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Risk Assessment Due to Debris Flows in Paz de Río-Colombia

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Abstract

Paz de Río is an important economic area of Colombia where iron mines produce most of the mineral for the steel production in the country. Along the La Chapa creek some debris flows have occurred since 1963 producing economic losses and human deaths at Santa Teresa village. Economical losses are related to disruption of the main access to La Chapa iron mine facilities, and flooding of Paz de Río due to damming of Chicamocha River, the main drainage system of the region, which is blocked by debris flows.

The local authority for Natural Disaster Management (CREPAD) jointly with the Universidad Nacional de Colombia carries out the risk evaluation related to potential debris flows along the creek. The study models the debris flow using the FLO2D software considering the geological, geomorphologic, topographic and hydrological setting of the area. As main sediment source we considered the potential volume of material supplied by a large landslide at the upper part of the creek basin, known locally as the Mesa Alta landslide, whereas sediment production due to landslides within the basin was considered as point inflows along the creek.

Physical vulnerability was evaluated by using the Leone (1999) approach, which considers the flow height and its relation with the structure height, whereas social vulnerability was evaluated by considering factors as population density, people age, literacy level and economical income. Risk assessment was based on the Liu and Lei (2003) approach in which risk is defined graphically considering critical threshold curves obtained from vulnerability and hazard values. Risk for different elements within the influence area of the creek was evaluated and mitigation measures including engineering works were proposed, the influence of these measures on hazard and risk was also evaluated.

Introduction

In 1933 the town of La Paz was destroyed by a earth flow and translated to a new location near the Chicamocha river and the named Paz de Río. This town was located in front of the mouth of the La Chapa creek, which started to generate catastrophic debris flows in 1963. Basin deforestation and cropping jointly with extensive landsliding have been considered the main causes of this process. Pictures in Figure 1 show the upper and lower parts of the basin. By 1985 the large slide (Mesa Alta Landslide) observed on the left image of Figure 1 was mobilised by intense rainfalls and favoured by constant tectonic activity along the complex faults system present in the area. Since the occurrence of this landslide two large debris flows have been observed in 1986 and 1995, the flow in 1995, which partially destroyed the Santa Teresa town at the bottom of the basin, is observed on the right image in Figure 1.

Figure 1. Left image is an overview of the upper part of the creek where a large slide is active. Right image shows sediment deposits after the 1995 debris flow, town shown is Santa Teresa.

Facilities of one of the mines of the Paz del Río S.A. company are crossed by the creek and during the past events the restaurant for workers have been buried by sediments and rock blocks. Although there has not been fatalities in this zone economical losses due to Mining interruption has been significant. On the other hand, flooding of the town of Paz de Río has become a hazard because the capacity of the flows to dammed the Chicamocha River. Although the problem has been studied for some consulting companies and some engineering works have been constructed, they have nor been effective in reducing risk, in consequence the Regional Disaster Management Office (CREPAD) and the Universidad Nacional de Colombia have started a new study in order to proposed solutions to this problem. Some preliminary results of this study are presented in this paper.

General setting

As part of the preliminary activities, topography, geology, geomorphology, geotechnics and seismic and climatic analysis were carried out. The following sections summarise the general environment where landslides and debris flow events occur. Locations described in this paper are identified in Figure 2, which shows an aerial photograph taken in 1993.

Topography. La Chapa creek has an average slope of 12.3° along a length of 6.4 km, however, locally some almost vertical slopes can be seen, which are related to strong geological units or correspond to alignments of geological faults. The basin has an area of 7.58 km^2 and a perimeter of 16.77 km, basin width is 2.3 km.

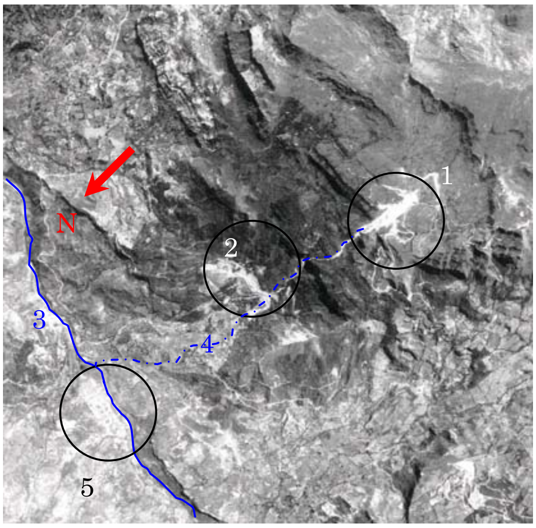

Figure 2. Aerial photograph of La Chapa creek area. 1) Mesa Alta landslide in the upper part of the basin; 2) La Chapa mine, 3) Chicamocha River, 4) La Chapa creek, 5) Paz de Río Town.

Geomorphology. The La Chapa area shows a mountainously relief, which is highly affected by tectonic activity that induced landsliding processes of different types. Morphodynamics was analysed from aerial photographs for 1959, 1963, 1965, 1988 and 1993. The earliest photograph shows that the upper part area was stable and only rock and soil falls were observed from the steep slope of the faults. In the middle of the basin scarps around the La Chapa mine, some incipient slides, associated to fault scarps, were observed which supplied sediments for the first debris flow in 1963 when size of the slides growth significantly. In 1963 intense erosion along a dense drainage system starts to induce generalised instability of coluvial deposits, it was found that this activity is related to intense rainfalls. In 1965 incisions by the drainage system starts to appear in the upper part of the basin which is formed by fluvio- glacial deposits. In 1988 the Mesa Alta slide in the upper part already exists and engineering works build for stabilising can be clearly seen, whereas the previous landslides are stable thanks to reforestation works. Figure 3 shows the geomorphologic map of the area along the La Chapa creek.

Geology. The geology is composed by sequences of siltstones, mudstones and sandstones from cretaceous and tertiary ages. Quaternary deposits are coluvial soils, some small alluvial deposits a along the creek. Stronger units form steep scarps very susceptible to rock falls, shallow residual deposits of softer rocks show to be very prone to landslides during rainy seasons. The upper part of the basin is formed by fluvio-glacial deposits composed of large block within clayey sands and gravels. Some artificial fills composed of mining residuals can be observed within the influence zone of the creek. At the bottom of vertical scarps, debris deposits associated with rock falls exist. Left image of Figure 3 shows the geologic sequence within La Chapa basin. Rock Formations are highly fractures due to tectonic activity; the basin is crossed by the axis of La Chapa anticline and is affected by different faults including the La Chapa fault and the Central Fault. These faults origin the vertical scarps and are responsible of landslides activity.

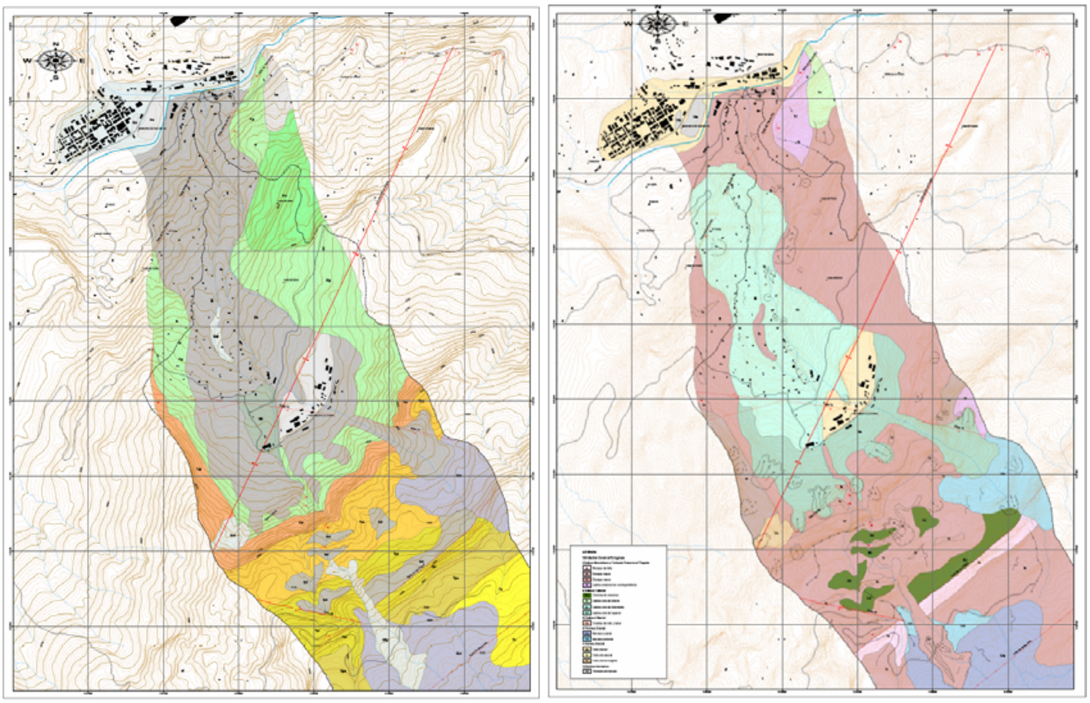

Figure 3. Left map shows the geologic sequence within the La Chapa creek; Grey colours are the quaternary deposits; yellow and orange colours are the Tertiary rocks and green colours are Cretaceous rocks. Right map is the geomorphologic map; Grey green and blue colours are the coluvial, glacial and landslides deposits, the Mesa Alta landslide is at the bottom of the map, whereas Paz de Río is at the top; in the middle of the map the La Chapa mine facilities can be distinguished. Red colours are rock units, which in general dip opposite to the slope face.

Climate and hydrology. The area shows a bi-modal annual rainfall distribution with peka values in April and October, whereas the driest months are January and July. Annual rainfall is between 800 and 1100 mm. Rainy months show rainfalls between 120 and 170 mm. The I-D-F curves averaged for the La Chapa basin is shown in Figure 4.

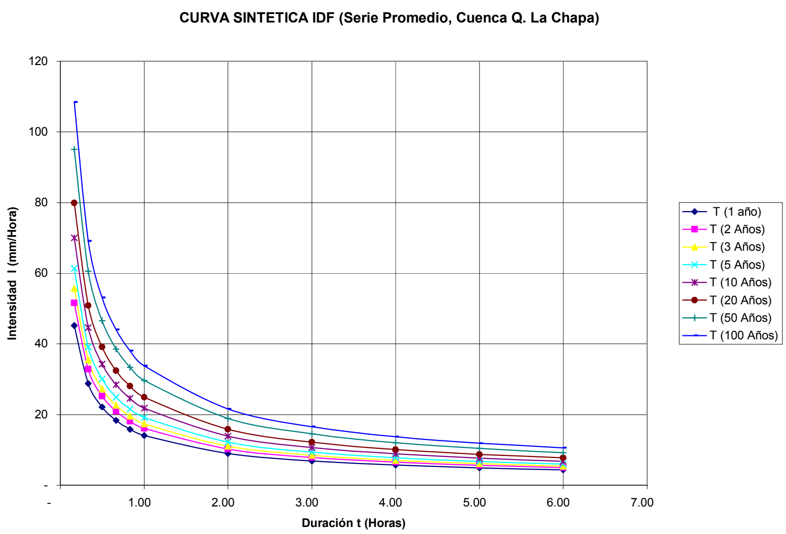

Figure 4. I-D-F curves for La Chapa basin, based on data for three stations around the area.

Based on rainfall data for the 1983, 1986 and 1995 debris flow events it was established a critical antecedent rainfall of 45 days with return period of 2,5 years, and a critical event rainfall of 2 hours. Assuming that the spatial distribution of the rainfall within the basin is uniform, hydrograms for different return period and for different control points along the creek were calculated in order to model debris flows transit. Control points were selected to represent the most significant sub-basins within the area. Figure 5 show schematically the control points along the creek and the hydrograms for a return period of 10 years, these hydrograms are composed by water discharges, estimated by using the Soil Conservation Service hydrological model, and sediment concentrations estimated by considering the potential volume of soil to fail in the upper part due to the rainfalls considered and by estimating a volume of sediments supplied by erosion of the basin and slope failures of the banks along the streams.

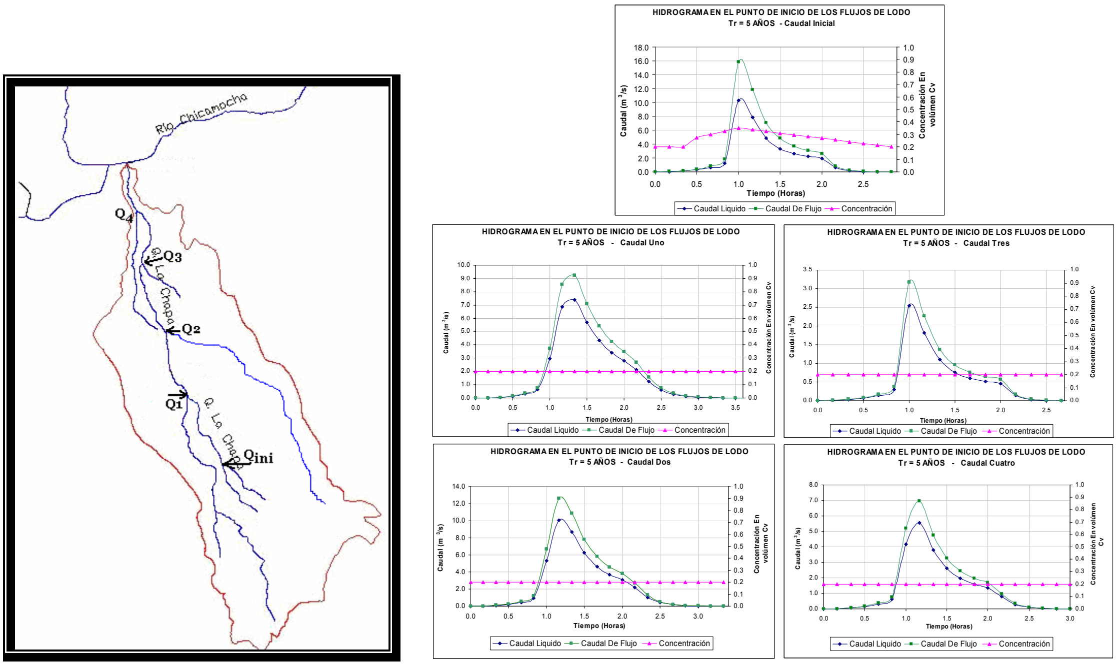

Figure 5. Left draw shows the control points assumed along the creek to represent sub-basins in the analysis. Right image shows the hydrograms for the initial point and for the four control points considered; blue and red lines are the water and sediment volumes and the green lines are the composed discharges.

Geotechnics. Geotechnical studies focuses on the stability analysis of Mesa Alta landslide as main sediment source for debris flows. Lab test were carried out in samples taken from the landslide mass and from coluvial deposits along banks of the creek. Table 1 show a summary of result found for these materials.

Table 1. Geotechnical properties of soil deposits within La Chapa basin.

Material	Unit weight kN/m^3	W_n %	c_p'/c_r' kPa	ϕ_p'/ϕ_r'
Glacial deposit				
Mesa Alta landslide	22	20	20/6	28.2°/23°
Coluvial deposits	21	17-21	9/0	28.5°/24°

Stability analyses

In order to determine sediment volume to be incorporated during debris flow events, stability analyses of the Mesa Alta landslide and stream banks were carried out by using the Slide software. The stream was divided into sectors that show similar geometry and material and stability analyses of each typical section were done. Figure 6 shows redults for one of those sections. The volume to be included in the analysis was defined by the most critical slope surface found.

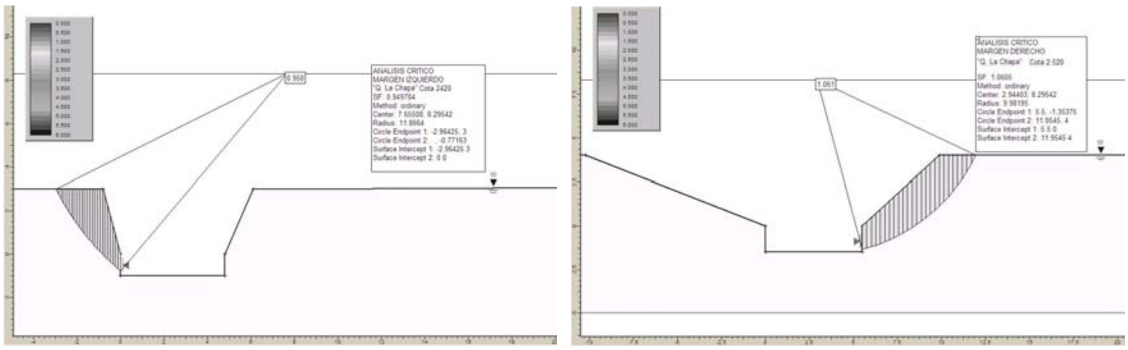

Figure 6. Stability analyses of stream banks for different geometries. Shaded areas are volumes defined by most critical failure surfaces.

The initial sediment concentration was assumed to be defined by the potential failed volume due to a reactivation of the Mesa Alta Landslide. Details studies were carried out for defining the geologic and geotechnical models for the slide and result are shown in Figure 7. Stability analysis shows that the slope is in limit equilibrium and almost any change in stress condition will induce the failure.

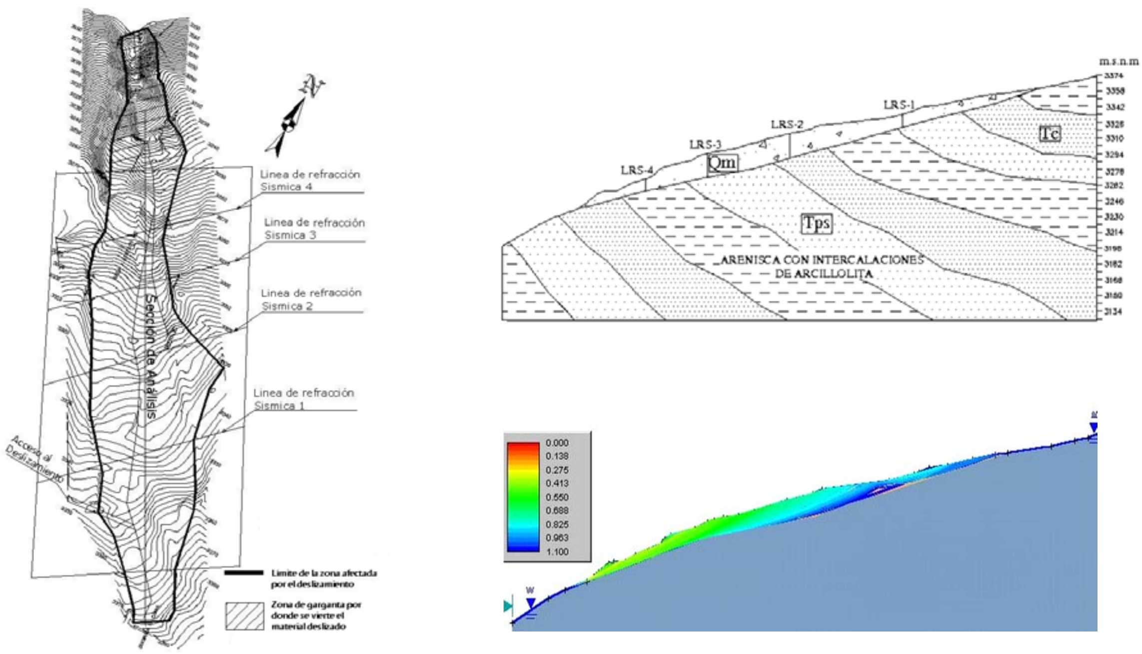

Figure 7. Mesa Alta Landslide. Left graph shows the topographic map of the slope. Upper right draw is the section analysed; Tps and Tc are Tertiary sedimentary rocks and Qm is the Glacial coluvion; lower figure shows the Slide analysis results in terms of Factor of Safety.

Debris flow hazard analysis

Debris flow was modelled by using the FLO2D software considering rainfalls of different return periods, hydrograms and sediment concentrations were taken as it was explained in previous sections. Results for hazard analysis were presented as maps of the areas potentially cover by debris flows for each return period. Hazard map was plotted by determining the hazard level for different cell for a grid of 12x12 m. Hazard was defined by a combination between the intensity of the debris flow in each cell and the recurrence period for each intensity, following the model proposed by Garcia et al. (2003). Intensity was defined by the product of the flow depth times velocity. Figure 8 shows the Hazard map based on this analysis.

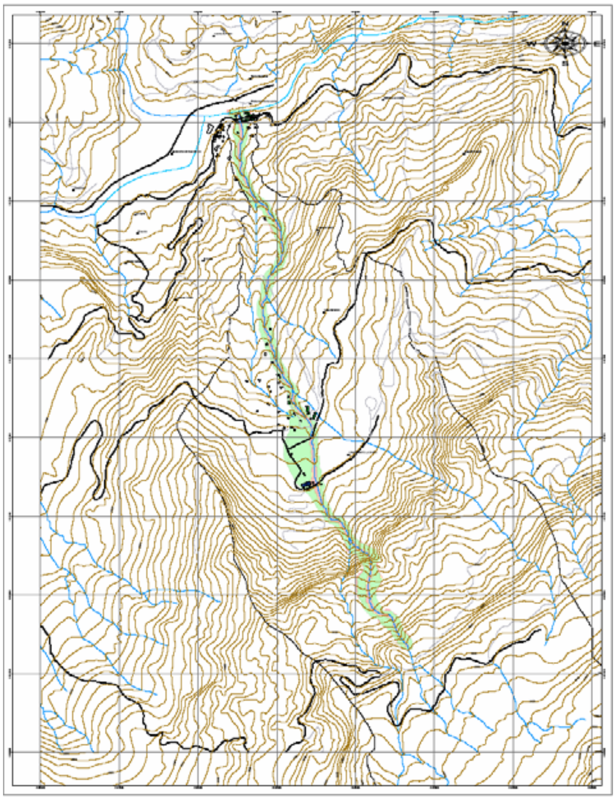

Figure 8. Hazard map due to debris flows along the La Chapa creek. Yellow, green and red correspond to low, medium and high hazard.

Risk assessment

In order to assess the risk level for structures within the area influenced by the creek, an inventory of exposed elements was done. This inventory includes structural, economical and social variables. In total 86 houses were inventoried. The social vulnerability was evaluated in term of the population density, age and literacy level according with the model proposed by Liu and Lei (2003). It was found that the maximum potential deaths are of 71.

The physical vulnerability was estimated by considering the structural system, the quality and maintenance of the buildings and structural condition of the ceilings. Model used was a lineal summation of values given arbitrarily to each category within each of those factors included, for each variable a different arbitrary weighting value was given.

Physical and social vulnerability were combined in order to define a Damage Index, which was defined as proposed by Leone (1996). This Damage Index was interpreted as a Vulnerability Index which was combined with hazard in order to define risk by using the model proposed by Liu and Lei (2003). Results are shown in Figure 9, which presents the risk space defined by Liu and Lei and the points representing the average vulnerability and hazard of the area. This figure shows the annual probability of deaths is low even for events with return periods of 50 years. On the other hand it can be seen that the probability of deaths in 50 years is very high suggesting that risk management actions must be taken in the short time.

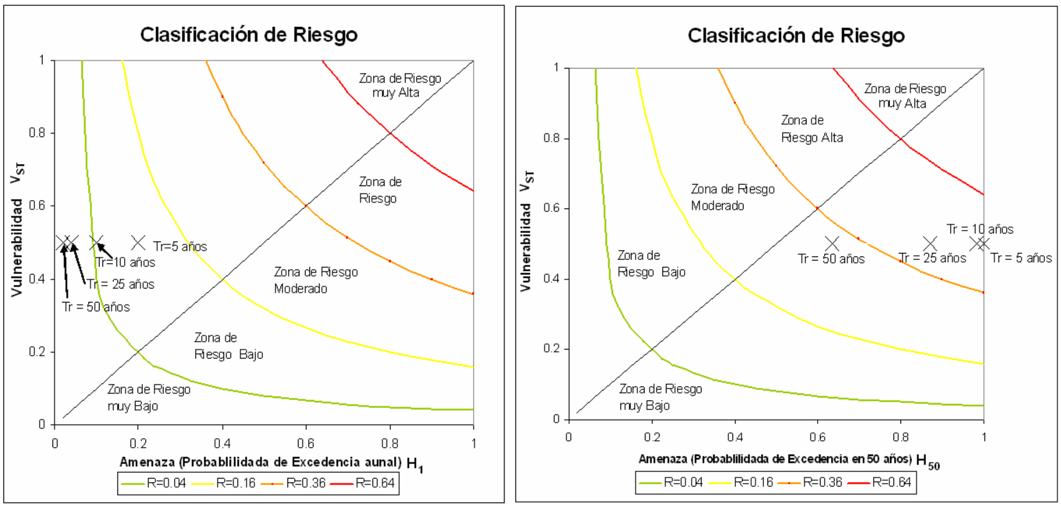

Figure 9. Risk assessment for La Chapa basin. Graphs show the annual probability of deaths (left) and probability of deaths in 50 years (right).

Conclusions

Risk assessment for population and structures within the La Chapa basin in Paz de Río-Colombia shows that there exist a high annual probability of debris flow to occur along the creek, and although the vulnerability level of the exposed housed in medium the possibility of deaths in the following 50 years is extremely high. In consequence mitigation measures must be taken in order to reduce this risk level. High hazard level is due to the marginal stability of slopes formed by quaternary deposits, which have shown to be an effective source of sediments during debris flow in the past; hence stabilising measures need to be implemented to reduce risk within the basin.

References

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