Landslides (2011) 8:269–278
DOI 10.1007/s10346-011-0259-7
Received: 21 October 2010
Accepted: 11 February 2011
Published online: 2 March 2011

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Rainfall-related debris flows in Carhuacocha Valley, Cordillera Huayhuash, Peru

Abstract Continuous heavy rainfall hit northern Peru in the second half of the 2008/2009 summer season. From the end of January to the beginning of March, the Cordillera Huayhuash experienced abnormally high precipitations that exceeded 270mm. The antecedent rainfall, aggravated with a severe rainstorm of 20mm on March 7 triggered a large debris flow in the upper Carhuacocha Valley early in the morning on March 8. The debris flow interrupted drainage from the upper part of the valley damming a lake in the narrow depression between the trough slope and the lateral moraine. As a result of the drainage interruption, water percolated through the moraine dam of Cangrajanca Lake where a secondary mass movement occurred in its inner slope. In September 2009, we mapped the debris flow and related landforms and estimated the total area and volume of both mass movements using geodetic measurements. About 104,000m^3 of sediments was moved from the trough slope towards the moraine from which 534,000m^3 flowed to Cangrajanca Lake subsequently. We analysed the rainfall conditions that triggered the debris flow using rainfall data from the nearby stations. We also compared the precipitation preceding the event with the rainfall thresholds for debris flow initiation.

Keywords Debris flow · Precipitation · Moraine · Lake · Cordillera Huayhuash · Peru

Abbreviation

a.m.	Ante meridiem
ASL	Above mean sea level
D	Rainfall duration
DEM	Digital elevation model
GPS	Global positioning system
I	Mean rainfall intensity
ID	Intensity–duration
M	Measuring distance
p.m.	Post meridiem
ppm	Parts per million
Q_{max}	Peak discharge
UTM	Universal Transverse Mercator
V	Total volume

Introduction

Climate factors in mountain areas affect the magnitude and frequency of a wide range of geomorphological processes including mass movements (Eybergen and Imeson 1989). In particular, precipitation is the most common triggering factor for debris flows and shallow landslides although it influences slope stability indirectly, through increased pore water conditions in debris (Caine 1980). Intense rainfall in mountain areas is also responsible for the highest rates of slope erosion (e.g. Beniston 2005). However, preparatory conditions of mass movements depend on a number of other factors such as topography, geology, soil types or vegetation. The effect of intense rainfall on slope processes has been studied mainly in mid-latitude mountain regions (e.g. Bacchini and Zannoni 2003). Relatively few studies have documented the response of mountain slopes to extreme rainfalls in the tropical or subtropical Peruvian Andes (Carlotto et al. 2000; Fídel et al. 2005; Vilímek et al. 2006).

This study describes the debris flow that occurred in March 2009 in the upper Carhuacocha Valley. According to local people, the debris flow initiated early in the morning on March 8 after 6 days of continuous rain. The mass movement-related landforms and subsequent changes in the drainage network are assessed, and the climate conditions that triggered the debris flow are analysed. Information from this report may contribute to determination of a rainfall threshold of debris flow in the Northern Peruvian Andes.

Regional setting

The study area is located on the Atlantic side of the Cordillera Huayhuash in the western Andean range (the Cordillera Occidental) of Peru. The mountain range extends for over 26 km between 10°11′ and 10°26′S latitude and between 76°50′ and 77°00′ W longitude (Fig. 1). The highest peak is Cerro Yerupaja with an elevation of 6,617 m above the mean sea level (ASL). A further five summits rise above 6,000 m ASL. The high elevation of the range, together with regional climatic conditions, has resulted in the extensive development of valley glaciers. The total glaciated area was estimated to be 85 km^2 (Ames 1988). Pativilca and Marañón Rivers drain the mountains into the Pacific and Atlantic Oceans, respectively. As a result of uneven glacial erosion and structural conditions, the eastern valleys are less incised than the valley floors situated west from the main drainage divide (Hall et al. 2009).

The study site is situated in a trough carved by the East Sarapo Glacier along the eastern (Atlantic) flank of the range. The western slope of the trough is characterized mostly by vertical rock walls covered by glaciers descending from Cerro Yerupaja, Nevado Siula Chico and Nevado Siula Grande (Fig. 2). The eastern side of the trough is incised into the less dissected relief of the Cerro Yanaccocha ridge, which was not recently glaciated. The ridge is built out of Lower Cretaceous sandstone; shale and quartzite build this ridge whereas Upper Cretaceous carbonates dominate the western part of the trough (Coney 1971).

The width of the trough bottom is locally restricted by alluvial fans and, more frequently, by large moraines that have been built away from side-valley snouts. In most cases, these moraines spread across the whole bottom of the trough, forming lake dams. The major part of the valley floor is occupied by Cangrajanca Lake dammed by the terminal moraine of the Yerupaja Glacier. The moraine extends down-valley for over 1.7 km restricting the drainage of the upper part

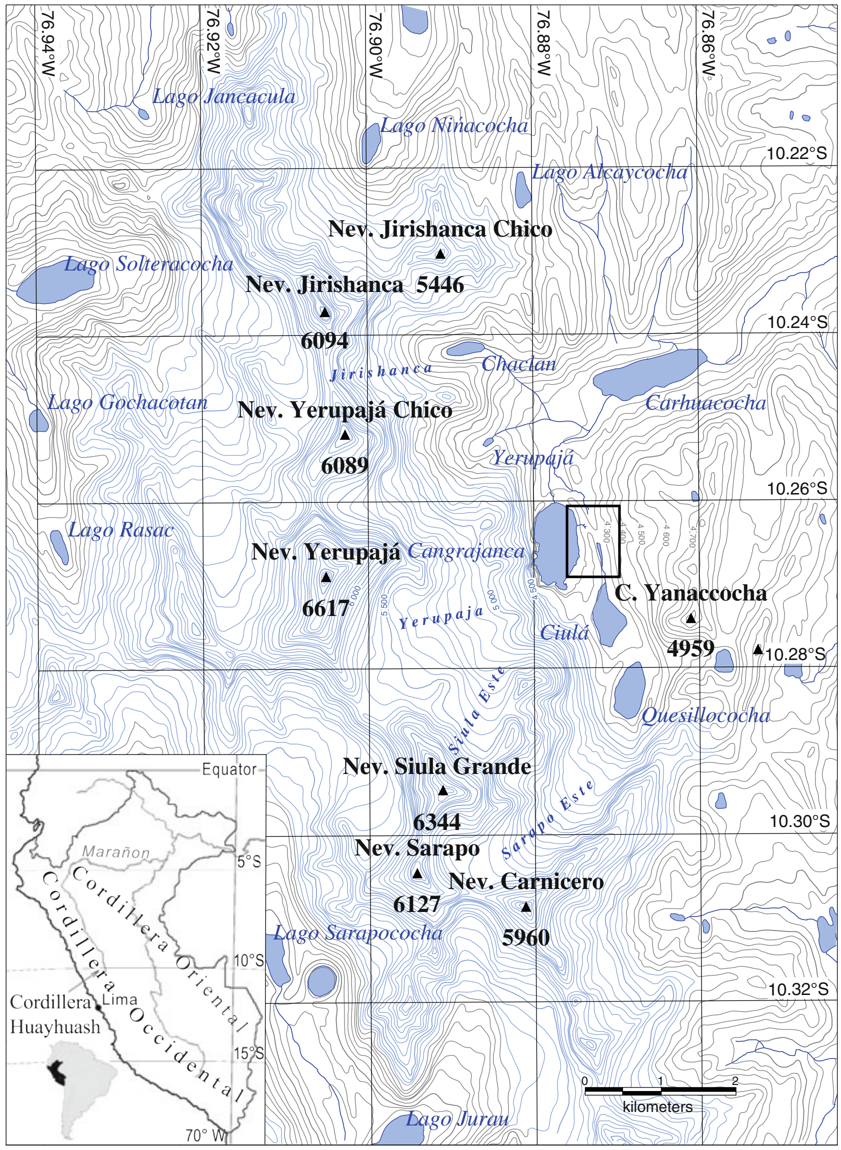


Fig. 1 The upper Carhuacocha Valley in the eastern part of the Cordillera Huayhuash. A *rectangle in the centre* marks the location of study area with the lake dammed by debris accumulation

Fig. 2 View from the north to asymmetric upper part of Carhuacocha Valley. Glacier termini at the right upper corner descend from Yerupajá and Siula eastern faces and hang above the moraine-dammed Cangrajanca Lake in the centre. The debris flow initiated on March 8 in the less steep trough slope on the left. East Sarapo glacier in the background (photo: Z. Engel)

of the valley to the narrow (<50 m wide) strip of the valley floor at the foot of Cerro Yanaccocha. The middle part of this narrow valley section between moraine and trough slope was affected by the debris flow in March 2009.

The climate in the study area is characterized by year-round low temperatures and by a rainy summer season. Eighty percent of the total annual precipitation occurs between December and March, when a southern shift of the intertropical convergence zone enables an increased transport of humid air from Amazonia (Johnson 1976), resulting in long-lasting and continuous rain. This seasonal precipitation regime confines rainfall-related mass movements almost exclusively to the summer season. No climatic data are available for the study area, but the annual precipitation at the nearby Cajatambo station is 563 mm (Table 1). Rainfall increases with altitude to about 1,100 mm per year in close mountain ranges. For example, the mean annual precipitation exceeds 1000 mm in the Yanahuanca (3,140 m) and Cerro de Pasco (4,260 m) with up to 50 mm of rainfall per day in summer months. Snow

Table 1 Mean annual temperatures and precipitation for meteorological stations in proximity to the study area

Station	Latitude [°S]	Longitude [°W]	Altitude [m ASL]	Drainage area	Temperature [°C][a]	Precipitation [mm][b]	Distance to study area [km]
Cajatambo	10.47	76.98	3,350	Pacific	10.8	563	25
Chiquian	10.15	77.15	3,349	Pacific	–	653	36
Oyon	10.67	76.77	3,630	Pacific	8.8	525	45
Yanahuanca	10.48	76.52	3,140	Atlantic	13.0[c]	1,090	46
Cerro de Pasco	10.69	76.25	4,260	Atlantic	5.6[c]	1,053	81

[a] Galán de Mera et al. 2004

[b] Agteca S.A.

[c] Instituto Geofísico del Perú 2005

accumulation occurs during the summer season, whereas ablation occurs year round, with higher rates in the summer season (Kaser and Osmaston 2002). The altitude and valley orientation affect the flux of humid air which determines the local variations in rainfall. According to Bookhagen and Strecker (2008), the largest precipitation in the Cordillera Huayhuash occurs east of the main drainage divide.

Methods

Geomorphological mapping and the field description of the debris flow sediments was done on October 6–9, 2009. Combined global positioning system (GPS)/geodetic mapping of landforms was realized in the study area to estimate the shape, surface area and volume of the two recent mass movements. The size of transported blocks was measured, and the overall texture of debris flow deposits was assessed using standard indices (e.g. Hubbard and Glasser 2005). Mass movements were delimited using an infrared rangefinder and reflecting prism, which was also operated in accessible areas of debris flows including both depletion zones. Steep surface was surveyed by means of a pulsed laser rangefinder of a total station in non-prism mode. Using a Leica TCRP 1202 extended by GPS Smart Station, data were collected in the UTM system. The declared accuracy of measurement in the prism and non-prism mode is 1 mm+1.5 part per million (ppm)×measuring distance (M) and 2 mm+2 ppm×M, respectively.

The geodetic data collected were used to construct digital elevation models (DEMs). The regular shape of the trough slopes and narrow stripes affected by debris flow allowed for the pre-failure surface topography to be estimated. Measured boundary data and straight connecting lines parallel to contours were used for this purpose. DEMs of debris flows at the foot of the trough slope and on the inner side of the moraine were calculated using 300 and 146 measurement points, respectively. Different interpolation techniques with optimized parameters were applied to both datasets. The accuracy of the models was cross-validated using the set of measurement points extracted from the original dataset prior to DEM calculation. A sum of residuals and appearance of the surface morphology was used for determination of the most reliable gridding method using Encom Engage 3D Professional software. The minimum curvature algorithm generated low mean square error and a realistic surface and was used to construct DEMs for ground surfaces prior and after the flow events. The total volume (V) of both debris flows was estimated using difference between pre- and post-

Table 2 Precipitation in the 2008/2009 summer season

Period	Cajatambo	Chiquian (1964–1981)	Oyon (1963–1982)	Yanahuanca (1965–1982)	Cerro de Pasco (1950–1979)
December 2008 to March 2009	661	496 (463)	454 (349)	570 (593)	507 (611)
December 2008	87	44 (70)	83 (69)	53 (125)	83 (133)
January 2009	160	112 (100)	101 (76)	140 (137)	119 (150)
February 2009	184	178 (147)	105 (99)	175 (175)	106 (162)
March 2009	230	163 (146)	165 (105)	202 (156)	199 (166)
January 25 to March 7 2009	270	242	156	248	200
10 days prior to flow	56.2	59.7	30.8	66.2	84.5
7 days prior to flow	42.1	38.7	22.7	36.6	75.1
24 h prior to flow	18.4	8.0	2.9	0.0	0.0
consecutive days with rain prior to flow	24	6	27	3	1

Mean precipitation for relevant periods shown in parenthesis (data: SENAMHI, Agteca)

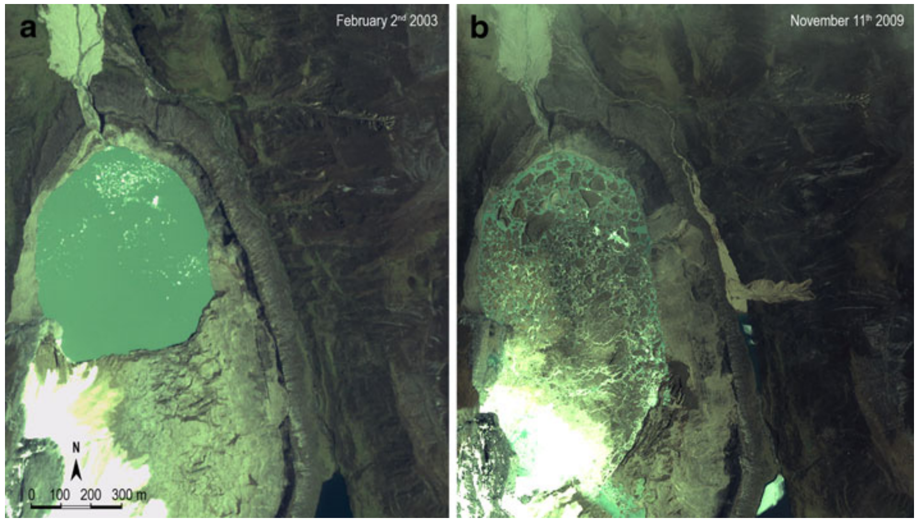


Fig. 3 QuickBird images of the study area. **a** Pre-failure (2003) and **b** Post-failure (2009). A reconstituted glacier forms below the termini of hanging glaciers in Cangrajanca Lake and its surface is gradually shrinking towards the end of summer (2003). East from the moraine dam, numerous gullies dissect the trough slope. An accumulation of the debris flow from March 2009 covers the narrow strip of valley floor between moraine and the trough slope damming the newly formed elongated lake

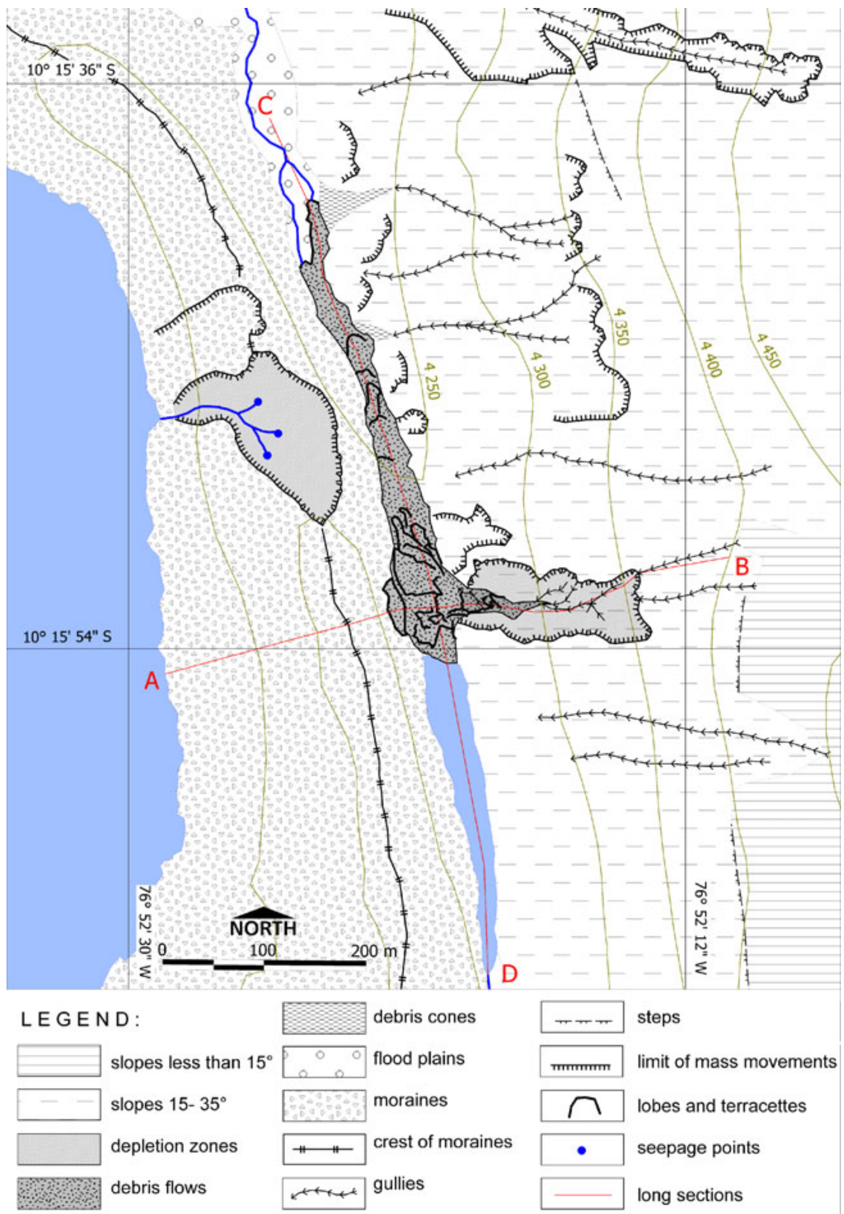


Fig. 4 Geomorphological map of the study area

Fig. 5 The debris flow transported material from a depletion zone (*a*) to an elongated depression between moraine and a trough slope. The accumulation zone consists of a cone-like upper part (*b*) including its impinged front on moraine (*c*) and a lobe-like debris accumulation (*d*). A new lake was formed above the flow accumulation (*e*) and a secondary mass movement (*f*) occurred in the inner side of moraine. Man in the centre of the cone for scale (photo: L. Šefrna)

event DEM pairs. The peak discharge (Q_{max}) of the primary debris flow was determined using equations

$$V = 13\, Q_{max}1.33 \quad (1)$$

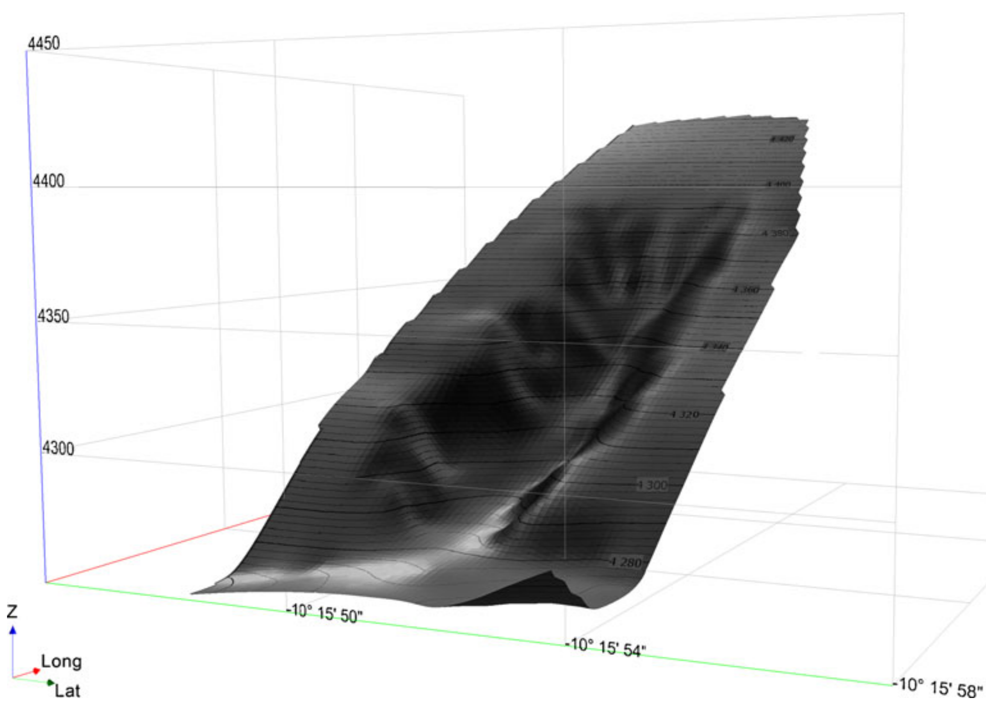
$$V = 28\, Q_{max}1.11 \quad (2)$$

derived for granular debris flows by Mizuyama et al. (1992) and Bovis and Jakob (1999), respectively.

The precipitation data for 2008/2009 summer and historical precipitation records from the nearest high-mountain meteorological stations were analysed. Yanahuanca and Cerro de Pasco stations represent the Atlantic side of the mountain range whereas Cajatambo, Chiquian and Oyon stations were selected as representatives for the Pacific side of the continental divide. Rainfall is recorded twice a day (7 a.m. and p.m.) at all these stations with the exception of Chiquian, where only the cumulative rainfall for 24 h is available. As was previously mentioned, no direct measurements of rainfall rates and intensities are available in Carhuacocha Valley where the mass movements occurred on March 8. The nearest station is located at Cajatambo (3,350 m ASL), 25 km to the SSW from the study site. The second nearest station is situated at Chiquian (3,349 m ASL), 36 km to WNW (Table 1). Precipitation records from all stations were analysed using long-term and 2008/2009 monthly data. Precipitation sums were counted for 10-day intervals from December 2008 to March 2009 and used for determination of precipitation trend in 2008/2009 summer season. As the regional distribution of precipitation was regular during the summer (Table 2), the nearest Cajatambo station may be considered as the most representative for the upper Carhuacocha Valley.

Precipitation from Cajatambo station was studied in detail, using 10-day, 3-day and 24-h precipitation sums. The rainfall conditions prior the debris flow event were analysed and compared with published thresholds for debris flow initiation. As the rainfall thresholds for debris flow triggering change over time and space (e.g. Innes 1983; Glade 1998), only globally defined thresholds were considered. Except for the global rainfall intensity–duration (ID) thresholds defined by Caine (1980), Innes (1983), Crosta and Frattini (2001) and Guzzetti et al. (2008), a four standard deviations

Fig. 6 The debris flow source area has a form of elongated deep gully with rugged flow slide path



threshold was applied (Rebetez et al. 1997). This threshold was defined as the 4σ level for the accumulated precipitation on three consecutive days. The 4σ threshold reflects climatic conditions preceding the event and allows the determination of relative extreme values. As a relative statistical parameter, this threshold can be used in areas without a dense network of rain gauges. Accumulated precipitation on three consecutive days before the debris flow event was also compared with the amount of rainfall in the previous 15 days. The 3-/15-day cumulative rainfall ratio was interpreted by Chleborad (2003) as an approximate lower-bound threshold for the rainfall-induced landslide.

Results

Debris flow morphology and impacts on environment

The topography of the west facing slope of Carhuacocha Valley and loose material on its surface represent very good conditions for a wide range of geomorphological processes among which debris flows and shallow landslides prevail. Mass movement-related features are very common in the whole slope which is extensively incised by gullies (Figs. 3 and 4). Recent debris flow activity is evident in the form of fresh debris lobes, unvegetated gullies and debris cones that have locally reached bedrock. Grass-covered stable gullies and debris cones were interpreted to indicate older activity, which timing remains unclear. Field reconnaissance revealed that during debris flow events, deposits extended completely across the narrow depression between the trough slope and the moraine. Toes of these accumulations are currently truncated by the river channel that is confined between deposits and outer slope of the moraine.

The rapid mass movement of March 8 occurred in a steep trough slope, which represents the relic of inner side of a Quaternary moraine. The debris flow started in a confined channel about 110 m above the foot of the trough slope. The slope consists of very poorly sorted glacial sediments with predominance of the sand-size clasts, which makes it particularly susceptible to sliding and flow (Ballantyne 1993). The described mass movement can be classified as debris flow, based on the rapid course of the event, sediment texture and geomorphological characteristics of both depletion and accumulation zones (Fig. 5). The location of the debris flow in a grass-covered gully shows that it belongs to channelized form of debris flow (Dikau et al. 1996).

The depletion zone of the debris flow consists of a steep scarp and a channel-like transport area (Fig. 6). The depletion zone is sharply incised into the valley slope that has a local gradient of 30°, which corresponds to the lower threshold gradient for debris flow initiation (Innes 1983). The gradient of the depletion zone is the highest below the crown of the scarp (60°–90°) and then decreases farther down the slope (Fig. 7). The rugged relief of the depression is highlighted by the presence of structural steps, which result in significant changes in slope gradient. For example, the floor of the axial incision drops by about 5.5 m as it traverses the bedrock outcrop in central part of the depletion zone. The depth of the depression varies along its central line being the most pronounced at the beginning of the debris flow accumulation (Fig. 8). The maximum width of the depletion zone is 71 m and the length measured along the axial line is 190 m. Elevation difference between the upper and the lower reaches of the depletion zone attains 111 m.

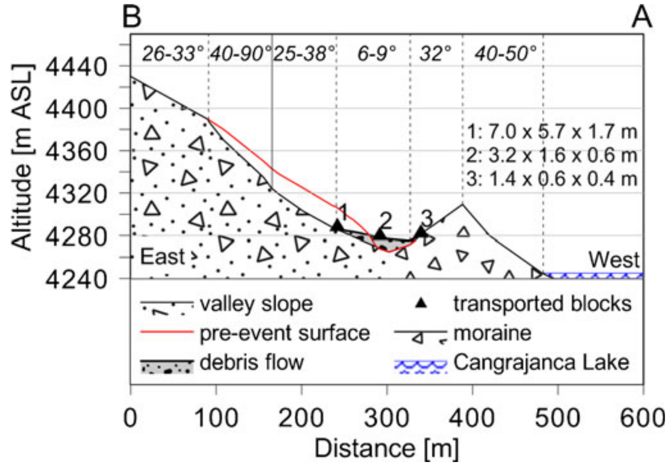


Fig. 7 Long section *A–B* across depletion zone, debris cone and moraine dam of Cangrajanca Lake. The *vertical axis* is exaggerated by a factor of 1.3

In the lower part of the depletion zone, the debris flow accumulation begins. The upper part of the accumulation has a form of a fan that turns into a lobe-like accumulation confined in the depression between the moraine and the trough slope (Fig. 5). A section A–B measured over the upper part of the accumulation shows a relatively low gradient (7.5°) of the surface that is characteristic for fans resulting from debris/water flow processes (Fig. 7). The lower part of this section demonstrates that deposits impinged on the opposing slope of the moraine during the debris flow event. The upper part of the impinged material is located 6.9 m above the apex of the debris cone and about 14.5 m above the valley-floor surface prior to debris flow. Longitudinal profile C–D along the debris flow lobe area shows relatively low gradient of the accumulation (Fig. 9). The mean gradient of the accumulation between its toe and the debris-flow-dammed lake reaches 5.6° (the mean gradient of the valley floor is 3.5°). The gradient of the lower lobe-like part of the debris flow is about 4.8°. Examination of the axial section of the debris flow also reveals a number of transversal ridges and relatively broad shallow lobes on the surface of the accumulation (Figs. 4 and 10). Some of the

Fig. 8 Depletion zone with debris cone at the upper part of the debris flow accumulation. *Arrows* mark transported blocks located and measured on long section A–B. Man with a tripod in the centre of the cone for scale (photo: Z. Engel)

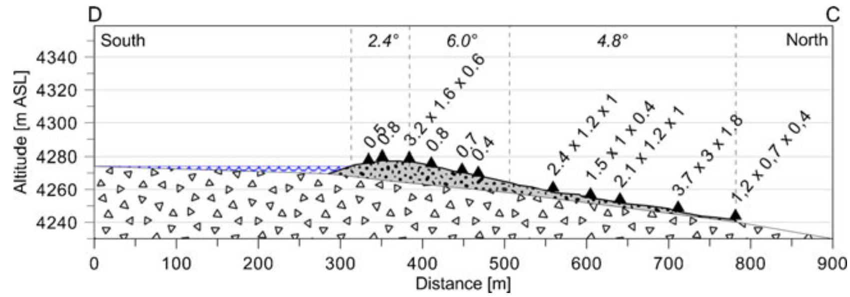


Fig. 9 Debris flow long section *C–D* plotted at a 2:1 ratio. *Symbols* as in Fig. 7 are used

lobes can be traced to the apex of the fan-like part of the debris flow accumulation, where they are accompanied by distinct levées.

The debris flow transported large amount of material for over 0.5 km. The total length of the accumulation including the upper cone-like part is 520 m. The maximum width of 60 m and thickness of about 12 m is reached below the depletion zone. The matrix-rich debris flow contains large floating boulders, which are concentrated at the terminal parts of individual surface lobes. The largest boulder (7.0×5.7×1.7 m) is located on the surface of the uppermost part of the accumulation where normal grading of size is apparent (Fig. 7). Along the long section of the lobe, the largest clasts show inverse grading with the largest transported boulder (3.7×3.0×1.8 m) located at the secondary toe of the debris flow at 4,245 m ASL (Fig. 9). The matrix-rich deposits and the lobate morphology of the deposits indicate a high-viscosity (cohesive) type of debris flow (Blikra and Nemec 1998).

Detailed topographic surveys revealed that the volume of the material transported during the debris flow event on March 8 was about 100,000 m^3. The differences between the volumes calculated using a variety of interpolation methods for the calculations of the DEM surface do not exceed 7%. The minimum curvature algorithm generated a volume of 104,000 m^3. The triangulation method, which also produced reasonable surfaces, gives similar results while other algorithms slightly overestimate the value of the volume. Peak discharge of the debris flow ranged from 900 to 1,600 m^3/s, based on Eqs. 1 and 2.

The material deposited in the narrow depression between the trough slope and the moraine, which dams Cangrajanca Lake, interrupted drainage from Siulá Lake in the upper part of the valley.

Fig. 10 Fragments of vegetation and soils cover the middle part of the matrix-rich debris flow accumulation (photo: Z. Engel)

The water collected above the debris flow gave rise to an elongated lake (Fig. 4). At the time of our fieldwork (October 2009), the lake was 321 m long, up to 43 m wide and 6 m deep. Seepage took the water from the lake towards a gully in the inner slope of the moraine and fed three seepage points at 4,234, 4,231 and 4,229 m ASL. The seepage points are located about 250–300 m to the NNE from the debris flow dam. The vertical difference between the lake level and the seepage points range from 40 to 45 m. The up to 45 m deep gully in the inner slope of the moraine (Fig. 11) was formed by a large mass movement that moved about 534,000 m^3 of unconsolidated glacial sediments to Cangrajanca Lake. No sign of a displacement wave was identified along the shoreline of Cangrajanca Lake.

Precipitation triggering conditions

The precipitation records from five stations near the study site show a gradual increase in rainfall since the beginning of the 2008/2009 summer season. The precipitation in December was up to 60% lower than average values for this month with the exception of the Oyon station where nearly 21% increase of rainfall was recorded. In January and February, the precipitation records indicate different trend for the Pacific and Atlantic side of the mountain range. Whereas records from the eastern mountain side show usual or lower (Cerro de Pasco) monthly values, increased monthly precipitation (up to 33%) was observed at stations west from the range. A substantial increase of precipitation followed in March when average monthly values were exceeded on both sides of the mountain range with the largest difference (+57%) at Oyon station. The rainfall values in March ranged from 163 mm at Chiquian to 230 mm at Cajatambo. The trend of increased precipitation continued in April when monthly precipitation were up to 120% higher (Chiquian) than average values. The total rainfall recorded from December 2008 to March 2009 was slightly higher than the average at stations on the western side of the mountain range and lower at stations east from the range (Table 2).

Precipitation records from Cajatambo station show that the rainfall has affected the study area almost continuously since January 25. Cumulative rainfall of about 270 mm during this period culminated shortly before the debris flow event. The highest 10-day precipitation average in 2008/2009 summer season (42.3 mm) was recorded at this station at the end of February (Fig. 12). During the next 10-day precipitation, values decreased (38.3 mm) but still remained above the average 10-day value for the summer season (32.1 mm). Continuous heavy rain was reported by local people from Carhuacocha Valley for the last 7 days before the debris flow event. Intense rainfall from March 1 to 7 was also recorded at Cajatambo station with the precipitation value of 42.1 mm (Table 2). The plot of cumulative rainfall

Fig. 11 Depletion area of the secondary flow with recent springs draining the upper part of Carhuacocha Valley above the debris flow (photo: Z. Engel)

indicates substantial increase of rainfall 1 day before the debris flow event (Fig. 13). On March 7, Cajatambo recorded 18.4 mm of rainfall that represents the highest daily precipitations recorded at this station. Information from local habitants suggests that similarly intense rainfall hit Carhuacocha Valley. During the debris flow event which occurred early in the morning on March 8, no rainfall was recorded at Cajatambo. At the same time, light shower occurred in Carhuacocha Valley according to local people from the Papa Machay settlement, which is situated 1 km north from the debris flow site.

The continuous rain that lasted until the debris flow event started on March 3 after 7 a.m. Regarding the duration (D) of rainfall (89 h) and the total rainfall value of 39.6 mm, the average rainfall intensity (I) for the rainstorm was 0.44 mm/h. This value is higher than the threshold values calculated based on both equations proposed by Guzzetti et al. (2008) and lower than other considered ID thresholds (Table 3). The cumulative rainfall value for 3 days before the debris flow reached 25.1 mm which is higher value than 4σ threshold (22.7 mm; Fig. 12). Antecedent 15-day cumulative rainfall that occurred prior to the last 3-day period reached 108.2 mm. This amount belongs to higher values of precipitation, for which the cumulative rainfall threshold was not well defined (Chleborad 2003).

Discussion

The location of the study area in the seasonally wet eastern slope of the Cordillera Huayhuash and the presence of numerous scars and gullies in the trough slope imply that mass-movement processes have been particularly frequent in the upper Carhuacocha valley recently. A fresh appearance of unvegetated landforms related with slope processes indicates that shallow landslides and debris flows are very active at present. Though data on precipitation in the area are scant, the occurrence of the debris flow on March 2009 evidenced the relation between mass movements and precipitation. Heavy rainfall affected the area within the whole 2008/2009 summer with higher than average precipitation on the western side of the mountain range and lower on the eastern flank. Similar anomalies are characteristic for the El Niño episodes when rainfall increases more than fourfold in the northern Peruvian Andes (Bookhagen and Strecker 2010). However, changes in rainfall of less than 30% in the Cordillera Huayhuash in the 2008/2009 summer may be attributed to the interannual variations which typically result from a few isolated intense convective events (Lenters and Cook 1999).

Heavy rainfall affected the area since December 2008 and culminated about 15 days before the debris flow event. Time lag between the culmination of the long-lasting rain and the debris flow triggering suggests that the flow initiation was connected with cumulative precipitation in the study area. However, the triggering effect of the antecedent rainfall could have been enhanced by a heavy rainstorm that occurred in the Cordillera Huayhuash 1 day before the debris flow event.

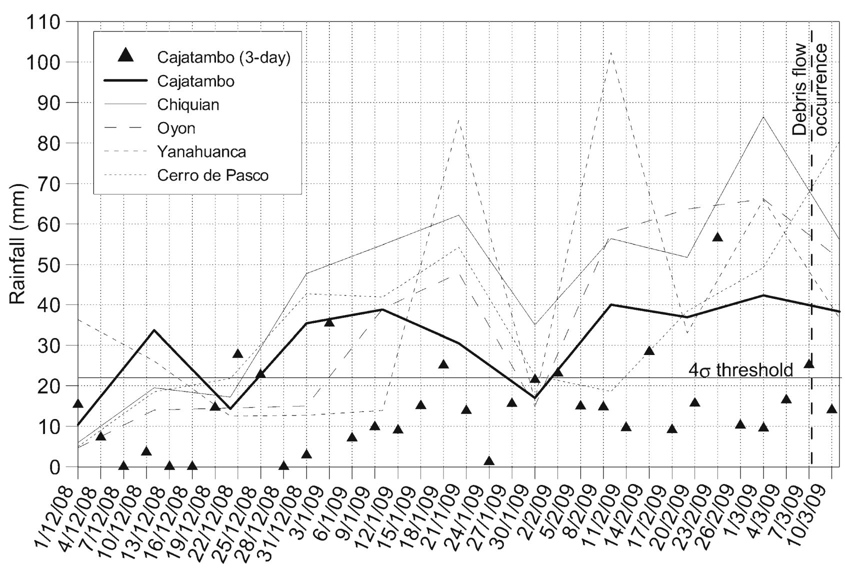


Fig. 12 Ten-day precipitation averages for stations near the study area and precipitation sums for 3-day intervals between December 2008 and March 2009 at Cajatambo station

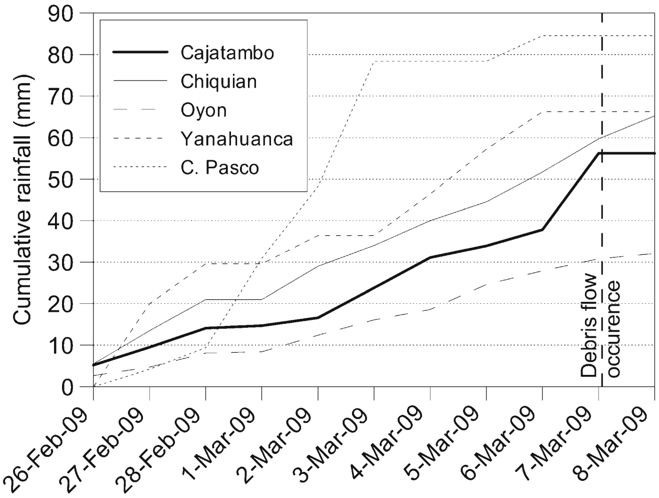


Fig. 13 Cumulative rainfall preceding the debris flow event

The average rainfall intensity for the continuous rainstorm preceding the debris flow, as well as the 3-day cumulative rainfall value, gives the first regional precipitation thresholds for triggering of landslides. Although these values are derived from a single event only, it implies a minimum rainfall amount and intensity above which the debris flow may occur in the study area. Comparison of calculated ID thresholds with the mean rainfall intensity during the rainstorm confirms the applicability of equations determined by Guzzetti et al. (2008). Both the single global threshold and the threshold for long duration of rainfall events were exceeded. Similarly, 4σ precipitation threshold was also valid and proved to be useful for evaluation of debris flow initiation in a given region.

A variety of mass movements including debris flow were reported from mountain ranges in the vicinity of the Cordillera Huayhuash (e.g. Evans et al. 2009). However, most of the described events were triggered by earthquakes and only few papers deal with rainfall-induced debris flow or shallow landslides (Vilímek et al. 2006; Rein 2007). The high precipitation that occurred in the Peruvian Andes during the rainy season of 2008/2009 caused a number of landslide events. While the succession of precipitation and a landslide event in the nearby Cordillera Negra (Klimeš and Vilímek 2011) suggests a substantial lag between critical rainfall and mass movement, the described debris flow in Carhuacocha Valley can be related directly to heavy rainfall. An analysis of rainfall in relation to the debris flow in the study area has shown that the cumulative rainfall combined with an extreme precipitation event were the main triggering factors of the debris flow that occurred on March 8, 2009. The triggering factor of the secondary mass movement in the inner slope of the moraine that dams Cangrajanca Lake remains unknown. The discharge and location of three seepage points in the gully imply a mass movement due to seepage of the lake formed by the debris flow on March 2009. However, the precipitation factor cannot be excluded either because two intense rainstorms of 43.6 mm (March 23–24) and 19.7 mm (April 11) occurred in the region from March 8. In the same period, cumulative rainfall triggered a large landslide in the nearby Cordillera Negra (Klimeš and Vilímek 2011).

The new lake formed due to the debris flow event between trough slope and moraine belongs to few mountain lakes in the Cordillera Huayhuash dammed by mass movements. Most of about 120 lakes in this mountain range arose after retreat of glaciers in troughs where large flat areas were inundated. The surface area of moraine-dammed lakes is therefore by one or two orders of magnitude larger than the area of the new lake (0.84 ha). This is also the case of Carhuacocha Lake (53.97 ha) that collects the water from the study area and reduces peaks of floods due to its high flood-control capacity. The difference between the area and the volume of the two lakes suggests that possible overflows or even outburst of the debris flow dam do not represent a threat to local settlements in a floodplain that are situated below the Carhuacocha Lake.

Conclusions

The mass movement that occurred on March 8, 2009 in Carhuacocha Valley can be classified as a channelized debris flow. A total volume of the transported material was about 104,000 m^3, and the peak discharge ranged from 900 to 1600 m^3/s. The debris flow transported large amount of material for over 0.5 km filling a narrow depression between trough slope and lateral moraine with 520 m long, 60 m wide and up to 12 m thick accumulation of debris. As a consequence of the mass movement, the surface drainage was interrupted and the water leaked through the moraine to Cangrajanca Lake. Water collected above the debris flow caused the rise of an elongated lake, and the seepage probably initiated a secondary mass movement at the inner slope of the moraine from where about 534,000 m^3 of sediments was moved to Cangrajanca Lake.

The analysis of rainfall records from the climatic stations in the vicinity of the Cordillera Huayhuash showed that higher than

Table 3 Minimum rainfall intensity for the likely occurrence of debris flows based on the applied ID thresholds

Author	Equation	Mean rainfall intensity (mm h^{-1})
Caine (1980)	$I = 14.82 \times D^{-0.39}$	2.63
Innes (1983)	$I = 4.93 \times D^{-0.50}$	0.54
Crosta and Frattini (2001)	$I = 0.48 + 7.2 \times D^{-1.00}$	0.57
Guzzetti et al. (2008)	$I = 2.2 \times D^{-0.44}$	0.31
Guzzetti et al. (2008)	$I = 0.48 \times D^{-0.11}(D > 48\ \mathrm{h})$	0.29

The mean rainfall intensity for the rainstorm that triggered the debris flow was 0.44 mm/h average amount of precipitation occurred in the study area in February and March 2009. Meteorological evidence also suggests increased amount of precipitation prior the debris flow event with a culmination of rainfall on March 7. The average rainfall intensity for the continuous rainstorm preceding the debris flow reached 0.44 mm h^{-1} exceeding the single global threshold and the threshold for long duration of rainfall events determined for debris flow initiation by Guzzetti et al. (2008). A total rainfall amount of 25 mm over a 3-day period prior the debris flow also meets the necessary rainfall conditions for debris flow triggering (Rebetez et al. 1997). It can be concluded that the debris flow was triggered by cumulative rainfall combined with an extreme precipitation event.

Acknowledgements

Fieldwork in 2009 was funded by the Czech Science Foundation (project no. 205/07/831) and by the Czech Ministry of Education (MSM 0021620831). The Agteca S.A. is thanked for providing compiled precipitation data for Peru.

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