Landslide Hazard and Risk Zonation Mapping in the Río Grande Basin, Central Andes of Mendoza, Argentina

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This paper presents an inventory of landslides and hazard and risk zonation mapping along the Río Grande basin in the Central Andes of Mendoza. The mapping was based on field work combined with interpretation of aerial photographs to provide a practical basis for rational land-use planning. Landslide risk zones were mapped, in view of the natural hazards and the degree of loss to a given element or set of elements at risk along roads and routes because of a particular phenomenon of a given magnitude. Landslides occurred in the study area during 2 periods of the year: in spring after snowmelt and in summer after severe rainstorms. A relationship was found between the lithology and the landslides. In addition, the occurrence of a reactivated landslide and the formation of a dam were detected on the satellite images.

Keywords: *Landslides; risk zonation mapping; natural hazards; Andes; Argentina.*

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Introduction

Natural disasters are normal natural processes. We cannot eliminate them, but we can attempt to reduce the damage and loss of lives that they cause. In the Andes of Argentina, as in other regions of the world, natural hazards such as avalanches and landslides are very common; landslides are among the most destructive. These natural phenomena must be taken into account in land-use planning and when trying to minimize hazards in order to improve the quality of life and preserve the infrastructure in the mountains. Detailed regional studies are therefore necessary for better prediction and location of areas prone to instability. At an advanced stage of planning, when construction locations and alternatives must be chosen or remedial measures developed to provide safer conditions on slopes, the first step is to recognize the existence of a landslide and to distinguish its type, activity, and probable causes. Changes in the natural environment (eg, as a result of human activities) may modify the degree of risk of landslides in a particular area. The present study provides a basic understanding of landslide recognition and risk analysis. It is possible to predict the location and time of a possible event in particular sites only by means of detailed mapping and very close monitoring.

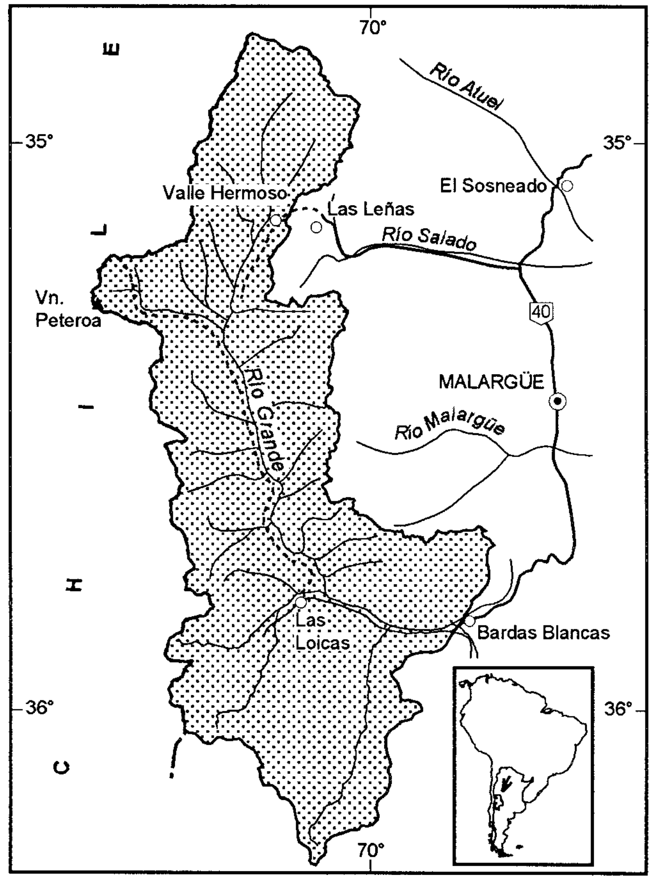


FIGURE 1 Location of the study area.

Study area

The study area, located between 34°50' and 36°17'S latitude and 69°40' and 70°35'W longitude (Figure 1), comprises about 5400 km^2. The objective of this study was to carry out hazard and risk or potential risk zonation mapping along the Río Grande basin in the Central Andes of Mendoza for better land-use planning. According to the definitions proposed by the United Nations Disaster Relief Office and the United Nations Educational, Scientific and Cultural Organization (UNDRO/UNESCO, see Coburn et al 1994), risk may be expressed as the product of natural hazard (probability of occurrence) and vulnerability (the expected degree of loss to a given element or set of elements at risk resulting from the occurrence of a natural phenomenon of a given magnitude). The elements or set of elements at risk (population, roads, highways, public services, properties, etc) along the Río Grande valley were considered in the risk analysis.

Types of landslides

A landslide was defined by Cruden (1991) for the Working Party on World Landslide Inventory as “a movement of a mass of rock, earth or debris down a slope." Although "landslide" is the popular expression, Hutchinson (1968) preferred the term "mass movement." There are numerous classifications within the landslide literature; most definitions provide a guide to the processes as well as the type of material involved in the displacement (eg, Varnes 1958; Hutchinson 1968; the European classification developed by the European Community EPOCH program [1991–1993], see Casale et al 1994). According to Varnes (1958) the term "landslide" denotes a downward and outward movement of slope-forming materials composed of natural rocks, soils, or combinations of these materials. The moving mass may proceed by any 1 of 3 principal types of movement, falling, sliding, or flowing, or by combinations of such movements. Normal surficial creep, solifluction, and avalanches composed mostly of snow and ice are excluded in this study.

In the present study we followed Varnes' classification (1958). The processes involved in slope movements comprise a continuous series of events from cause to effect (Cruden and Varnes 1978). The principal factors contributing to the instability of earth materials in the area are geology (ie, weathering, discontinuities such as bedding planes, joints, strata inclined toward free face, alternation of friable and massive beds), erosion by streams and rivers, valleys deeply cut by glaciers, creation of new slopes by previous rockfalls, subsidence, heavy rains, snowmelt, and human activity.

Methodology

The work was based on photointerpretation, using aerial photographs at a scale of 1:50,000 taken in March 1963–April 1963, and Landsat satellite images (MMS) at a scale of 1:250,000 from March 1985, a compatible Landsat Multispectral Scanner (CCT) from March 1985, and Landsat Thematic Mapper (TM) satellite images from February 1986. Photointerpretation was accompanied by in situ observations. Because of deficiencies in the existing cartography, a base map at a scale of 1:100,000 was drawn from a georeferentiated satellite image from February 1986.

An inventory map shows the distribution and classification of landslides. The map is accompanied by texts with brief information on each landslide, including total length, width, geomorphological characteristics, orientation, geology, lithology, slope, structure, erosion by streams and rivers, lakes formed by landslides, probable climatic conditions, hydrology, and potential causes of landslides.

Data about earthquakes that occurred in the region, with the location of the epicenters and magnitudes, were also compiled. In addition, temperature and precipitation records from 2 meteorological stations were considered. Because the area is not very populated, there are almost no historical records about the occurrence of landslides, except for scarce information obtained from the inhabitants and field observations made by the authors.

Physical environment

Topography and geology

The Andes of Mendoza have a north–south orientation and extend between 33° and 37°S latitudes. At 33°S latitude the highest peaks range up to 5000 m, culminating in the Cerro Aconcagua (6959 m), the highest peak in the Western Hemisphere, whereas to the south the highest altitudes range between 3000 and 4000 m. The Andes act as a barrier for most of the humidity coming from the Pacific Ocean westerlies, so the eastern side has a semiarid climate. To the south, decreasing altitudes gradually allow for the penetration of moist westerly winds.

The study area lies in the Cordillera Principal geological province (Yrigoyen 1979). The Cordillera Principal, or Main Andes, was the focus of Andean orogeny during late Mesozoic and Cenozoic times. A thick sequence of marine and continental Mesozoic deposits unconformably overlies the volcanic Choiyoi Group of the Frontal Cordillera. The Choiyoi Group, dating from the Permotriassic age, outcrops along 40 km in an elongated north–south strip. The Jurassic–Cretaceous sediments are in turn covered unconformably by a thick Tertiary volcanic sequence. The Tertiary volcanic rocks are well exposed south of Valle Hermoso. Numerous Tertiary intrusive bodies are found throughout the region, with scarce areal development and composition varying from acid to mesosilicic terms.

Close to the border with Chile there are several basalt flows from the upper Tertiary–Quaternary that flowed from effusive centers. The Río Grande valley was extensively and repeatedly invaded by glaciers during the Pleistocene (Espizua 1998). The valleys are deeply cut by Quaternary glacier advances, and the slopes are subject to mass movements. Structurally, the study zone is characterized by a predominance of foldings with subordinated fracturation, a trend that increases toward the south.

Climate

The relationship between the amount of precipitation and landslide events has been studied by many authors, and it has also been indicated in the valley of the Río Mendoza (Espizua et al 1993). Rainfall intensity and duration play a major role in triggering debris flows, mudflows, and rockfalls, depending on climatic conditions, topography, the geological structure of slopes, and permeability. Movements of material generally

FIGURE 2 Monthly mean precipitation and temperature in Valle Hermoso and Bardas Blancas meteorological stations.

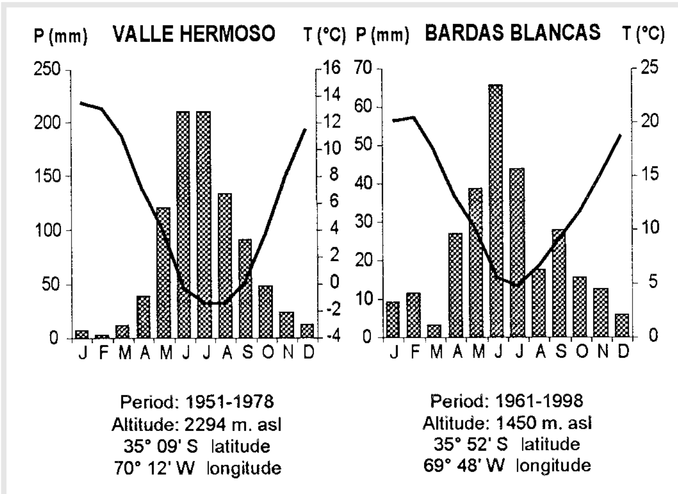
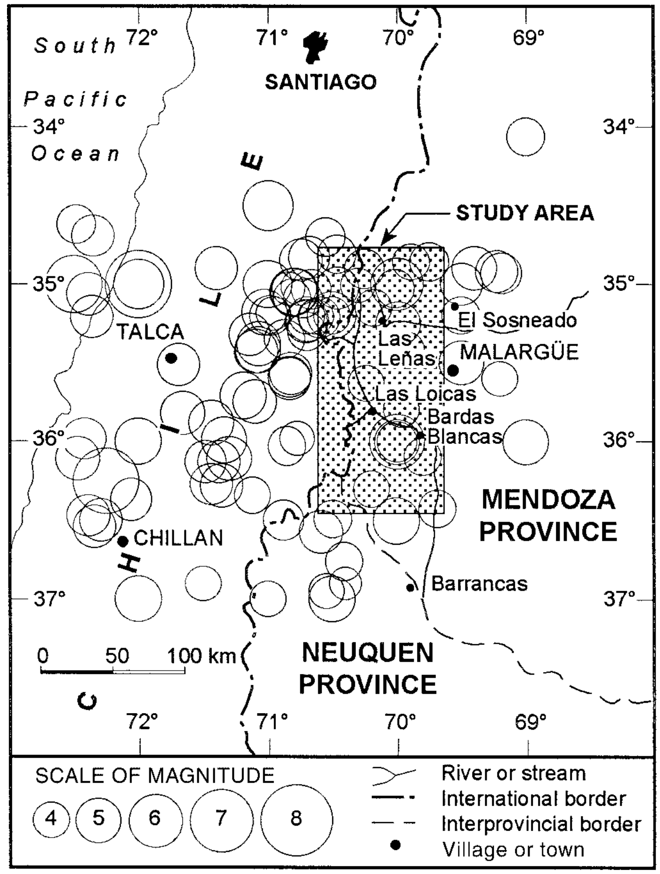


FIGURE 3 Location of earthquakes (epicenters and magnitudes).



occur during 2 periods of the year: in spring during snowmelt and in summer after severe rainfall. This was clearly observed in the study area by the authors, where the rockfalls, debris flows, and mudflows are associated with torrential rainfall. On 25 March 1990 a mudflow resulting from a torrential rainstorm occurred in Ñancao Creek, a tributary of the Poti-Malal River, damaging a small house.

There are 2 meteorological stations in the zone, with interrupted records: (1) Valle Hermoso (35°09'S, 70°12'W) at 2294 m, and (2) Bardas Blancas (35°52'S, 69°48'W) at 1450 m. The mean monthly precipitation and temperature records show 2 well-defined periods, one in winter and the other in summer (Figure 2). The monthly mean maximum precipitation coincides with the monthly mean minimum temperature. In Valle Hermoso the mean monthly temperature from June to August is below 0°C. At this station the higher monthly precipitation occurs in the winter as snow, whereas in Bardas Blancas it can be snow or rain and occurs from May to June. Annual mean precipitation varies from 400 mm in Bardas Blancas to 940 mm in Valle Hermoso.

Vegetation

Vegetation cover has been used as an indicator of the relative degree of landslide activity. Surfaces free of vegetation are an indication of active landslides, whereas vegetation promotes more stable conditions.

The vegetation in the study area is closely related to altitude. Thus, the temperature gradient defines vegetation zonation by elevation. Bustos (1983) and Roig (1982) considered morphoclimatic steps, and Carretero and Dalmasso (1990) studied the communities in the area:

- *Glacial:* above 3700 m, without vegetation.
- *Periglacial:* between 3000 and 3700 m, with low covering vegetation (20%). *Milinum ovalleanum, Milinum echegarayi, Oreopulus glacialis, Adesmia aegyceras, Barneoudia major, Nassuavia lagascae, Leucheria candidissima,* etc, are common up to 3000 m.
- *Low periglacial or niveo-torrential zone: Stipa speciosa, Chuquiraga oppositifolia, Adesmia pinifolia, Poa holciformis,* and *Stipa chrysophylla* are common communities below 2700 m. The piedmont is characterized by the following communities—*Neosparton aphyllum, Prosopis flexuosa* var. *depressa, Anarthrophyllum rigidum, Panicum urvilleanum, Poa durifolia,* and *Colliguaja integerrima.*
- The outwash terraces contain riparian vegetation, and the dominant communities are *vegas, Cortaderia rudiuscula, Chacaya trinervis,* etc.

Seismic activity

We compiled seismic information on 587 earthquakes at several magnitudes on the Richter scale that occurred between 1928 and October 1992 for the region between 69° and 73°W longitudes and 34° and 37°S latitudes by obtaining a list from the Instituto Nacional de Prevención Sísmica (INPRES), San Juan, Argentina, and the Geology Department of the Univer-

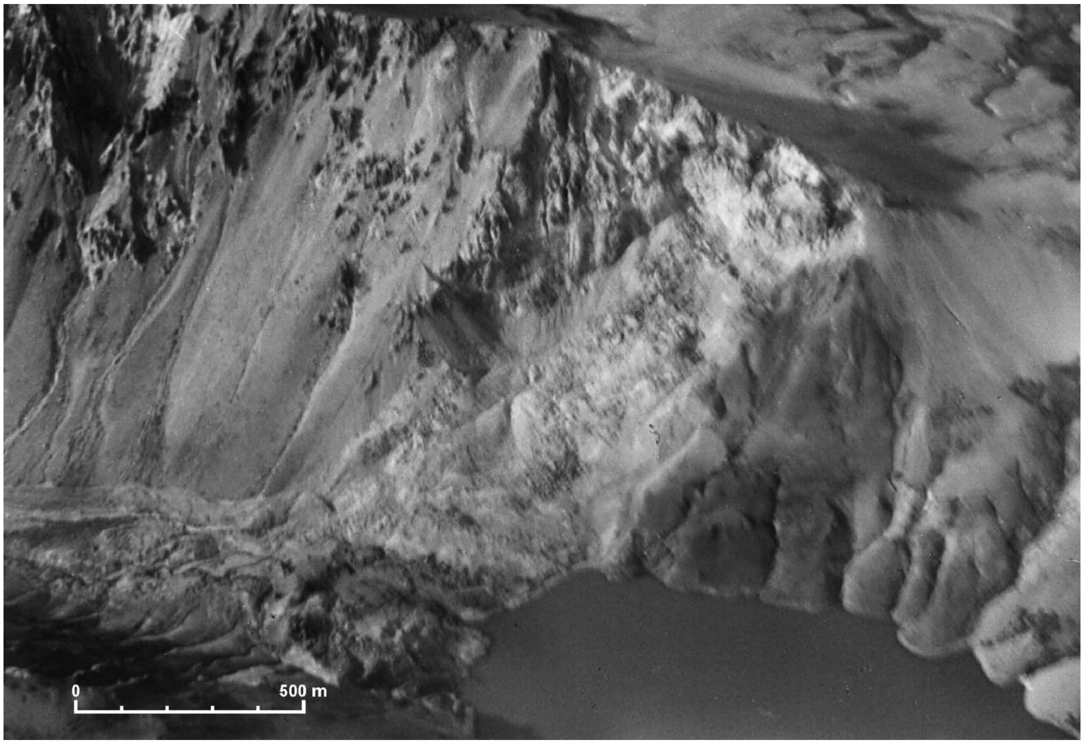


FIGURE 4 South aerial view of a landslide and the resulting dam at the headwaters of the Cajón Bayo creek in the Río Pehuenche basin. (Photo by Luis Lenzano and Carlos Aguado)

sity of Chile. Ninety earthquakes with magnitudes greater than 4 have occurred in the area. Figure 3 shows the location of the epicenters and magnitudes in the study area and the surrounding zones; the figure shows that there is an increase in the number of earthquakes and in their magnitudes toward the west.

Seismic activity is recognized as the predominant factor in triggering landslides. Because of scarce historical information on the occurrence of landslides, it was not possible to relate them to earthquakes, except for a reactivated slide that occurred in the subbasin of the Cajón Bayo creek, a tributary of the Río Pehuenche. On the basis of satellite images, it was calculated that this slide (Figure 4) occurred between March 1985 and February 1986. The landslide may have been induced by 7 earthquakes (Richter magnitude > 5) that occurred in the general vicinity of the Cajón Bayo area (estimated epicentral location between 70 and 200 km).

Evaluation of landslides

A total of 198 landslides were mapped. These involve the known ones (historical landslides) as well as those that occurred in the past, the majority probably occurring during the Quaternary period (prehistoric mass movements) after the glacial recession. Large-scale mass movements in the Western Hemisphere are interpreted in many cases as having been caused by oversteepening of relatively weak slopes during Pleistocene glaciations, when no natural talus could accumulate, thus depriving some slopes of natural support (Voight and Pariseau 1978). The Río Grande valley was invaded by glacial advances during the Pleistocene (Espizua 1998), which cut the valleys deeply. Landslides could have occurred up to the present day since the ice retreated.

The historical occurrence of landslides in the study area remains unknown because of the lack of historical data. Slides and flows are the phenomena with greater dimensions, and flows are the more frequent. Extensive areas have been grouped where rockfalls occur, associated with massive fractured and jointed rocks, such as volcanic rocks, and with severe rainstorms or winds. Even though such areas are subject to events of less magnitude but greater frequency, construction should be avoided, and the potential danger along roads or other routes requires preventive steps to avoid accidents.

Frequently large landslides cross the valley floor and extend way up the opposite wall, thus damming a river or a creek. Although the persistence of barrier lakes is generally limited, the hazard connected with a sudden evacuation of lakes in which large amounts of water may be stored should not be underestimated. In the case of potential riverbed obstruction, and after rapid depletion of a lake, inhabited areas and infrastructure located downstream of the area can be at high risk. Examples of this type of disaster are abundant in the Cordillera de los Andes in South America (Voight and Pariseau 1978) as well as in other mountainous regions worldwide. Former lakes related to landslides were detected in the Mendoza valley (Espizua and Bengochea 1991; Espizua et al 1993). Through the analysis of satellite images and field observations in the study area, it was possible to detect a reactivated landslide (slump) at the headwaters of the Cajón Bayo creek, at the Río Pehuenche basin. Between March 1985 and February 1986, the occurrence of a reactivated slide and the formation of a lake upstream were observed thanks to satellite images (Figure 4). At the Cajón Grande valley a landslide (B47, Figure 5) dammed the stream, and a lake was formed upstream. Lake sediments were drilled to a depth of 2 m, and a sample was dated as C_{14} 1010 ± 65 years BP (LP 383—LATYR—CONICET Lab., 1 sigma calibrated result).

Distribution and orientation of landslides

The Río Grande valley has a north–south trend. Analyzing the orientation of 198 landslides represented in Figure 5, the flows, slides, and complex landslides are preferably oriented toward the west, south, and southwest. The predominance of flows and slides oriented toward the south and to the west is partly the result of those slopes being colder; they accumulate more snow and it remains there longer. Therefore, during the snowmelt season the amount of water is higher. The snow that remains in the cold slopes produces a more intense chemical and physical weathering of the rock, because of the presence of water in cracks and caverns, which freezes and thaws, and the hydration of clays and anhydrite.

Rockfalls were not considered because in this process orientation does not intervene much.

Relationship of landslides to lithology

In the Río Mendoza basin a high correlation was found between the types of landslides and the lithology. The areas where massive, compact, and very resistant rocks produce outcrops have been found to be more prone to slides and rockfalls, whereas those covered by friable rocks have been shown to be related to debris flows and mudflows (Espizua et al 1991, 1993). At the Río Grande basin there is a similar trend, but the relationship is not as strong because the resistant and friable formations are more closely combined in meridionally elongated narrow strips. Flows occurred in zones where a great proportion of friable rocks prevail, among them Permotriassic tuffs, sedimentary rocks from the Jurassic–Cretaceous, and weathered intrusive outcrops belonging to the Tertiary. Within these zones some slides also occurred in the rare outcrops of resistant and massive rocks, because of either the presence of resistant and massive rocks over friable rocks or the removal of soluble material such as gypsum from beneath firmer material, creating instability conditions. Rockfall was found to occur on volcanic porphyritic rock.

Landslide hazard and risk zonation map

We prepared 2 maps. The distribution and classification of landslides are shown on the first map (inventory map; Figure 5). The second—a landslide hazard and risk zonation map (Figure 6)—was prepared taking into account the zones subject to landslide hazard and the degree of loss to a given element or set of elements at risk in the region because of the occurrence of a particular phenomenon of a given magnitude (Coburn et al 1994).

Landslides are identified on the maps and classified according to Varnes (1984), on the basis of the type of movement and material involved, and they are individualized as follows: (A) rockfalls, (B) slides, (C) flows, (D) complex landslides. The number following each capital letter indicates the number of the landslide in each category.

A brief description is provided for each landslide including classification, geographic coordinates, maximum and minimum altitude, longitude, width, orientation, geology, gradient slope, structure, erosion by streams or rivers, former lakes dammed by the occurrence of a slide, probable climatic conditions, potential causes of the landslides, and nearby infrastructure and activity of the process, which can be active or inactive. Classification of the activity of the process was based on the assessment of stability conditions (Crozier 1984).

- *Active:* Slopes where movements of material presently occur or where processes occurred very recently and landslide forms are fresh and well defined. Among the features indicating the degree of activity according to Crozier (1984), we took into account the presence of scarps and sharp edges, secondary mass movement on scarp faces, fresh fracture surfaces, many ponds and undrained depressions, and absence of vegetal cover. Rockfalls were considered an active process. Movements may be continuous or seasonal.
- *Inactive:* Slopes that have not moved within recent years but may later renew their activity or may remain inactive. The events present smooth, rounded geoforms, absence of mass movements on the scarp faces, and presence of vegetation on the rupture surface. Záruba and Mencl (1982) refer to these as fossil landslides.

Three criteria were applied to the assessment of slope stability, according to Crozier (1984): (1) the

FIGURE 5 Inventory and location of landslides in the study area in the Río Grande basin.

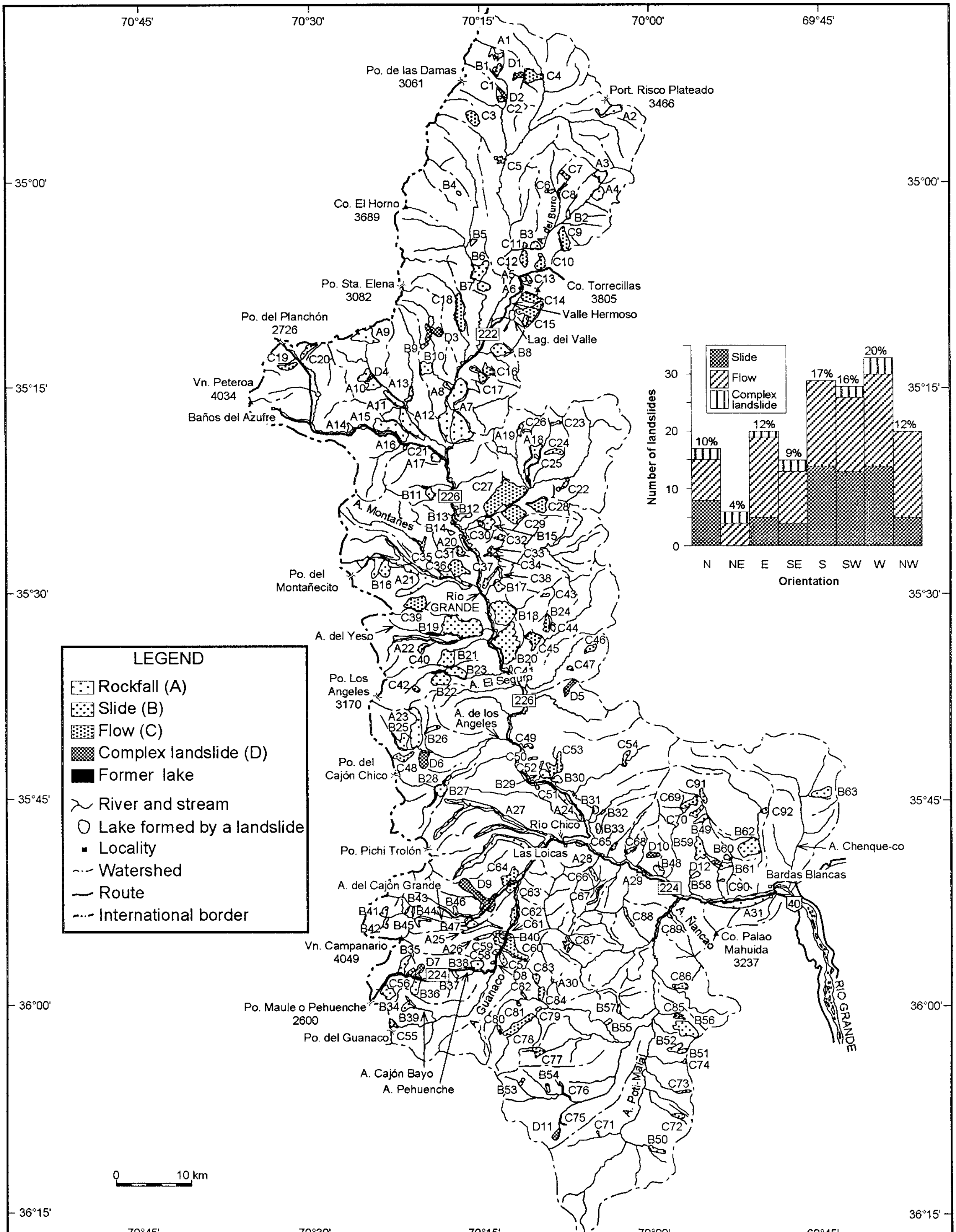
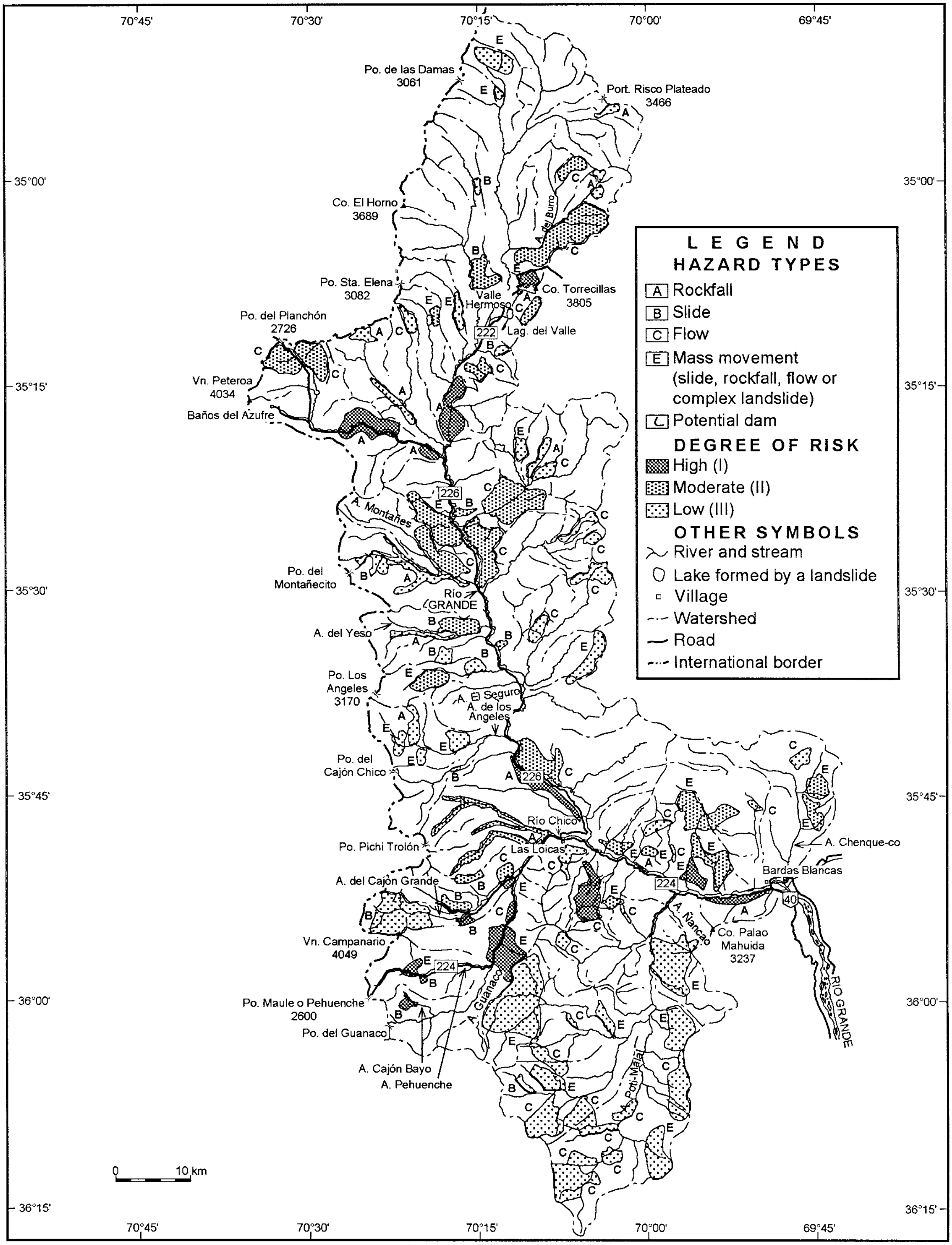


FIGURE 6 Map of landslide hazards and risk zonation in the Río Grande basin.



main conditions that cause landsliding, (2) the magnitude of the impact, and (3) the infrastructure likely to be damaged. The frequency with which a slope experiences mass movements has not been considered because, unfortunately, the history of landslide occurrence is not documented in the area, except for the landslide activity observed by the authors in the field. Another obstacle was the lack of daily rainfall records.

Among the main factors contributing to the instability of earth materials, analyses were made of the structural, geologic, lithologic, and climatic characteristics, the slope gradient, river erosion, and the presence of previous landslides in the area. With regard to the magnitude of the impact, the type of landslide that could occur and the dimensions (total area) it could reach, as well as the infrastructure that could be damaged, were taken into consideration.

A landslide risk map was obtained showing the hazards and elements at risk according to UNDRO/UNESCO (See Coburn et al 1994) definitions. The risk map shows that the major hazards and the greatest potential risk are concentrated along the Río Grande valley and its tributaries where the roads, routes, and settlements are located. Three risk degrees were distinguished as follows (Figure 6):

- *Degree I (high risk)*. This is the category with the highest degree of hazard and risk, where rockfalls, flows, or slides that could occur would affect Provincial routes 222 and 224, roads, bridges, or small, populated centers. Rockfalls are probably the most frequently observed mass movements in mountain areas. The areas where rockfalls occur are subject to events of lesser magnitude that occur more frequently; therefore, construction should be avoided.
- *Degree II (moderate risk)*. This category covers areas vulnerable to the potential occurrence of landslides, but the threat to infrastructure in the area is not as great because the hazard zones are far away. Through field observations in March 1996, it was possible to detect the occurrence of a debris flow that flowed from the headwaters of Arroyo Chenque-Co after a heavy rainstorm (Degrees II and III; Figure 6). Highway No. 40 and a small bridge were damaged (Degree I; Figure 6).
- *Degree III (low risk)*. The occurrence of a potential landslide is relatively remote, and the expected damage to the infrastructure is very slight.
- *Potential dam.* The potential occurrence of a specific hazard induced by large mass movements that could cross the valley floor up to the opposite slope, thus damming a river or a creek, was considered as a slide hazard zone. In case the dam is broken, a catastrophic flood could occur, posing high risk to inhabited areas and infrastructure located downstream.

In the study area it was possible to detect a reactivated landslide (slump) at the headwaters of the Cajón Bayo creek at the Río Pehuenche basin. Tuffs of the lower Tilhuelitense (lower Quaternary age) are characterized by outcrops about 300–400 m thick, in subhorizontal position, with andesitic composition arising from eruptions of Volcano Campanario. A small 600-m-long landslide that deviated the creek about 50 m to the north can be observed in the 1963 aerial photos. In the satellite image of March 1985, no change was detected in the sector. Instead, on the 1986 images, a 1500-m-long lake that formed upstream from the landslide was detected (Figure 5; slump B39). In March 1992 the region was observed from a plane. A reactivated slide had occurred in the same sector as the one before, but this time it was more important, and the mass movements crossed the valley floor and extended far up the opposite wall. A lake was formed after the landslide obstructed the Cajón Bayo valley floor in 1986 (Figure 4). In March 1992, minor drainage of the lake through the base of the mass was also observed. This characteristic, and the prevailing lithology (friable tuffs), a steep slope, and the presence of snow ablation water, are negative factors that may affect stability. It is quite probable that at some time the natural dam will break. Were the water mass to drain suddenly, catastrophic downstream flooding would affect the Pehuenche road (Provincial Route 224) and the locality of Las Loicas.

Conclusions

The landslide risk zones along the Río Grande basin were mapped, taking into account the natural hazard and the degree of loss to a given element or set of elements at risk in the region because of a particular phenomenon of a given magnitude. Based on aerial photographs, satellite images, and field observations, 2 maps at regional scale of the Río Grande basin in the Central Andes of Argentina were produced, one with aerial distribution and classification of landslides (landslides inventory) and the other with landslide hazards and risk zones. Three criteria were applied to the assessment of slope stability: (1) the main conditions that cause landsliding, (2) the magnitude of the impact, and (3) the infrastructure likely to be damaged. A total of 198 landslides (rockfalls, slides, flows, and complex landslides) were mapped. Flows and slides are oriented toward the south, southwest, and west. A relation between lithology and the occurrence of landslides was found. Flows are related to friable rocks. Slides and rockfalls are usually associated with rocks that are resistant and massive. It was observed that flows and rockfalls usually occur after snowmelt and after torrential rainstorms. Some examples were observed during the summers of 1990, 1992–1994, and 1995–1996. At the headwaters of the Cajón Bayo creek, in the Pehuenche river basin, a reactivated landslide occurred, forming a lake upstream. The landslide may have been triggered by 7 earthquakes (Richter magnitude > 5) and occurred during 1985 in the general vicinity of the Cajón Bayo area (estimated epicentral location between 70 and 200 km). The landslide risk map in the region can be considered a basic and valuable tool for use in selecting stable areas in the terrain for any developmental activity.

AUTHORS

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