in northern Chile, in a narrow coastal belt (<3 km wide) between the coastline and the coastal escarpment, which is a major geomorphological unit that reaches more than 500 m a.s.l. It constitutes the western limit of the Coastal Cordillera (Fig. 3), a mountain range characterized by elevations higher than 1000 m a.s.l. adjacent to the city. This unit is drained by several ravines, or *quebradas*, characterized by sporadic alluvial discharge in a dominantly arid climate (<4 mm of mean annual rainfall). This geomorphological setting favours the generation of debris flows during rare heavy rainfall episodes in this area (Vargas et al., 2000). The geology of the western side of the Coastal Cordillera is characterized by volcanic Jurassic rocks of the La Negra Formation and, in the southern part of the city, by Cretaceous conglomerates of the Caleta Coloso Formation (Ferraris and Di Biase, 1978).

Major drainage basins in the city area are associated with the Salar del Carmen and La Negra ravines, with catchment areas of 33 and 43 km^2, respectively (Fig. 2). The gradients of the ravine channels exhibit a change from a mean of 1° within the Coastal Cordillera to 2–5° in the area of the coastal escarpment before the coastal belt. Other important catchments are associated with La Chimba and La Cadena *quebradas*, with areas of 26 and 21 km^2, respectively. A change in the mean channel gradient from 5–6° in the area of the mountains to 8–9° in the coastal escarpment also characterizes these ravines. Finally, a series of minor catchments with areas between 0.5 and 9.2 km^2, such as El Toro and Baquedano, among many others, also drain the western side of this mountain range in the city area. In these last cases, the change in the gradient of the ravines reaches its maximum, from 3–20° in the mountain area up to 16–30° in the coastal escarpment (Fig. 2).

These gradient changes, which most probably characterize a knick point associated with the erosion of the coastal escarpment during Pliocene–Pleistocene times (Vargas et al., 1999), impart additional stream power to the debris flows above the coastal belt, where the city is located. The

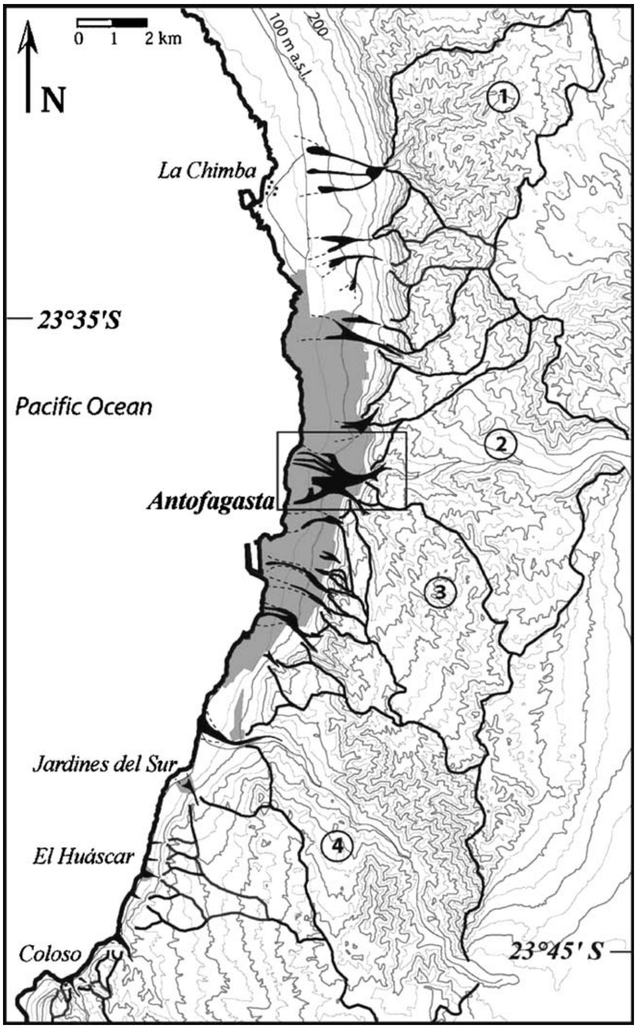

Fig. 2. Map of Antofagasta, showing the catchments that drain the Coastal Cordillera to the west, and areas affected by the 1991 debris flows (in black) in the coastal belt (modified from Vargas, 1996; Hauser, 1997; Vargas et al., 2000). Major catchment areas: (1) La Chimba, (2) Salar del Carmen, (3) La Cadena and (4) La Negra. (modified from Vargas et al., 2000). Contour intervals every 50 m. Rectangle indicates the location of Fig. 3.

availability of material is a product of the high density of fractures in the volcanic rocks of the La Negra Formation, which forms gravel and boulders typically between 5 and 15 cm in diameter, and in the conglomerates of the Caleta Coloso Formation. Furthermore, the availability of aeolian sand in the drainage basins and the occurrence of dunes at the base of the coastal escarpment in the southern and northern segments of the city are responsible for the sandy fractions in debris flow deposits of these areas, in comparison with large gravel and boulder content in debris flow deposits in the central part of the city.

The coastal belt is constituted by Late Pliocene, Pleistocene and Holocene marine terraces, characterized by altitudes ranging from the coastline (Holocene) up to 200–300 m a.s.l. (Late Pliocene; Ortlieb et al., 1997; Vargas et al., 1999). Alluvial fans constituted by debris flow deposits are developed over these marine terraces (Fig. 4). The most recent Holocene unit pro-graded from the mid- and late-Pleistocene units as the result of (1) the continuous regression of the coastline due to continental uplift during the Late Pliocene–Pleistocene period, (2) the succession of high and low sea level stands associated with the occurrence of glacial and interglacial periods and (3) the occurrence of hydrological variations, most probably related to climate changes during the Pleistocene and Holocene (Vargas, 1996; Vargas and Ortlieb, 1998; Vargas et al., 1999, 2000). Most of the city is built over Holocene alluvial fans along the coastal belt, which are constituted mainly of massive debris flow deposits with boulders and gravel (Fig. 4) with, locally, channel facies at the bottom of the ravines. This setting constitutes an evident risk during the occurrence of debris flows, as happened in the major 1991 event.

2.2. *The 1991 debris flows*

The last major debris flow event in Antofagasta occurred on 18 June 1991. According to Garreaud and Rutllant (1996), the occurrence of heavy rainfalls in this area was associated with a series of climatic anomalies that favoured atmospheric convergence and precipitation, associated with the arrival of convective storms concomitantly with the characteristic weakening of the South Eastern Pacific Subtropical Anticyclone during El Niño episodes (Rutllant and Fuenzalida, 1991). El Niño corresponds to the warm phase of the El Niño Southern Oscillation (ENSO) climatic phenomenon, intensively studied in recent years.

The recorded rainfall intensity at downtown Antofagasta attained a maximum value of 24 mm/h, with a total accumulation of 42 mm in 3–4 h (Garreaud and Rutllant, 1996). Heavy rainfalls began at 00:30 h and stopped at 03:30 h. Three hours after the beginning of heavy rains, inundations and minor debris flows occurred, and after 3.5 h, major debris flows affected most of the city (Hauser, 1997; Vargas et al., 2000).

The most important alluvial discharges occurred in the Salar del Carmen, La Negra, La Chimba and La Cadena *quebradas* (Fig. 2), which left massive debris flow deposits 1 m thick in proximal areas of the alluvial fans along the coastal belt (Vargas et al., 2000). These deposits were characterized by 50–80% angular gravel and boulders of 5–15 cm diameter, 20–45% sand and <3% fines. Particularly coarse deposition occurred in those proximal areas of the Holocene alluvial fans associated with minor ravines in the central part of the city, where 1 m diameter boulders were commonly observed and deposits were locally 2–3 m thick. Immediately to the south and north of the city, the availability of aeolian sand in the catchments and/or the coastal belt produced debris flow deposits with 40–70% sand. Traces of fine particles along the ravine slopes allowed the determination of the corresponding maximum flow-height.

In the Salar del Carmen, La Negra and La Cadena ravines, maximum flow-heights of 3 m observed in slopes

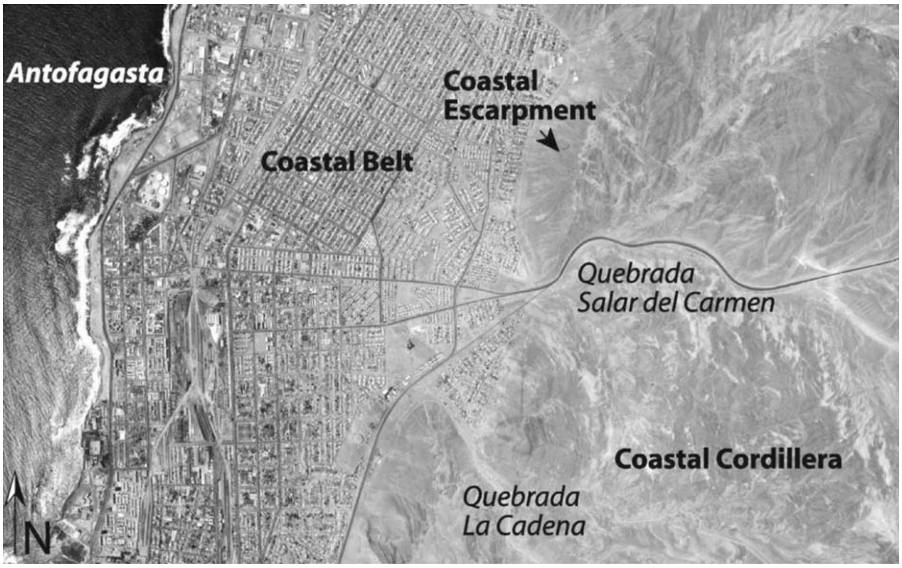

Fig. 3. Aerial photograph of Antofagasta in the discharge area of the Salar del Carmen and La Cadena Ravines (location in Fig. 2). This area was the most strongly affected by the debris flows during the 18 June 1991 event. According to Vargas et al. (2000), most of the city is located over Holocene alluvial fans.

Fig. 4. Detail of historic debris flow deposits associated with a minor ravine in central Antofagasta, in the middle zone of the alluvial fan.

Fig. 5. Debris flow deposits from the 1991 event at *quebrada* El Toro, south of La Cadena (Figs. 2 and 3) in central Antofagasta, which destroyed and covered installations of the Chilean Army.

above the coastal belt were associated with 1 m thick deposits, while in minor *quebradas* in the central part of the city, maximum flow-heights of 2–6 m were associated with 1–3 m thick deposits (Vargas et al., 2000). According to Hauser (1997) and Vargas et al. (2000), the development of waves in the debris flows could be partly related to the collapse of artificial dams associated with the artificial extraction of material at the bottom of the ravines.

The most important damage was produced in the central-northern part of the city, in Holocene alluvial fans associated with the Salar del Carmen and La Cadena *quebradas*. Important damage also occurred in ravines and proximal areas of alluvial fans located downstream from minor ravines, particularly in the central part of the city (Fig. 5).

Damage associated with this catastrophic event is well documented. The disaster resulted in 103 fatalities, and 16 people disappeared. Hundreds were injured. About 500 houses were completely destroyed and 2500 were severely damaged (ONEMI, 1996). In order to provide the basic necessities, 8000 people had to be sheltered. The debris flows destroyed and interrupted several roads. All the access routes to the city were interrupted, the northern access being recovered in the short term while the southern access was reopened only after one year. Most of the city streets were covered by flow sediments.

According to Hauser (1997), debris flows transported at least 7–8 × $10^5\,m^3$ of sediments. Of this quantity, $4.2 \times 10^5\,m^3$ of material was removed from the central part of the city. Schools, hospitals and surgeries, sporting areas and public buildings were partially destroyed. An electrical power shutdown due to the damage to six electrical suppliers affected 25,315 people. Electrical service was restored only 8 days later. The flows also produced serious damage to water supply and sanitary drains. Three potable water main pipes were damaged, causing an emergency due the lack of this vital element. Part of the necessary water was brought from the south of the country (ONEMI, 1996).

The total cost of the catastrophe reached US$66 million, 75% corresponding to property and infrastructure and 25% to a decrease in economic activities. The greater losses were in basic social infrastructure: 62% corresponding to urban and interurban infrastructure and 22.5% to housing (ONEMI, 1996). Mining and industry were the most affected private sectors.

3. The 1993 Event in Santiago, Central Chile

3.1. Geomorphological and geological context

The city of Santiago (33.5°S) is located in a valley filled with fluvial and alluvial sediments of the Maipo and Mapocho Rivers. The eastern fringe of the city is composed of a north–south trending mountain range that delimits the valley between both rivers, with a length of about 25 km (Figs. 6 and 7). The peak altitude of this range is 3253 m a.s.l. (Mt. San Ramón), being more than 2000 m above the city. This range forms the foothills of the Andes Main Cordillera in the area, which is drained towards the city by several ravines with average gradients exceeding 15° and tributary gullies that may have gradients exceeding 30°. The main ravines of this system are San Ramón and Macul, with drainage basins of 38 and 23 km^2, respectively.

The San Ramón Range is composed of Palaeogene stratified volcanic and sedimentary rocks of the Abanico Formation (Thiele, 1980). The unit is faulted and folded, the upper part of the mountains showing subvertical dips and moderate to strong jointing, whereas lower down it dips gently to the east. The subvertical bedding creates a structurally controlled network of small gullies that form a very efficient drainage system (Naranjo and Varela, 1996). The steep slopes (20° to >40°) combined with jointing and weathering processes generate important colluvial deposits

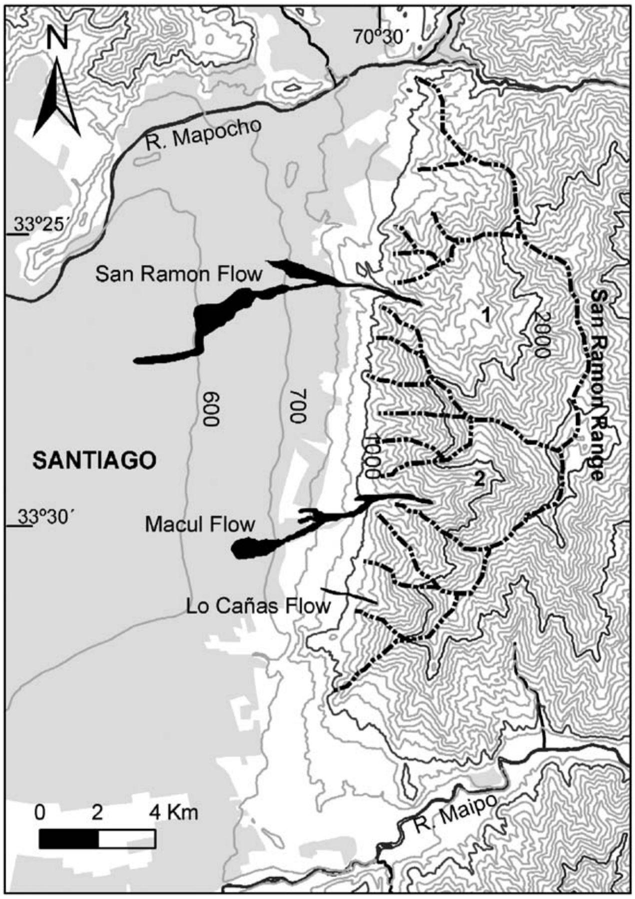

Fig. 6. Map of eastern Santiago, showing the zones affected by the 1993 debris flows (deposition areas) and the boundaries of the drainage basins (dashed lines) that drain the San Ramón Range. (1) San Ramón, (2) Macul. Contour intervals every 100 m.

Fig. 7. Panoramic view of the San Ramón Range next to the city of Santiago.

formed by loose rock blocks and boulders in a fine matrix, as well as old landslide deposits of similar composition. These materials are gradually transported by the drainage system and accumulate in ravines and stream confluence areas, where they can be remobilised as debris flows during heavy rain episodes. The main ravines have an associated alluvial fan along the border of Santiago Valley. These fans are composed of alluvial and mass movement materials, and are increasingly being occupied by houses and buildings.

Santiago has a Mediterranean climate. Precipitation falls mainly in winter, whereas the summer is dry and warm. The annual average humidity is just above 70%. In winter, snow usually falls above 1500 m a.s.l. The average annual rainfall ranges from 312 mm in the city centre to over 350 mm in the foothills. The temperature difference between daily minima and maxima is 14–16°.

3.2. The 1993 debris flows

On 3 May 1993, a number of debris flows that originated in the ravines of the San Ramón Range invaded the eastern neighbourhoods of Santiago. The main flows occurred in the *quebradas* of San Ramón and Macul (Naranjo and Varela, 1996), while some smaller flows in minor ravines were also reported (Sepúlveda and Rebolledo, 2000). From the evening of 2 May until the midday of 3 May, a frontal system produced heavy rainfall over the Andean Precordillera of central Chile, concomitantly with warm conditions in the troposphere, during a moderate El Niño event (Garreaud and Rutllant, 1996). Although the total daily rainfall in Santiago City was around 30 mm, the maximum rainfall intensity reached 12 mm/h in eastern Santiago at 11:00 h, which is a high value expected only every 25 years (Garreaud and Rutllant, 1996). Rainfall recorded in the previous evening was less than 10 mm (Naranjo and Varela, 1996).

Due to orographic control, the expected average rainfall in the drainage basins of Macul and San Ramón ravines was 67 mm/day, with intensities of up to 18 mm/h (Lara, 1996). These values are just over the triggering rainfall threshold of 60 mm/day estimated for debris flows in the Andean Precordillera at the latitude of Santiago (Hauser, 1985), or the predictive relationships for triggering rainfall intensity-duration proposed by Caine (1980). Altogether, anomalously warm tropospheric conditions associated with the influence of tropical air masses produced a rise of the 0 °C isotherm from its average altitude around 2600 to 4000 m a.s.l. at 20:00 h on 2 May, dropping to 3850 m a.s.l. at 08:00 h on 3 May. These anomalous conditions have a return period of 10 years (Garreaud and Rutllant, 1996).

On 3 May, the heavy rain on the loose, partially saturated soil deposits in the ravines and slopes, together with an increase of runoff, saturated and fluidized the soils, forming the debris flows. The same meteorological event produced mudflows, river overflows and flooding in the Main Cordillera east of Santiago (Maipo Valley) and in two other regions north and south of the city, isolating ten towns and interrupting the transit on 26 roads (ONEMI, 1995).

The flows of Macul and San Ramón mobilized over $2\times10^6\,m^3$ of material. The dense and viscous mass transported rock blocks of several metres, as well as trees and vehicles. According to witnesses and observations after the event, the flows moved with velocities exceeding 30 km/h and the waves reached heights of over 10 m (Naranjo and Varela, 1996). The flows reached the city in a few minutes, destroying or damaging more than a thousand houses. The overflow of the channels greatly expanded the area affected by the flows, which changed into mudflows in the more distal parts that ran following streets and avenues, and flooding the houses with mud and water (Fig. 6). For example, the discharge at the "Zanjón de la Aguada", an artificial channel that drains *quebrada* Macul across the city, suddenly rose from $7\,m^3/s$ to well over $50\,m^3/s$, causing flooding (ONEMI, 1995).

The flows left deposits that varied according to their location. Deposits left in the ravines are generally scarce, due to the steep and narrow morphology and the great energy of the flows. Isolated blocks of 5–10 m diameter were deposited (Naranjo and Varela, 1996). In some parts levées formed along the edge of the channels, leaving angular blocks in a sandy and gravelly matrix (Naranjo and Varela, 1996; Sepúlveda, 1998). In the alluvial fans, the flows formed deposits around 1 m thick on average, with silt, sand and blocks of up to 5 m, plus an important number of tree trunks in the case of Macul. Deposits of fine-grained materials with isolated blocks were formed toward the edges and toes of the fans, due to muddy overflows of the channels and the reduction in flow energy (Naranjo and Varela, 1996).

According to government accounts (ONEMI, 1995), 26 people died and eight were reported missing. Over 5000 houses were damaged or flooded by the flows, and 307 were destroyed. Over 28,000 people were affected by the event. As the area of the disaster is mainly residential and the flows occurred around noon on a workday, many people were not at home at the time of the event, which considerably reduced the number of direct victims. A rough estimate based on different sources accounts for around US$5 million in damage and costs (ONEMI, 1995).

4. The 2004 event at Lake Ranco, central-southern Chile

4.1. Geomorphological and geological context

Lake Ranco (40.2°S) is one of a series of lakes formed by moraines deposited during the last glaciation. It is located in the Andes foothills in the municipality of Futrono, administrative province of Valdivia in the Chilean Lakes District. The area has a rainy temperate climate with rain distributed throughout the year, but showing a peak in winter, with a yearly total over 1800 mm. The rainfall distribution is locally affected by orogenic factors, with

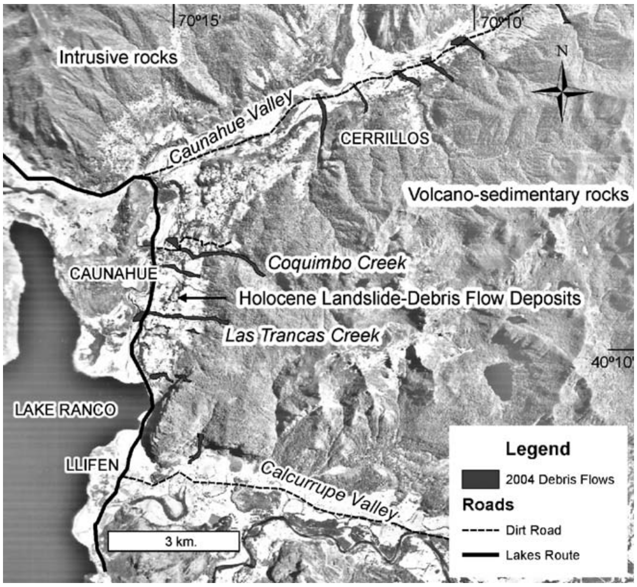

Fig. 8. Aerial photograph of the north-eastern shore of Lake Ranco showing the morphology of the area, and marking the extension of the debris flows triggered on 28 August 2004.

Fig. 9. View of part of the overflow of the Las Trancas Creek, Lake Ranco area, which destroyed three houses and around 500 m of road, with one fatality. The house at the right was displaced about 20 m by the flow.

Fig. 10. Gully formed by the Coquimbo Creek debris flow in Lake Ranco, due to erosion of Holocene landslide and alluvial deposits. Note the dirt roads cut by the gully.

higher precipitation on the western slopes and foothills of the mountains. This climate generates a dense montane vegetation cover, particularly below 2000 m a.s.l.

The morphology of the area adjacent to the north-eastern shore of the lake, where debris flows are abundant, is characterized by glacial valleys with steep slopes that form a network draining into the lake, the main ones being the Calcurrupe and Caunahue River valleys. The geology is dominated by a massif of Oligocene–Miocene volcanic and sedimentary rocks known as the Lake Ranco Strata (Campos et al., 1998), intruded by Miocene granitoids. This massif has steep ($>30^\circ$) slopes and is drained by narrow and deeply incised ravines. The foothills of the massif between the Caunahue and Calcurrupe Rivers are covered by Holocene landslide and debris flow deposits (Fig. 8).

4.2. *The 2004 debris flows*

On 28 August 2004, around a dozen debris and mud flows were triggered in the rural areas of Caunahue and Cerrillos, north-east of Lake Ranco (Fig. 8). The flows occurred about 5 h after the beginning of heavy rainfalls, which were recorded at 178 mm/day in a station located about 15 km from the sites. The flows were characterized by a large content of tree trunks, plus rock blocks and mud. The event caused one fatality, about 55 people were directly affected and significant damage was caused to rural houses and several roads, including the recently inaugurated tourist "Lakes Route" (Fig. 8). This road was destroyed over ~500 m due to the blocking of a culvert in the crossing of the Las Trancas Creek (Fig. 8), which caused an overflow that destroyed three houses (Fig. 9) and severely injured two people, one of whom died soon thereafter.

All the flows were triggered in gullies and ravines that drain the massif of volcanosedimentary rocks. They originated as shallow soil slides and by the remobilization of unconsolidated sediments deposited in the ravines. The abundant vegetation and some illegal wood exploitation contributed to the addition of trunks to the flows. In some cases, the trunks may have produced transient dams that produced pulses of flows downstream when they broke. The flows generally remained inside the channels until reaching the low-gradient areas near the rivers, where they deposited the material and stopped. Some of the flows were of high kinetic energy. For example, in the Coquimbo Creek (Fig. 8), the flow was dammed naturally at some point by blocks and trunks and diverted, eroding Holocene landslide and alluvial deposits, forming a gully about 10 m

Table 1
Triggering and antecedent rainfall for debris flow events cited in the text

Place	Date of debris flow event	Triggering rainfall (mm/day)	1-week antecedent rainfall (mm/week)	1-month antecedent rainfall (mm/month)
Antofagasta	18 June 1991	42.0	0	0
Santiago	3 May 1993	35.8	15.5	153.5
Lake Ranco	7 May 1995	26.4	290.5	493.4
Lake Ranco	28 August 2004	178.8	91.6	144.5

Source: Hauser, 1997; Ministry of Public Works database.

wide and up to 8 m deep (Fig. 10), transecting a rural road and isolating the people who live upstream. Overflow deposits in the Las Trancas Creek suggest that the flow at this site reached heights exceeding 7 m.

The debris flows originating in the main ravines left deposits of blocks, sand and mud usually no more than 1 m thick. The blocks were in general 30–50 cm in diameter, with a maximum of 3 m. In contrast, smaller mud flows generated closer to the edge of the rocky massif formed deposits usually less than 0.5 m thick, composed mainly of mud and sand, with a low content of blocks. Tree trunks are common in both types of flows.

Although the level of damage was not extremely high because of the absence of large urban areas and because the flows took place during the low tourist season, their recurrence as observed in Holocene deposits suggests that they pose an important hazard. Furthermore, according to local people, small flows are common in winter. An important event similar to that of 2004 also occurred about 40 years ago. In May 1995, a number of flows also produced some local damage in the Coquimbo Creek and north of the Cerrillos area, triggered after a week of accumulated rainfall (Toro, 2005; Table 1).

5. Discussion: some key issues for geological hazard assessment of debris flows

5.1. General properties of flows and triggering factors

The significance of debris flows in Chile is large from a statistical point of view, being the type of landslide hazards of higher impact in the last decades. Despite this, the development of detailed studies and hazard assessment is still insufficient because of the low number of specialists and the low priority given by local authorities to the preventive evaluation of the associated hazard and risk. The climatic and geological diversity along the country makes difficult the use of a common approach to the studies that are largely site dependent.

The events described in this paper show diversity, with examples of flows of rather different volumes, runout and deposit characteristics. One common feature that appears in the studied events is that flows are usually generated in more than one ravine for the same event, and that the source materials are generally loose sediments deposited in the higher parts of the drainage basins rather than landslides from the slopes. In small ravines such as those in the Lake Ranco area and tributary gullies of the main ravines in Antofagasta and Santiago, the flows can clean out the channels during the event (Naranjo and Varela, 1996; Hauser, 1997; Vargas et al., 2000; Toro, 2005). However, the main ravines usually keep an important amount of sediment available to be remobilised in a future event. Field observations suggest that the erosive capacity of the flows is generally not enough to mobilise all the sediment in the main ravines, which in the case of Santiago is combined with the active weathering and erosive activity in the catchment areas along the San Ramón Range, keeping an important amount of loose material that can be incorporated in future flows.

In contrast to the case of arid northern Chile, debris flows in central Chile do not necessarily happen in years of significant annual rainfall anomalies, as the most important factors seem to be the daily or even hourly rainfall rate—most events are triggered by one- or two-day-long storms (Rutllant and Fuenzalida, 1991; Garreaud and Rutllant, 1996)—and the rainfall that has occurred in the previous days or weeks, the so-called antecedent rainfall. An example is 1993 in Santiago, where the annual record does not show any exceptional amount of total accumulated rainfall (Fig. 11). However, the antecedent monthly rainfall (Table 1) was significant for the period of the year (mid-autumn). The antecedent rainfall helps to partially saturate the soil, reducing the amount of rain needed to fully saturate it, creating excess pore pressures that destabilize the soils. This factor has been recognized as an important condition for the triggering of many landslides and debris flows in Chile (Hauser, 2000) and elsewhere (Terlien, 1998).

Unlike Antofagasta and Santiago, the Lake Ranco area in central-southern Chile is characterized by a mean annual rainfall of 1887 mm. In this context, debris flow constitutes a common process in the region, with annual recurrence, induced most probably by the saturation of soils and slopes in the drainage basins during the rainfall season, with critical combinations of antecedent and triggering rainfall to induce the flows. The 2004 event seems to have been largely controlled by the triggering rainfall, which is larger than the rainfall accumulated in the previous month (Table 1). In contrast, a previous debris flow event in the area in 1995 appears to be significantly influenced by a large accumulated rainfall in the previous week and the

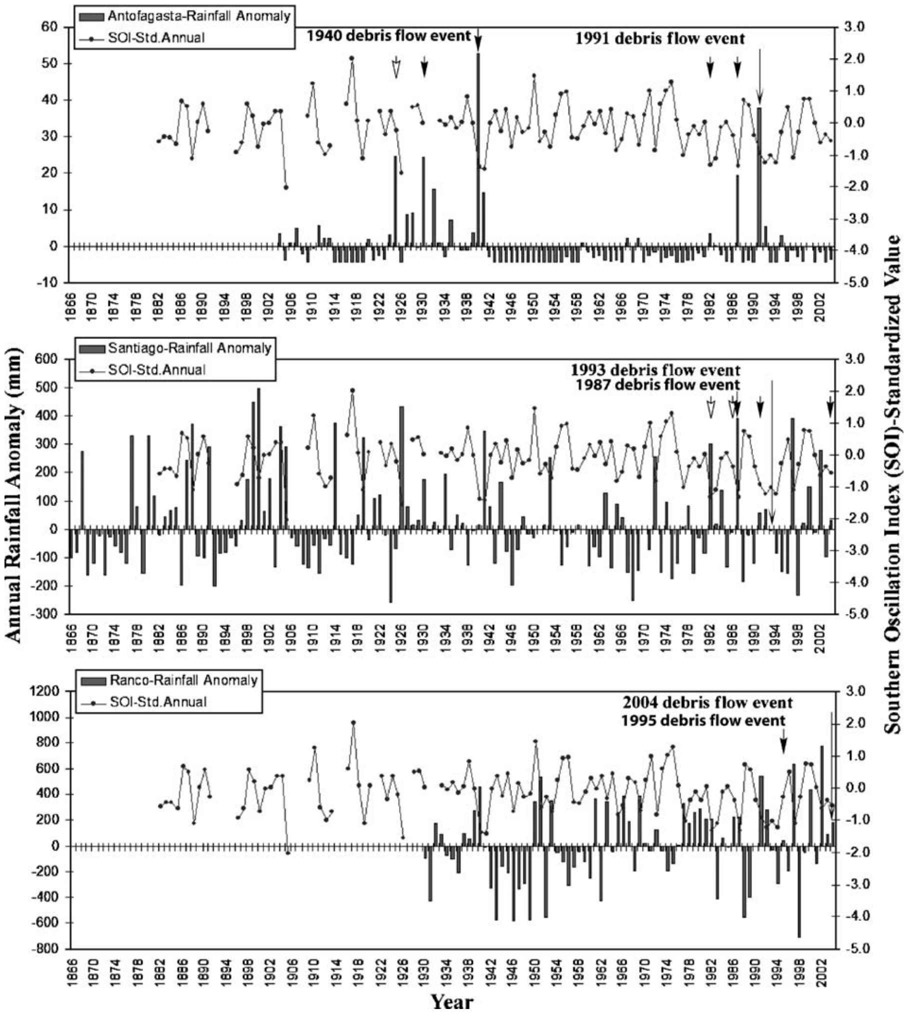

Fig. 11. Comparison between annual rainfall anomaly in Antofagasta (1904–2004, above), Santiago (1866–2004, centre) and Lake Ranco (1930–2004, below), with respect to the SOI. The mean annual rainfall is 4 ± 9 for Antofagasta, 323 ± 141 for Santiago and 1887 ± 315 mm for Lake Ranco. Major debris flow events (black arrows and text), minor debris flows (black arrows) and inundations with minor debris flows in the upper segments of the drainage basins (white arrows) are indicated in the Antofagasta (Vargas et al., 2000), Santiago (García, 2000) and Lake Ranco (Toro, 2005) areas, respectively.

previous month, despite a relatively small amount of triggering rainfall on the day of the event (Table 1).

Therefore, the antecedent rainfall appears to be an important factor in the generation of debris flows in central and central-southern Chile. However, the period of rainfall to consider as significant can be difficult to determine, as it depends on geological and geomorphological conditions of the site. In some cases, in the same site, the importance of the antecedent rainfall against the triggering rainfall is much larger for some events but not for others, as was illustrated for two events in Lake Ranco. Further detailed investigations on the role of antecedent rainfall are necessary to find relationships of accumulated rainfall and thresholds of triggering rainfall for the different regions.

Another factor that may be of importance in the generation of debris flows is snow and ice melting. In Chile, there are examples of volcanic debris flows, also known as lahars, which can be triggered during volcanic eruptions (e.g., Hauser, 2000; Naranjo and Moreno, 2004). In contrast, the melting of snow due to high temperatures has not been a common trigger in historic records. For the case of 1993 in Santiago, the position of the snowline was also found to be another important factor, which must be considered in hazard analyses. Seismic activity may in some cases trigger debris flows, as was the case during the 1960 earthquake (M 9.5) in central-southern Chile (Hauser, 2000).

5.2. Debris flow recurrence and climatic relationships

Looking at an annual timescale, different relationships between debris flows and climate anomalies can be suggested from the analysis of previous and new data from the different areas analysed here, which are certainly related with different patterns of rainfall anomalies and ENSO in northern, central and central-southern Chile (Rutllant and Fuenzalida, 1991; Garreaud and Rutllant, 1996; Vargas et al., 2000; Montecinos and Aceituno, 2003). Similarly that for the last major debris flow event on 18 June 1991 (Garreaud and Rutllant, 1996), from the analysis of historic information, recorded rainfall data and geological outcrops in the area around Antofagasta, Vargas et al. (2000) showed that the 20th century debris flow events were associated with heavy rainfalls during the austral winter of the development phase of El Niño events: in August 1930, June 1940, May 1982, July 1987 and June 1991, concomitantly with low Southern Oscillation Index (SOI) values, which represent the difference in sea level pressure between Tahiti and Darwin, Australia. The two major events occurred on 13 June 1940 and 18 June 1991, with total accumulation values of 39 and 42 mm, respectively (Fig. 11). Flooding in the city without debris flows occurred also in 1925 and 1940.

An analysis similar to that for the Antofagasta area was performed for the Santiago area for the last 25 years, when the information was abundant and unequivocal. Besides the major event in May 1993, from 1980, well documented major debris flows in eastern Santiago occurred in 1987, minor events in 1991 and 2004 and important inundations with debris flows in the upper segments of the drainage basins in 1982 and 1986 (Lara, 1996; García, 2000). A number of debris flows in these and other years also occurred within the main Andes range at the same latitude, the most important being the 1987 rock avalanche and resulting debris flow in the Colorado River (Hauser, 2002). As in the case of coastal northern Chile and except for the 1986 event, debris flows and inundations occurred concomitantly with climate anomalies during the development phase of El Niño episodes, associated with low SOI values (Fig. 11).

As mentioned above, the most important climatic factors for the occurrence of debris flows on 3 May 1993 in Santiago were the high rainfall intensity during the event, the abundant antecedent rainfall and the occurrence of warm temperatures in the troposphere, which raised the snowline increasing the catchment area for liquid precipitations. Similar relationships between rain-triggered landslides and El Niño episodes have been found in the Frontal Cordillera in Mendoza Province of Argentina, at the same latitude of Santiago (Moreiras, 2005), showing that the influence of the Pacific Anticyclone on slope processes is common on both sides of the Andes.

Climate teleconnection patterns inducing rainfall anomalies related to ENSO in central and, more infrequently, coastal northern Chile are similar and well described by Rutllant and Fuenzalida (1991) and Garreaud and Rutllant (1996). Rainfall events lasting a few days to a week in central Chile occur during the austral winter synchronously with anomalously low SOI values. Heavy rainfall events in central and eventually coastal northern Chile occur concomitantly with the characteristic weakening of the south-eastern Pacific Subtropical Anticyclone during El Niño events and with anomalous anticyclonic cell over the south-western extreme of South America that shifts convective storms from mid-latitudes toward the subtropical areas. The analysis of historic information suggested that this pattern, clear for central Chile and more frequent, although not exclusive, of El Niño years (Rutllant and Fuenzalida, 1991), was repeated during all the debris flow events that affected the Antofagasta area during the 20th century (Garreaud and Rutllant, 1996; Vargas et al., 2000).

The decadal to interannual return periods estimated for these climatic anomalies in both areas (Garreaud and Rutllant, 1996) can explain the sporadic occurrence of this type of geological process. For the Santiago area, in particular, the occurrence of minor debris flows in 1986 suggests that other additional factors could be involved in historic debris flow events in this region, which is a matter of current investigations. As it was previously discussed, the flows in central Chile do not necessarily occur in years of significant annual rainfall anomalies, as they tend to be controlled by the rainfall intensity and the antecedent rainfall.

The Lake Ranco area in southern Chile is characterized by a mean annual rainfall of 1887 mm, which is higher than the mean annual rainfall values around 4 and 323 mm, which characterize Antofagasta and Santiago, respectively. In this area, which does not exhibit a relationship between positive anomalous rainfall and El Niño events (Montecinos and Aceituno, 2003; Fig. 11), heavy rainfall episodes are common during the austral winter, as a result of the seasonal influence of the Southern Westerlies. Therefore, debris flows constitute a common process in the region.

5.3. *Hazard assessment methods*

The scientific work on debris flow hazards is strongly influenced by the lack of clear government policies (discussed below), so studies are mainly individual and not coordinated. Until the 1980s, debris flows as well as other geological hazards were treated in a descriptive manner, based mainly on observation of past and recent events. A good summary of landslide cases in Chile, including debris flows, was made by Hauser (1993), and updated later in 2000 (Hauser, 2000). Greater concern of debris flows after the Antofagasta and Santiago events has increased hazard studies at the local and regional level, mainly by the Geological Survey (Sernageomin) and universities, as well as research by consultants for specific engineering and housing projects, increasingly required by new environmental and construction laws published in the 1990s.

Most of the debris flow hazard studies in Chile have been and are still being performed using qualitative methodologies. Among these, the most used is Field Geomorphological Analysis (according to the landslide hazard assessment classification by Aleotti and Chowdhury, 1999). It consists of a zonation of the hazard areas with different degrees of hazard, based mainly on the recognition of debris flows paths, alluvial fans and other geomorphological features associated with flow occurrence. These studies are usually supported by some rough statistical analysis of rainfall associated with the most recent events (e.g., Hauser, 1985; Antinao et al., 2003). The main problem of this method is that the evaluation of the hazard is subjective, based on the scientist's experience.

The other method used in recent years is the Overlay and Combination of Index Maps or Parameter Maps with Weights (Aleotti and Chowdhury, 1999). Basically, each relevant parameter (e.g., slope gradient or loose soil availability) is divided into classes to which a weighted value or rating is attributed, after which a hazard map is developed by the overlay of parameter maps. A step-by step methodology for debris flow hazard assessment using this technique was proposed by Sepúlveda (1998, 2000). This method adds some objectivity to the hazard assessment, as a number of rules have to be followed, although there is still an important amount of subjectivity in the election of what description agrees best with the class defined by the methodology. A hazard assessment of the Caunahue area in Lake Ranco has been recently completed using this method (Toro, 2005).

Most advanced methods, such as multivariate statistical analysis, geotechnical models or the use of neural networks are seldom used. One of the main problems in using these hazard assessment methods is the lack of sufficient data, especially rainfall and geotechnical data, which are quite rare, although in recent years the data are increasing in number and geographical distribution. Rainfall data are absent in many areas, and where present are usually for relatively short periods of time, which preclude good statistical correlations. Rainfall is also generally recorded in daily values, which is not the best method as it does not show the real intensity of the rain, a key triggering factor for debris flows, for which rainfall should be measured hourly. Another problem inherent to the geography of the country is related to the strong differences in climate regimes and associated geomorphological patterns. For example, although as mentioned before the rainfall for the 1993 Santiago flow was effectively over thresholds proposed by the central Chile region (Hauser, 1985) or using world records (Caine, 1980), it is necessary to define with a higher precision the rainfall thresholds for specific areas that can be considered a geological and geomorphological domain.

Current research by the authors is aimed at determining statistical relationships between landslide occurrence and triggering and antecedent rainfall, as well the snowline position, in Santiago, and at obtaining statistical threshold values for the triggering rainfall using multivariate statistical analysis. Thereafter, for a full hazard analysis, the relationships between debris flow occurrence and climatic anomalies related to ENSO must be also considered. The results will be included in a new assessment of the landslide hazard in eastern Santiago using a more developed methodology that also includes more detailed geological and geotechnical characterization of the geological units and the use of geotechnical and physical models for stability analysis.

5.4. *Comments on social impact and human reaction to debris flow hazards*

Disasters due to debris flows as well as other geological hazards generate an alteration in the normal developing of a region. For large events such as the flows in Antofagasta and Santiago, plans for communal development and the total budget had to be reformulated in view of the emergency. Public services stop giving preferred attention to their normal tasks and redirect their duties during many months, to solve problems associated with the emergency. Furthermore, the use of schools as shelters interrupts educational activities.

In Chile, there is no real consciousness about the hazard of debris flows, so that people tend to build in dangerous areas such as alluvial fans or near ravines and other channels. Even in sites where debris flows have occurred recently, the re-occupation of the affected areas, if not prevented by the authorities, is quite rapid, as the sense of property and economic and social pressures is higher than the sense of risk; the population of *quebradas* by low-income groups, through illegal land occupation, is common due the low cost of the land without urbanization. On the other hand, from ignorance or a lack of historical conscience with respect to the flow phenomena and the fact that people tend to forget disasters rather quickly and take a fatalistic attitude, assuming the flows to be unforeseeable natural catastrophes (Hauser, 2000), the authorities have not acted against social pressures, allowing the people to stay in hazard areas.

In the country there is an institutional order to respond to different type of disasters such as earthquakes, floods, snowstorms or landslides in a relatively rapid and efficient manner. This response is mainly coordinated by the National Emergency Office, dependent on the Ministry of the Interior (ONEMI), together with regional and communal authorities. In general, the authorities' attitude to natural disasters in Chile is mostly reactive rather than preventive. While the reaction to emergencies has a procedure that works reasonably well, the prevention and planning for debris flow hazards is not yet systematic and part of clear public policies. With some local exceptions, hazard maps are only of regional scale or reduced to very specific new housing or infrastructure projects, and in most parts of the country are simply non-existent.

The main focus of the authorities in dealing with debris flow risk has been the construction of mitigation works and changes in land use regulations in areas badly affected by flows, such as Antofagasta and the Macul Ravine in Santiago. For example, before the 1991 disaster, the regulatory plan of Antofagasta did not consider the alluvial torrents that came from the mountain range. In an immediate reactive measure to the flows, the City Council prohibited construction and reconstruction in the widely affected zone. The Ministry of Housing and Urbanism incorporated into the New General Decree on Urbanism and Construction a special article, which established that regulatory plans will define restricted areas based on risk assessment studies. Low-quality soils, flooding, steep slopes, volcanic activity or geologic faults are considered to constitute a potential hazard to urban development and should be evaluated. However, the restricted areas are usually smaller than recommended, as the economic pressure to build in the plains is high.

In Antofagasta, considering the general diagnosis of the catastrophe and the fact that the city was built along the old natural drainage channels, the Government launched engineering studies to find solutions to similar disasters. First of all, considering different solutions, they chose to re-establish 15 natural channels directly to the sea, constructing fluvial engineering works to accomplish that. In a similar way, a number of energy dissipation pools were built in *quebrada* Macul in Santiago to prevent future disasters such as the 1993 flows. The effectiveness of these kinds of engineering works is yet to be tested in future major debris flow events, but have shown to work well in minor events related to intense rainfall (Hauser, 2000). These mitigation works, worth several million dollars of investment, are a significant effort to reduce the risk in areas recently affected by important flow events. The next step is to incorporate these procedures into a proactive policy of hazard assessment and mitigation procedures to be applied throughout the country, in areas where no significant flow events have occurred in the near past but that can be assessed as dangerous by hazard evaluation studies.

6. Summary and conclusions

Debris flows are an important type of geological hazard in Chile. Cities, towns and villages located at mountain foothills are frequently affected by flows generated by heavy rainfall in catchments that drain through ravines and stream channels toward the valleys. Debris flows are triggered throughout the country despite the variability in climatic regimes, which vary from dry tropical in the north to rainy template in the central-southern part and to tundra in the extreme south. In northern and central Chile, debris flow occurrences seem to correlate with El Niño events, associated with low SOI values, whereas in central-southern Chile the normally large amount of rain tends to induce these processes independently of such climatic anomalies. In all regions, heavy rainfall is the main triggering factor, with an important role of antecedent rainfall in central and central-southern Chile. Further, in central Chile the position of the snowline also seems to be of some significance. Due to the differences in climate and vegetation patterns between the three regions, the rainfall thresholds to trigger the flows as well as the mechanisms of soil destabilization are different and should be studied separately for hazard assessment.

Recent debris flows events in Antofagasta, Santiago and Lake Ranco, in northern, central and central-southern Chile, respectively, have demonstrated that this kind of mass movement may cause great disruption, in some cases with a similar or an even greater amount of damage and fatalities than earthquakes. Besides direct victims and damage to infrastructure, the flows affect the normal development of a city or rural area. The effects and actions taken before and after the recent events described in this paper show that in the country there is a reactive rather than proactive policy towards geological hazards, with still limited research on prevention, prediction and hazard assessment, although this tendency is changing. In areas recently affected by flows, costly mitigation works have been carried out to prevent repetition of the disasters. The lack of consciousness about the hazard of debris flows among the people and an inclination to re-occupy affected areas soon after catastrophic events makes hazard assessment vital for the definition of restricted areas. The problem is becoming increasingly important as the risk zones tend to expand due to urbanization on alluvial fans and other areas with clear indications of debris flow activity, as a result of the population growth and the restricted availability of terrain suitable for construction in the plains.

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