Landslides (2014) 11:481–491
DOI 10.1007/s10346-014-0480-2
Received: 4 October 2013
Accepted: 21 February 2014
Published online: 11 March 2014

Sergio A. Sepúlveda · Sofía Rebolledo · James McPhee · Marisol Lara · Mauricio Cartes · Eduardo Rubio · David Silva · Nicolle Correia · Juan P. Vásquez

Catastrophic, rainfall-induced debris flows in Andean villages of Tarapacá, Atacama Desert, northern Chile

Abstract In March 2012, during the rainy season in the Altiplano plateau, a >100-year return period rainfall event affected the deeply incised valleys of the Precordillera of the Tarapacá Region, northern Chile. This extreme event in a very arid region triggered a number of debris and mud flows that caused severe damage and destruction in several small villages along the Camiña and Tarapacá valleys. The highly vulnerable location of the villages on top of alluvial fans due to socioeconomic and cultural reasons is a key factor to explain the level of destruction in most villages. In this paper, this unusual, remarkable landslide event is described, and the hazard faced by these settlements for future rainfall episodes and possible mitigation measures are discussed.

Keywords Debris flows · Landslides · Atacama · Altiplano

Introduction

The Atacama Desert in northern Chile is the world's most arid region. Some areas have null recorded rainfall in historic times. However, during the southern hemisphere summer, the Andes Cordillera highlands suffer short, intense rainfall periods. This phenomenon is locally known as the "Altiplanic Winter" and produces flash floods and debris flow events in the high mountains and large ravines or *quebradas* that drain the mountain range. Towns and villages of the Tarapacá Region, mainly located in the Precordillera region below 3,000 m a.s.l on the valley sides, are used to present floods in the main valley stream, originated upstream (Arrau 2009), but that rainfall activates small lateral gullies is rare and poses a high risk to the settlements that are located at the bottom of these gullies.

In late February and early March 2012, extreme rainfall events affected the Camiña and Tarapacá deeply incised valleys of the Tarapacá Region, Atacama Desert (Fig. 1), triggering several debris and mud flows in lateral gullies during the second week of March. The peak event took place on 11–12 March, when rainfall had a return period of over 100 years in Camiña. The flows caused severe damage and destruction in the town of Camiña and small villages, mostly inhabited by native Aymaras, along the Camiña and Tarapacá valleys. According to official reports, about 165 houses in Camiña valley and 27 houses in Tarapacá valley were destroyed or severely damaged. Loss of recently constructed street pavements was officially valued in over US$1 million. The area was declared a catastrophe zone by the government of Chile, due to the strong damage on villages and devastation of irrigation zones, being agriculture the major economic activity of the villagers.

Fortunately, the time of the main event (about 4 p.m. in Camiña, while people was working on the agricultural fields down in the valley) and the unusual amount of rain prevented the local people who self-evacuated before the destructive flows arrived, resulting in no fatalities.

In this paper, a description of the 2012 debris flows in Tarapacá and Camiña valleys, their effects on populated areas and some key geomorphological and hydrological characteristics are presented. The risk associated with the location of villages in high hazard areas and possible mitigation measures for future events are discussed.

Geological and geomorphological setting

Geomorphology

The study area is located in the central Andes, which at this latitude (19–20°S) is characterized by four, roughly NS trending major morphostructural units that are located in the western fringe of the Altiplano plateau (Fig. 1). These are, from west to east, the Coastal Range, the Central Depression, the Precordillera and the Western Range. These units are crossed by deeply incised valleys or *quebradas*, formed by steep rocky slopes and usually presenting gigantic landslides inside (Pinto et al. 2008; Farías 2012; Letelier 2013). From Camiña valley to the north, the *quebradas* cross the Central Depression and the Coastal Range ending in the sea, while to the south dominates an endoreic drainage system in which the *quebradas* terminate in the Central Depression. The drainage pattern changes from dendritic in the Western Range, where rainfall occurs periodically, to parallel downstream, where precipitations are scarce to null.

The two study sites, the Camiña and Tarapacá valleys within the Precordillera and partly in the Central Depression, are some of the largest of the region. The Camiña valley is characterized by a slope change around the Moquella village, caused by a west vergent flexure, named as Moquella flexure (Pinto et al. 2004, Fig. 1). To the west of the flexure, the slope is gentle and the valley crosses with little incision the Central Depression plains, while to the east, the valley has been deeply incised (up to 700 m) due to the tectonic uplift, marking the starting point of the Precordillera domain. In this section, the slopes can be quite steep, up to 70 and 30° in average. The valley is narrow with a large number of lateral gullies that reach heights up to 3,000 m a.s.l. The drainage basin has maximum height of about 5,000 m a.s.l., east of the study area. The Tarapacá valley in this domain has somewhat less steep slopes, although the incision still reaches over 500 m. The local deformation is controlled by the west vergent, NS striking Aroma flexure, which generates a monocline structure close to the town of Mocha (Fig. 1).

Geology

The geology of the study area is composed by Mesozoic to Neogene volcanic, sedimentary and intrusive rocks. The basement of Camiña valley consists of Upper Cretaceous continental clastic rocks belonging to Fm. Cerro Empexa that crop out east of Moquella flexure, deformed by gentle folds and granodioritic and rhyolithic intrusions (Pinto et al. 2004). They are overlain in disconformity by an Oligocene-Miocene volcano-detritic sedimentary sequence (Fm. Lataguala) deposited in alluvial fan

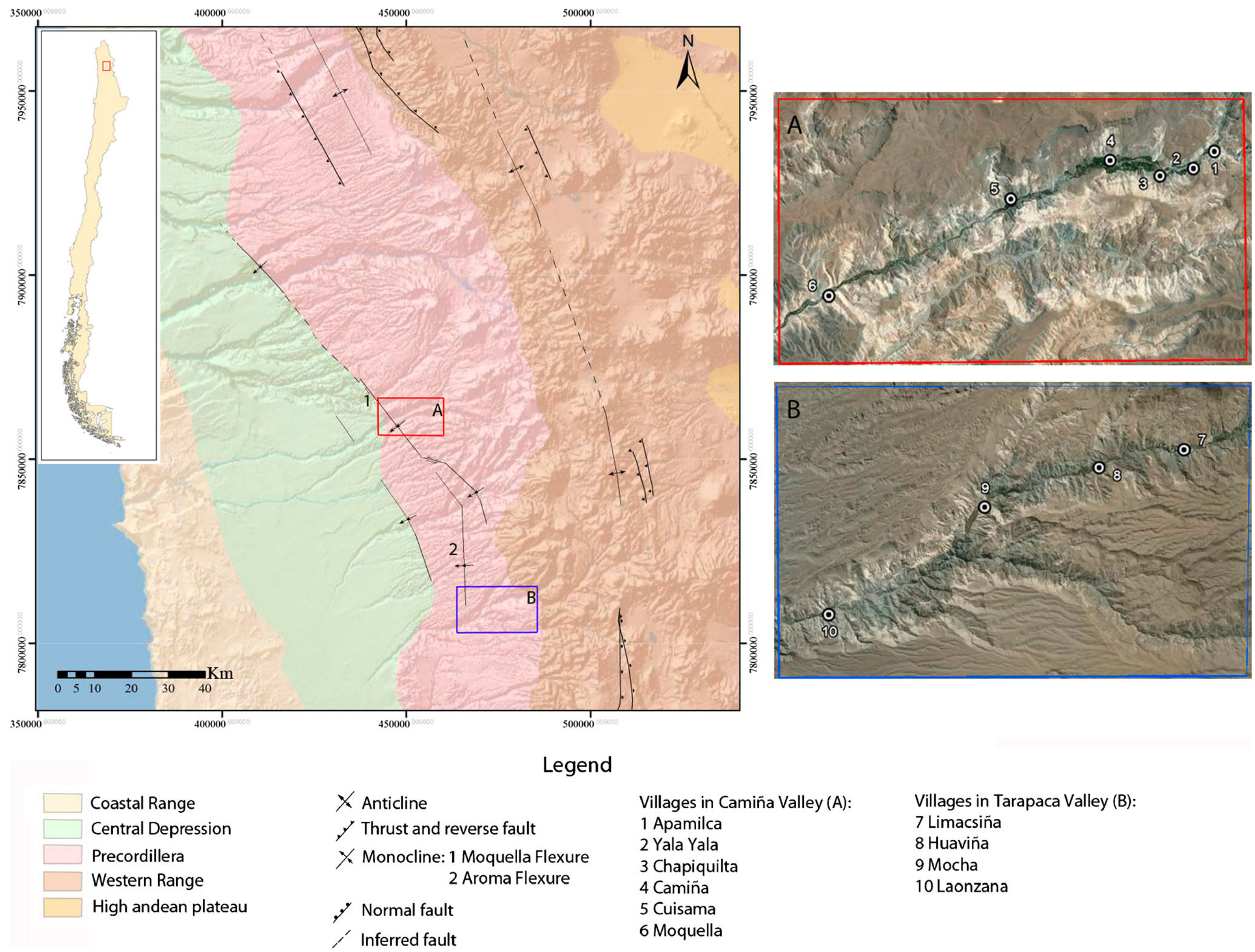

Fig. 1 *Left* Location map with indication of regional structures and morphostructural units. *Red* and *blue boxes* indicate the Camiña valley (**a**) and Tarapacá valley (**b**) study areas, respectively (modified after Farías 2012) *Right* Satellite image of study areas, with location of villages affected by the 2012 debris flow event

environments and Miocene andesitic lavas that form the superficial plain that crowns the valley (Tana Pampa) (Pinto et al. 2004). The sequence is deformed by the NS trending Moquella flexure (Fig. 1) and reverse faults. Inside the valley, large volume deep-seated landslides and rock avalanches of Pliocene-Holocene age are common (Farías 2012), along with debris flow deposits and the alluvial fans in lateral gullies and the valley alluvial infill. One of the rock avalanches located just west of the town of Camiña presents evidences of valley damming, such as lacustrine deposits, which is consistent with silty, organic soils found in a 50-m deep borehole core located upstream the natural dam in the river shore of the town (IDIEM 2013). The rock slopes are usually covered by a thin colluvial blanket formed by gravel and blocks mainly originated from rock falls and mechanic weathering (IDIEM 2013).

The Tarapacá valley in the studied section present volcanic and sedimentary rocks belonging to Fm. Cerro Empexa, Oligocene-Miocene dacitic-to-rhyolitic pyroclastic sequences (Fm. Altos de Pica) and an alluvial sedimentary pediment on top, as well as Upper Cretaceous to Lower Tertiary intrusive granitoids. Similarly to Camiña valley, inside the valley develop alluvial deposits with fluvial terraces in wider sections (IDIEM 2013), while some valley sections present lateral, large volume, deep-seated landslides (Sernageomin 2003; Muñoz 2007). Slopes have a thin colluvial cover, and lateral gullies are infilled with fallen blocks and debris flow deposits.

Climate

The regional climate show strong west to east variations dominated by altitudinal gradients and by the blocking effect of the Andes Range. The high Andes in this sector, formed by the Western Range and the Altiplano Plateau, as described above, constitute a formidable climatic barrier, with few passages lower than 4,000 m a.s.l. and several peaks higher than 6,000 m a.s.l. The westernmost region of the mountain chain presents an extremely dry weather and great atmospheric stability due to the subsidence in the eastern edge of the South Pacific subtropical anticyclone. In contrast, low lands east of the Altiplano present a tropical-continental precipitation regime, where convective precipitation maxima occur during summer months (December, January and February). Between these two different zones, the Altiplano exhibits a transition regime, described by Schwerdtfeger (1976), Aceituno and Montecinos (1997), Aceituno (1998), Garreaud

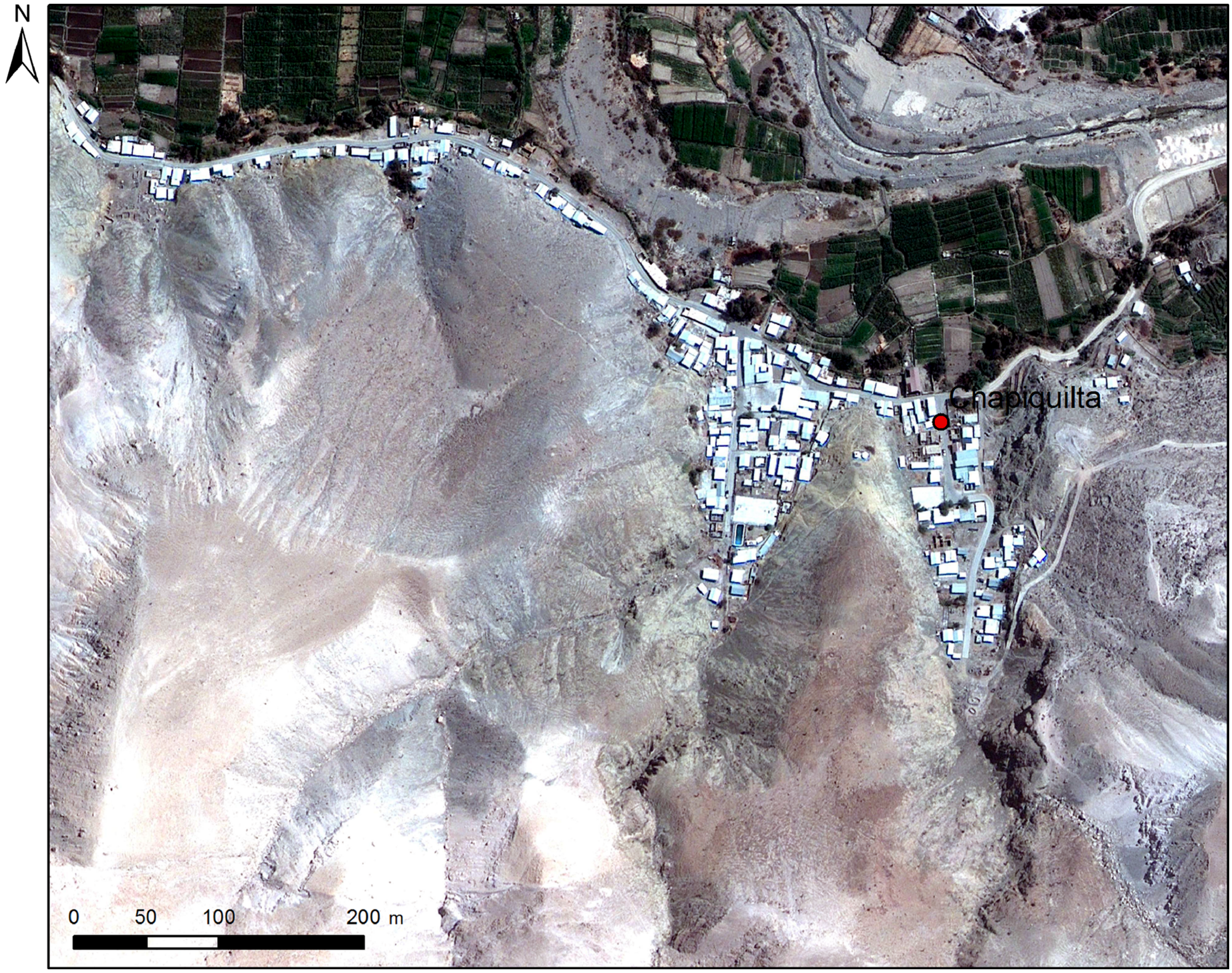

Fig. 2 Example of settlements on top of alluvial fans, village of Chapiquilta, Camiña Valley. In this case most of the village is built on two fans, leaving farming land on fluvial terraces free for subsistence agriculture. Location in Fig. 1 (Image source: Google Earth)

(2000) and Garreaud and Seluchi (2003). Spatially, the annual precipitation ranges from 900 mm towards the northeastern zone of the Titicaca Lake in Bolivia to 150 mm southwest of the great salt flat sector.

The largest fraction of annual precipitation in the study area concentrates between the months of November to March, with a maximum in January. During this season, locally known as Altiplanic winter, precipitation derives from convective storms, developed during the afternoon and the first hours of the night. The days with convective activity usually group in weekly sequences (rainy episodes) followed by periods of no convective activity and similar duration (dry episodes). In occasions, these storms can acquire large intensities and long durations, causing alluvial floods and large floodplains.

The March 2012 debris flow events

In the afternoon of March 12, 2012, an unusually extremely intense rainfall episode affected the Camiña valley. According to local witnesses, after about 20 min of rainfall, several debris and mud flows started to generate in the valley's lateral gullies, while the main stream discharges quickly increased causing local flooding and terrace erosion. A similar episode occurred in the Tarapacá valley, starting in the afternoon of 11 March.

Table 1 Location of meteorological stations and period of precipitation data in the area of study

Station	BNA Code	UTM S (m)	UTM E (m)	Altitude (m a.s.l.)	Period data
Camiña	016 11 001–9	7,864,392	456,168	2,380	1971–2012
Mocha	017 30 019–9	7,809,524	471,401	2,150	1988–2012

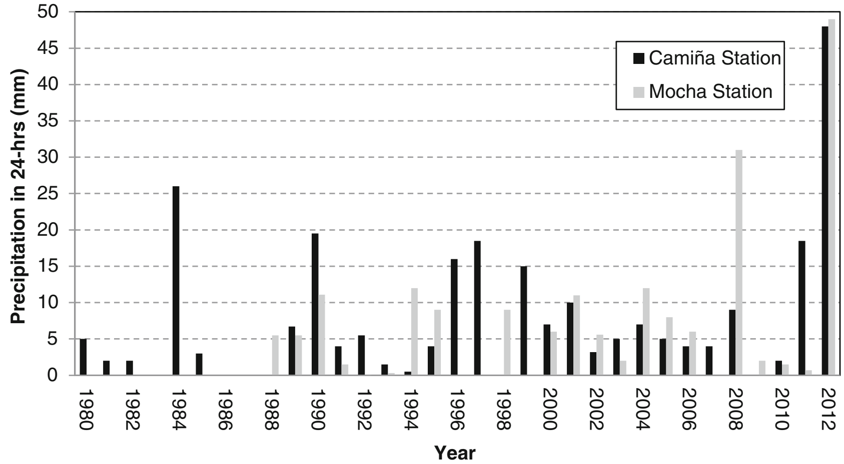

Fig. 3 Annual maximum precipitation in 24 h at Camiña and Mocha (Tarapacá valley) meteorological stations

Several villages were damaged in different degree by the debris flows. Most affected were the small villages of Chapiquilta and Yala Yala and the town of Camiña, all in the Camiña valley and the village of Laonzana in Tarapacá valley (Fig. 1). These have the particular condition of be built in an important proportion on top of lateral alluvial fans; therefore, they suffered a direct hit by many of the flows (Fig. 2). This dangerous and highly vulnerable location can be explained by the interest of keeping most of the fluvial terraces and valley bottom deposits free for agriculture, which is the base for subsistence in this very arid region, mainly inhabited by native Aymara population. They also use the gullies upstream the alluvial fans to locate their animal corrals, which were totally destroyed by the flows resulting in high cattle mortality. Other villages such as Apamilca, Cuisama, Moquella (Camiña valley, Fig. 1), Limacsiña, Huaviña and Mocha (Tarapacá valley, Fig. 1) suffered destruction in the minor parts of the settlements and/or road interruptions in the gully crossings, which are not designed for high discharges. Most relevant data and field observations of this event, as well as a hydrological analysis to estimate the amount of discharges are described below.

Meteorological data

From the historical data of maximum rainfall in 24 h, the largest recorded events in the 2012 summer period correspond to the ones registered on 13 March (records are taken at 8 a.m.) in the Camiña valley (Camiña station) and 26 February in the Tarapaca valley (Mocha station, Table 1 and Fig. 3), with a total daily rainfall of 48 and 49 mm, respectively. The March event was not captured by the Mocha station; however, in the Chusmiza station located close to the valley at 3,400 m a.s.l., a total of 101 mm was recorded during the 11th–14th March period, showing the local nature of the convective storms that cause the flows.

According to the statistical analysis of the timeseries of Camiña and Mocha stations, the events in 2012 exceeded the 100-year return period and are the largest in at least the last three decades (Table 2 and Fig. 3). The peak rainfall duration is estimated between 1 and 2 h. Studies in the last 15 years by Arrau, (2009) report the occurrence of mud flows in January 26, 1998 and March 10, 2001 in Camiña valley.

Debris flows in Camiña valley

The debris flows in Camiña valley affected at least six villages in a section of about 15 km, from Apamilca down to Moquella (Fig. 1). Other flows were deposited on farmlands along the main valley fluvial terraces.

In Apamilca village (Fig. 1), settled on top of a gigantic deep-seated landslide (Farías 2012), the flows mostly affected the main road and a few settlements next to a large lateral gully. A borehole drilled in the alluvial fan showed a thickness of 15 m of coarse alluvial materials (IDIEM 2013), which overlain the landslide deposit that reaches over 50 m in depth. The 2012 flow left gravel and blocks mainly less than 0.4 m, with blocky levees on the sides.

The village of Yala Yala (Fig. 1), downstream Apamilca, was severely affected by a debris flow that directly impacted main village installations such as the adobe church and the surgery, as well as several solid masonry houses, built on an alluvial fan (Fig. 4). The flow reached about 3-m high in the fan apex. Granulometry tests returned that 20 % correspond to blocks over 35 cm, while about 40 % are fragments over 75 mm (IDIEM 2013). As observed in other places, the flows quickly stopped at the end

Table 2 Frequency results of rainfall (mm) at Camiña and Mocha meteorological stations. Best statistical adjustment was obtained using the Log-Pearson distribution

Station	Return period (years) for 24-h rainfall						
	2	5	10	25	50	100	200
Camiña	7.1	17.1	24.7	34.3	41.0	47.1	52.7
Mocha	5.4	15.1	23.1	33.8	41.6	48.9	55.7

Fig. 4 Debris flows in Camiña valley. **a** Debris flow impact on the first upstream house in Yala Yala. Note the flow deposits on the roof; **b** damage by a large flow in Chapiquilta school; **c** Blocky flow deposit in Camiña town; **d** large block over 2 m in diametre in Camiña, the largest found in the urban area; **e** mud splash marks in the same location of the block of (**d**), height of about 2.5 m. The flow deposit inside the house is 0.5 thick; **f** sports field already cleaned and wire fence in the back that helped to retain the coarse part of a debris flow in the apex of an alluvial fan in the town of Camiña. Location on Fig. 1

of the alluvial fans where the slope gradient diminishes. A second flow triggered in a steep but a very small microcatchment covered with about 70 cm of sand, gravel and blocks the village sports field, before being stopped by a perimeter fence. The generation of short runout flows in such small basins is another characteristic that was repeatedly observed in the area.

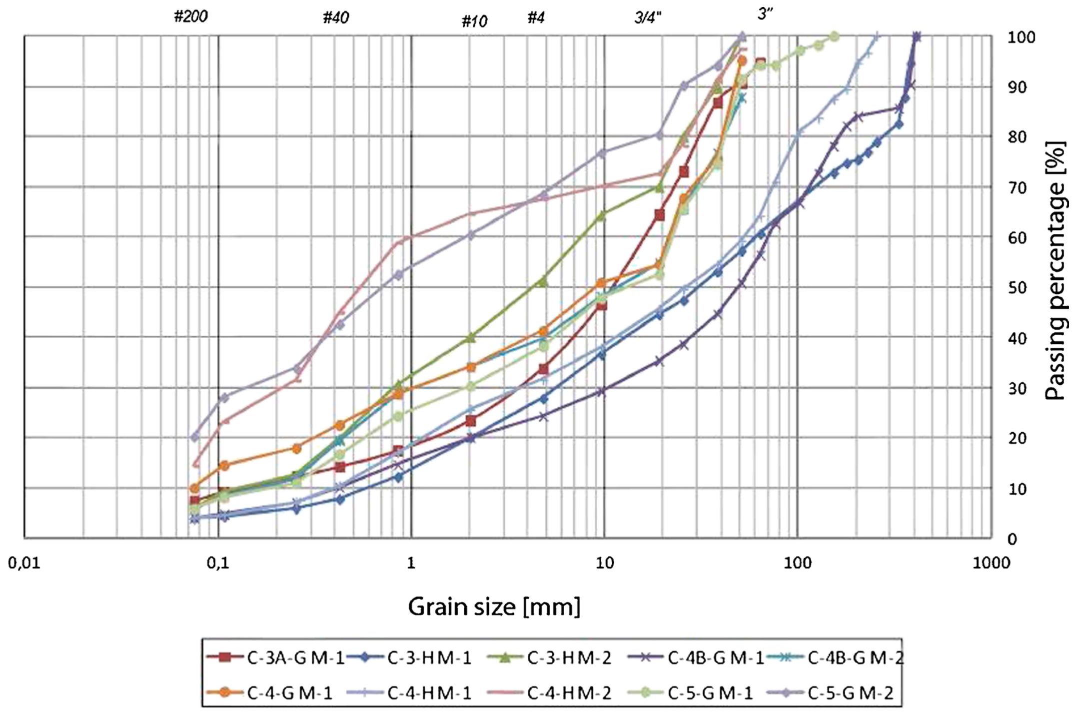

Fig. 5 Granulometric curves from debris flow deposits in alluvial fans in Camiña area (IDIEM 2013)

The Chapiquilta village (Fig. 1), placed on top of two alluvial fans (Fig. 2) was probably the most destroyed settlement due to this climatic event. Eighty four houses, streets and even the village school were completely destroyed or badly damaged by debris flows of heights up to 3 m according to splash marks (Fig. 4). The gullies are about 700-m long and incised in rock until reaching the alluvial fan. The deposit reaches up to 2 m of thickness, spreading on most of the fans until reaching the Camiña valley fluvial terraces at the fan toes. Deposited material is sandy and gravelly, with blocks up to about 1.2 m (IDIEM 2013; Fig. 4).

The valley main town of Camiña (Fig. 1) located on the northern side of the valley has its downtown built on top of a fluvial terrace, while residential areas are spread on part of the terrace and the rest on four alluvial fans, all of which presented debris flows. The flow material is originated in the volcanic rock valley scarps and in loosen blocks of a large landslide that fall into the gullies and are entrained by the flows. The deposits (Fig. 4) are composed of centimetric to decimetric rock blocks, with a few blocks larger than 1 m, even over 2 m (Fig. 4) and a gravel and sand matrix of variable proportion, as shown by field observations and granulometric tests from test pits (Fig. 5). The depth of alluvial materials from this and older flows in the distal part of the fan reaches 13.5 m according to a borehole (IDIEM 2013). Several houses were destroyed or damaged, and the narrow streets parallel to the fan axis served as a channel for the flow and were eroded, which was observed in several villages. Splash marks in house walls show that flows reached up to 2.5 m in height (Fig. 4).

One interesting feature already observed in Yala Yala and also present in one of the Camiña alluvial fans is the combined effect of small sports field that acts as a slope break that helps to reduce the velocity of the flows and the presence of wire fences that trap most of the coarse sediment (Fig. 4). In Camiña, a large part of the blocks were stopped by the fence and field, detouring the rest of the flow to the sides of the field.

Downstream Camiña, the flows diminish in quantity. A hyperconcentrated flow in a large lateral gully crossed the village of Cuisama (Fig. 1), destroying a culvert on the main valley road, a lateral street and a couple of houses next to the gully. A small flow in a neighbouring gully made little damage. In Moquella village (Fig. 1), located on two fans originated from 1.5-km long creeks in ignimbritic rocks, small gravelly and sandy flows run down the streets, leaving deposits of around 20 cm. The gullies upstream the fan have metric blocks, suggesting that the 2012 event was a small one, possibly due to a lesser amount of rainfall than in the gullies upstream the valley.

Debris flows in Tarapacá valley

The March 2012 hydrometeorological event also affected a large section of Tarapacá valley in the Central Depression, of about 20 km. The villages that suffered the most damage were (from East to West) Limacsiña, Huaviña, Mocha and Laonzana (Fig. 1). According to villagers, this kind of event is not so rare as it is in Camiña, and some debris flows have occurred in the past few years during the Altiplanic winter. For instance, a local flow larger than that in 2012 would have occurred in Huaviña in February 2010. These flows cause further distress to villages already heavily damaged by the 2005 Tarapacá earthquake (Astroza et al. 2005).

The village of Limacsiña (Fig. 1) is located on top of a megalandslide deposit. Small gullies dissect the slide mass, three of which drain on the town sides before reaching fluvial terraces of the main stream. Coarse-grained material of blocks up to 1 m^3 in a gravelly sandy matrix was remobilized by the flows (Fig. 6). A couple of houses and the access road were damaged by the flows. Deeper and longer are the gullies that drain the southern valley slope draining into the village of Huaviña (Fig. 6). In the western

Fig. 6 Debris flows in Tarapacá valley. **a** Coarse-grained deposits in Limacsiña; **b** panoramic view to the south of Huaviña village; **c** Alluvial plain in Laonzana with signs of flooding erosion and in the foreground debris flow deposits coming from a lateral gully; **d** Damaged houses in the easternmost gully of Laonzana. Location on Fig. 1

gully, a debris flow with sand and gravel that filled the village hostel and neighbour houses was triggered. The gully at the centre of the town has deposited material composed of sand, gravel and blocks up to 1 m^3. Most of the coarse material was deposited behind the village and in low gradient streets, before reaching the fluvial terrace with sand and gravel. The third gully was naturally channelized without damaging the houses. The village of Mocha (Fig. 1) is placed on the south granitic slope of the valley that presents a thick colluvial cover, next to a large lateral gully in which a debris flow destroyed the access road by erosion and

Table 3 Solid volumetric concentration obtained by combining the range of values of bed inclination angle (α) and internal friction angle ($\varnothing$), for five ranges of parameter α

Range	1		2		3		4		5	
Parameter	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
$\varnothing$ (degrees)	30.00	40.00	30.00	40.00	30.00	40.00	30.00	40.00	30.00	40.00
Tg ($\varnothing$)	0.58	0.84	0.58	0.84	0.58	0.84	0.58	0.84	0.58	0.84
α (degrees)	3.68	3.85	5.75	8.26	8.96	9.87	12.39	14.98	9.09	14.04
Tg (α)	0.06	0.07	0.10	0.15	0.16	0.17	0.22	0.27	0.16	0.25
ρ (t/m^3)	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
ρ_S (t/m^3)	2.65	2.65	2.65	2.65	2.65	2.65	2.65	2.65	2.65	2.65
C^*	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65
C_d	0.05	0.08	0.08	0.20	0.14	0.26	0.21	0.52	0.14	0.48

Table 4 Liquid streamflow, minimum and maximum estimations for the debris flows for a 100 year return period

Basin	Liquid streamflow (m^3/s)	Debris flow minimum (m^3/s)	Debris flow maximum (m^3/s)
Apamilca	66.3	71.8	75.5
Cuisama	9.1	10.4	13.3
Moquella	2.4	2.7	3.0
Limacsiña	0.7	0.8	1.1
Huaviña	1.8	2.1	2.8
Mocha	1.5	1.8	2.5
Laonzana	0.7	0.9	1.1
Camiña	1.4	1.8	5.3
Yala Yala	1.6	2.0	6.1
Chapiquilta	1.5	1.9	5.6

formed a fan in the lower terrace, with blocks between 0.3 and 0.5 m^3. Other small gullies in the colluvial slope behind the town produced small flows with fragments generally less than 20 cm and mud and water that produced limited damage.

The most severely damaged village in the Tarapacá valley was Laonzana (Fig. 1). Four gullies of different size produced debris flows that caused destruction. A small catchment in the centre of the village, similar to the one described in Yala Yala, produced a flow that destroyed a community centre and damaged several houses. Two large gullies on the west cut the access road and destroyed a few houses before converging and producing a large fan, with blocks up to 0.8 m^3, deposited on the fluvial terrace, which in turn was eroded by the flood coming from upstream in the main valley (Fig. 6). The easternmost gully, a narrow canyon incised in volcanic rocks, produced a finer-grained flow that filled several houses with sandy material (Fig. 6), before running through a street down to the fluvial terrace.

Hydrological analysis

No streamflow data exists in the area, so it is not possible to obtain a direct estimation of the magnitude of the hydrological event causing the documented damage. Likewise, no direct observations of debris movement are available. Therefore, we applied an indirect methodology in order to quantify the approximate debris flow discharges associated with this event. This method combined a hydrological-hydraulic modelling analysis and empirical estimations of debris flow volumes based on liquid peak streamflow values. These were estimated using the rational and the synthetic unit hydrograph methods and were run through a hydraulic model in order to compute approximate peak flow stages. Subsequently, these stages were verified against markings left on-site by the passing of the debris flow, so ensure that realistic flow-stage combinations are obtained from the model in this very poorly monitored area. For the hydraulic modelling exercise, streambed and floodplain cross-sections were acquired specifically by topographical surveys at several locations in the main channel as well as in lateral gullies contributing to the main flow. Manning's roughness coefficient, a key parameter for ensuring realistic results, was estimated from field measurements of surface roughness derived from the statistical properties of sediment diametres.

According to Takahashi (1978, 1981), most of debris flow phenomena are related to storms with high intensities exceeding 24–42 mm/h on average, with antecedent soil moisture playing a rather minor role. In addition to the intensity, the channel slope plays an important role, with debris flows starting to occur with values range between 7 and 10 %.

The calculus procedure of a debris flow is documented by Takahashi (1978, 1981) and also by Montserrat (2005). Takahashi (1978, 1981) estimate the debris flow maximum streamflow with the following expression:

$$Q_d = Q_o \frac{C^*}{C^* - C_d} \qquad (1)$$

where Q_d is the debris flow peak flow rate, Q_o is the peak liquid streamflow, C_d is the solid volumetric concentration and C^* is the maximum theoretical solid concentration (around 65 %). C_d can be estimated as follows:

$$C_d = \frac{\rho}{\rho_S - \rho} \frac{\tan\alpha}{\tan\phi - \tan\alpha} \qquad (2)$$

where α is the bed inclination angle and $\varnothing$ is the internal friction angle of the material deposited (about 30–40º, IDIEM 2013), ρ is the water density (1 t/m^3) and ρ_S is the soil density (about 2.65 t/m^3). Takahashi defined C_d as an equilibrium concentration, reached in stationary conditions.

Nevertheless, considering that the necessary data is little and uncertain, the use of expressions or sophisticated models is unsuitable. In such cases, the use of simple and direct expressions is suggested (Armanini et al. 2000). In this case, α took values from 4 to 15° while $\varnothing$ ranges between 30 and 40°. The values of channel slope were previously classified in ranges in order to group similar behaviours of the flows. Results are shown in Tables 3 and 4.

Results show that an increase in the bed inclination (α) means an increase in the solid volumetric concentration (C_d), and that differences between slope values explain an important increment of solids in the debris flow. Table 4 presents differences between streamflow and maximum debris flow obtained with Takahashi's method. The debris flow discharge is three or four times higher depending on the conditions of the phenomenon and soil properties.

The debris flow routing along a channel was simulated by numerically solving the system of one-dimensional governing equations composed of the momentum conservation equation for the mixture of solids and fluid (HEC-RAS 4.1), the respective mass conservation equations for the debris flow and information about the stage reached by the flow on the walls of houses. The footprint of the flow in the walls allowed the validation of numerical simulation and estimation of debris flows.

Discussion

The 2012 debris flows in Camiña and Tarapacá valleys, which caused catastrophic damage at the local level in several settlements, although fortunately with no fatalities, left a number of observations that can be taken into account for preventive mitigation measures and urban planning in these and other similar *quebradas* in the region.

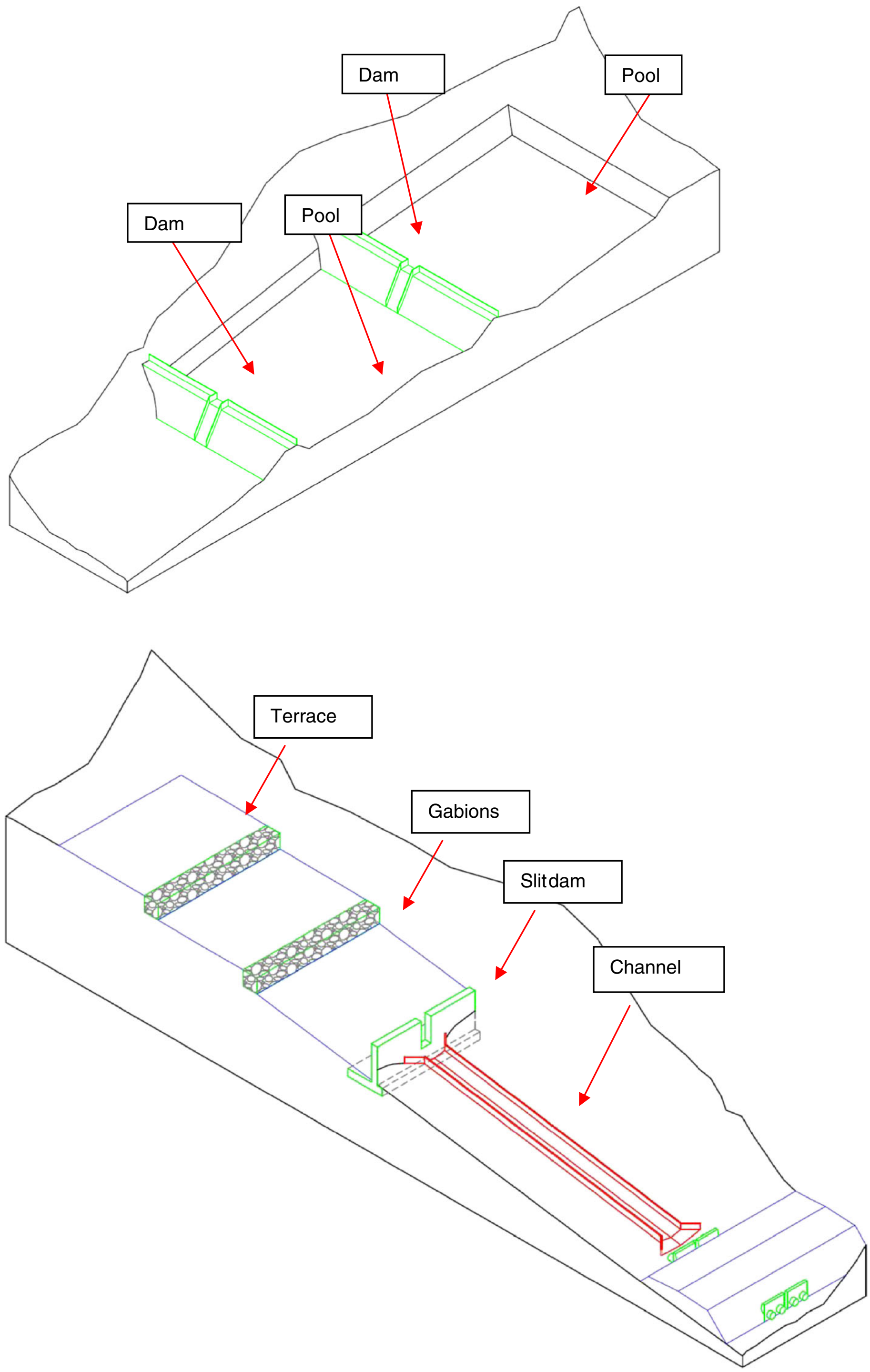

Fig. 7 Examples of conceptual design of some mitigation measures to be applied in areas affected by the 2012 debris flows (IDIEM 2013)

It is clear that the location of houses and critical infrastructure such as schools or surgeries on top of alluvial fans is a high risk one. The 2012 flows showed that, depending of possible channelization by streets or other constructions, the flows may reach different parts of the alluvial fans down to their tip on the main valley fluvial terraces. Therefore, the whole alluvial fan has some degree of hazard, which can be discriminated by detailed hydraulic modelling and geomorphological mapping, taking into account the built structures that can detour the flow (IDIEM 2013).

The relative structural vulnerability, which combines structure type and exposition, was evaluated as high or medium in most towns, especially those built on alluvial fans (IDIEM 2013). The most logic solution, moving the settlements somewhere else on the slopes or to the fluvial terraces away of recurrent flooding areas, is not a realistic option. Field observations and hazard studies of the area

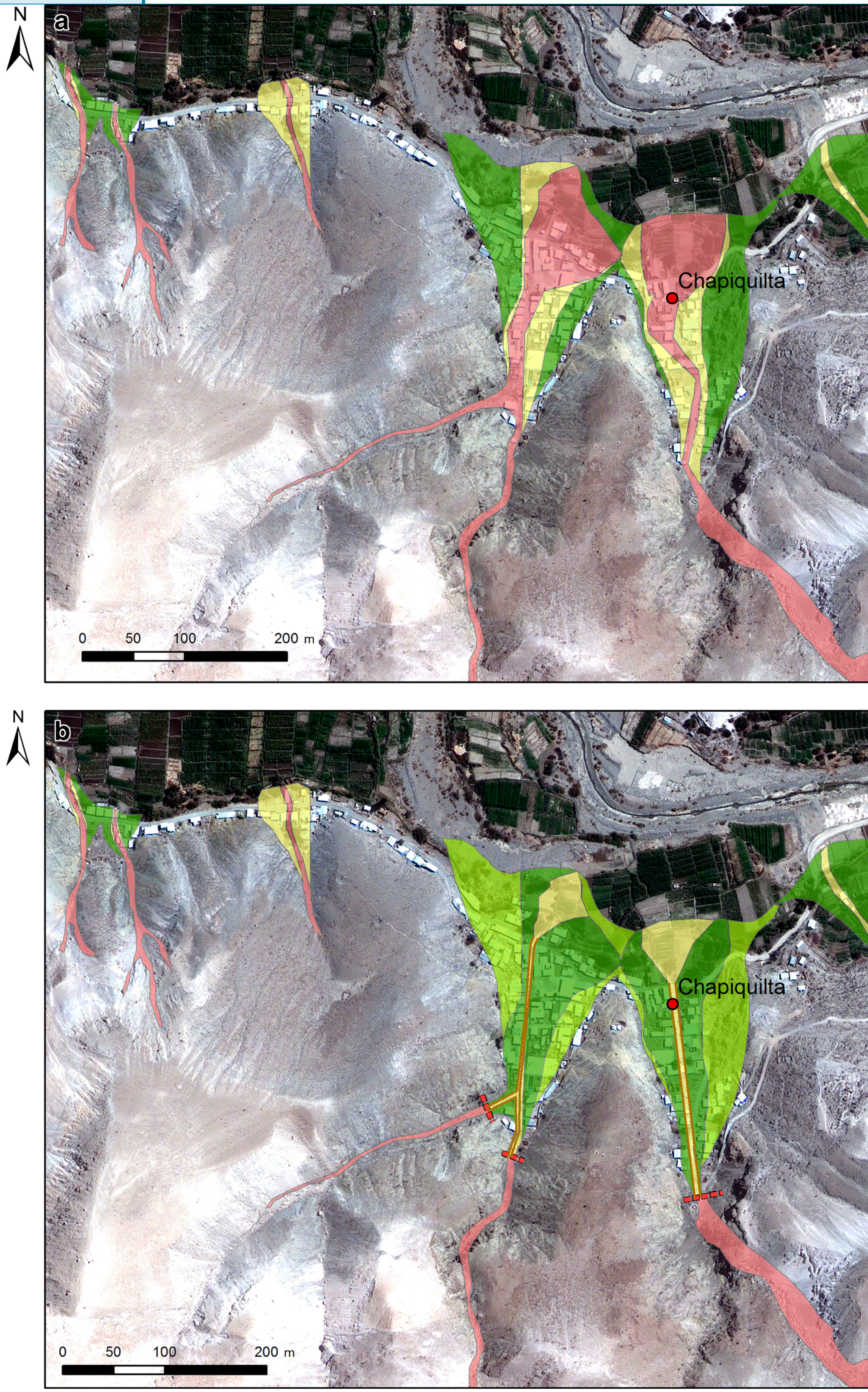

Fig. 8 Example of debris flows hazard maps without (**a**) and with structural mitigation measures (**b**) in the two main gullies in Chapiquilta village. Hazard levels indicated as follows: high (*red*), medium (*yellow*), low (*dark green*) and very low (*light green*). High hazard degree is based on <100-year return period events. In this case, proposed mitigations solutions are terraces and slit dams in fan apexes and channelized streets (modified after IDIEM 2013)

(IDIEM 2013) show that slopes are generally rock fall or landslide-prone areas. Therefore, they should be disregarded by the authorities. On the other hand, occupying the fluvial terraces would reduce the little agricultural land that is the base of subsistence for the Aymara local communities and would be against their tradition and culture of occupying such terraces for their crops. Furthermore, the lower terraces are susceptible to flooding by the main valley streams (Arrau 2009). That option might be only considered for controlled expansion of towns like Camiña, but is impractical for the small villages.

Having that in mind, the best option to mitigate future catastrophes, which frequency may be even enhanced by global warming, seems to be construction of mitigation structures for debris flow control, along with a proper redesign of the villages. As it was observed, the streets along or parallel to the alluvial fan axes are quite effective to channelize the flows reducing the impact on houses, but they must have a special design to avoid being destroyed and eroded by the flows as it happened this time. Other useful observation is the role of flattened surfaces at the fan apex, which may be used for recreation, that have a positive effect in reducing the coarse sediment load and the flow velocity. Detention of gravel and small blocks by normal wire fences indicate that these types of elements are also useful. Based on those observations, the size of gullies and the hydraulic models of discharge and sediment loads, IDIEM (2013) proposed conceptual engineering solutions that combine elements such as artificial terraces, fences, slit dams, gabions, retaining pools and channels would reduce the level of hazard in the villages (Fig. 7 and 8). These mitigation measures must not only be applied in steep and long lateral gullies, but also in short gullies from small area catchments such as those observed in Yala Yala and Laonzana. Design criteria for these structures are flow grain size and volumetric concentration reduction, energy reduction and channelization (IDIEM 2013). All these measures should be applied along with an urban planning that accounts for this type of hazard, including restrictions in high hazard areas, avoid increases in population density and proper building materials. Finally, design of road gully crossings must be revised to avoid lack of connectivity during and after rainfall events.

Concluding remarks

The March 2012 debris flow events that destroyed several villages along the Camiña and Tarapacá deeply incised valleys in northern Chile were produced by a ca. 100-year return period rainfall, related with convective storms during the so-called Altiplanic winter. Estimated discharges of the debris flows varied from 1 to 75 m^3/s, depending on the size of the lateral gullies, bed inclination and soil properties. Even small debris flows were able to cause catastrophic damage due to the high-risk location of the villages, many of them placed over active alluvial fans. To reduce such risk for future events, moving the settlements to fluvial terraces or slopes is not a realistic option, as slopes are prone to landslides, and the fluvial terraces are key for subsistence of the local communities which economy is based on small-scale agriculture. Therefore, risk reduction should be carried out by combining territorial planning with debris flow mitigation structures.

Acknowledgments

This work is part of a hazard study carried out by IDIEM-Universidad de Chile for the Chilean Government. We thank the Hydraulic Works Direction of the Public Works Ministry for the permission to publish data. We also thank local communities and municipalities for supporting the fieldwork providing valuable information and allowing geotechnical investigations.

References

Aceituno P, Montecinos A (1997) Meteorological field experiments in the South American Altiplano. Preprints, Fifth Int. Conf on Southern Hemisphere Meteorology and Oceanography, Pretoria, South Africa, Amer Met Soc. 330–331

Aceituno P (1998) Elementos del clima del Altiplano Sud Americano. Rev Geofisica - IPGH 44:37–55

Armanini A, Larcher M, Majone B, Rigon R, Benedetti G, Hideaki M (2000) Restoration of the Basisns Quebrada San José de Galipán and Quebrada el Cojo. International Workshop on the Debris Flow Disaster of December 1999 in Venezuela

Arrau (2009) Estudio de Diagnóstico "Plan de Manejo de Cauce Quebrada de Camiña". Empresa Luis Arrau del Canto. Dirección de Obras Hidráulicas, Ministerio de Obras Públicas, Technical Report

Astroza M, Moroni MO, Norambuena A, Astroza R (2005) Intensities and damage distribution in the June 2005 Tarapacá, Chile earthquake. Newsletter EERI, Special Earthquake Report, Earthquake Engineering Research Institute, California, USA

Farías V (2012) Análisis geomorfológico de megadeslizamientos entre las quebradas Camarones y Tiliviche, región de Tarapacá. Dissertation, Dept. of Geology University of Chile

Garreaud RD (2000) Intraseasonal variability of moisture and rainfall over the South American Altiplano. Mon Weather Rev 128:3379–3346

Garreaud R, Seluchi M (2003) Pronóstico de la convección en el Altiplano Sud Américano empleando el modelo regional ETA/CPTEC. Meteorológica 26:25–38

IDIEM (2013) Diagnóstico de la situación de riesgo en quebradas laterales a los cauces de las quebradas de Camiña y Tarapacá. Report Nº 762.474-C. Centro de Investigacion, Desarrollo e Innovacion de Estructuras y Materiales (IDIEM), Universidad de Chile

Letelier V (2013) Estudio geomorfológico de mega-remociones en masa en la Quebrada aroma, región de Tarapacá. Dissertation, Dept. of Geology, University of Chile

Montserrat S (2005) Experimental study of protection structures against aluvial floods. (Estudio experimental de obras de protección contra aluviones.). Master thesis, Dept. of Civil Engineering, University of Chile

Muñoz V (2007) Evolución morfoestructural del piedemonte altiplánico chileno durante el Cenozoico superior entre la Quebrada de Tarapacá y la Quebrada de Sagasca (19º45'-20º15'S). Dissertation, Dept. of Geology, University of Chile

Pinto L, Hérail G, Charrier R (2004) Sédimentacion sintectonica asociada al flexuramiento neogeno en el borde oriental de la Depresion central en el área de Moquella, norte de Chile. Rev Geol Chile 31(2):19–44

Pinto L, Hérail G, Sepúlveda SA, Krop P (2008) A Neogene giant landslide in Tarapacá, northern Chile: a signal of instability of the westernmost Altiplano and palaeoseismicity effects. Geomorphology 102:532–541

Schwerdtfeger W (1976) High thunderstorm frequency over the subtropical Andes during summer: cause and effects. In: Schwerdtfeger (ed) Climate of Central and South America., Elsevier, pp 192–195

Sernageomin (2003) Mapa Geológico de Chile: Versión Digital. Servicio Nacional de Geología y Minería, Publicación Geológica Digital 4

Takahashi T (1978) Mechanical characteristics of debris flow, Journal of the Hydraulic Division, Proceedings ASCE 104 HY8, p 1153–1169

Takahashi T (1981) Estimation of potential debris flows and their hazardous zones: soft countermeasures for a disaster. J Nat Disaster Sci 3(1):57–89

S. A. Sepúlveda (✉) · S. Rebolledo · M. Lara
Departamento de Geología,
Universidad de Chile,
Plaza Ercilla 803, Santiago, Chile
e-mail: sesepulv@ing.uchile.cl

J. McPhee · M. Cartes · E. Rubio
Departamento de Ingeniería Civil,
Universidad de Chile,
Blanco Encalada 2002, Santiago, Chile

D. Silva · N. Correia · J. P. Vásquez
IDIEM,
Universidad de Chile,
Plaza Ercilla 883, Santiago, Chile