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Evolution of landslide activity, and the origin of debris flows in the el niño affected payhua creek basin, matucana area, huarochiri, peru

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Abstract: Matucana, Perú (population 5800; elevation 2390 m), is located in Andes Occidental, approximately 75 km east of Lima. Matucana shares the Río Rimac (RR) flood plain with a strategic highway and railway. Debris flow-prone Quebrada Payhua (Payhua Creek (QP) joins RR at the upstream end of Matucana. Debris flows from QP dammed the RR and diverted it through Matucana in 1959 and 1983. These large debris flows originated in different parts of the QP basin. The steep ravine systems that produced them are supply-limited with respect to debris flow generation. Based on the volumes of debris flows that were produced by ravine systems in 1983, and channel surveys, a maximum volume of ~250 000 m^3 is estimated for the total discharge of a basin-wide debris flow event. Large debris flow events that are conditioned by regional rains are the greatest threat during an El Niño year and in the following year. The area of active landslides near Payhua village, has increased by a factor of five since 1951. Although landslide movement in the recent past has been slow and channel blockage by landslides has not been linked to large destructive debris flows, past events cannot be regarded as confident predictors of future events in this case.

Résumé: Le village de Matucana, Pérou (population : 5800; élévation :2390 m) est situé dans les Andes occidentales, à environ 75 km à l'est de Lima. Matucana, est situé de façon stratégique en partageant la plaine alluvial de la rivière Rimac (RR) avec l'autoroute et la voie ferrée. Le Quebrera Payhua (QP, aussi appelé ruisseau Payhua), prédisposé aux coulées de débris, se deverse dans la RR en amont du village de Matucana. En 1959 et 1983, deux grandes coulées de débris ont bloqué et ont fait dévier la RR passant par Matucana. Ces deux grandes coulées de débris ont été déclenchées à différents endroits dans le bassin QP. Les coulées de débris déclenchées dans ce système de ravins à pentes raides sont dépendantes du montant limité de sédiments alimentés. Selon les volumes des coulées de débris produites en 1983 et les relevées de chenaux, nous avons calculé un volume maximum de ~250 000 m^3 pour une grande coulée de débris s'étendant à la largeur du bassin. Les grandes coulées de débris sont activées par les pluies régionales et sont plus menaçantes lors des années El Niño ou juste après ces années. Depuis 1951, le nombre de glissements de terrain, près du village Payhua, a augmenté d'un facteur de cinq. Même si le nombre de glissements de terrain est faible depuis quelques années et que le bloquage de chenaux n'a pas été relié aux grandes coulées de débris destructives, nous ne devons compter là-dessus comme paramètre de prévision.

Keywords: engineering geology, geological hazards, geomorphology, landslides

INTRODUCTION

The Quebrada Payhua (Payhua Creek) basin (QB) is typical of many small and extremely rugged debris flow-producing drainage basins in the Andes Occidental of Peru. In 1959 and 1983, debris flows from it diverted the Río Rimac (Rimac River) (RR) into the nearby small city of Matucana. The 1959 event destroyed almost 90% of Mantucana with numerous fatalities. In 2003, the QP basin was chosen as a pilot study area as a part of the Multinational Andean Project: Geoscience for Andean Communities (MAP:GAC). This project, which began on 28th June 2002, includes Argentina, Bolivia, Canada, Colombia, Chile, Ecuador, Peru, and Venezuela. Its mission is to contribute to improving the quality of life for the people of the Andes by reducing the negative impact of natural hazards (earthquakes, landslides, and volcanic eruptions). This paper reports on the findings of the Quebrada Payhua-Matucana pilot project with respect to the hazards posed to Matucana by debris flows and from the QP basin. It builds upon interim results detailed in Fídel Smoll *et al.* (2005).

PHYSIOGRAPHY AND SETTING

The Matucana-Quebrada Payhua area is located in Huarochirí Province, Perú (Fig. 1) approximately 75 km east of Lima in the Andes Occidental, a tectonically active mountain belt. Although there are no quantitative estimates of uplift rates for the study area, rates in the order of 0.2 to 0.3 mm/yr since the Miocene have been determined for the adjacent central Andes (Gregory-Wodzicki, 2000). This rapid uplift is apparent from the local geomorphology and surficial geology in the Matucana area: unconsolidated deposits of debris-flow-dominated fans that preceded the contemporary QP fan can be found hundreds of metres above RR. Evidence of attendant mass wasting processes such as landsliding and rock fall is ubiquitous throughout the area.

Matucana (population approximately 5800) is situated on a 100 to 300 m wide floodplain along the floor of the deep and steep-sided RR canyon (Fig. 2) at an elevation of 2390 m above sea level (a.s.l.) (area of 11º 50.489’ S, 76º 22.857’ W). Adjacent ridges and mountain peaks rise to 5000 m within 10 km of Matucana. Two strategic transportation arteries follow RR and pass through Matucana: the Carretera Central, the only highway in Perú connecting the Amazon basin to the Pacific Coast, and the Ferrocarril Central, which services mines and communities in the Andes to the east. The present course of RR through Matucana is controlled by a dyke-causeway structure built by the Ministerío de Transportes del Peru (MTP) following the 1983 debris flow and flood to elevate and protect the Carretera Centra.. This structure confines RR to the northern portion of its former floodplain. Matucana occupies the remainder of the floodplain. Consequently, parts of Matucana are lower in elevation than the bed of RR, rendering Matucana particularly vulnerable to flood damage if RR is diverted from its engineered course.

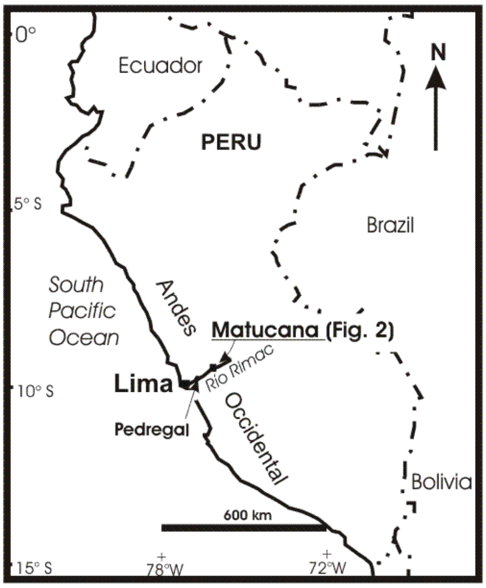

Figure 1. The lLocation of Matucana/Payhua Creek project area.

Quebrada Payhya basin

The QP basin lies immediately to the north of Matucana (Fig. 2 and 3). It is an elongate basin 6.1 km in length and less than 3 km in width at the widest point, with a total area of 14.9 km^2. It rises to 4760 m a.s.l. QP traverses a narrow to gorge-like valley with an overall gradient of 21°. However, its profile is marked by numerous waterfalls along nearly vertical reaches of the channel, particularly along the lower two km. The basin is underlain by Cenozoic flows, breccias and pyroclastic complexes of andesitic to rhyolitic composition (Instituto Geologico Minero y Metalurgico, 1995). The basin is asymmetric from west to east reflecting a general dip of flow complexes to the east and south. Scarp slopes along the east side of the basin are as steep as 50° over elevation-changes of 1000 m. Slopes along the western margin of the basin are in the 35° to 40° range over elevation-changes of about 1000 m. Rockfalls are a hazard along the base of many slopes. The mountain village of Payhua (Fig. 3) is impacted by large rockfall blocks several times a year.

Mountainsides in QP basin have been extensively terraced for farming and grazing for at least 600 years based upon the finds of pottery from the late intermediate (pre-Inca) period (Colque Tula, 2004 written communication). These terraces extend to ridge-tops in many parts of the basin. The terraced fields are irrigated up to about 3500 m and support a variety of crops including maize and beans. Terraced fields above the limits of irrigation presently serve as small pastures. Fídel Smoll *et al.* (2005) applied archaeological investigation of these terraced fields as a tool for demonstrating the long-term stability of slopes. These terraces have controlled erosion and added to slope stability in many areas.

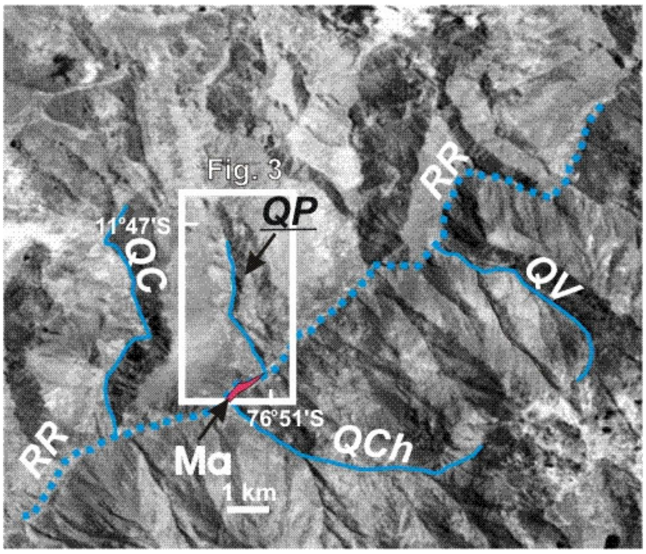

Figure 2. Eros satellite image (2005) of the Payhua- Matucana area: Ma- Matucaca, QP- Quebrada Payhua, QV- Quebrada Viso, QCh- Quebrada Chucumayo, QC- Quebrada Collana, RR-Rimac River (Ferrocarril Central and Carretera Central).

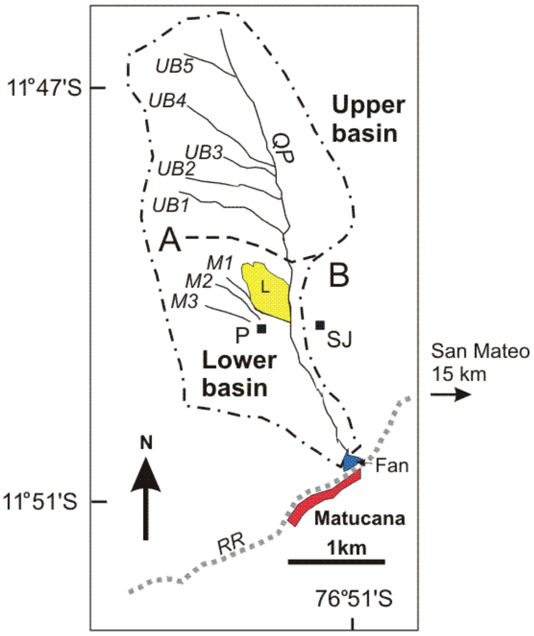

Figure 3. Matucana (red), Quebrada Payhua (QP) basin (dot-dash border) and features referred to in text: P- Payhua village, SJ- San Juan de Allauca village, M1-3, UB1-5 are eroding ravine systems (known or likely sources of debris flows), L-Payhua village landslide complex, RR- Rio Rimac and Central Highway and Central Railway. The blue area indicates QP fan. The dashed line A-B indicates the boundary between the upper basin (prominent cliff-forming andesite flows) and lower basin (predominantly recessive volcanics).

CLIMATE, HYDROLOGY, AND THE IMPACT OF EL NIÑO CLIMATIC EVENTS

The climate at the elevation of Matucana is temperate and dry: maximum daily temperatures range from 27 °C during the summer (mid December to March) to 19 °C during the winter (mid June to September) with a mean annual temperature of 15.3 °C (Servicio Nacional de Meteorología e Hidrología (SENAMI), unpublished data). Temperature decreases progressively with altitude: below-freezing temperatures occur every night at elevations above about 4300 m. and seasonally as low as 3700 m. Total annual rainfall averages 239 mm at Matucana, about 70% of which falls between January and March. Virtually no rain falls between May and September. The aridity of Andes Occidental is due to the east-to-west flow of moisture from the Atlantic Ocean, which is intercepted by the Andes central. However, rainfall patterns are disrupted by El Niño climatic events in the equatorial Pacific Ocean and atmosphere. During these events, moist air from the adjacent Pacific Ocean moves eastward into the Andes Occidental, bringing heavy rains that commonly trigger landslide activity, including debris flows (Kuoiwa, 2002, p. 268). These events have occurred three to seven years apart during the past 50 years: 1957-58, 1965-66, 1972-73, 1976-77, 1982-83, 1986-87, 1991-93, 1997-98 Fig. 4). Destructive debris flows predominantly occur during these El Niño years in drainage basins in the Matucana area (Martinez Vargas and Medina Rengito, 2000). The 1959 event occurred in the year following the 1957-58 El Niño.

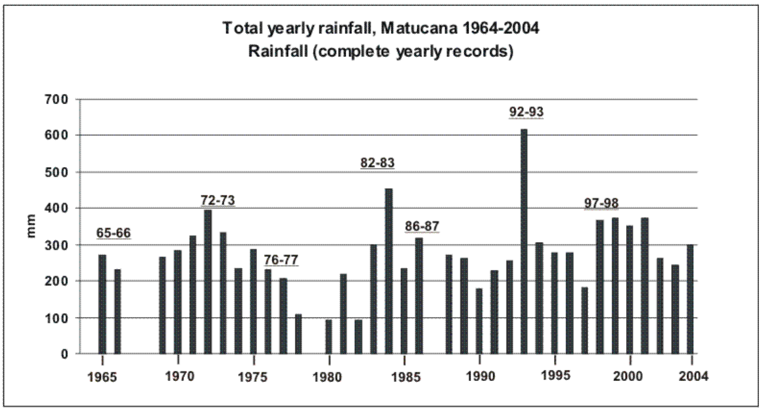

Figure 4. Total yearly rainfall for Matucana Perú. Missing years indicate incomplete data. Underscored numbers indicate El Niño years.

Large debris flows from QP blocked RR diverting it through Matucana in February 1959 and March 1983. The dam created by the debris flow deposits remained for four days until explosives were used to divert RR into its former course. Smaller events that did not cause damage to Matucana occurred in 1941, 1950 and 1985, but exact dates are uncertain. Reliable records of debris flows prior to 1941 do not exist. Local weather records are not available for the 1959 debris flow event. However, a local weather station was established at Matucana in 1964, since which total 24-hour rainfall has been recorded.

The discharges of QP and RR predominantly vary with rainfall. Much of the flow of QP is diverted into irrigation channels supplying terraced fields around Payhua and San Juan de Allauca villages during the dry months. Hence, little or no water reaches RR from QP during the dry months. Continuous drainage to RR only occurs during the wet months between January and April. As there is no stream gauge along QP, the 20, 50 and 100-year return values have been computed by the MTP through probabilistic analysis of 24-hour rainfall data from 18 weather stations in the region (Ministerío de Transportes, 2000). Hydrographs were computed for these for 24 hour rainfall events (the shortest rainfall interval time series available) using the HEC-HMS model (U.S. Army Corps of Engineers, 2000). Computed rainfall values and peak discharge data are presented in Table 1.

Table 1. Estimated peak discharges for Quebrada Payhua from 24-hour rainfall intensites

	Return period (years)		
	20	50	100
24-hour rainfall (mm)	38.2	47.5	50.3
Discharge (m^3/s)	3.2	7.1	8.4

The nearest stream gauge on RR is at San Mateo, 15 km upstream from Matucana (Fig. 3). This gauge provides an estimate for RR discharge at Matucana because only minor tributaries enter RR between San Mateo and Matucana. The mean monthly discharge of RR ranges from 20-27 m^3/s during the wettest months (February and March) when debris flows that can dam RR are most likely to occur (JAICA, 1988)

PREVIOUS INVESTIGATIONS

The Japan International Cooperation Agency (JAICA) formulated a disaster prevention plan for the RR basin following damaging floods and debris flows during rains associated with the 1983 and 1987 El Niño events (JAICA, 1988). JAICA surveyed volumes of debris flows generated by El Niño rains in March 1987. The largest was a 157,200 m^3 debris flow from the Quebrada Pedregral basin (Fig 1). The rainfall associated with it was considered by JAICA to be a low probability event. The sediment yield value of 14,800 m^3/km^2 was assumed to be a limiting value for debris flows events caused by low probability rainfall events within the Pedregral basin, which is largely devoid of vegetation. JAICA extrapolated this yield ratio to other basins within RR but used a correction coefficient based upon the extent of vegetation cover within a given basin (0.4 in the case of QP basin). Matucana was recognized as being at risk from debris flows from the QP basin. JAICA recommended building two debris dams along the course of QP, but these structures have not been built. There was no analysis of historic debris flows or debris-flow-induced flooding that had previously impacted Matucana as a part of the JAICA study.

In the 1980s and 1990s, PREDES (the Peruvian national disaster preparedness agency) investigated the vulnerability of Matucana to debris flow inundation and debris-flow induced floods as well as hazards posed by mass wasting from the steep slopes immediately to the south of the city through. A series of unpublished maps and reports detailed these hazards. Retention structures were locally constructed in the Matucana area but none were built along the main channel of QP. Disaster plans, including the establishment of designated refuge areas and evacuation routes, were implemented. Martinez Vargas and Medina Rengito (2000) investigated historic debris flow events in the Matucana area and carried out a reconnaissance investigation of the geomorphology of QP basin pertaining to the origin of debris flows there. They recognized the debris flow potential of smaller tributaries to QP as well as the potential for landslides to form temporary dams that could fail and generate outburst floods.

MTP commissioned an investigation of the hydrology of the Quebrada Collana (QC) basin which borders the QP basin along its west margin (Fig. 2) as a part of a bridge design investigation (Ministerío de Transportes del Peru, 2000). Debris flows occurred in QC basin in 1981, 1996 and 1998. Because of the proximity of QC to QP, many of the hydrometeorological findings from the MTP study can be scaled to QP.

Fídel Smoll *et al.* (2005) detailed preliminary findings of the present investigation up to 2004. Since this report, archival air photographs of the QP basin have been discovered. These have yielded valuable information concerning the 1983 debris flow event. Also, hydrometeorological data formerly unavailable to this project has been integrated into this study. This has altered some of the preliminary conclusions.

THE PRESENT STUDY

The principal goals of the present study were to investigate landslide hazards in the QP basin and to evaluate the scale of debris hazards to Matucana. This evaluation includes estimation of the volume of the maximum debris flow likely to be produced from QP basin. The following tasks were undertaken:

- A terrain inventory map (including the extent of landsliding within the basin) was completed at a scale of 1:10,000. An inventory of landslides was judged to be particularly critical because they commonly impinge upon the channel of QP and they have the ability to create temporary dams. The map base was a Quickbird satellite image (resolution 1 m) taken on 13th August 2004. The map legend scheme was adapted for the Spanish language from Howes and Kenk (1997). Archaeological techniques were used to determine the long-term stability of fans and terraced hillsides (Fídel Smoll *et al.* 2005).
- Major landslides within the basin were investigated in order to determine their geological and geomorphological settings and conditions prior to slope failure.
- Highly accurate control points were surveyed within the basin using dual frequency global positioning system (GPS) technology to facilitate the creation of a digital elevation model (DEM) of the basin (April though June 2005). This DEM is useful for draping the surficial geology upon as well as for estimating flood hydrographs and two-dimensional modeling of debris flow events. A stereo pair of EROS satellite photos were added in 2005 for the purpose of aiding in the creation of a digital elevation model of the basin.
- An analysis of archival air photographs was carried out in order to determine the magnitude of past debris flows and to identify debris flow deposits and changes in extent and activity of other landslides with time.
- A survey of the sediment fill was carried out along the channel of QP through the lower half of the basin following the general methodology of Hungr *et al.* (1984) in order to estimate the volume of sediment that could be mobilized by a debris flow.
- An analysis of rainfall records was completed in order to determine antecedent conditions prior to the 1983 debris flow and to determine if these conditions were repeated during subsequent years without debris flow occurrence.
- Long-time residents were interviewed in order to determine where and when debris flow events have occurred, including where the debris flows originated, weather conditions at the time, and intensities of the events. Oral accounts make up almost all of the historic evidence of debris flows in the Matucana area prior to the 1990s.

BEDROCK AND SURFICIAL GEOLOGY OF QP BASIN

The QC basin is divisible into a fan and a lower and upper basin based upon underlying bedrock and surficial deposits. These in turn determine the type and density of landslide and debris flow activity.

QP fan

The fan of QP (Fig. 3) is approximately 7.5 ha in area and terminates in 5 to 6 m cliff-banks where it is truncated by RR. It has an overall slope of approximately 8°. QP has cut a deep box canyon through the fan that is up to 20 m in width and 8 m deep. Natural exposures along cliff-banks reveal that the QP fan is composed of massive bouldery debris flow diamictons with secondary fluvial sediments. Prehistoric debris flows covered extensive areas of the fan to depths of 2 or 3 m. The lack of buried soils or other indicators of significant time breaks between depositional events suggest that the fan is geologically active and that its sediments are of Holocene age.

Granulometric analysis, determination of Atterberg limits and clay mineralogy of three debris flow matrix samples from QP fan and higher in the QP basin indicate them to be a low plasticity to a non-plastic silty sand ranging from SC to SM in the Unified Soil Classification scheme. The mineralogy of the clay size fraction, as determined by X-ray diffraction, is dominated by clay-size, non-clay minerals such as quartz, plagioclase, augite, calcite, muscovite and hematite. True clay minerals such as chlorite or montmorillonite make up only one or two percent of the clay-size fraction. This mineralogy reflects rapid erosion and the predominance of physical weathering over chemical weathering in a tectonically-active, arid drainage basin. The plasticity index of values for the matrices of debris flow sediments range from 8 to 11 per cent. This places them within the mudflow classification of Hungr *et al.* (2001).

Lower basin

The lower basin stretches from approximately 1 km upstream from the mountain village of Payhua to the head of the QP fan. The slopes are dominated by colluvium and exposed rock. Areas adjacent to the gorge-like canyon of QP are underlain by erosional remnants of uplifted Pleistocene debris flow fans (Fidel Smoll *et al.*, 2005) as well as currently active complexes of debris flow and rock-fall fans. These fan complexes have been modified into agricultural terraces and they are irrigated by small open irrigation channels up to an elevation of about 3500 m a.s.l. Underlying bedrock consists of extensively jointed and fractured andesitic or dacitic flows and pervasively fractured pyroclastic rocks. Bedrock exposures along the QP canyon suggest that these volcanic rocks dip in the general direction of the QP basin drainage. However, the amphitheatre-like morphology of the lower basin in the Payhua village area suggests that this part of the basin may have been shaped by cycles of landsliding so that is difficult to know whether successions seen in canyon walls along QP are *in situ* bedrock.

The most active and continuous areas of landslides in QP basin occur along the reach of the QP canyon adjacent to Payhua village about 2.2 km north of, and 1000 m in elevation above, Matucana. This will subsequently be referred to as the Payhua landslide complex (Fig. 3, L). Approximately 16 ha of active rock and debris slides, rockfall cones and complex landslides that include old debris flow fan remnants and portions of active debris flow fans border on approximately one km of the QP channel. This reach is the most significant contributor of coarse and fine sediment to the QP channel in the basin. These landslides locally blocked QP in the past and have the potential to create an outburst flood if the landslide blockage were thick and rapid enough to actually dam the creek and form a temporary lake. Furthermore, three rapidly expanding ravines within a talus/debris-flow cone complex above Payhua village (M1, M2, M3 on Fig. 3) produced debris flows in 1983. The debris flow from M1, the largest of these ravines, was the ultimate source of the 1983 debris flow according to long-time Payhua residents.

Stratigraphic and structural architecture and slope instability in the lower basin

The ultimate cause of the slope failure along the approximately 70 m deep canyon of QP is the progressive reactivation of parts of a 61 ha Payhua landslide complex (Fig. 3, L) immediately east of Payhua village (further described below). This reactivation began sometime after 1955 based on comparison of air photographs taken in 1955 and 1983. An apparent basal shear zone of this landslide is approximately 20 m thick and is visible along the trail connecting Payhua village with the village of San Juan de Allauca. The failure is within a pervasively fractured red tuff that overlies more coarsely jointed andesitic lava flows (Fig. 5). The red tuff is apparently at least 40 m in thickness but it may have been thickened locally by landsliding. Where this tuff underlies more resistant andesite flows, the resistant over recessive succession leads to undermining of the andesite flows and rock falls along nearly vertical canyon walls or rotational or translational type failures with the failure plane or planes seated within the red tuff. Active landsliding is rapidly expanding into slopes immediately east of Payhua village.

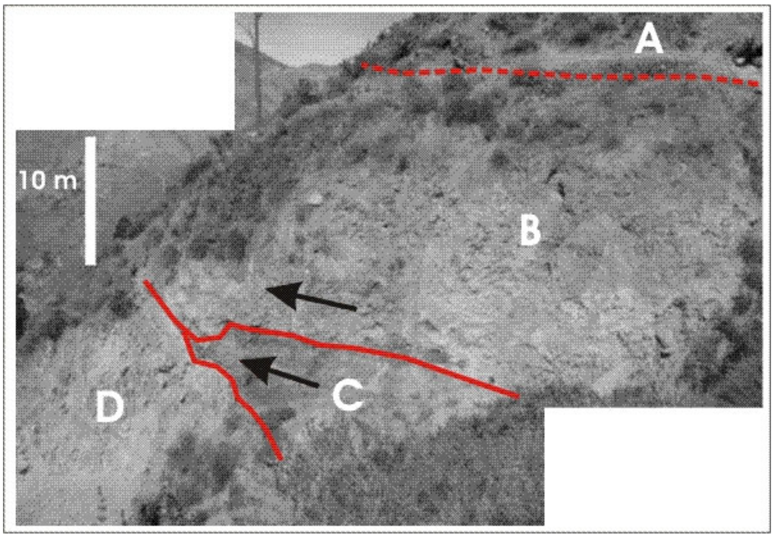

Figure 5. The sheared and thrust-faulted base of the Payhua landslide complex exposed along ephemeral stream M1 near its confluence with QP. Lines indicate shear planes separating differing lithologies and the arrows indicate the general direction of movement: A: debris flow diamicton and muddy bouldery gravel forming the fan of M1; B: red tuff and grey andesite mixed by shearing; C: red tuff with drag folds and diapirs along sheared contacts; D: sheared grey andesite that grades into unsheared andesite about 5 m below the field of view.

Upper basin

The upper basin (Fig. 3) changes character from east to west with QP forming the boundary between apparent scarp slopes (east) and dip slopes (west). The east side of the upper basin is a scarp slope composed of cliff-forming andesite flows or flow complexes. Agricultural terracing extends to ridge crests along the east side of the basin. Archaeological evidence and historical changes in land use (including depopulation) following the Spanish conquest (beginning in the 1530's A.D.) date these structures as pre-conquest and likely pre-Inca (ca. 1200 to 1400 AD or older). The preservation of these terrace structures across slopes and tributary ravines indicate that they have been stable for the past 600 to 800 years. Landslides in the upper basin are confined to rockfalls and rockslides where the massive andesite cliffs have failed along joint-planes or flow boundaries. These can be dated to the past 600 to 800 years where they have removed the pre-conquest agricultural terraces. Three such major failures dating from this period are present in the upper basin. The west part of upper QP basin is underlain by volcanic rocks that are cut by five small tributaries numbered as UB1-5 on Figure 3. These are similar in size to the M1-3 tributaries immediately north of Payhua village. Fan deposits from these small UB series tributaries and adjacent slopes have been modified to terraced agricultural fields. The UB ravine systems are the main sources for debris flow sediments in the upper basin and at least one of them was the source of the 1959 debris flow according to Payhua village residents (see below).

HISTORIC DEBRIS FLOW AND LANDSLIDE ACTIVITY

Air photos were taken of QP basin in 1951, 1955, 1962, and 1983 at scales of approx. 1:30 000. Although only the 1951 air photograph coverage included the entire QP basin, all covered the lower half of the basin in which all of the significant active landslides occur. Active and inactive landslides were mapped for each epoch of historic air photos. Landslides were interpreted as active if disturbed ground was detected or terraced agricultural fields had been destroyed between successive flights. The photo that covered the greatest area of the basin was selected from each set and geometrically corrected for distortion using GPS survey points and the georeferencing tool of ArcMap®. The areas of active landsliding for each historic flight were outlined and their planometric areas were determined using Arcpad®. These results were integrated with eyewitness accounts of debris flow events in the basin in order to reconstruct changes in landslide activity and to document when and where debris flows occurred. The small scale, fair to poor resolution of some air photo coverages and extensive shadowing by steep high-relief slopes limited the mapping to landslides >0.2 ha. Thus, comparison with the high resolution 2004 Quickbird image (resolution 1 m) can only be made with respect to features larger than 0.2 ha. Furthermore, comparison of landslide features in the upper basin can only be made between the 1951 air photograph and Quickbird satellite coverages. The areas of landsliding measured are presented in Table 2.

The total area of inactive and active landslides in the QP basin has remained approximately constant at about 80 ha with all but about 3 ha of the landslides within the lower basin. The greatest area is within the Payhua landslide complex with a total area of active and inactive landslides of about 61 ha. Fídel Smoll *et al.* (2005) concluded that the area of active landslides in the lower basin had increased by a factor of about five between 1951 and 2004. With the addition of better resolution photography from 1955 and 1983, it now appears that there was little change in the area of landslides along the east side of the lower basin. It was not possible to accurately measure the landslide areas along the heavily shadowed east side of the canyon using the small scale and low resolution air photos (trial efforts yielded areas about twice the areas determined from the satellite photo). With regard to areas of the lower basin that were reliable for air photo interpretation, the most dramatic increase in landslide area was in the reactivation of a part of the Payhua landslide complex. The area of active landslides increased from <0.4 ha in 1955 to 5.8 ha in 2004. Field evidence indicates that another 4.6 ha may be moving based upon tilting and toppling of trees and offsets in irrigation channels. Disregarding this questionable area, active landsliding within the Payhua landslide complex has increased by a factor of approximately 15 since 1955. Active landslides immediately downstream from this complex on the same (west) side of the canyon also increased dramatically.

Field evidence indicated that movement of the toe of the Payhua landslide complex completely blocked the channel of QP in the recent past to a depth of perhaps 4m. However, there is no evidence directly linking this to the major debris flows of 1959 or 1983.

Table 2. Areas of active landsliding in lower QP basin (figures in italics are areas suspected of being active)

Year	Payhua landslide complex (PLC)	West side of QP canyon below PLC	East side of QP canyon below PLC
1955	**0.4**	**0.4** *1.7*	**-**
1983	**2.1**	**0.5** *0.2*	**-**
2004	**5.8** *4.6*	**3.0**	**6.4**

Conditions antecedent to the 1959 and 1983 debris flows and triggering mechanisms

The destructive 1959 event preceded the establishment of a weather station at Matucana in 1964. Information on antecedent conditions comes solely from eyewitnesses. There was no rainfall the day of the 1959 event in Matucana but rain had fallen in the mountainous QP basin. A long-time resident of Payhua village stated that the 1959 debris flow started in the upper basin and not in the Payhua village area. There were no direct observations on the intensity of rainfall in that area of the basin prior to the debris flow. The debris flow destroyed the irrigation water intake structure along QP about 1 km upstream from the Payhua landslide complex. Study of the 1962 air photo coverage found no evidence of contribution to the debris flow from landslides or debris flows in the lower basin including the Manayco (M1-3) ravines above Payhua. This is consistent with the oral account of the debris flow initiating in the upper basin.

Weather data for the 24-hours of 3rd March 1983 show that only light rain fell in Matucana (Fig. 6). The data for more than a month before and after this event indicate only one exceptional rainfall event on 22nd February.

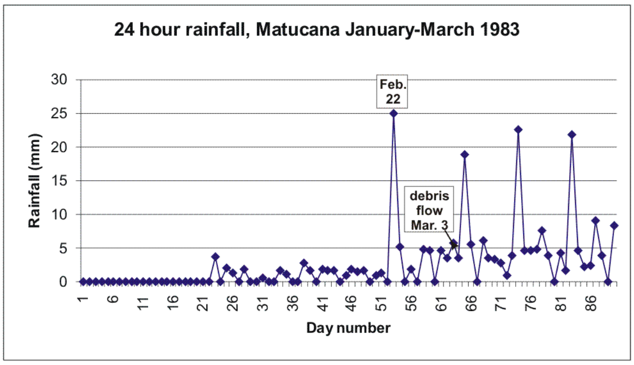

Figure 6. Total daily rainfall for Matucana between 1st January and 31st March 1983 (Jan. 1 = day 1). The cumulative rainfall at the time of the debris flow on day 64 was 89.4 mm, of which 58.7 mm fell within the previous 12 days including 22 Feb., one of the wettest days ever recorded in Matucana. No more debris flows occurred that year despite an additional 154.7 mm falling over the following 30 days.

Only three other 24-hour totals during the period of record exceeded the 22nd February 1983 rainfall (the largest being 30 mm). No debris flows were associated with any of these events in the Matucana area. Eyewitnesses indicate that the debris flow in the main QP channel was initiated by a debris flow from M-1 which entered the channel and incorporated water from a small (<10 m diameter) irrigation reservoir in the process. Sediments from this debris flow are plainly visible in the 1983 air photo coverage along with fresh debris flow deposits from M2 and M3. The debris flow from M1 may have temporarily dammed QP or loaded channel sediment including the toe of the Payhua landslide complex, which was active by 1983. The origin of the 1983 debris flow in M1 and not in the upper basin is also consistent with testimony from a Payhua village resident who recalled that the irrigation channel intake (upstream from the M1 confluence) was not damaged in 1983 but was replaced after the 1959 event. If a debris flow had traversed the irrigation intake in 1983, it would have been destroyed. This structure is vital to agriculture in the Payhua village and San Juan de Allauca areas and its destruction would have been noticed had it occurred. The 1983 debris flow was followed by three significant 24-hour rainfalls spaced at approximately 1 week intervals (Fig. 6). However, no debris flows were recorded at Matucana.

No debris flows are known to have occurred within the QP basin during the El Niño of 1992-93 (Fig. 4). Debris flows occurred on April 3, 1998 in the Quebrada Viso (QV) and Quebrada Chucumayo (QC) basins (Fig. 2) but not in the QP basin. The debris flow from QV destroyed the village of Tambo de Viso. No correlative heavy rainfall was recorded in Matucana (Fig. 7, day 63). However, photographs of QV immediately after the debris flow event shows it to be a muddy torrent indicative of significant rainfall in its headwaters.

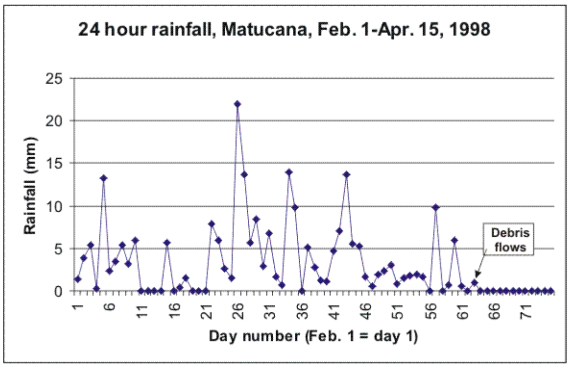

Figure 7. Daily rainfall at Matucana between 1st February and 31st March 1998. Debris flows occurred in the Matucana area at the end of the rainy season after a total of 248.1 mm was recorded at Matucana. However, only 33 mm fell during the 12 days prior to the event with a largest single 24 hour of 9.8 mm.

The lack of correlation between rainfall at Matucana and debris flow events during the wet season suggests that the record at Matucana does not reflect precipitation events that trigger debris flows within the surrounding uplands. We tentatively conclude that debris flows are triggered in QP and adjacent basins by local intense rainfall that is controlled by local orographic effects rather than by regional rainfall of longer duration that is documented in the 24 hour rainfall record of Matucana (a valley bottom setting).

The estimated volume of 1983 debris flow

Deposits from the 1983 debris flow are obvious on the 1983 air photo coverage (taken three months after the event). Debris flow deposits appear on the QP fan and also on the fan partly occupied by Payhua village below the M1, M2 and M3 ravines. The thickness of these deposits is about 1.5 m on the QP fan and about 1 m on the Payhua village fan. The extent of deposits in the RR floodplain downstream from QP fan is not apparent on the photographs and if it were, the thickness of the deposit could only be guessed because the floodplain was extensively modified following 1983 when a causeway was built to elevate the Carretera Central. An estimate of the volume of the debris flow can be made based upon the volume of the debris flow deposits on the fan (area ~9700 m^2) assuming a 1.5 m thickness (total estimated volume of ~14 000 m^3) plus the volume of the incised fan channel which was filled at the time that the debris flow spilled on to the surface of the fan. If the present estimated volume of the channel is used, then an additional 103 000 m^3 of debris is computed for an estimated total volume of about 117 000 m^3. The possible error of this value is considered to be in the direction of overestimation because the volume of the channel was probably less in 1983: there has been significant post-1983 incision of the lower part of the fan channel. Furthermore, the channel is assumed to have a rectangular cross-section in this calculation when in reality, the channel cross-section is rhombohedral in shape.

Estimated debris flow volume below M2 and M3 ravines and debris yields from these basins

The 1983 debris flow is known to have originated from the M1 ravine system. The adjacent M2 and M3 ravine systems also produced debris flows but these were totally contained on fans adjacent to Payhua village. The areas of these flow deposits were measured from the 1983 air photograph coverage. Assuming an average thickness for the deposits of 1 m (from field observations), these ravine systems had yield ratios of approximately 106 000 and 39 000 m^3 of debris flow sediment per km^2 respectively.

ESTIMATION OF DEBRIS FLOW VOLUME FROM A BASIN-WIDE DEBRIS FLOW EVENT

The JAICA (1988) study predicted a basin-wide unit yield of 7104 m^3/km^2 for a low probability debris flow event from the QP basin. This figure was derived by multiplying the Quebrada Pedregal yield value of 14,800 m^3/km^2 by a correction coefficient of 0.4 (to correct for what was considered QP's greater vegetation cover relative to Pedregal) and the multiplication of that product by an additional empirical uncertainty coefficient of 1.2. The total volume of a low probability debris flow from QP is 105,850 m^3 (Table 3, E). Our estimate of 117,000 m^3 from field evidence for the total volume of the 1983 debris flow (which we consider to be an overestimation) is close to the JAICA prediction of low frequency debris flow discharge from QP. However, our work has determined that only the lower QP basin was involved in the 1983 event and that the source of the 1959 event was in the upper basin. Consequently, debris flows produced simultaneously in the upper and lower basins, a truly low probability event, would produce a considerably larger total discharge than occurred in 1983. The JAICA approach did not factor differences in lithology between basins (plutonic rocks at Pedregal vs. the fragmental andesitic flows, tuffs, and breccias underlying QP basin) and the greater elevation and relief of QP basin in applying a vegetation correction factor. The elevation and relief also increase the orographic effect on moist air masses encountering the QP basin. The orographic effect causes increased rainfall intensity and duration between the coast and the Andes (mean annual rainfall increases up to 35 times from the coast to about 70 km inland (JAICA 1988). However, the runoff and sediment available for erosion is not necessarily reduced proportionally by more extensive vegetation cover in QP as was assumed in JAICA study. The QP basin rises to 4760 m a.s.l. compared to 2330 m a.s.l. at Pedregal. This endows higher parts of QP basin with a more severe physical weathering environment as daily freezing and thawing occur in the higher parts of the QP basin. This is not a factor in the Pedregal basin. Also, vegetation cover at higher levels in the QP basin is sparse and approaches the conditions in the Pedregal basin. The greater relative relief of the QP basin (2360 m) compared to the relative relief of Pedregal basin (1480 m) provides greater overall potential energy for mass wasting in the QP basin.

The volumes of debris flows from the M1, M2 and M3 ravines in 1983 give a direct indication of the yield ratios of areas of QP basin that actually produce debris flows. Steep ravine systems along the west side of QP basin such as M1 are the primary sources of debris flows. Air photo interpretation indicates that these largely unvegetated small and steep basins are rapidly expanding into adjacent mountainsides. In contrast, the east side of the basin is dominated by steep rock or has been extensively terraced, and these terraces show no evidence of debris flow modification (Fídel Smoll *et al.*, 2005). The areas of steep ravine systems and estimates of debris flow volumes that would be yielded from them based on yield values from M2 and M3 are presented in Table 3, A (flows from M2 and M3 are assumed to be confined on the fan immediately east of Payhua village and are not included). The total of these values represent the volume of debris flow sediment that would be introduced into the main QP channel. An additional unknown volume would be added to these figures through mobilization of channel sediments and landslide sediments. A survey of the accessible reaches of the channel of QP between the head of the QP fan and the area of Payhua village was undertaken to determine the volume stored in the channel that could be mobilized by a debris flow. Only approx. 1 km of channel had significant sediment in it out of about 2.3 km surveyed. This reach also contains the greatest concentration of landslides. The remainder of the channel was steep, largely exposed rock. The minimum estimate was 9000 m^3 of sediment in the channel assuming a fill of 1 m, or about 9 m^3 per linear m of channel. Local reaches may have three times this amount or more. The amount of sediment from the main channel that would be added to debris flows originating in sub-basins is difficult to predict and is the source of greatest uncertainty for this approach. However, the 248 040 m^3 figure itself is regarded as an extreme value as will be subsequently discussed.

A second estimate for the maximum volume of debris flow discharged from QP basin during a low frequency event was made using the Flo-2D® model (Flo-2D Software Inc.). A DEM prepared for this task was employed as a part of the model. Variables assigned to the model are detailed in Castillo Navarro (2005). The output from the model in Table 3 assumes 100, 50 and 20 year 24-hour rainfall values from Table 1 as triggering events. The 100-year and 50 year rainfall values are taken to be the low probability events. Output for this model is shown in Table 3, C.

Table 3. Debris flow volume estimates from various methods for the Quebrada Payhua basin and debris flow-producing sub basins

		A	B	C			D	E
Sub-basin	**Area (km^2)**	**Total debris flow volume (m^3) assuming yield value of 106,000 m^3/km^2 (M2 yield rate)**	**Total debris flow volume (m^3) assuming yield ratio of 39,000 m^3/km^2 (M3 yield rate)**	**Total debris flow volume (m^3) calculated by the Flo-2D® model for entire QP basin**			**Total debris flow volume (m^3) assuming basin-wide yield ratio of 14,800 m^3/km^2 (JAICA, 1988)**	**Total debris flow volume (m^3) assuming an adjusted basin-wide yield ratio of 7,104 m^3/km^2 (JAICA, 1988)**
				1	**2**	**3**		
M1	0.22	23,320	8,580	Assumes a 24 hr. rainfall of 50.3 mm (100 year return). Total indicates the sum of 110 789 m^3 of water and 152 669 m^3 of sediment	Assumes a 24 hr. rainfall of 47.5 mm (50 year return). Total indicates the sum of 93 300 m^3 of water and 120 715 m^3 of sediment	Assumes a 24 hr. rainfall of 38.2 mm (20 year return). Total indicates the sum of 31 313 m^3 of water and 42 819 m^3 of sediment	Debris from source area and channel averaged over the entire basin	Debris from source area and channel averaged over the entire basin
UB1	0.53	56,180	20,670					
UB 2	0.24	25,440	9,360					
UB 3	1.13	119,780	44 070					
UB 4	0.13	13,780	5,070					
UB 5	0.09	9,540	3,510					
Total (m^3)		248,040	91,260	263,458	214,015	74,202	220,520	105,849

The total volume of a basin-wide debris flow using the lower (M3) yield value (Table 3, B) is approximately 0.9 times the volume of a low frequency debris flow estimated for the basin by the JAICA study (105,849 m^3) whereas the higher M-2 yield value estimate is about 2.4 times the JAICA estimate. The Flo-2D estimate based on 100 year 24-hour rainfall intensity (Table 3, C1) is volumetrically slightly higher than the M2 estimate. But, because of the way that the Flo-2D output is reported, the sediment content is only about 0.6 of the M2 value when the water content is subtracted (Table 3, C2).

DISCUSSION

We considered the 248,040 m^3 volume (Table 3, columns A) to be limiting upper estimate for extreme debris flow volumes discharged from high altitude sub-basins in the QP basin. This volume assumes that all sub-basins identified in Figure 3 discharge nearly simultaneously with the largest documented (M2) yield values. There is simply insufficient data to evaluate its accuracy compared to the Flo-2D values assuming the 100-year return 24 hour rainfall value. The Flo-2D model uses a rainfall intensities as well as DEM specific to the basin. However, the M2 yield value does not include contribution of sediment from the main channel that could represent a potential addition of tens of thousands of m^3 whereas the Flo-2D scenario does. Either discharge value would be a massive event significantly in excess of the 1959 and 1983 debris flows. An event in the range of 250 000 m^3 would cover the entire QP fan to depths of about 3 to 4 m. In reality, much of the flow would travel beyond the fan, dam RR, and bury the adjacent flood plain including parts of Matucana.

As a check on these two approaches, the unadjusted yield value for Quebrada Pedregal basin (14,800 m^3/km^2) is applied to the 14.9 km^2 QP basin in Table 3, D. The resulting total sediment discharge value of 222,000 m^3 is intermediate between the M2 yield scenario and the Flo-2D output assuming 100-year return 24 hour rainfall (Table 3, A, C1, and D). The Pedregal yield value is the largest known basin-wide yield value in the region. The fact that the direct application of this yield value to QP basin generates a total discharge smaller than the M2 scenario may indicate either that:

- Application of a vegetation correction factor to the benchmark Pedregal yield value may not be appropriate when extrapolating it to extreme events in high elevation and high relief basins such as QP.
- Or, conversely, it may indicate that the M2 scenario is unreasonable and the limiting value for rainfall-induced debris flow discharge from QP basin is considerably smaller.

We tentatively conclude that the 248,040 m^3 discharge figure overestimates maximum debris discharge from a low frequency (highly intense) basin-wide rainfall event because field evidence suggests that the M2 value is extreme and not representative of most QP sub-basins (see further discussion below). However, application of it for engineering purposes would offer a sizeable margin of safety.

Although massive debris flows with the volume ranges of those in Table 3, A, C1, C2 and D are a possibility, we consider events on the scale of the two destructive historic debris flows to be the greatest hazard to Matucana for the following reasons:

- Matucana has been impacted by two destructive debris events of comparable magnitudes during the past 50 years but neither has involved debris flow production over the entire basin. Debris flows of all sizes have been sporadic with debris flows occurring during only one of the three most severe El Niño events since 1980. This suggests that the debris-flow-producing areas of QP basin are supply-limited with respect to debris flow occurrence. That is, debris flows only occur in the ravine systems following periods sufficiently long after a previous debris flow to recharge sediment (Jakob 2005). This is in contrast with transport-limited basins, such as are commonly found on stratovolcanoes. Debris is present in superabundance in such settings and debris flows are routinely triggered when a rainfall intensity threshold is equalled or exceeded. This does not appear to be the case in QP basin based upon the sporadic debris flow occurrence there.
- Secondly, the Manayco ravines (Fig. 3, M series) are among the most active in the basin with respect to drainage density and level of erosional activity. Most of the other similar sub-basins within the upper basin (UB series, Fig. 3) do not appear to be as erosionally-active and consequently likely have lower yield values (as discussed above in relation to the M2 yield value) and discharge debris flows less often. It would take an unusual synchronicity of factors to create conditions so that all ravine systems throughout the basin have the same high yield value at the same time.

Based upon these two points and our estimation of the volume of the 1983 debris flow at 117,000 m^3, it appears that application of the adjusted basin-wide JAICA yield value (7,104 m^3/km^2) provides a reasonable estimate for the volume of more frequent but damaging events capable of damming RR and directly impacting Matucana (Table 3, B and E). Flo-2D also appears to generate a reasonable but lower sediment volume estimate for destructive debris flow event of higher frequency (Table 3, C3). Only detailed investigations of future debris flows in QP basin will determine which is the better method for estimating debris flow discharge from rainfall events.

Special hazards posed by the reactivation of Payhua village landslide complex

Active landslides within the Payhua landslide complex have the potential to block the QP channel and become sources of debris flow through ponding and outburst of a landslide-dammed lake. Field evidence indicates that minor blocking of the channel by landslides has occurred. However, there is no evidence to indicate that this minor blockage has directly resulted in a debris flow since 1951 when air photo coverage began. Although the movement of active landslides within the QP basin appears to be slow, acceleration in the movement is a possibility. Such an event would be more likely during the heavier rainfall of an El Niño year when pore water pressure would be at its highest in the landslide complex. The estimated maximum debris flow discharges discussed above would not necessarily apply to such an event. Consequently, close monitoring of the activity of this landslide is a necessity.

CONCLUSIONS

Large debris flows from QP basin and adjacent basins are apparently triggered by local intense rainfalls that are not reflected in the rainfall recorded at Matucana. Their occurrence during or shortly after El Niño years suggest that these wet years are instrumental in creating antecedent conditions conducive to debris flow. Destructive large debris flows in 1959 and 1983 originated in different parts of the QP basin. This further suggests that the steep ravine systems along the western margin of the basin are supply-limited with respect to debris flow generation. Once a debris flow has mobilized sediment from these systems, it may take decades for sufficient sediment to accumulate before another debris flow can occur whether or not the ravine system experiences a rainfall event similar to the one that triggered the previous debris flow.

Extrapolation of the largest debris flow yield value measured within the QP basin suggests a maximum debris flow event at around 250,000 m^3. This would be a rare basin-wide debris flow event triggered by rainfall. Debris flow events larger than historic ones have occurred based upon investigation of exposures along the QP fan, but it is not possible to determine the total volume of these flows based upon the limited exposures nor can it be determined whether these very large debris flow events were triggered by basin-wide intense rainfall events or landslide dam outburst floods. Historic debris flow events and field and air photo interpretation indicate that it is more likely that subsequent large debris flow events will originate in isolated parts of the basin and not simultaneously throughout it, based upon historic debris flow events. Direct application of the JAICA (1988) adjusted basin-wide yield value (7,104 m^3/km^2) is provides a useful approximation for the volume of more frequent damaging debris flows such as those that struck Matucana during the 20th century. The 250,000 m^3 figure for a maximum debris flow discharge would offer a sizeable safety margin considering the limited climatic and debris flow data for the QP basin.

The progressive reactivation of the Payhua village landslide complex over the past 50 years is a major concern. A rapid acceleration of this landslide could dam QP and cause an outburst flood. The estimated maximum debris flow volume (250,000 m^3) does not take such an event into account. Monitoring of the Payhua landslide complex is therefore mandated. Although landslide movement in the recent past has been slow, past events cannot be regarded as confident predictors of future events in this case.

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