

Landslides in Colombia and their impact on towns and cities

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Abstract: Each year landslides in Colombia cause loss of life and widespread damage to towns and cities. Many of the major cities, such as Bogotá and Medellín, have experienced rapid, uncontrollable expansion of the population over the past few decades, due to migration from the rural areas to urban centres. Due to the relatively high cost of living space, homes are built on the steep, middle and upper valley slopes which are susceptible to mass wasting. The slopes above Medellín have resulted in at least three known catastrophic landslides. The failure of thick residual soils, overlying intensely fractured bedrock, occurs during torrential storms or following prolonged heavy rainfall. In 2003 for example, at least 13 persons were killed, 20 remain missing, and more than 300 homes were destroyed after overnight rains in western Colombian towns in the Caldas district. Landslides may also be induced by earthquakes, such as those which occurred in 1999 in the Eje Cafetero, central part of Colombia and in 1995 in Tauramena. These block roads, damage communications and utilities and often isolating small towns. This has significant impacts on the economy preventing the export of crops such as coffee. Earthquake triggered landslides and volcanic landslides continue to be generated near Nevado del Ruiz and Nevado del Huila, volcanoes. It was a huge lahar in 1985, which buried the town of Armero killing at least 25,000 people. Small scale artisanal coal mining in Central Cordillera, in Antioquia, frequently results in subsidence of the ground surface and the generation of destructive landslides. Several cities in Colombia have established legislation and organisations to mitigate against landslide hazards. The objectives of this paper are to draw attention to the causes, consequences and management of landslides in the towns and cities of Colombia.

Résumé: Chaque année en Colombie de nombreuses pertes de vie sont attribuées aux éboulements qui détruisent maintes cités et villes. En effet, plusieurs grandes villes comme Bogota et Medellin sont confrontées à une rapide expansion de la population depuis les dernières décennies. La raison est une délocalisation massive humaine du milieu rural vers le milieu urbain. Par ailleurs, les coûts d'habitation expliquent la construction de plusieurs maisons sur des pentes moyennes et raides des vallées. Par exemple, la pente située au-dessus de la vallée de Medellin a déjà connu certains éboulements catastrophiques. La fracture des sols épais résiduels, qui reposent sur un rocher déjà fracturé, a été créée par les fortes pluies torrentielles, suivies de lourdes précipitations. En 2003, au moins 16 personnes ont été tuées, 20 se portent disparues et plus de 300 habitations ont été détruites à cause des pluies provenant de l'ouest de la Colombie, notamment du comté de Caldas. En outre, le tremblement de terre a déclenché d'autres éboulements. Il y en a aussi des volcans Nevada del Ruiz et Nevada del Hila. En 1985, un énorme "lahar" a détruit la ville d' Amero tuant au moins 25.000 personnes. L'extraction du charbon d'une façon artisanale en Antioquia a provoqué l'affaiblissement de la surface des sols et des éboulements destructifs. C'est pourquoi quelques états colombiens ont adopté une loi pour protéger les habitants de ces incidents. Pour clore, l'objectif principal de cet article est d'attirer l'attention sur les causes et conséquences des éboulements afin de protéger les comtés et villes de la Colombie.

Keywords: landslides, geology of cities, geological hazards, geomorphology, mass movements, engineering geology.

INTRODUCTION

Risks to life and infrastructure due to landslides have increased throughout the urban parts of Colombia, over the past few decades. Most of Colombia's 46 million inhabitants now live in mountainous regions and around 62% live in urban zones. This may be partially attributed to the increasing migration of the population to the towns and cities, due to poverty, security and political reasons. The upper and middle valley slopes have been gradually populated by the migrants since the lower valley slopes and valley floors tend already to be occupied or are expensive, forcing the occupation of the valley sides. A combination of steep slopes, thick regolith, highly deformed and fractured bedrock (caused by tectonic ground movements), prolonged tropical rainstorms, intense weathering and seismicity contribute to the occurrence of landslides. Landslides are also induced by civil engineering projects, small scale localised building and mining. There are high frequencies of damaging landslides during the rainy seasons, due to earthquakes or volcanic activity (Denness 1973; Hermlin 1990; Donnelly 1997a; Donnelly 1997b). Major geological disasters in Colombia, such as the Armero mudflows in 1985 and the Popayán earthquake in 1984, have alerted the government to act in order to mitigate disasters. Government agencies responsible for disaster prevention, mitigation, preparedness, development and regulation are fully aware of the severity of this situation and have implemented a set of measures for risk reduction. For instance, new laws have been established to promote the construction of seismic resistant structures, land regulation, appropriate land use, preservation, geohazards zonation and disaster prevention in higher

risk areas. An act on territorial regulating, in 1997, now requires every urban region to take into account landslide hazards for future developments (Congreso de Colombia 1997) (Table 1).

Table 1. Distribution of population in the mountainous regions of Colombia (total population is approximately 46 millions, after DANE 2005)

	Inhabitants (millions)	Proportion of total population (%)
Urban zones	21	45.6
Rural zones	7.8	16.8
Total	28.8	62.4

PHYSIOGRAPHICAL AND TECTONIC SETTING

Colombia is dominated by three, north-south trending, mountain belts; the western central and eastern Andean Cordilleras. The north-south trending, fault controlled Magdalena and Cauca valleys divide the three principal ranges. The basement consists of polymetamorphic schists, known as the Palaeozoic Schist Belt. Colombia is traversed by several active, major crustal fault systems, with a general south-west to north-east trend direction. These faults are related to the tectonic setting and evolution of Colombia since the entire country is situated in the Nazca-Southamerica-Caribe plate convergence zone. The relative movement of these three plates, during the Cenozoic period, resulted in the generation of the three cordilleras (Pardo & Molinar 1987). The relative movements along these faults are responsible for numerous moderate to high magnitude earthquakes, which may subsequently induce landslides on steep slopes. Furthermore, the faults increase landslide susceptibility due to the increase in rock mass discontinuities and higher weathering rates in faulted bedrock. The Central Cordillera is the oldest and highest of the three mountain ranges, it reaches up to 5750 m above sea level (mASL). Geologically, it is the most complex comprising Tertiary continental sediments, Cretaceous intrusive and extrusive volcanic sequences and Palaeozoic schists. These have been subjected to multiple phases of folding, faulting, metamorphism and intrusion by batholiths and suites of dacite porphyries (McCourt & Feniniger 1984; McCourt 1984) (Figure 1).



Figure 1. Map showing the Andean Cordilleras and landslide sites referred to in this paper.

In general, the Central Cordillera comprises the Mesozoic-Cenozoic orogenic belt on its western flank and a major Palaeozoic belt to the east (Aspden *et al.*, 1987). Mesozoic detritus and volcanoclastic sediments are intruded by granodiorite stocks and batholiths of Jurassic and Paleogene age (Aspden, McCourt & Brook 1987). In the Late Pliocene and Early Pleistocene, the basement was overlain by pyroclastic and volcanoclastic deposits, and andesitic-dacite lavas. The most significant geological structures in the region are the Romeral fault complex on the western flank (Cretaceous), the Magdalena fault complex on the eastern flank and the Palestina fault complex within the Central Cordillera (Palaeozoic). These major structures are NNE dextral slip related. The Ibagué batholith (Jurassic) was emplaced within the Mesozoic rocks of the Central Cordillera. The Palestina fault complex, displaces rocks of Cretaceous age, and is interpreted to be older than the other fault systems. The Eastern Cordillera consists of Cretaceous sedimentary rocks including shales, mudstones and limestones. Metamorphic, granitic and pyroclastic rocks of Paleozoic age, crop out in the north east of this belt. In many places these are covered by more recent glaciofluvial and colluvial deposits (Montero 2003; Montero, Cortes & Ojeda 2002). The Western Cordillera is dominated by interbedded sequences of sedimentary and igneous rock, in some places covered by talus deposits.

Climate

Colombia is located within the 'Intertropical Convergence Zone' which controls rainy seasons. The region is also affected by the El Niño and La Niña climatic phenomena. There is a recorded increase in landslide events, in May and November, which can be related to the rainy seasons (Gonzalez-Garcia & Mayorga-Márquez 2004). The western (Pacific Ocean) flank of this Cordillera is one of the most humid parts of the country with annual rainfall that can reach 9000 mm; this region often experiences high frequencies of landslides.

GENERAL OVERVIEW OF LANDSLIDES IN COLOMBIA

Colombia has been divided into five landslide hazard zones, by the state geological survey of Colombia INGEOMINAS (Instituto Colombiano de Geología y Minería). These zones provide a relative indication of landslide susceptibility, range from very high to very low hazard (INGEOMINAS 2002; Montero & Ojeda 2005) (Figure 2).

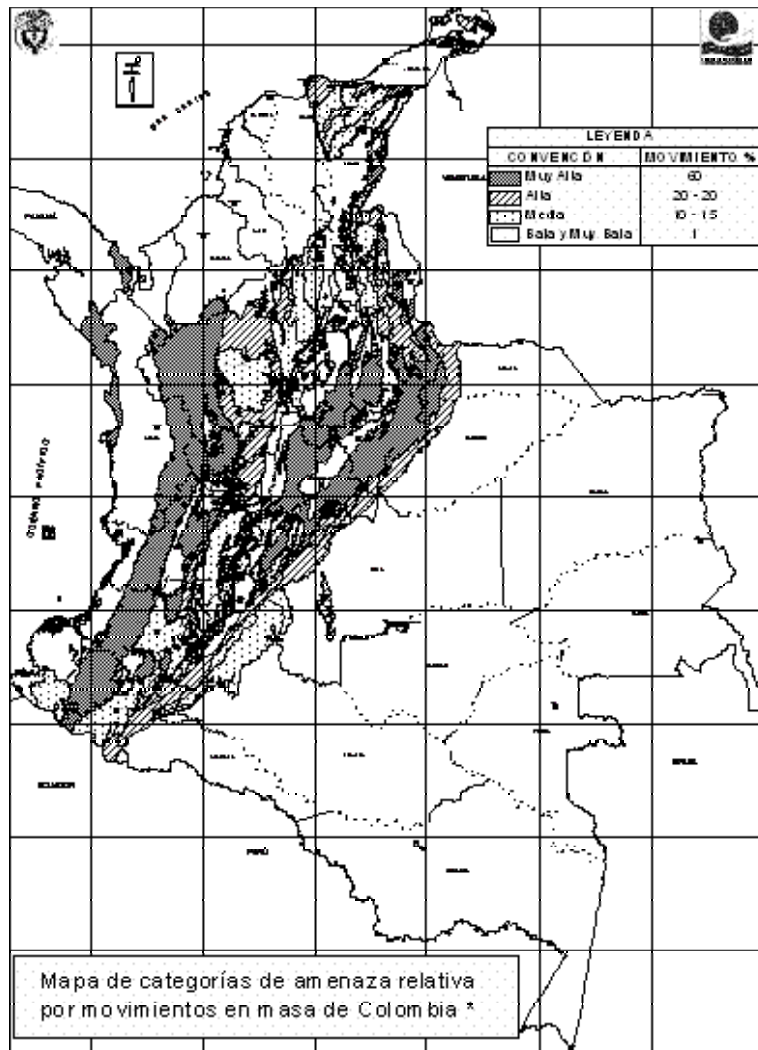


Figure 2. Landslide hazard zonation for Colombia (INGEOMINAS 2002).

Landslide inventory

Landslide hazard zones were identified according to the attributes given in tables 2 and 3. This study was based on a landslide inventory of approximately 1000 landslides throughout Colombia. About 60% of the landslides were found to occur in the 'very high' hazard zones and around 25% in the 'high' hazard zone. It was also found that 90% of landslides which were investigated were located along geological fault systems and that the most frequent trigger was rainfall (Montero & Ojeda 2005). Furthermore, 28% of all towns and cities, and 65% of the country's road network were adversely affected by landslides. The majority of the landslides investigated were found to be active, or dormant, and many were reactivated by human activities, especially those situated along highways, in areas of deforestation, in regions of poor land management or by the building of homes into steep mountain slopes.

Table 2. Factors influencing landslides in Colombia.

Factor	Description
Lithology	Interbedded or weak sedimentary sequences
Weathering	Intense weathering of saturated, regolith
Structure	Regional trends and patterns associated with faults

Table 3. Types of landslide triggers in Colombia.

Factor	Description
Rain	Increase in landslides in rainy season
Seismicity	Tectonic fault corridors
Volcanic	Recent activity
Human	Deforestation, land use management and mining

Records of fatalities due to landslides

The actual number of deaths caused by landslides in Colombia is not known. Records of deaths related to landslides have been estimated by the Colombian Bureau for Disaster Relief (DGPAD 2005) for the period 1993 to 2004. An estimated 97 landslide events took place each year, during this time period, with 59 deaths per year (Figure 3).

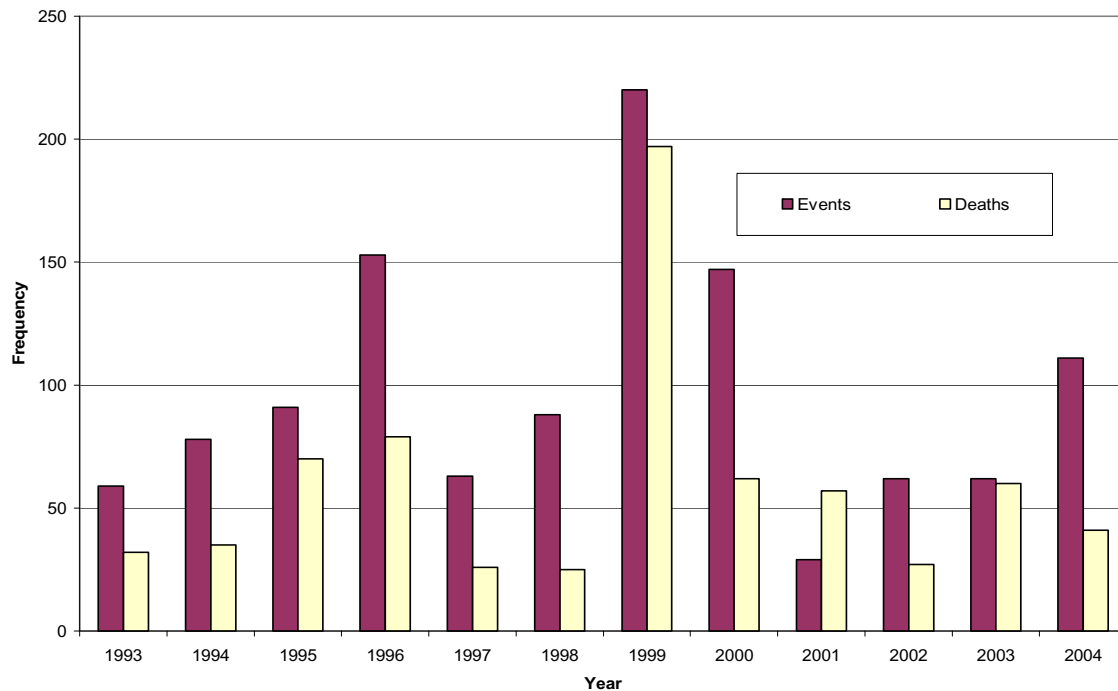


Figure 3. Number of landslides and deaths in Colombia, from 1993 to 2004 (source, Colombian Bureau for Disaster Relief, DGPAD 2005).

Over a longer time period, from 1912 to 1997, it was found that there were 32 landslide events per year and 73 deaths (Montero & Ojeda 2005). However, the death toll of annual deaths rises to 340 per year if the 1985 Armero lahar is taken into account. Landslides account for almost half of all geological hazards in Colombia, which may be regarded as catastrophic events (Figure 4).

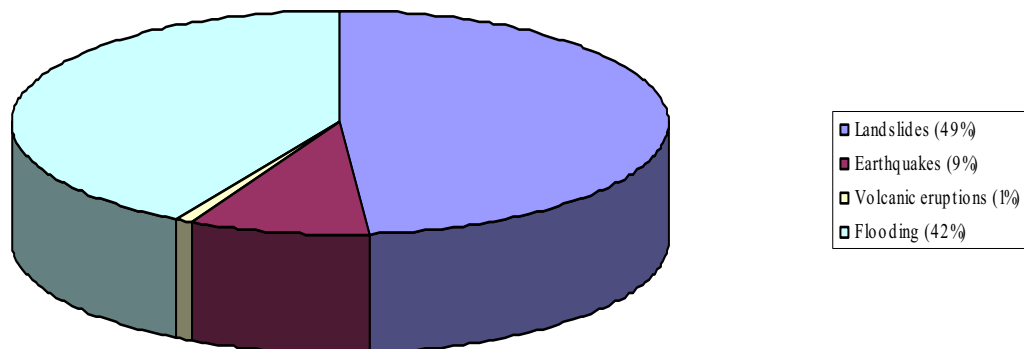


Figure 4. Distribution of Catastrophic Events in Colombia, 1920 to 1990 (source: INGEOMINAS)

EXAMPLES OF LANDSLIDES FOR SOME PLACES IN COLOMBIA

Bogotá

Bogotá, the capital city of Colombia, has an estimated population of approximately 7 million. Most of the inhabitants have settled on ancient lacustrine deposits at about 2600 mASL, now underling most of the city. This forms a basin which is surrounded by mountainous terrain with high relief, belonging to the Eastern 'Andean' Cordillera. The urban development of the city has progressed from the south, in a northerly direction along the flanks of the mountains. These areas of higher relief are composed of sedimentary rocks, which are highly fractured and covered by thick colluvium, alluvium, river terrace sand and gravels, fluvio-glacial and fan deposits. Natural denudation processes, mining (for construction material and brick manufacturing), have given place to potentially unstable ground conditions. These have been subsequently occupied by human settlements (Figure 5).

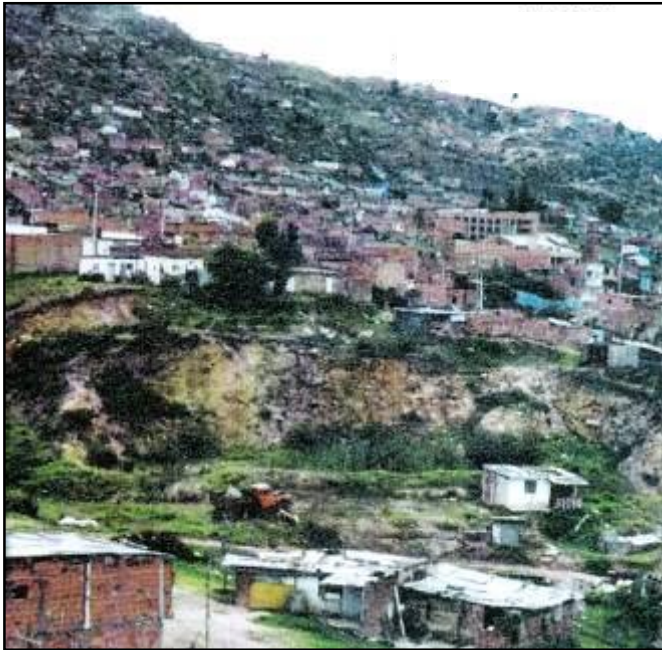


Figure 5. Crowded and poorly planned settlements on steep hill slopes around Bogotá (Gonzales 2005).

Landslides are naturally common on these slopes and are exacerbated by the activities of man, especially where slopes have been over steepened by excavation and tipping. A landslide hazard evaluation investigation, carried out by INGEOCIM Ltd (INGEOCIM-UPES 1998) was implemented by the City Disaster Prevention Office (DPAE 1999) to establish a long term prevention and mitigation development plan. This generated a hazard map and identified about 11% out of the total areas of high relief around Bogotá to be within a high risk hazard zones; 61.3% of these high relief areas were situated in the medium risk hazard zone and 27.7% in the low hazard zone (Gonzalez 2005) (Figure 6).

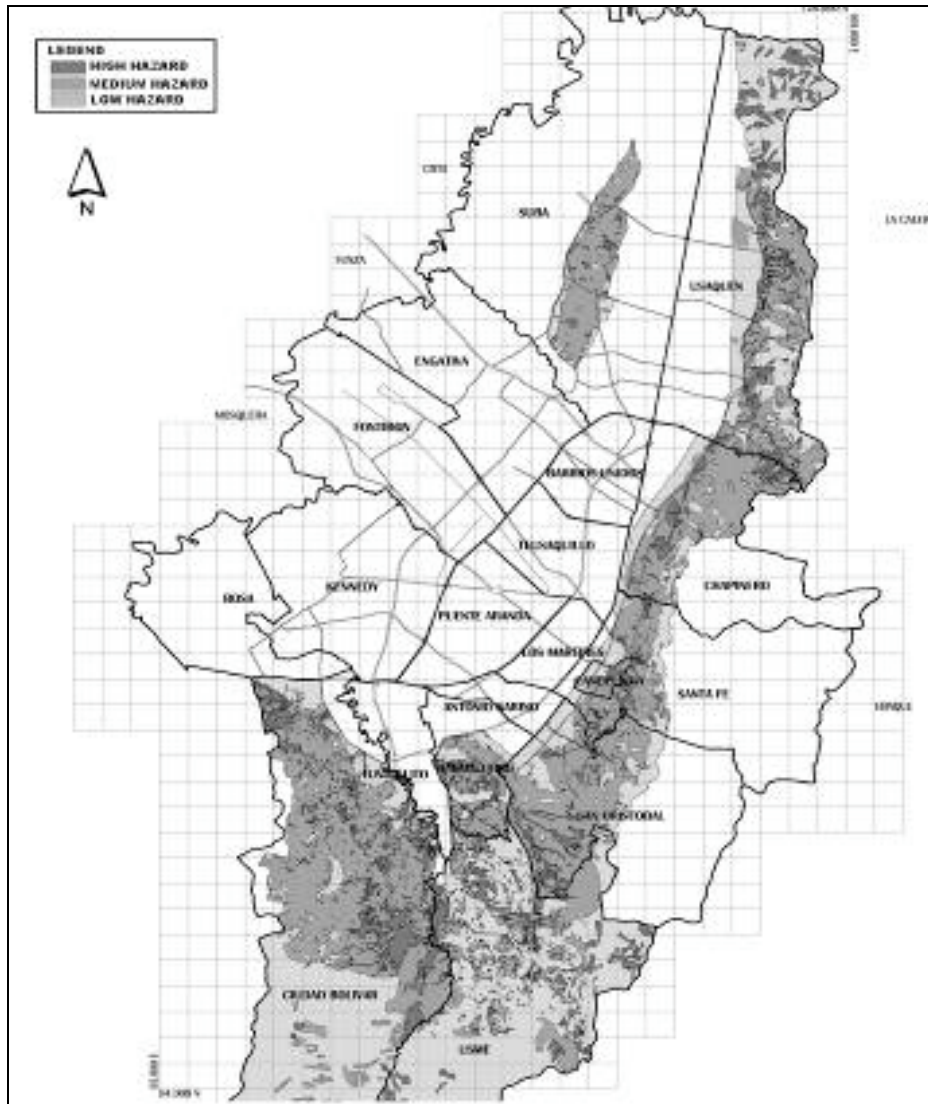


Figure 6. Landslide hazard map of Bogotá (DPAE 1999).

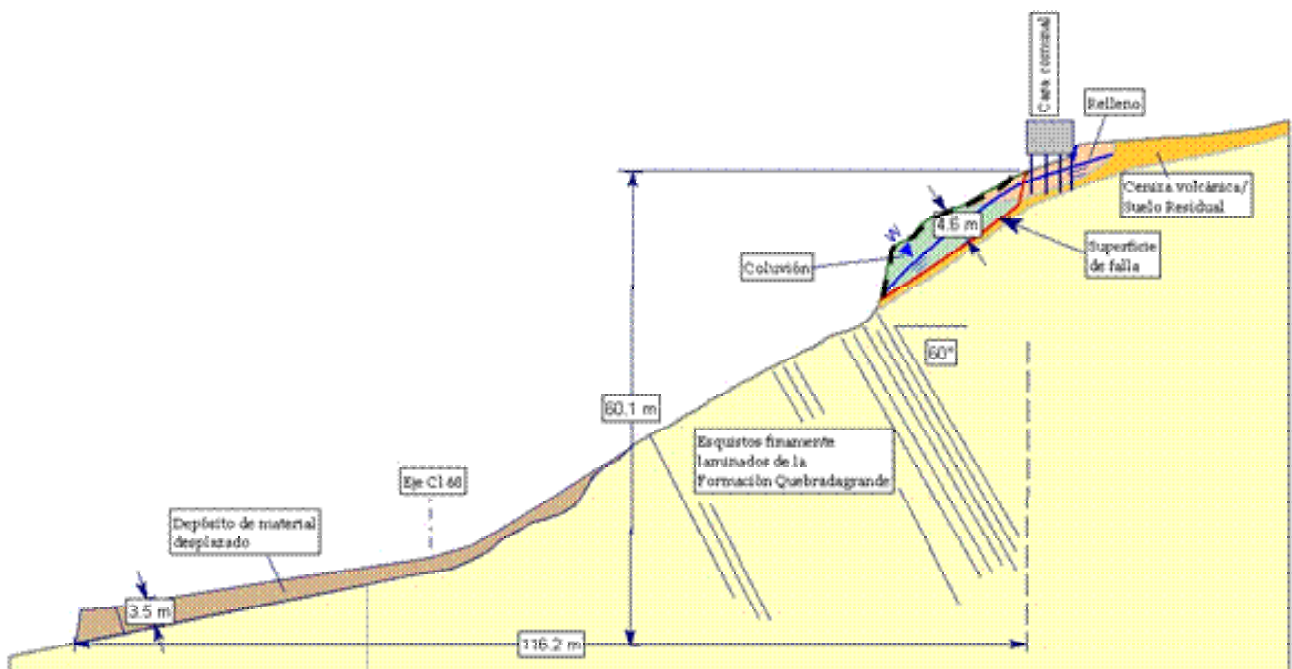


Figure 7. Cross section of slope depicting slope condition before (green) and after landslide (brown) in La Sultana landslide (Ojeda & Barreto 2005).



Figure 8. La Sultana (Manizales) landslide looking down slope (Photograph: R. Mendez)

Manizales

This city of about 700,000 inhabitants is located in the western flank of the Central Cordillera at approximately 2150 mASL. The city is dominated by steep slopes and high relief. Many of the houses, buildings, roads and infrastructure have been constructed by cutting into, or filling slopes. Weak, unconsolidated, volcanic ash covers many parts of the city and in places this reaches 50 m thick (Aguirre 1993). This covers older, but geologically ‘recent’ volcanic and volcanoclastic bedrock. Manizales experiences anomalously high rainfall. In 2003, rainfall registered a maximum 24 hours ‘peak of precipitation’ since 1970. At least 200 landslides were triggered by the rainfall. The most disastrous landslide occurred in the neighborhood of La Sultana, at mid-day, on 4 December 2003. This was a relatively small, translational slide-debris flow, about 2400 cubic metres in size, which traveled a horizontal distance of 73 meters. The landslide killed 16 people, destroyed 8 houses and affected another 46. The slipped mass included a component of the deposit from a former landslide, composed of volcanic ashes, which became displaced along the contact with the underlying schist bedrock. This event was triggered by an increment increase of pore water pressure due to rainfall infiltration and runoff, emerging on the upper parts of the slope (Ojeda & Barreto 2005) (Figure 7 and Figure 8).

Armero and Nevado del Ruiz

Colombia has at least 20 volcanoes, of which 12 are known to be active. These are mainly located in the Central Cordillera. Areas up to one hundred kilometres around these volcanic zones are covered by thick deposits from ‘ancient’ eruptions and ‘recent’ ash falls. Nevado del Ruiz Volcano, close to the town of Manizales, erupted in 1985. This generated a lahar that buried the town of Armero. Nevado del Ruiz Volcano is located at the northern end of the Andean volcanic chain in the Cordilleran Central of Colombia, approximately 100km west of Bogotá. It is a composite strata-volcano which rises approximately 5390 m above sea level. The summit of Nevado de Ruiz rises more than 5000 m above the Rio Magdalena valley to the east and approximately 4400 m above the Rio Cauca valley to the west. Prior to the 1985 eruption a 25 cubic kilometres ice cap covered the broad flat summit. The glacier was covered by approximately 2 m of fresh snow and 6-8m of coarse recrystallised snow (firn). The summit crater (Crater Arenas) is situated near the north-east edge of the ice cap. The slopes adjacent to the ice cap were mantled by unconsolidated glacial gravel and pyroclastic deposits, which supported sparse alpine-type vegetation. On 13 November 1985, a plinian eruption occurred from the summit crater. This generated a series of pyroclastic flows which interacted with snow and ice on the summit ice cap. The rapid transfer of heat from the eruption, combined with the seismic shaking generated lahars (hot mud flows) and avalanches of saturated snow, ice and rock debris. The eruption triggered lahars flowed to the west, north and east along the three major drainage systems: the Chinchina, Guali and Lagunillas drainage basins. Within four hours of the beginning of the eruption, these lahars had travelled over 105 km, descending 5100 m, leaving a wake of catastrophic destruction, and obliterating everything in their path. These were the deadliest lahars in recorded history. An estimated 25,000 people were killed or missing, presumed dead, 4420 injured, 5092 homes destroyed, and 210,000 hectares of land buried beneath a blanket of mud. The town of Armero, situated at the mouth of the Rio Lagunillas, 74km downstream from the summit crater, was virtually obliterated and 75% of its inhabitants perished. Additional lahar related fatalities occurred in the Guali and Chinchina valleys. The flanks of the volcano became deeply incised by canyons with near vertical inner walls. Prior to the

eruption the canyons contained large quantities of unconsolidated sediment. Landslides were common throughout the volcanic massif. In one instance a single landslide dammed an approximate 25 m deep lake, which was impounded in the lower Rio Lagunillas canyon. The eruptive history of Nevado del Ruiz is well documented for the Quaternary (Williams 1990a, 1990b) (Figure 9 and Figure 10).

Medellin

Medellin is one of the biggest towns in Colombia, it is the country's second city, after the capital Bogotá, it has a population of about 4 million people. It is situated at the northern part of Central Cordillera at 1500 mASL. The city extends along the Aburra Valley and it is surrounded by mountains that reach at least 3000 mASL. The valley consists of deposits of volcanic ashes, alluvium and colluvium which overlie igneous basement rocks. The serpentinised bedrock is susceptible to intense, tropical weathering, resulting in a thick residual regolith comprising weathered bedrock and soil (Toror 1988). A catastrophic landslide occurred on 27 September 1987 in the neighborhood of Villatina. This was triggered by water leakage from a small, artificial channel located in the upper part of the mountain slopes. This landslide involved the movement of approximately 40,000 cubic metres of residual soil. This killed about 500 people, affected a further 1300 and destroyed 120 houses (Ojeda & Velásquez 1996; INGEOMINAS 2002; Suarez 1997) (Figure 11 and Figure 12).



Figure 9. The Upper Lagunillas valley, close to the summit of Nevado del Ruiz. The Lagunillas valley carried the deadly lahars to Armero. The walls and floor of the valley were scoured and eroded to produce a steep sided canyon. Secondary landslides and rock falls may be observed on the flanks of the over steepened valley (Donnelly 1997c).



Figure 10. Armero covered by the lahar; the mouth of the Lagunillas river valley in upper part of the photograph (INGEOMINAS 2002)

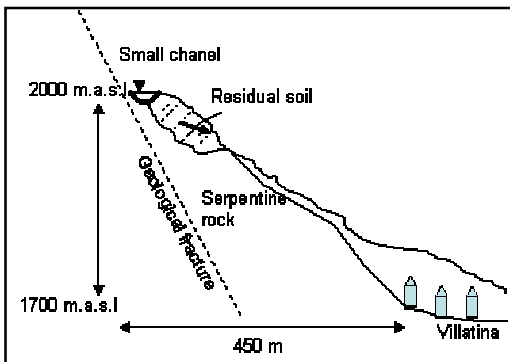


Figure 11. Schematic cross section to illustrate the Villatina landslide, Medellin (Modified after Suarez 1997).



Figure 12. The Villatina landslide, Medellin, which killed 500 people in 1987.

Bucaramanga

Bucaramanga is a city of about 1.5 millions inhabitants and is located in the Eastern Cordillera, in the north-east of Colombia at 1000 mASL. The geomorphology of the region is strongly influenced by two, intersecting major fault systems, and associated tectonic processes. Lateral movements along these faults have generated a tectonic basin which subsequently became filled with sedimentary deposits. In places alluvial fans, along the valley sides exceed 250 m thick. The alluvial fan deposits consist of four distinct units. The upper part is composed of yellow, redish clayey sand, gravels and silt. This overlies a sandy-clay with interbedded gravel and subrounded boulders up to 800 mm in diameter. This in turn, overlies interbedded clay and sandy silt. The fourth, basal member, crops out throughout the city on roadside cuttings and scarp slopes. This is known as the 'Organos member' and is composed of boulders and gravels within a sandy clay matrix that is easily eroded by surface run-off generating gullies and erosion channels. Prolonged heavy rains, from 9 to 12 February 2005, resulted in about 142 mm of rain falling in 24 hours. Widespread flooding resulted and this induced at least 1000 landslides. Approximately 5082 houses were destroyed and 39 people killed by mud and debris flows (Castro 2005) (Figure 13 and Figure 14).



Figure 13. Gullying and channel erosion in alluvial fan deposits (Organos member), Bucaramanga (Castro 2005).



Figure 14. Debris flow in Bucaramanga (Castro 2005).

Antioquia

Amaga, Angelopolis, Venecia and Bolombolo are small towns, located in Antioquia, approximately 40 km southwest of Medellin. The region is often locally referred to as the ‘Sinifana Coal Basin.’ The basin is surrounded by a suite of distinct batholiths and metamorphic terrain that form the steep and mountainous ground of the Central Cordillera of the Colombian Andes. Mining has been practised in this region for a period of at least 100 years. This mining has mainly been small-scale, poorly mechanised and restricted to shallow room and pillar workings. Recently, the semi-mechanisation of some mines has enabled coal to be extracted by longwall mining methods. This has resulted in subsidence that has caused landslides which have damaged houses, roads and agricultural land. Thick, residual tropical soils and weathered bedrock have facilitated the generation of landslides (Donnelly *et al.* 2001). Where geological faults, affected by subsidence, intersect the valley sides, or have developed near and sub-parallel to slopes, they severely reduce the strength of the rock mass and thick residual soils they intersect. Faults provide a means by which vast volumes of groundwater can be rapidly channelled to the hillside slopes. Many large landslides have developed in association with faults and it appears that they may play an important role in the initiation of first-time slope movements and the reactivation of existing landslides (Donnelly, Perez & De La Cruz 2001)

Páez

On 6 June 1994, the Páez river valley region, in southwest Colombia, experienced an earthquake of magnitude 6.4 Ml. This triggered multiple landslides that generated huge debris flows along the Páez, Mora and San Vicente rivers. The debris flows reached 60 m high in some places, and velocities between 15 to 20 metres per seconds (INGEOMINAS 1994). The landslides were mainly translational slides with thickness between 1.5 and 7.0 m.

Estimated volume of displaced debris was in the order of 318 million cubic meters (Calderón, Avila & Ojeda 1997). This event devastated around 5500 cubic kilometres of land, buried two villages, destroyed almost 1700 houses, 6 bridges and about 100 km of roads. Approximately 900 people were estimated to have been killed (INGEOMINAS 1994; Ojeda *et al.*, 2004) (Figure 15).



Figure 15. A view of landslides and debris flow along Páez River (INGEOMINAS 1994)

CONCLUSIONS

It may often be difficult to obtain up-to-date, reliable information on geological hazards in Colombia. This paper presents a general overview of landslides in Colombia and by the use of case studies draws attention to how, each year, landslides have caused deaths and damage to Colombia's major towns, cities and villages.

Landslides in Colombia account for almost half (approximately 49%) of all natural catastrophic events, exceeding by far those disasters which are caused by flooding (42%), earthquakes (9%) and volcanic eruptions (1%). From 1993 to 2004 alone, there were at least an average 47 landslides and 59 deaths each year. In 1985, the eruption of Nevado del Ruiz volcano, near to the town of Manizales, generated a series of lahars (volcanic mudflows) which buried the town of Armero killing virtually all of its 25,000 inhabitants. This was recorded as one of the world's worst natural disasters of the twentieth century. If these events are taken into account the average number of people killed each year by landslides rises to 340, between 1912 and 1997.

Landslides are naturally occurring geological hazards throughout Colombia caused by a combination of the steep mountain slopes (many of the country's major towns are situated in the Andean Cordilleras), undulating terrain, thick regolith and soil cover (caused by deep tropical weathering), highly deformed, fractured and tectonised bedrock, prolonged tropical rainfall and earthquakes.

Landslides may also be induced, or exacerbated, by the activities of man. The most common events are caused by cutting into slopes, drainage of water onto slopes, small scale localised building, major civil engineering construction (such as highways, dams, reservoirs, bridges, buildings), mining and mineral abstraction, mining subsidence, poor land management, loading of slopes by the tipping of domestic and industrial waste and deforestation.

In general there are increases in destructive landslides during 'the rainy season' following prolonged freak rainstorms or simultaneous with moderate to high magnitude earthquakes.

The apparent increase in landslides in the past few decades may be attributed to, firstly; increased awareness and therefore increased reporting and recording of landslides, and secondly (but more important); increasing migration of the population to the towns and cities due to poverty, security and political reasons. This results in the colonisation of, and building on, steep upper and middle mountain slopes because the valley floors tend to be already occupied, or the land prices are too expensive.

The problems caused by landslides throughout Colombia are recognised and appreciated. The Colombia Government, in conjunction with geological expertise (such as INGEOMINAS, the Colombian Geological Survey; academics in universities and consultants) implement landslide monitoring, mitigation and stabilisation programmes. Furthermore, since 1997, legislation has been set up to promote safer urban developments (this legislation was influenced after the 1984 Popayán earthquake). These include improved methods for mining subsidence prediction, better building control, improved engineering practice and communications. Landslide hazard zonation, risks and vulnerability maps are now available for major urban areas, such as Bogotá, Medellín and Bucaramanga.

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