SHIA_Landslide:

Developing a physically based model to predict shallow landslides triggered by rainfall in tropical environments

by

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*"...even if it were the case that the natural laws had no longer any secret for us, we could still only know the initial situation **approximately**. If that enabled us to predict the succeeding situation **with the same approximation**, that is all we require, and we should say that the phenomenon had been predicted, that it is governed by laws. But it is not always so - it may happen that small differences in the initial conditions produce very great ones in the final phenomena. A small error in the former will produce an enormous error in the latter..."*

Henri Poincaré (1854-1912)

Initial conditions (Science and Method, 1914, p.68)

Cover photograph: Landslides triggered by rainfall in the September 21, 1990 rainstorm in La Arenosa catchment, to the northern of the Colombian Central cordillera taken from Mejía & Velásquez (1991).

SHIA_LANDSLIDE: DEVELOPING A PHYSICALLY BASED MODEL TO PREDICT SHALLOW LANDSLIDES TRIGGERED BY RAINFALL IN TROPICAL ENVIRONMENTS

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To my brother, you will be with me forever, I love you.
For my son, thank you for giving meaning to my life again.

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Abstract

Landslides are one of the main causes of human and economic losses worldwide. Therefore, landslide hazard assessment and the capacity to predict these phenomenon has been a topic of great interest within scientific community for implementation of early warning systems. Although, several models has been proposed to forecast shallow landslides triggered by rainfall, no model has yet incorporated geotechnical factors into a complete hydrologic model, one that simulates the storage and movement of rainwater through soil profile, providing multiple components that can be calibrated along with measurements of surface discharge and perched water table fluctuation. The present paper develops a conceptual and physically based model, named SHIA_Landslide, for shallow landslide prediction triggered by rainfall in tropical environments and complex terrains supported by geotechnical and hydrological aspects occurring over a basin wide scale. SHIA_Landslide is an original and significant contribution that offers a new perspective to analyses shallow landslide processes, incorporating a full and comprehensive distributed hydrological tank model that includes water storage in the soil, coupled with a geotechnical and classical analysis of infinite-slope stability under saturated conditions. SHIA_Landslide can be distinguished by: (i) the capacity to capture the surface topography and its effects concerning the overland flow and the concentration cells of subsurface flow; (ii) it uses DTM to establish the relationships among cells, geomorphologic parameters, slope angle, direction, etc., needed for the model; (iii) rainfall dataset can be incorporated with the spatial and temporal resolution preferred and available; (iv) continuous simulation for long periods of rainfall data (years) or event simulations for specific storms; (v) consider the effect of horizontal and vertical flow; (vi) is at a basin scale; (vii) includes a hydrologically complete water process that permits perched water table calibration. All these conditions of SHIA_Landslide make the model as an interesting tool to be implemented in early warning system, combined with real-time rainfall monitoring and dissemination of alerts and communication.

Keywords: Landslides, rainfall, physical model, tropical environments.

Resumen

Los deslizamientos son una de *las* principales causas de pérdidas humanas y económicas alrededor del mundo. Por lo que la evaluación de la amenaza por deslizamientos, y la capacidad de predecir estos fenómenos ha sido un tema de gran interés e la comunidad científica para la implementación de sistemas de alerta temprana. Aunque diferentes modelos se han propuesto para el pronóstico de deslizamientos superficiales detonados por lluvia, ningún modelo ha incorporado elementos geotécnicos en un modelo hidrológico completo, que simule el almacenamiento y el movimiento del agua lluvia a través del perfil del suelo, proporcionando nuevas variables que pueden ser calibradas con mediciones como caudales y flujo subsuperfical. En el presente trabajo se desarrolla un modelo conceptual y con base física, denominado SHIA_Landslide, para la predicción de deslizamientos superficiales detonados por lluvias en ambientes tropicales y terrenos complejos, soportado en aspectos geotécnicos e hidrológicos a escala de cuenca. SHIA_Landslide es una contribución original y significativa que ofrece una nueva perspectiva al análisis de los procesos de deslizamientos superficiales, que incorpora un modelo hidrológico distribuido de tanques que incluye el almacenamiento del agua en el suelo, con un análisis geotécnico y clásico de estabilidad de talud infinito en condiciones saturadas. SHIA_Landslide se distingue por: (i) la capacidad de capturar la topografía de la superficie y sus efectos sobre el flujo superficial y las áreas de concentración de flujo subsuperficial , (ii) utiliza el DTM para establecer las relaciones entre las celdas necesarias para el modelo como los parámetros geomorfológicos, ángulo de inclinación, dirección, etc; (iii) la precipitación puede ser incorporado con la resolución espacial y temporal preferida y disponible; (iv) simulación continua durante largos períodos de datos de lluvia (años) o simulaciones de eventos para tormentas específicos; (v) considera el efecto de flujo horizontal y vertical; (vi) es en una escala de la cuenca; (vii) incluye un modelo hidrológico completo que permite la calibración del flujo subsuperficial. Todas estas condiciones hacen de SHIA_Landslide una herramienta interesante para ser implementado en un sistema de alerta temprana, combinado con el monitoreo en tiempo real de la lluvia y la difusión de alertas.

Palabras clave: deslizamientos, lluvia, modelo físico, ambientes tropicales.

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INTRODUCTION

In tropical and complex terrains, landslides are one of the main causes of human and economic losses worldwide (Schuster, 1996; Sidle & Ochiai, 2006). Expanded land urbanization is increasing the vulnerability to landslides due to high concentration of population and lifelines along areas of higher landslide susceptibility. Therefore, landslide hazard assessment and the capacity to predict these phenomenon has been a topic of great interest to the scientific community (Aleotti & Chowdhry, 1999; Chacon et al., 2006; Godt et al., 2012; Cepeda et al., 2009).

In regards to the magnitude of the landslide issue, numerous studies have been developed in recent years and have increase the understanding of the causes involved in these morphodynamic processes. However, because of the complexity related to landslide occurrence, there is still great uncertainty in predicting their occurrence. Landslides are caused by a variety of geologic, and anthropologic factors – compelling researchers to take an interdisciplinary approach in order to predict them, integrating concepts of soil mechanics hydrogeology, and geomorphology (Crosta & Frattini, 2008). Landslide hazard is a function of slope susceptibility, which depends exclusively on conditional factors, and the frequency and magnitude of the phenomenon, which is related to triggering factors (Brunsden, 2002). Some authors consider that the biggest challenge for landslide investigation is the need to predict landslide occurrence in terms of time, thus it is essential to understand and characterize their triggering factors (Aristizábal & Yokota, 2006).

Although multiple causes play an important role on landslide occurrence, usually just a single factor becomes the triggering element, generating an almost immediate response, which is to mobilize slope materials, either by the rapid increase stresses or by reducing shear strength (Wang & Sassa, 2003). This triggering factor is generally rainfall, earthquakes, volcanic eruptions or human activities. In tropical environments and complex terrains like the Colombian Andes, a high percentage of these landslides are triggered by heavy or prolonged rainfall (Aristizábal & Gómez, 2007).

Rainfall induced shallow landslides are a common problem in many tropical areas covered by thick residual soils and subjected to tropical rainfall regimes. The modeling of shallow landslide triggered by rainfall has great interest within scientific community for implementation of early warning systems –EWS- (Caine, 1980; Montgomery & Dietrich, 1994; Finlay et al., 1997; Crosta, 1998; Terlien, 1998; Crozier, 1999; Polemio & Petrucci, 2000; Iverson, 2000; NOAA-USGS, 2005; Restrepo et al., 2008; Larsen, 2008). The warning of the community of shallow landslide occurrence can be provided based on landslide modeling combined with rainfall forecasts and real-time detection.

A comparative analysis of the frequencies and impacts of various natural disasters by the International Early Warning Programme (2005) and Guzzetti et al. (2005) have shown that overall damages arising from natural disasters occur more often than the capacity for society to prevail via their economic resilience. Therefore, new approaches must focus on land use planning and developing and implementing early warning systems in order to minimize loss of life and infrastructure. Although EWS are currently considered one of the most practical and effective measures for disaster prevention, just few EWS for shallow landslides have been implemented around the world based on empirical thresholds, and there is not any EWS supported by physical models. Much more work need to be carried out on this subject to reduce human and economic losses.

Most of the models proposed for shallow landslide prediction show very complex relationship with a great number of input parameters, or very simple functions letting out fundamental variables which play an important role on this subject. Furthermore, all these models available are applied just for very special environmental conditions that do not allow adjusting them to particular rainfall and terrain complexities such as the Colombian tropical Andes.

The present research project aims to develop a conceptual and physically based model for shallow landslide prediction triggered by rainfall in tropical environments and complex terrains supported by geotechnical and hydrological aspects occurring over a basin wide scale, which is named SHIA_Landslide.

SHIA_Landslide is an original and significant contribution that offers a new perspective to analyses shallow landslide processes for a basin scale, incorporating a full and comprehensive distributed hydrological tank model that includes water storage in the soil, coupled with a geotechnical and classical analysis of infinite-slope stability under saturated conditions. With this new conceptual model, it was built a complete algorithms and Fortran code with a graphical user interface that allows users to easily implement the model. Finally the model was tested using a real case in the Colombian Andes validating the high capacity of prediction.

This research was conducted to improve the understanding of the mechanism associated with slope instability and rainfall infiltration in mountainous areas located in rainy environments, where population pressure is leading to the expansion of development into landslide-prone areas.

The model is validated by using a real case which occurred in the La Arenosa catchment on September 21, 1990, more specifically at the Central Cordillera of

Colombian Andes. During this rainstorm, more than 838 shallow landslides were triggered, removing from the steep slopes approximately 1.5 Mm^3 of soil.

SHIA_Landslide is a potential tool for local and regional risk management offices for emergency planning purposes focused on prevention measures, as well for land-use management, since it can be used to evaluate landslide susceptibility of an specific area that is going to be urbanized.

Chapter 1

STATEMENT OF THE ISSUES

1.1 Background

Human and economic losses generated by landslides occur every year in all countries; however, the impact of landslides varies considerably according to the local geological conditions and socio-economic vulnerability (Alcantara - Ayala, 2002; Harp et al., 2009). Although landslides do represent changes in terrain morphology within the natural and continuous geomorphological cycle (Scheidegger, 1998) their occurrence in recent decades has been closely tied to world population growth and consequent urban expansion on susceptible slopes to this type of processes. The urban population of developing countries has increased by 5 times in 40 years and continues to increase rapidly (UN; 2006a; UNFPA, 2007). The greatest landslide losses occur in the Ring of Fire countries (Alcantara - Ayala, 2002). Estimation made by Varnes (1981) indicates that 89% of deaths due to landslides take place in those countries. Data presented by Sidle & Ochiai (2006) pointed that the Asian continent gathers the largest number of landslide victims, where Nepal stands at 186 deaths per year, followed by Japan and

China, with 170 and 140-150, respectively. In Latin America, Brazil holds the first place with an average of 88 people killed per year. In economic terms, Japan is the country most affected by landslides, with an estimated loss of 4 billion dollars annually, followed by Italy, India and the United States with losses ranging from 1 to 2 billion dollars per year (Cruden et al., 1989; Schuster, 1996; Schuster & Highland, 2001; Sidle & Ochiai, 2006).

Although the occurrence of landslides has impacted the Colombian Andes for a long time, specific studies on this subject remark such events only from the 80's (Shlemon 1979). Essentially, these studies evaluated landslide susceptibility through methodologies based on morphological criteria (Chica, 1987; Ingeominas 1990; Florez et al., 1996 & 1997; García, 2004); also, few studies considering rainfall as a triggering factor have been carried out in our country.

Early studies appear at the beginning of the 90’s in Colombia. Paz & Torres (1989) concluded that landslides which occur in the northern Colombian Central Andes take place during normal precipitation events on any day of the year where most landslides occur under normal conditions.

Gómez (1990) studied the relationship between distant rainfall infiltration with deep landslides and the relationship between local storms and shallow landslides in Bucaramanga, through a predictive model of groundwater levels from rainfall. Van Westen et al. (1994) proposed for the Chinchina river basin a bidimensional hydrological model to estimate the position and seasonal fluctuations in water table.

Castellanos (1996) and Castellanos & González (1996, 1997) studied the relationship of rainfall with landslides in Colombia. These authors relate critical rainfall with annual rainfall and critical duration with critical rainfall. Terlien (1997) carried out a hydrological study in volcanic soils in the city of Manizales (Colombia) with the objective to find areas with positive pore pressure, which are defined as locations of potential failure with significant vertical changes in hydraulic conductivity. This analysis revealed that landslides are triggered by daily rainfall above 70 mm, while deep landslides are triggered by antecedent rainfall over 200 mm in 25 days. Terlien proposed a finite element one-dimensional hydrologic model which was calibrated with real data from piezometers and tensiometers installed on the field.

Arango (2000) studied groundwater levels and their impact on the safety factor of slopes in the city of Manizales. The results found by this author show that the best indicators are antecedent rainfall of 30 days with a lag of about one month between the rainfall and landslides, and 15 days between rainfall and rising water table.

Mayorga (2003) studied the relationship of rainfall with landslide occurrence across Colombia, according to previously defined characteristics of landslide types. This work presents a statistical methodology using the linear regression method for building critical rainfall thresholds based on cumulative rainfall and daily rainfall.

Echeverri & Valencia (2004) analyzed landslides that occurred in La Iguaná catchment in the city of Medellín during the period ranging from 1980 to 2001. These authors consider as most important parameter the 15 days preceding the rainfall and the previous 3 days, and they found critical rainfall depths of 60 mm for antecedent rainfall for 3 days and 120 mm for preceding 15 days rainfall.

Vélez et al. (2004) developed a distributed, physically based model for shallow landslide, coupling a hydrological model with an infinite slope stability model. The model defines the flow directions according to watershed morphology. These authors recommended using scales of the order of minutes for rainfall and a spatial resolution of $100m^2$.

Moreno et al. (2006) studied the relationship between rainfall and landslides in the region of Antioquia from the period of 1929 to 1999, and they proposed thresholds as well as regions according to rainfall records of the previous 15 and 3 days. They presented these results as a first approach in order to establish an early warning system for critical areas in Antioquia. These authors highlighted the need to refine the methodology based on real time rainfall data and the need to integrate geomorphologic, hydrologic, geological and anthropic factors.

Aristizábal & Gómez (2007) compared the Aburrá Valley disaster database with the rainy seasons in the period of 1880 to 2007, finding a close relationship between precipitation and landslide occurrence, with a bimodal seasonal cycle with maxima during May and October, and minima during January and July (Figure 1.1).

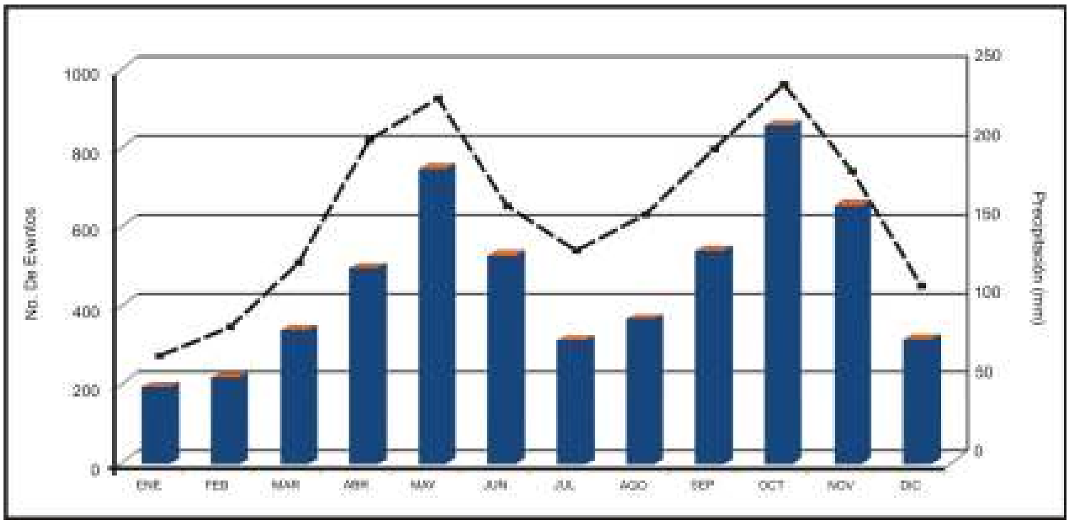

Figure 1.1 Average seasonal cycle of distribution of landslide occurrence in the period 1880 - 2007 (blue bars) versus average monthly precipitation for the Aburrá Valley (black line) (Hormaza, 1991; Saldarriaga, 2003; Aristizábal & Gómez, 2007).

Suárez (2008) analyzed historical records until 2005 for the city of Bucaramanga and proposed landslide alert levels using a decision tree, from which critical thresholds were obtained such as an accumulated rainfall of 150 mm for 15 days, 55 mm rainfall record of 24 hours and magnitudes of 120 mm for a single event.

Aristizábal et al. (2011) analyzed critical rainfall thresholds for landslides forecasting in the Aburrá Valley by means of an empirical procedure, using a database of landslides and precipitation. The results show that the major determinant for the occurrence of landslides in the Aburrá Valley is the antecedent rainfall. Data indicate that landslides used in the analysis occurred for antecedent rainfall over 60 mm for 30 days, 160 mm for 60 days and 200 mm for 90 days.

1.2 The need of a landslide early warning system for the Aburrá Valley - Colombia

The Aburrá Valley, with an area of 1,326 km^2 and a length of 65 km, is located in the northern region of the Central Cordillera of the Colombian Andes. Its approximate geographical coordinates are between latitudes 6° 00" N and 6° 30" N and longitudes 75 ° 15" W and 75 ° 45" W (Figure 1.2). The climatic conditions of the valley are typical of tropical environments, with an average temperature of 22 ° C and relative humidity of 70%. Precipitation has a bimodal distribution, with rainfall peaks during May and October. The mean annual rainfall varies from 1,400 mm in the valley's central part and 2,700 mm in its north and south regions.

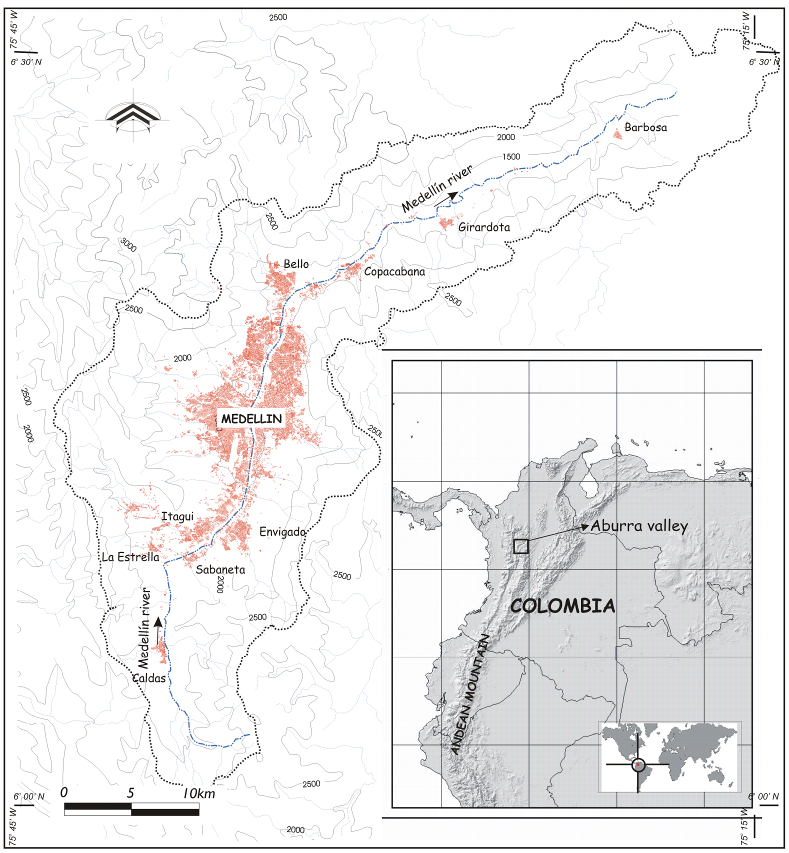

Figure 1.2 Location of the Aburrá Valley. Red color represents urban development.

The Aburrá Valley has an estimated population of 3.3 million inhabitants, where 95% corresponds to its urban population located in only 26% of the territory (340 km^2 of urban area) (Table 1.1). The most populated municipalities, Medellín (2.2 million), Bello

(372 K), and Itagüí (230 K), concentrate much of their population over the valley slopes (DANE, 2005). Such population growth has been extremely fast, as in a century the valley's population has multiplied by 30; from 103,305 people in 1905, the population increased to 3'317,166 in 2005. Since 1950, thousands of immigrants have occupied areas exposed to natural disaster, and even areas that had been impacted by major events.

1.3 Hazard and vulnerability in the Aburrá Valley

The Aburrá Valley has been impacted by a large number of disasters, most of them with a magnitude ranging from small (<10 deaths) to moderate (10 – 100 deaths). According to Aristizábal & Gomez (2007), during the period of 1889 – 2007, 6750 disasters were registered. From this period, 42% of the total events correspond to floods, 35% to landslides, and 15% to forest fires. These three types of natural phenomena account for 92% of all disasters. It means that from 10 disasters that occurred in the Aburrá Valley, 8 are due to floods or landslides, reflecting the close relationship between natural disasters and the hydrometeorological conditions of the valley. It is clear that rainfall events combined with antecedent moisture conditions are driving forces triggering most disasters in Aburrá Valley. However, in the last two decades the recurrences of disasters have increased, as well as human exposure to risk.

Table 1.1 Population and population growth in the Aburrá Valley (Data from DANE, 2005).

CITIES	POPULATION IN 1951	POPULATION IN 1964	POPULATION IN 1973	POPULATION IN 1985	POPULATION IN 2005
Medellín	385,189	772,887	1’151,762	1’468,089	2’223,078
Bello	34,307	93,207	1’29,173	212,861	371,973
Envigado	28,797	61,546	73,057	91,391	175,240
Itagüí	20,151	68,086	103,898	137,623	230,272
Sabaneta	----------	----------	16.518	20.491	44.820
Barbosa	15,507	15,242	22,271	28,623	42,537
Caldas	12,431	25,081	33,630	42,158	67,372
La Estrella	8,698	16,479	23,619	29,918	52,709

Girardota	10,956	12,729	17,879	23,684	42,744
Copacabana	10,720	19,403	29,997	40,309	61,421
TOTAL	526,756	1'084,660	1'601,804	2'095,147	3'317,166

These geological and hydrological hazards, associated to the origin and evolution of the valley, have been recurrent (Aristizábal et al., 2005). However, in the last five decades, the hazard dynamics have changed due to the human occupation on the valleys slopes and flooding plains, causing hundreds of deaths and millions in economic losses. The most populated cities in the valley are the most affected, Medellín with 72% of disasters, followed by Itagüí (5.4%), Envigado (4.9%), and Bello (4.8%). The city located inside the valley with the lowest number of disasters recorded is Barbosa with only 1.2% of the total.

According to Aristizábal et al. (2005) disasters generated by floods are concentrated in Medellín (74%), followed by Itagüí (8.5%), Bello (5.5%) and Envigado (4%). Regarding landslides, 82.4% of them occurred in Medellín, followed by Caldas (3.6%), and Girardota (3%).

Nine moderate disasters with fatalities ranging from 11 to 100 have been recorded in the Aburrá Valley, as well as two events classified as major disasters, with more than 100 deaths, which correspond to (i) the Media Luna landslide that occurred on July 12, 1954 with an outcome of more than 100 people dead, from which 77 had their bodies found and an undetermined number were missing of approximately 70 people, and (ii) Villatina landslide on September 27, 1989, although it has never been possible to determine the exact number of victims, a number of approximately 500 people is considered for this matter, where only about 200 bodies were rescued.

Landslides verified in the Aburrá Valley are mainly soils slips and debris/mud flows (Table 1.2). Some of the most memorable landslides due to their great impact are:

Rosellon (1927), Media Luna (1954), Santo Domingo Savio (1974), Villatina (1987), La Cruz (2007), El Socorro (2008), El Poblado (2008), and La Gabriela (2010).

1.4 Risk condition of the Aburrá Valley

The Aburrá Valley still lacks rigorous databases related specifically to the assessment of damages and economical losses by disasters. According to partial results shown by Aristizábal & Gomez (2007) using a disaster database named DesInventar and developed by LA RED (La Red de Estudios Sociales en Prevención de Desastres en America Latina), the disasters recorded have left a tragic toll of 1,390 deaths during the last century, most fatalities generated by landslides (74%) and flash floods (13%). Although floods are the most recurrent disaster, they represent only 5% of the total fatalities. The number of homes impacted is mainly associated to flooding (53%), followed by landslides (33%), and the highest proportion of people impacted is in the city of La Estrella, which is 41% followed by Medellín with 28%.

Table 1.2 Main landslides occurred in the Aburrá Valley (Hormaza, 1991; Saldarriaga, 2003; Aristizábal & Yokota, 2006). Landslides in 1954, 1974, 1987, and 2010 have been the most deadly disasters.

PLACE	DATE	LANDSLIDE TYPE	DEATHS
Rosellón (Envigado)	18 June 1927	Mudflow	22
Media Luna (Santa Elena)	12 July 1954	Mudflow	>100
La Manguala (S.A. Prado)	25 June 1973	Debris slide	13
Santa Domingo (Medellín)	29 September 1974	Mudflow	>70
Medellín	4 February 1975	Landslide	18
San Antonio (Medellín)	20 October 1980	Debris flow	>18
Santa Maria (Itagüí)	23 November 1984	Debris slide	10
Villatina (Medellín)	27 September 1987	Mudflow	>500
El Socorro (Medellín)	31 May 2008	Complex rotational slide	27
El Poblado (Medellín)	16 November 2008	Complex rotational slide	12
La Gabriela (Bello)	5 December 2010	Complex rotational slide - debris flow	84

Landslides alone are responsible for 1,030 fatalities and huge economic losses. Aristizábal & Gómez (2007) reached a figure of a minimum value of US$10 million for the period concerning 1880 to 2007 and using just the information.

In regards to Medellín, a total of 29,174 households are located in areas of high risk, equivalent to 112,697 people or 4.9% of the total households of the municipality. For the rest of the Aburrá Valley, recent studies have showed that there are 16,847 homes in high risk areas, which corresponds to 62,057 inhabitants (UNal, 2009). These data, together with the results obtained in Medellín in 2005, reveal a total of 174,384 people located in high risk areas, which is equivalent to 5.1% of the total population (Table 1.3).

Table 1.3 Homes and population located in high risk areas (UNal, 2009). 5% of Aburrá Valley inhabitants are located on high risk areas.

MUNICIPALITIES	HIGH RISK POPULATION	HIGH RISKHOMES
Medellín	112,697	29,174
Barbosa	3,646	961
Bello	21,391	5,381
Caldas	2,357	614
Copacabana	4,345	1,172
Envigado	6,856	2,260
Girardota	457	123
Itagüí	17,954	4,942
La Estrella	4,489	1,199
Sabaneta	562	195
TOTAL	174,754	46,021

1.5 The target area for the implementation of the model

Considering spatial extension, human intervention and the lack of reliable landslide database concerning the Aburrá Valley, a detailed search of landslide databases related to watersheds in tropical and mountainous terrains was carried out. Only two landslide cluster events were found in the literature referring to the Antioquia region: La Arenosa, in September 1990, and Tarazá, in 2007. However, only the La Arenosa case was devoted the attention of several detailed studies and an undergraduate thesis, in which a partial landslide inventory was made.

According to these elements, the La Arenosa catchment was selected for the implementation of the model. La Arenosa is located 160 km to the east of the Aburrá

Valley, on the southeaster side of the Central Cordillera in the Antioquia region. The catchment is part of the upper San Carlos River Basins, and it is formed by the confluence of the La Arenosa and Betulia rivers, with an extension of 9.91 km^2 (Figure 1.3).

Elevation ranges between 1,000 m and 1,900 m a.s.l. The basin is highly dissected with hillslope lengths at the order of 40-60 m.

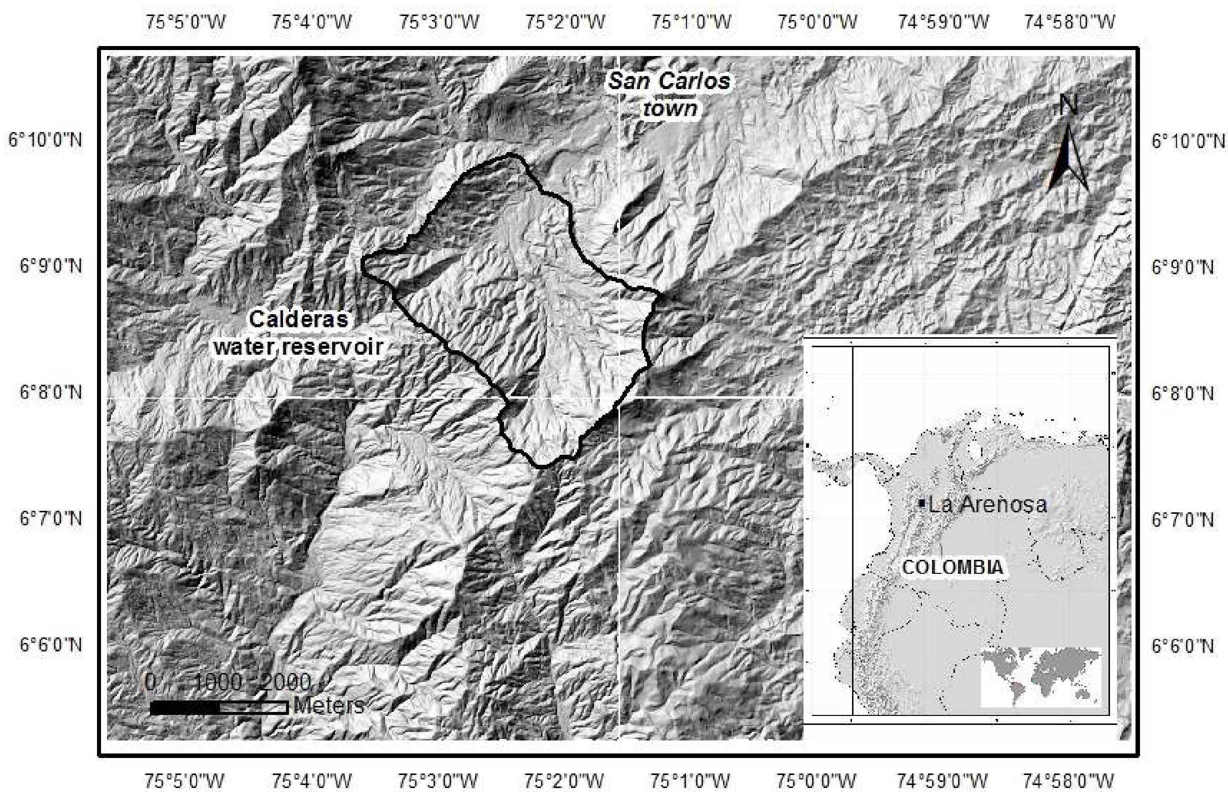

Figure 1.3 Location of the La Arenosa catchment, in the southeastern side of the humid tropical and complex terrains of Central Andean Cordillera in Colombia.

The area has a tropical humid climate with a mean annual precipitation of 4,300 mm and a mean annual temperature of 23° (IGAC, 2007a). The precipitation regime is dominated by high variability at both interannual and interseasonal scales (Figure 1.5). Monthly rainfall distributions reveal an evident seasonal pattern, with a clear difference between the rainy season that extends from September to November, and from March to May, and the dry season with a minimum of rainfall level in July.

Figure 1.4 shows the general topography and the distribution of slope gradients in the Territory. Most of the land area has slope angles ranging from 20 to 40 degrees.

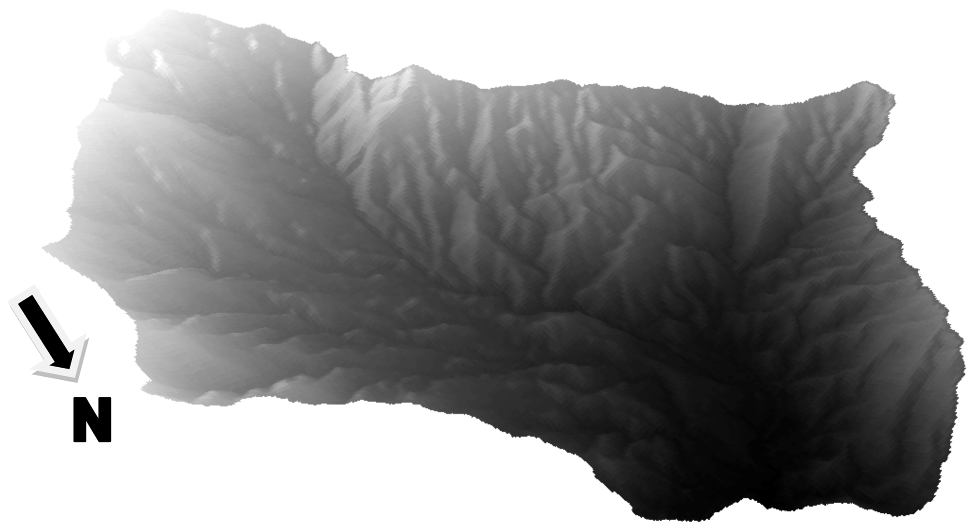

Figure 1.4 General topography of the La Arenosa catchment. The basin is highly dissected with steep hillslopes.

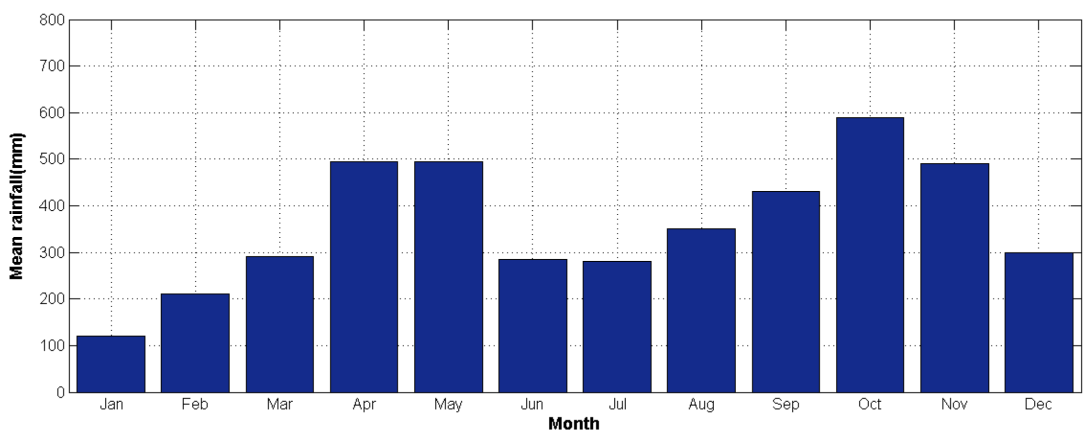

Figure 1.5 The average monthly accumulation of rainfall is characterized by a bimodal distribution, with maximum peaks in May and October (average monthly precipitation in millimeters) (Mejía & Velásquez, 1991).

Granitic sandy residual soil covers the hillslopes, except for narrow ridges or steep slip scars with bedrock exposures. The majority of the study area is covered with crops and pasture.

The geology of the study area consists of residual soils from granodiorite rocks covered in the gently sloping areas with slopes and fluviotorrential deposits, with a depth ranging from 3 m to 20m. Its dominant, granitic component is grey and medium to coarse-grained, and consists of cream or pale yellow feldspar, smoky quartz and smaller proportions of reddish-brown biotite and dark hornblend.

These rocks have been severely weathered in situ. The progressive spheroidal decomposition of the granite has been rapid and extensive, with an average weathering depth of 30 m and is primarily due to chemical decomposition under the humid tropical climate (Mejía & Velásquez, 1991).

The saprolite is fairly well graded, being sandy silt to silty sand in texture with some gravel and small amount of clay. Relict joints of the parent rock are preserved in the saprolite zone, and can significantly alter the observed hydraulic conductivities of the surrounding soil matrix (INTEGRAL, 1990).

The deposits are matrix supported and formed by granitic boulders and residual soils and vegetation debris. About 15% of the land area of the territory is covered with colluvium. Colluvium generally accumulates at footslopes or in gullies at upper levels. These deposits have resulted from landslide which took place in the geological past and are usually poorly consolidated with high cobble-boulder content, and abundant natural soil pipes (Mejía & Velásquez, 1991).

1.6 The September 21, 1990 rainstorm in the La Arenosa catchment

A short duration, high intensity rainfall event impacted the basin of La Arenosa on 21 September 1990. In less than 3 hours a precipitation of 208 mm fell within the study area, triggering many landslides (Figure 1.6). The September 21, 1990 event is unique considering the huge number of failures that took place (Figure 1.7).

During this event, the population was strongly affected, 20 people were killed and 260 had to be evacuated, 27 houses were destroyed and 30 others were damaged, several bridges and more than 100 m of highway were ruined. The Calderas Hydropower Energy Plant was flooded and severely damaged by large blocks carried by La

Arenosa stream (Figure 1.8). Total losses were estimated at more than US $ 6 million (Hermelin et al., 1992).

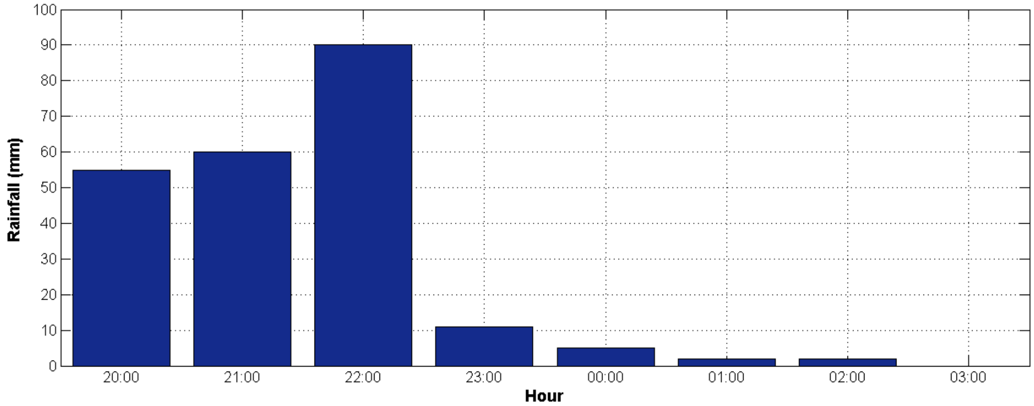

Figure 1.6 Hourly rainfall histogram of the September 21, 1990 rainstorm. In less than 3 hours a precipitation of 208 mm fell within the study area, triggering 808 landslides in La Arenosa catchment (Mejía & Velásquez, 1991).

Prolonged low-intensity precipitation characterized the two preceding months with approximately 621 mm of rain. The statistical analysis of historical rainfall carried out by Mejía & Velásquez (1991) indicated that the event was exceptional, according to the rain gauge of San Carlos, with a return period of 200 years.

Figure 1.7 General view of the La Arenosa upper catchment with distribution of shallow landslide triggered by rainfall in the September 21, 1990 rainstorm (Taken from Mejía & Velásquez, 1991).

Figure 1.8 Landslides material removed from the upper catchment slopes was later carried away by runoff producing torrential floods that destroyed 27 houses (left picture) and severe damaged to the Calderas Hydroelectric Plant of ISAGEN (right picture) (Taken from Mejía & Velásquez, 1991).

The analysis of post event aerial photos and field investigations allowed performing a partial reconstruction of the pattern and characteristics of the landslides in the La Arenosa catchment. INTEGRAL (1990) and Mejía & Velásquez (1991) offer a detailed landslide inventory and a comprehensive description of the landslides triggered during the event, which was obtained through the analysis of post event aerial photos, field investigation and an exhaustive survey. According to the INTEGRAL's report (1990), aerial photographs and topographic maps of the entire catchment were not available, reason why it was not possible to properly determine the total number of landslides. Although the landslide inventory and description consider the whole catchment, landslide inventory maps cover only about 70% of the catchment.

Mejía & Velásquez (1991) reported 838 soil slips in the entire upper basin for the San Carlos river, and most of them transformed into debris flows. For the La Arenosa catchment, 699 landslides were reported; all classified as soil slips and mud/debris flows, from very to extremely rapid, with high water content.

Figure 1.9 maps the locations of landslides observed in the field. The occurrence of these landslides was triggered by the rainstorm.

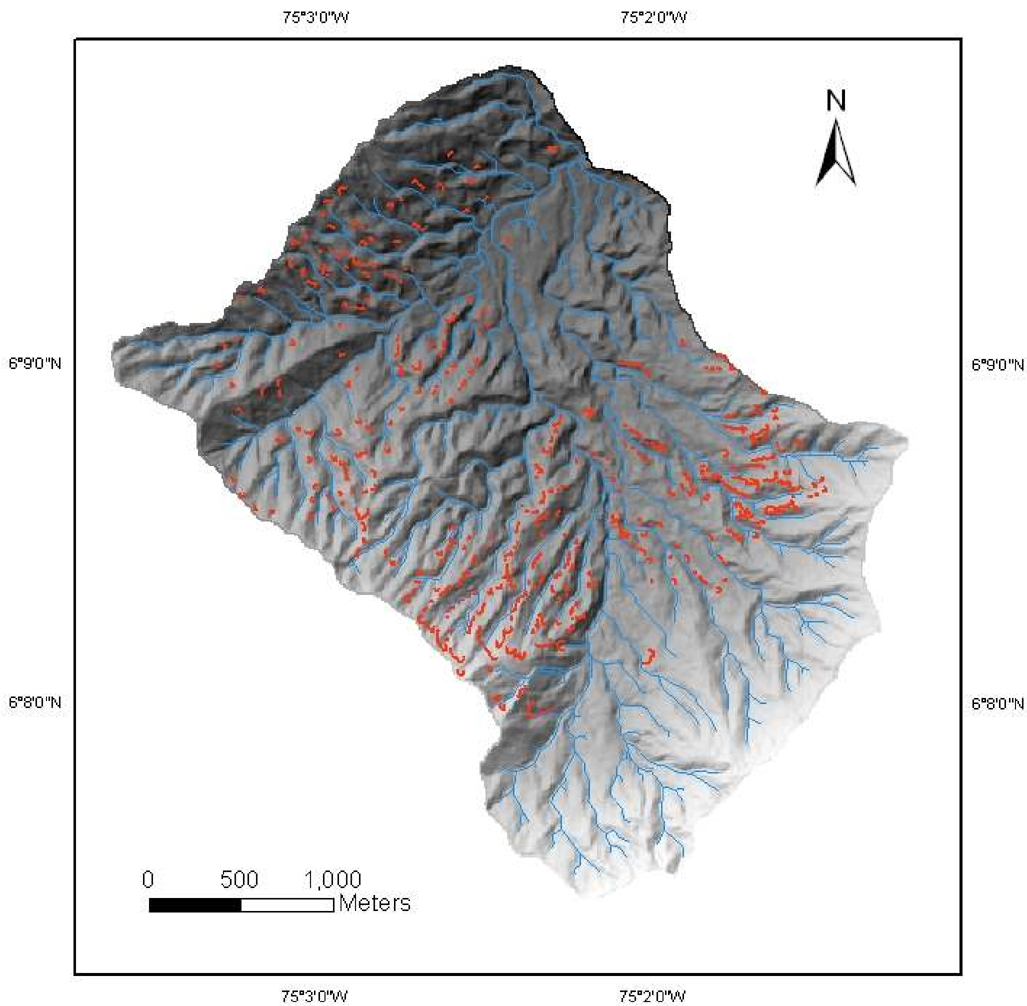

Figure 1.9 Landslides scars produced by the September 21, 1990 rainstorm. Read lines shows the landslide scars according to landslide database elaborated by Mejía & Velásquez (1991) and INTEGRAL (1991).

The landslides commenced as shallow translational slides. After the initial mobilization, a rapid displacement occurred in a chaotic mixture, containing a variable amount of water and scouring the residual soil and vegetation downward, incorporating soil and bedrock fragments. The movement evolved along the slopes under a quasi-viscous flow in high speed, increasing the sediment transport for superficial erosion along the channels.

The landslide bodies were small with respect to the flow length and slip surface, parallel to the slope surface. Field studies showed that the depth of failure surface was around 0.6 – 1.5 m. and corresponded to contact residual soil – saprolite (Figure 1.10). In all cases observed, the failure surface matches the contact area of the residual soil with underlying saprolite. The majority of landslides were initiated within residual soils in hollows and open slopes with slope steepness ranging from 35° to 42° (Mejía & Velásquez, 1991).

Figure 1.10 Detailed photo of shallow landslides that were triggered by the September 21, 1900 rainfall at the La Arenosa catchment (taken from Mejía & Velásquez, 1991).

Chapter 2

FORMULATION OF THE PROBLEM

2.1. Objective

To develop and evaluate a model for predicting landslides triggered by rainfall in tropical mountainous environments based on physical principles.

2.2. Specific objectives

1. To propose a conceptual and mathematical model that responds to the physical process involved in shallow landslides triggered by rainfall in tropical mountainous environments.
2. Based on the conceptual model, to develop a computational model supported by hydrological and geotechnical aspects for the prediction of shallow landslide triggered by rainfall in tropical mountainous terrains.

3. To calibrate, validate and evaluate model performance and coherency by means of computer simulations, comparing the model result with a real case in the Colombian Andes.

2.3. Working hypothesis

Landslide occurrence results of a highly complex nonlinear system; however, it is possible to fit a simplified model with acceptable confidence levels according to the degree of understanding reached on the variables and parameters.

Landslide occurrence is a function of rainfall infiltration as a triggering factor for slopes rendered susceptible as a result of many other important variables. This function is complex, and it is based on shear strength reduction by pore pressure increasing or suction reduction. However, considering that saturated conditions prevail during rainfall, the model only will simulate shallow landslide triggered under saturated conditions.

A physically-based model of rain-triggered landslides can be adjusted for complexity based on scale and assumptions that adequately characterize the spatial variability of both the geotechnical and hydrological conditions and mechanisms.

2.4. Research questions and hypothesis testing

Numerous research questions could be tested through the computational model in order to ensure the accuracy and coherency of the model by using a real case in the tropical mountainous terrains of Colombia. Some of those research questions to be analyzed are:

How do hydrologic processes influence the location, timing, and rates of landslides?

How can this new model achieve high predictive capacity without overestimating the landslide hazard areas?

What are the most important variables that contribute to shallow landslides triggered by rainfall in tropical and mountainous terrains?

How is the topography representative of the geomorphology and a fundamental element which controls both shallow subsurface flow and reflects areas of positive pore pressure build-up?

How does rainfall accumulation and antecedent soil moisture play an important role in landslide occurrence for tropical mountainous terrains?

How can a hydrologically and geotechnically coupled model be optimized so that it can become the foundation of an early warning system?

2.5. Scope

Shallow landslides triggered by rainfall in tropical environments under saturated conditions generally present irregular fault surface but planar trend, and can be classified into soil-slip or shallow translational slides rapidly changing to debris or mud flows. The analysis of this project will not include deep landslides with complex surface fault or displacement behavior after slope failure, but instead focus on predicting slope failure. Simulating landslide displacement behavior is another key element to hazard and risk assessment, which involves a detail analysis of rheology, although out of the scope of this study.

The project aims to understand, explain and model the *simplest* process involved on landslide occurrence, which essentially considers natural terrain conditions, but no external factors such as human disturbances will be incorporated into the analysis. We acknowledge the high degree of human intervention in most terrains plays a crucial role in increasing the number of landslide occurrences over time.

The project is designed to perform a process of calibration, validation, and performance evaluation in the La Arenosa catchment. Although there are some limitations regarding spatial variability of the geotechnical and hydrological parameters of the soil, and limitations with an incomplete landslide inventory, the information available is considered enough for the purpose of the model

The model developed is expected to be incorporated into an early warning system. However, the scope of this research project has the sole intent of developing the model and proposing a conceptual development of the early warning system. The implementation of the model in the Aburrá Valley and the creation of a detailed early warning system are beyond the scope of this research.

Chapter 3

RAINFALL – INDUCED SHALLOW LANDSLIDES

Generally, landslides result from various elements, in locations where the configuration and morphological evolution of slopes play a critical role (Brunsden, 2002; Griffiths et al., 2002; Hutchinson, 1995). The simplest widely accepted definition is given by Cruden (1991), who defines the term as the movement of a mass of rock, debris or earth along a hillside. According to this definition, there are a variety of landslides. Some are slow, small and imperceptible, while others involve large volumes of material and reach high speeds with great destructive power (GEMMA, 2007). The classification of landslides widely known and formally accepted is proposed by Varnes (1978) and updated by Cruden & Varnes (1996). These authors use the type of movement and type of material as the main criterion for classification. The types of mass movements are: falls, toppling, slides, flows, and lateral spread. A great complexity of movements may arise from the combination of these simple criteria.

Landslides are product of the progressive weakening of the mechanical properties of slope materials by means of natural processes such as weathering, uplifting, and human activities that trigger slow and usually imperceptible landslides (Costa & Baker, 1981; Soeters & van Westen, 1996). Nevertheless, a single factor, usually an intense rainfall event or an earthquake, is considered an external stimulus that can generate an almost immediate response to mobilize slope materials, either by a rapid increase of stresses or by reducing shear strength (Wang & Sassa, 2006).

The factors controlling the occurrence and distribution of landslides can be divided into two categories: quasi-static variables or dynamic variables. The quasi-static variables such as soil properties and topography contribute to slope susceptibility and define the spatial distribution of landslides (Figure 3.1). Meanwhile, dynamic variables such as rainfall and degree of saturation control the triggering factors on landslide-prone-slopes, and characterize landslide temporal patterns (Crosta & Frattini, 2003).

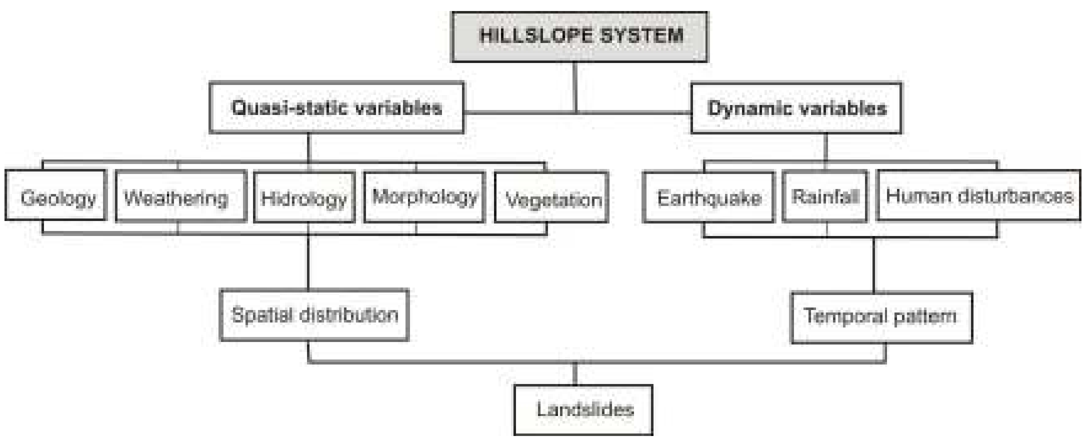

Figure 3.1 Factors controlling the occurrence and distribution of landslide in the hillslope system.

3.1. Characteristics and mechanisms of shallow landslides triggered by rainfall

Shallow landslides triggered by rainfall, which are usually called soil slips, have a planar slip surface. They are characterized by their shallow thickness (0.3 - 2 m), much smaller than their flow length, as well as by the slip of surface fault parallel to the slope and escarpment small area (Anderson & Sitar 1995). These movements are generated during intense rainfall events by the rapid increase in pore pressure or by the loss of apparent cohesion component (Wang & Sassa, 2003; Terlien, 1998; Crosta, 1998; Crosta & Frattini, 2003). Subsequently, the displaced material, by means of processes of static liquefaction and rapid reduction of shear strength in undrained conditions (Anderson & Sitar, 1995), becomes a flow that spreads down, transporting sediment eroded from the channel and increasing the initial displaced volume of the material (Wang & Sassa, 2003; Wieczorek & Guzzetti, 2000). Some authors describe the initiation of the movement and its mobilization as simultaneous and not distinguishable (Eckersley, 1990; Anderson & Sitar, 1995).

For unsaturated soils, Li et al. (2005) describe this process as a result of infiltration of rainfall, which reduces soil matrix suction: such reduction, in its turn, reduces soil shear strength. Once the soil is completely saturated, the suction disappears and the water table develops positive pore pressure. As a consequence, this positive pore pressure reduces shear strength and increases slope instability.

Gostelow (1991) and Iiritano et al. (1998) affirm that rainfall can act in two different ways on slope stability: (1) very intense rainfall events that cause a reduction of shear strength by reducing the cohesion and generating shallow landslides, and (2) rainfall events that cause long-term increase in pore pressure over an area of potential failure, generating much deeper landslides and often along pre-existing shear surfaces. Shallow landslides are usually triggered by short, intense rainfall (Crosta, 1998), while deeper landslides are more related to rainfall distribution and variation throughout long periods (Aleotti, 2004).

Collins & Znidarcic (2004) propose two different failure mechanisms generated by infiltration. In the first mechanism, failure occurs due to positive pore pressure increase caused by static liquefaction of the material, while the second failure mechanism occurs in negative pore pressures where the material is still in an unsaturated state, failure takes place due to reduced suction and mass behaves like a rigid body. In general, shallow landslides are associated with positive pore pressure development, while deeper landslides are associated with loss of suction (Collins & Znidarcic, 2004).

Wilson & Wieczorek (1995) suggest precipitation may induce the generation of a saturated zone with the subsequent increase of groundwater level, especially for shallow weathering profiles. On the other hand, Rahardjo et al. (1995) suggest the creation of a temporary perched water table between the land surface and the wetting front, reducing the negative pore pressure and initiating a flow parallel to the slope that contributes to the instability of the slope (Crosta, 1998). These considerations allow evaluating positive pore pressure generated by rising saturated layer on a predefined critical failure surface, or conversely assess the development of pore pressure from a wetting front advance (Figure 3.2).

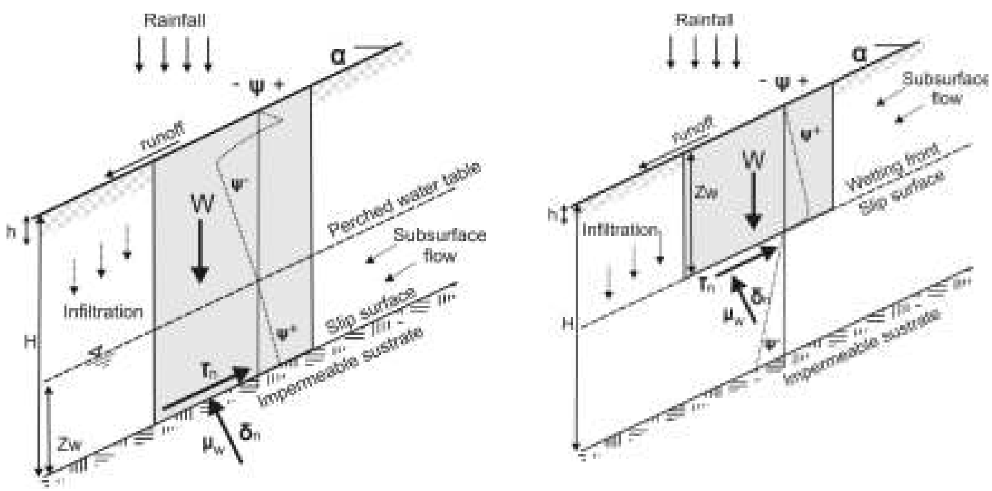

Figure 3.2 Two possible mechanisms for saturation for shallow landslides triggered by rainfall: Left: rising perched water table parallel to weathered soil boundary; Right: wetting front advancing from the slope surface (modified from Xie et al., 2004).

3.2. Variables of landslides triggered by rainfall

The complexity in finding the probability of reaching a critical height of saturation and therefore predict landslide occurrence triggered by rainfall is a function of a large number of parameters involved and intimately related (Figure 3.3). The water flow entering into the soil depends on soil properties, rainfall and local geomorphology, hydraulic characteristics and matrix suction are dominant soil properties, while rainfall intensity and duration are external conditions that affect soil saturation (Crosta, 1998;

Wang & Shibata, 2007; Rahardjo et al., 2007). Other factors controlling the duration and amount of precipitation are critical soil moisture content and antecedent rainfall. In conclusion, mechanical, physical and hydraulic properties of soils, thickness of the weathering profile and vegetation cover contribute to the strength of soils and to the conditions of subsurface flow, inducing varying conditions of instability in response to rainfall patterns (Crosta, 1998).

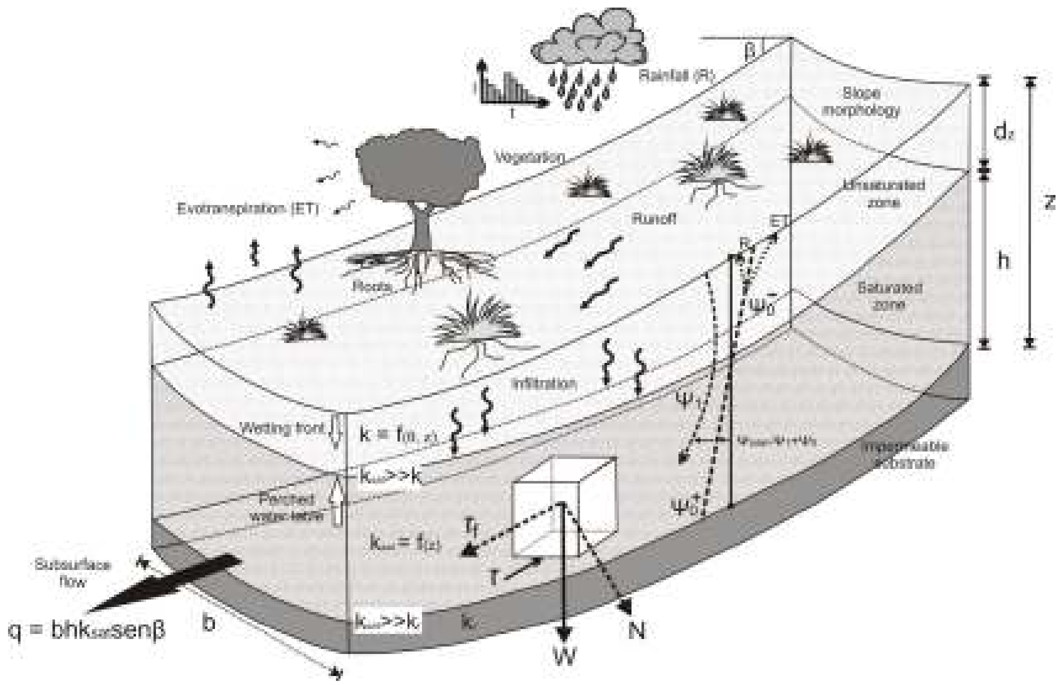

Figure 3.3 Schematic three-dimensional weathering profile of a convergent morphology slope under rainfall conditions. (Θ) volumetric water content (Ψ) pore pressure, (k) permeability, and (W) weight.

Few studies have investigated the influence of permeability upon the occurrence of shallow landslides triggered by rainfall (Pradel & Raad, 1993; Wang & Sassa, 2003; Li et al., 2005; Setyo & Liao, 2008; Rahimi et al., 2010). Permeability is a basic property of the soil, and undoubtedly plays an essential role from the point of view of the balance that must exist for the generation of pore pressure dissipation, which is essential for the initialization of a movement (Wang & Shibata, 2007). Slopes formed by homogeneous soils with low saturated permeability coefficient (ks ≤ 10^{-6} m/s) are safer with short rainfall events (Tr ≤ 24 h) regardless of the intensity of rainfall, while for homogeneous soil slopes with high values of saturated permeability coefficient (ks ≥ 10^{-5} m/s), slope stability is strongly affected by rainfall of short duration and high intensity; this means that the effect of antecedent rainfall is critical for homogeneous soil with low values of k_s (Rahardjo et al., 2007; Rahimi et al., 2010).

Some authors explain the need for long-term rainfall or antecedent rainfall for slope failure with low permeability in the fact that the time required for rainfall to infiltrate the slope with low permeability long and the recovery of the safety factor after rainfall is very slow. Moreover, pore pressure in shallow weathering profiles begins to change in periods much shorter than in deep profiles (Hengxing et al., 2003; Rahardjo et al., 2007; Setyo & Liao, 2008). In profiles with low permeability, pore pressure decreases slowly and high values of pore pressure remains high, even after the rainfall stops. This also explains why failure mechanisms are not similar for homogeneous soil slopes with high and low k_s. Under heavy rainfall, high k_s slopes often failed by water table accumulation, while low k_s slopes fail by reducing suction. For slopes with high k_s, most of the water infiltrates into the soil and causes failure by a rising water table, while in low-k_s slopes short rainfall events do not increase groundwater level, regardless of rainfall intensity or if the remaining water becomes runoff (Tsaparas et al., 2002; Rahardjo et al., 2007).

Although rainfall is known as an important predisposing condition for slope instability, it is difficult to quantify its influence as it depends on various factors, including the heterogeneity of soil and regional climate variations. Some authors even hold a debate on the role of antecedent rainfall and triggering factors; different investigations around the world have reached different conclusions (Frattini et al., 2009). Although many researchers believe that the importance of antecedent rainfall is equal to the intensity of rainfall and depends on soil permeability (Guzzettti et al., 2005; Rahardjo et al., 2007); Brand et al. (1984) found that antecedent rainfall has no impact on shallow landslide occurrence in Hong Kong. Rahardjo et al. (2001) explained the Hong Kong case considering the high local permeability of the soil, which creates a greater draining potential of the soil and consequently reduces pore pressure. In general, there is a common understanding over the fact that for soils with low permeability, antecedent rainfall plays an important role, because it reduces soil and increases the permeability coefficient, resulting in enhanced permeability of soil infiltration. As a result, shear strength reduces and consequently the factor of safety also reduces during rainfall (Hengxing et al., 2003; Rahardjo et al., 2008). For tropical high mountainous environments, Terlien (1998) found that the difference in the number of the previous day´s rainfall depends on the depth of the fault surface, where landslides triggered by high daily rainfall are shallow with depths less than 2 m, and landslides triggered by antecedent rainfall present deep fault surfaces in excess of 6 m.

Highly porous soils show higher effective capacity for maintaining and storing water, and thus delay infiltration into the soil. Consequently, the increase of pore pressure is also delayed. For moderate storm, shallow landslides do not occur when there are high values of effective porosity. However, such high values tend to increase the water content of displaced mass, which eventually generates landslides that travel faster and farther and settle on larger areas. These three conditions give much more destructive characteristics of landslides in soils with high effective porosity (Mukhlisin et al., 2006).

Small variations in hydraulic conductivity control the location of landslide occurrence, which explains the randomness in the distribution of movements over an apparently homogeneous similar slope (Reid, 1997). Cho & Lee (2001) and Cho & Lee (2002) studied slope failure mechanisms comprised of unsaturated residual soils. They found that the effort field is modified by the pressure distribution of pores, which are controlled by spatial variations of hydraulic conductivity during rainfall infiltration. Although slopes are texturally homogeneous, hydraulic conductivity has no homogenous distribution as a function of water content or matrix suction.

Suction is one of the most important variables regarding effort in the theory of unsaturated soils (Fredlund & Morgerstern 1977; Fredlund & Rahardjo, 1993; Huat et al., 2006). For unsaturated soils, the coefficient of permeability and hydraulic conductivity depend on saturation degree or matrix suction due to the heterogeneous distribution of pores and water or water content and suction within the soil mass. The amount of water stored depends also on matrix suction and moisture retention characteristic of soil structure (Ng & Shi, 1998). In virtue of the increase of the suction, volumetric water content suction and consequently hydraulic conductivity decrease because of the smaller number of fluid connected pores within the soil structure, decreasing the number of channels available for water flow (Collins & Znidarcic, 2004). The existence of suction increases the resistance of the soil.

Shallow landslides occur in residual soils on steep slopes after heavy or prolonged rainfall as the water begins to infiltrate the soil, and suction slowly reduces in shallow horizons and becomes zero when the soil reaches a saturated condition (Huat et al., 2006). It is widely known that rainfall induces an increase in water table as well as in pore pressure, generating slope failure. However, in many cases, there is no evidence of increase in water table enough to trigger such landslides; in these cases, the failure is attributed to the wetting front advance in soil profile until it reaches a depth that triggers the landslide, and this situation arises for the reduction of shear strength reduction caused by suction (Rahardjo et al., 1995). Gofar et al. (2008) studied the response of suction distribution to rainfall infiltration in two slopes with two different soils: a fine size soil and a large size soil. The results show that distribution of bulk soil suction is more influenced by short, intense rainfalls, while suction in fine soils is governed by rainfall duration.

Few studies have been done in regards to the effect of vegetation on landslide occurrence. Some studies are O'Loughlin (1986), Gray (1995), Wu & Sidle (1995), Ziemer (1981), Normaniza & Barakban (2006), Tosi (2007) and Normaniza et al. (2008). In general, most authors have evaluated the mechanical effects generated by plant roots on slope stability, attributed mainly to an increase in soil shear strength. This increase is attributed to root anchorage forming a network within the horizons of shallow soils. Nevertheless, it is known that vegetation influences slope stability essentially in two ways: (1) by removing soil moisture by evotranspiration and (2) by generating cohesion through roots in the soil mantle (Sidle & Ochiai, 2006). The first manner is not considered particularly important in regions of shallow landslides that are generated in rainy periods, except possibly in the tropics and subtropics where evotranspiration is high throughout the year. Roots, on the other hand, are recognized as a major factor in slope stability, which can respond to cutting force in three different forms: stretching, slipping or breaking (Tosi, 2007). Recent laboratory work has yielded interesting results which show that the effect of roots affects significantly the cohesion but not the angle of friction (Normaniza et al., 2008) and that additional peak shear strength that generates the roots increases markedly with increasing moisture content (Chia-Cheng & Chih-Feng, 2008)

Another line of research is the use of intensity – duration return period for rainfall threshold. However, it is necessary to note that these return periods correspond to a simplification to be made carefully, because intensity - duration return periods have different probabilities of recurrence according to initial conditions of soil moisture (Frattini et al., 2009; Crosta & Frattini, 2008; Borga et al., 1998; Iida, 1999; Iida, 2004; Hennrich & Crozier, 2004; D'Odorico et al., 2005). Hyetograph shape affects pressure head value, for some rainfall, hyetograph with peaks at the end of the rainstorm generated peak pressures higher than for uniform hyetograph, reducing storms return period that generate landslides (D 'Odorico et al., 2005).

Minder et al. (2009) studied the effect of changing spatial patterns of rainfall in mountainous environments on landslide susceptibility by using a high-resolution atmospheric model, supported on rain gauges and a stability physical model (SHALSTAB). These authors found that the use of average precipitation in the study area to estimate landslide susceptibility generates an underestimation of the likely areas to fail due to extreme rainfall events, which can exceed 20%, whereas the use of data from rainfall stations located in the lower parts of the mountains similarly produces an underestimation of up to 64%. These effects are comparable to the effect generated by medium and high variability of soil parameters; therefore, they recommend that for different regions in mountainous areas, spatial patterns of rainfall should be a factor considered in landslide analysis.

One of the most important recent advances that allows us to consider all these variations of soil properties, the morphology of the slopes and the rainfall pattern has been the use of physical and hydrological distributed models (Borga et al., 1998; Crosta, 1998; Burton & Bathurs, 1998; Griffiths & Collison, 1999; Frattini et al., 2004). Watershed scale, distributed models represent an approach that incorporates spatial heterogeneity of rainfall and production issues that affect runoff and slope stability and integrate the great potential of GIS (Wu & Sidle, 1995; Vélez et al., 2004). A fundamental problem in the use of physical models is how to parameterize distributed soil properties as well as the necessary considerations that hence influence the quality of results (Casadei et al., 2003).

3.3. Models for hazard assessment and prediction of landslides triggered by rainfall

A variety of techniques have been developed for landslide susceptibility and hazard assessment (Varnes, 1984; Soeters & Van Westen, 1996; Barredo et al., 2000; Dai & Lee, 2001a; Guzzetti et al., 1999; and Hutchinson, 1995). Essentially, these methodologies can be grouped into: (1) heuristic methods based on the a priori knowledge of all causes and instability factors of landsliding in the area under investigation, (2) statistical methods based on the analysis of the functional relationships between instability factors and the past and present distribution of landslides, and (3) physically based methods based on the understanding of the main physical laws controlling slope instability and applied to specific mathematical models expressed in terms of the factor of safety (Figure 3.4).

Moreover, there are some new, modern analyses. According to Turcotte et al. (2005) despite of the variety of conditions that cause landslides, the analysis of landslide inventories has shown that landslide events associated with different triggering factors can be characterized by the same probability distributions as a consequence of self-organized critical behavior, exhibiting two regimes: an increasing behavior for small landslides and a power-law scaling, also called fractal or scale-invariant distributions, with a negative scaling exponent, for large landslides (Bak et al., 1988; Guzzetti et al., 2002; Piegari et al., 2009). Malamud et al. (2004a) related the landslide-event magnitude for individual events to the total area and volume of associated landslides, as well as the area and volume of the maximum landslides, estimating regional erosion rates due to landslides.

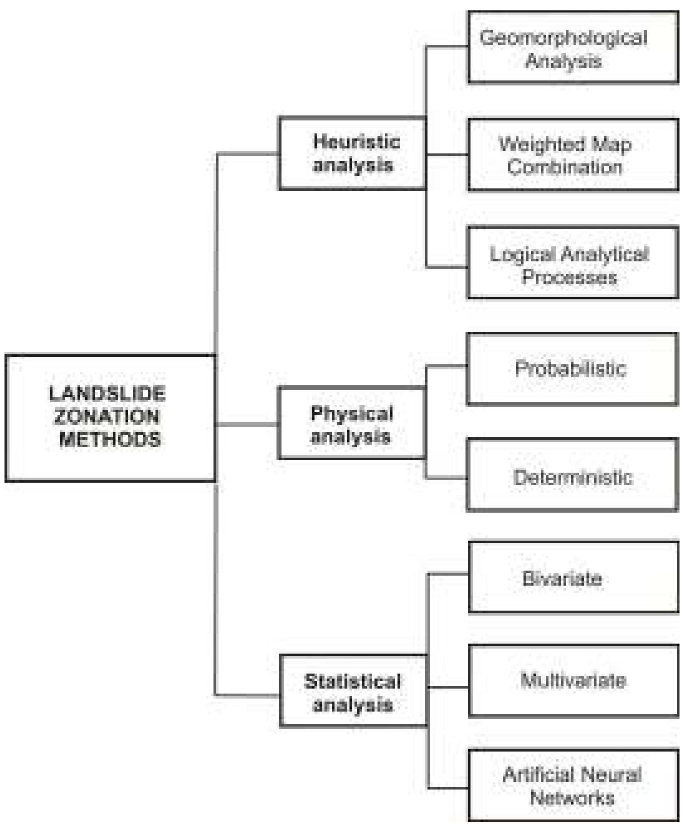

Figure 3.4 Classification of landslide zonation methods.

Malamud et al (2004b) proposed a magnitude scale (m_L) for a landslide event based on the logarithm to the base 10 of the total number of landslides associated with the landslide event. Some models predict that the power-law tail scaling is an inverse function of the internal angle of friction of the soil or bedrock, and mean cohesion appears to set the mean landslide area (Stark & Hovius, 2001).

The methods based on statistical considerations define critical thresholds that usually relate rainfall intensity and magnitude with landslide occurrence. These studies depend largely on data quality in both the inventory of landslides and record rainfall.

In general, neither of these methods take into account dynamical variables or triggering factors, nor the short and long term behavior of these variables (Crosta & Frattini, 2003; van Beek & van Asch, 2004), so that those analysis only reflect the susceptibility of slopes to landslide occurrence. In order to characterize landslide hazard, there is a need to evaluate slope susceptibility to fail and the probability of landslide in terms of time (Crosta & Frattini, 2003). In regards to hazard, the triggering factors must be converted in terms of frequency and magnitude, in this case rainfall, which are very specific and dynamic to occurrence site (van Westen et al., 2006).

Among all methods proposed in the literature, physically based methods are the only ones that explicitly include the dynamic factors that control landslide triggering. For this reason, they allow forecasting both the temporal and the spatial distribution of shallow landslides.

These methods have faced this problem from the mathematical point of view, developing physical models based on geotechnical and hydrological patterns that relate rainfall, pore pressure and slope stability. These models have the ability to assess the activity of spatial and temporal instability of slopes but depend heavily on input variables and boundary conditions (Crosta & Frattini, 2003; Aleotti, 2004; van Beek & van Asch, 2004). Quantifying triggering mechanisms is an essential step towards landslide hazard prediction, so currently the challenge focuses on quantifying physical processes related to infiltration of rainfall, recharge of subsurface flow and consequently landslide occurrence (van Westen et al., 2006).

Statistical and physical methods have allowed defining thresholds, which constitute the minimum or maximum amount of some critical level necessary for a process to occur (Reichembach et al., 1998; NOAA-USGS, 2005; Restrepo et al., 2008). In this sense, establishing the appropriate critical rainfall thresholds is necessary to consider specific conditions of each area and consequently to determine the relationship between local and regional conditions of rainfall with soil characteristics and slope morphology (Crosta, 1998).

3.4. Statistical methods to determine critical thresholds of rainfall

When landslides are shallow (<3m) and continuous series of rainfall are available, it is possible to establish correlations between the intensity and duration of rainfall events with landslides. Statistical thresholds can be grouped into three categories (i) thresholds that combine measurements of rainfall (ii) thresholds obtained for specific events, including antecedent conditions and (iii) other thresholds which include hydrological thresholds (Guzzetti et al., 2008).

The most common parameters investigated are: (1) total rainfall (cumulative), (2) antecedent rainfall (pre-event), and (3) the duration and intensity of rainfall, or their combination. Based on this information, thresholds are defined considering: (1) the intensity of rainfall, (2) the relationship between duration and intensity, (3) duration on a previous defined intensity level, (4) accumulated rainfall in a certain period, (5) the relationship between antecedent rainfall and daily rainfall, (6) the relationship between the rainfall event and average annual rainfall defined by Guidicini & Iwasa (1977) as Normalized cumulative event rainfall, (7) the relationship between daily rainfall and antecedent rainfall excess (Guzzetti et al., 2005).

Three different approaches can be implemented with respect to thresholds: (1) as a lower limit of storms triggering landslides, (2) as a curve that limits and separate which storms trigger and which storms do not trigger landslides, (3) and as the upper limit of storms which do not trigger landslides (Cepeda et al., 2009).

The first discussions about critical rainfall thresholds as landslide triggering were presented by Campbell (1975); however, Caine (1980) was the first author who verified the empirical relationship between landslide occurrence and rainfall characteristics (intensity and duration of rainfall). Empirical Intensity-Durations thresholds assume a power law of the form:

$I = \alpha D^{-\beta}$

In which: I is the rainfall mean intensity (in mm hr-1), D is the duration of the rainfall event, α is a scaling constant (the intercept), and β is the shape parameter that defines the slope of the power law curve.

Caine (1980) suggested a worldwide threshold using landslides from different periods:

$\mathbf{I}=14{,}82\mathbf{D}^{-0{,}39}$

During last year, different statistical methods have been proposed for the definition of objective rainfall intensity-duration (D) thresholds. Guzzeti et al. (2008) propose the Bayesian inference method to determine minimum-ID and normalized-ID thresholds for the initiation of landslides in central and southern Europe. In this method, a probability approach is used to obtain estimates for the scale α (the intercept) and the shape β (the slope) of the power law curve representing the thresholds, based on a set of rainfall intensity (I) and the duration (D) condition that have resulted in landslides (Bruneti et al., 2009).

Brunetti et al. (2009) proposed a method based on the Frequentist approach, and recently, Jaiswal & van Westen (2009) proposed a method using excedence probability of a rainfall critical threshold in accordance to the Poisson model, and landslide occurrence probability according to a given threshold rainfall. The rainfall thresholds were set based on the relationship of antecedent rainfall with daily rainfall.

Guzzetti et al. (2008) suggested a new global intensity-duration threshold based on the threshold proposed by Caine (1980). It is supported by a database of 2,626 landslides reported around the world triggered by rainfall:

$\mathbf{I}=2{,}2\mathbf{D}^{-0{,}44}$

Another important research has been made in this direction in order to generate landslide occurrence forecasting in different parts of the world (Brand, 1984; Reichenbach et al., 1998; Crozier, 1999; Chleborad, 2000; Glade et al., 2000; Dai & Lee, 2001b; Chleborad, 2003; Jakob & Weatherly, 2003; Gabet et al., 2004; Guzzetti et al., 2005; Cannon, 2005; Godt et al., 2006; Giannecchini, 2006). Nevertheless, it is necessary to keep in mind that these thresholds do not consider antecedent conditions, and they are not applicable for deep surfaces or landslides triggered by continuous rainfall of low intensity, or where complex conditions associated with groundwater flow occur within slopes areas.

Finally, it is necessary to consider rainfall is not the direct cause of instability. Landslides are generated by the increase of pore pressure in the soil. Assuming that higher rainfall intensity, greater failure probability is not always true (Reichenbach et al., 1998).

3.5. Physical methods to define temporal and spatial landslide occurrence

Physical methods generally explain landslide occurrence combining geotechnical analysis to determine critical pore pressures and hydrologic analysis to assess rainfall amount that is required to raise such critical pore pressures (Terlien, 1998). Physical models define thresholds relating measured rainfall at the regional and local terrain features, and they are calibrated using rainfall events for which triggering rainfall, location and timing are known (Guzzetti et al., 2005).

3.5.1 Hydrological analysis in physical methods

A variety of hydrological triggering systems for landslides have been presented for several decades; there are many types of systems based on a wetting front descending into the soil or a perched water table at the contact between soil and bedrock (van Asch et al., 2009).

One of the best known models is based on the idea of increasing density and reducing hydraulic conductivity of the regolith with depth, in which rainfall rate exceeds the percolation rate in depth, creating a perched subsurface water flow in the regolith and assuming that the saturated zone flow is parallel to the slope. In this model, the most critical situation for slope stability is considered when a saturated zone reaches the slope surface and water pressure in soil pores is limited by its height (Anderson & Sitar, 1995).

According to this view, there are simple considerations that propose hillside hydrology as a subsurface flow in a static state and evaluate topographic control on pore pressure (Montgomery & Dietrich, 1994), which have a tendency to overestimate the hazard spatially depending on data quality (Crosta & Frattini, 2008) and hydrological models for unsaturated slopes initially considered transient dynamic flows, assessing landslide hazard for specific storms. Pore pressure that develops in soils, in these cases, occurs as a transient process according to vertical infiltration movement; additional shear strength depends on suction degree or negative pore pressure (Sharma & Nakagawa, 2005; Huat, et al., 2006; Collins & Znidarcic, 2004). For D'Odorico et al. (2005), the horizontal sub-scale watershed is in the order of hundreds of meters, whereas soil thickness is usually of a few meters, so that unsaturated flow parallel to slopes occurs on time scales greater than infiltration, and effect on water pressure variability may be negligible on vertical infiltration time scale.

Different models have incorporated slopes geometry to describe hydrologic behavior of a given point in a watershed. The most commonly used are: TOPOG (O'Loughlin, 1986); TAPES (Moore et al., 1988), which ignore flow through unsaturated zone; and models such as TOPMODEL (Beven & Kirkby, 1979), which assumes that flow through unsaturated zone occurs as a vertical flow with magnitude equal to precipitation. In general, these models are based on the assumption that, under a static water balance; subsurface water flow levels are directly related to the topographic index:

$$\lambda = \quad log\left(\frac{Ac}{\tan\beta}\right)$$

In which: Ac is the upstream contributing area per unit contour length (m), and tanβ is the topographic slope. The topographic index has been used for most authors as dimensionless; however in the SI unit system the unit of λ is the logarithm of a ratio dimensioned in meters. For this reason, Ducharne (2009) proposes rearrange the original equation of TOPMODEL to obtain a dimensionless index.

High values of λ reflect a high potential to be saturated during rainfall. The topographic index reflects the water tendency to accumulate at any point in the basin (in terms of Ac) and the tendency of gravitational forces to move water down (in terms of tanβ as an approximate hydraulic gradient) (Quinn et al., 1991).

Lanni et al. (2009) studied the effects of lateral and normal water flow in landslide occurrence and their relation to soil moisture conditions, rainfall intensity and duration, using a distributed hydrological model called GEOtop (Bertoldi & Rigon, 2004). The numerical simulation results suggest that for antecedent moisture conditions, low intensity and long duration of rainfall lateral water flow effect tends to be amplified. For these cases, hydrological models based on a one-dimensional flow (perpendicular to the slope) may have limitations. For particularly dry antecedent soil moisture, short durations of rainfall and fine-grained soils, failure depends on pressure redistribution normal to the slope direction, where lateral flow is negligible until fault occurs. But for long-standing cases of rainfall or more permeable soils, lateral effect becomes even more relevant during an event. In this case, one-dimensional and two-dimensional forms of equations of Richards give divergent results. The two-dimensional effect causes a faster increase in pressure head at the bottom of the slope and a loss in conditions of instability, which is not detected through dimensional analysis.

Some authors consider that the subsurface water flow assumption of a static state is not appropriate to assess triggering landslide causes due to short periods of response of pressure head in some soils (Matsushi et al., 2006; Chiang & Chang, 2009). To assume rainfall in a static state consequently removes the effect of the redistribution of water pressure on the floor perpendicular to the slope associated with transient rainfall infiltration, and so these models cannot predict temporal response of landslides to rainfall variable patterns (Iverson, 2000). Borga et al. (2002) considered unrealistic the assumption of a static state for wet indexes, since these models consider that sub surface flow anywhere in a landscape depends on the upstream drainage area, which is valid only if subsurface water flow recharge occurs by the time required for each point to reach equilibrium of sub surface drainage and generate drainage from its entire upstream contributing area. Nevertheless, due to low sub surface flow velocity, this assumption is very difficult to achieve, usually only when it receives input from a small portion of total drainage area.

However, the topographic controls of subsurface flow affect the long-term moisture patterns within a watershed and determine pressure head before the beginning of a storm. Therefore, water pressure head within weathering profile can be expressed as the sum of two components, the pressure head produced by long-term infiltration in a static state, and the response of pressure head in short term caused by a given storm (Iverson, 2000; D'Odorico et al., 2005).

Other models based on static state in kinematic wave hydrology have been used for saturated hillside slopes in a large number of researches (Troch et al., 2002; Paniconi et al., 2003; Rezzoug et al., 2005). They generally used the Boussinesq equation for Hillside Storage Capacity formulated according to Darcy's equation and continuity in terms of water storage capacity on the ground as the dependent variable (Troch et al., 2003).

One of the dynamic and vertical hydrological models most known and used worldwide was developed by Iverson (2000), who considered the transitional flow regime and partially saturated soil from Richard's equation (1931), requiring as input rainfall intensity-duration and a characteristic of hydraulic diffusivity. Iverson acknowledges different states and considerations, specifically to conduct long- and short-term models. Iverson' s long-term model presented a static water flow behavior similar to Montgomery & Dietrich (1994)'s model, with the characteristics of static state and water flow parallel to slopes on an impermeable layer. It holds only if: rainfall duration is very long, depth is relatively small, rainfall intensity is very low and slope perpendicular component of hydraulic conductivity exceed by far the parallel component.

Iverson (2000) proposed that, for short periods in partially saturated soils and transient flow, the variation of water pressure head is function of time, maximum hydraulic diffusivity, slope angle, and soil profile depth. In the model of Iverson, infiltration capacity is assumed to be equivalent to saturated hydraulic conductivity. However, the infiltration capacity may vary according to rainfall duration, and infiltration rate is significantly related to variable infiltration capacity. To avoid unrealistic pressure head values, Iverson uses the beta-line correction, stating that given pressures must be adjusted below the line. Tsai & Yang (2006) showed that these pressures are due to unrealistic overestimation of infiltration in rates induced by assuming that infiltration capacity equals saturated hydraulic conductivity, and propose a modified Iverson's model that avoids this situation.

Amaral et al. (2009) applied a distributed model for transient response of slope stability analysis, which combines an analysis of infinite slope stability with a modified version of Iverson's (2000) transient response model for vertical water infiltration in quasi-saturated soil conditions. The validation of this model was conducted on two scales;

the first one on a slope scale to a specific case occurred in the Quente river valley in the Azores Island, and the second, for a basin scale using a landslide database from the area and widespread soil parameters. The results for the slope scale were very accurate, and it was possible to predict the occurrence time of the event to this point. For the basin scale, the results were conservative; even the model predicted all events mapped and many more.

Another model of vertical infiltration widely known is the Green-Ampt model, which is defined as a simple infiltration model with very consistent results with the Richard´s equation (Ekanayabe & Phillips, 1999; Xie et al., 2004; Qiu et al., 2007). Originally, this model was developed for water infiltration on horizontal surfaces where ponding occurs, so for its use on slopes modifications are necessary (Setyo & Liao, 2008). The model of Green-Ampt infiltration assumes that the following conditions are met (Setyo & Liao, 2008; Qiu et al., 2007; Xie et al., 2004):

a) surface soil moisture is kept constantly on surface ponding,
b) suction head in the wetting front is constant,
c) deficit of volumetric water content is uniform before and after moisture,
d) coefficient of hydraulic conductivity is constant and equal to saturated hydraulic conductivity.

These conditions mean that the soil is completely saturated from the surface to the wetting front, while below the wetting front there is a saturation degree equal to initial saturation. Advancing wetting front models are based on moisture gravitational movement, which is only partially true. In reality, wetting front has a variable moisture distribution and depends heavily on soil characteristics and rainfall intensity (Sharma & Nakagawa, 2005).

Multiple variations and adjustments have been made for the Green & Ampt model. Pradel & Raad (1993) developed a method based on the Green & Ampt model to estimate slope failure probabilities under prolonged rainfall, which takes into account rainfall intensity and duration for several return periods. The method requires that two conditions are met: that rainfall intensity is greater than soil infiltration capacity and that rainfall is greater than the critical time necessary to saturate the soil to a critic depth. Cho (2009) used a one-dimensional model of infiltration and infinite stability analysis to determine infiltration influence on slope stability by considering two horizons. Cho used the Moore infiltration model, which is based on the Green & Ampt model, but it covers a more general situation, including when water moves upward by a perched water table generated by a lower permeability horizon. Some authors such as Cho & Lee (2002) modified the Pradel & Raad method taking into account rainfall intensity and duration for various return periods in order to assess the likelihood of failure for a particular rainfall event.

Crosta & Frattini (2003) compared three hydrological models for the same area: the static-state model (Montgomery & Dietrich, 1994), the transient wetting front model (Grenn & Ampt, 1911) and the transient diffusive model (Iverson, 2000). The three models are combined with a slope stability analysis of infinite dimensionality. The results of this comparison showed that the transient diffusive model works better than the others, generating smaller polygons or unstable areas, but without increasing the error. The static state model presents higher prediction skills, but it showed large areas as unstable, overestimating the hazard, which explains the high levels of prediction. The transient diffusive model, even taking into account the difficulties in calibration for the diffusion value for which the model is very sensitive, is apparently able to correctly simulate the processes that are generated during a rainfall that triggers shallow landslides.

Finally there are some considerations applicable to both static or dynamic hydrological model that have not been incorporated into the hydrological analysis, such as the influence of reduction of porosity with soil depth and lateral control of the flow through preferential pathways named pipes or macro pores (Vélez et al., 2004). Empirical studies have found that lateral flow through pipes controls the response of catchments, which brings serious problems to hydrological model applications that assume isotropic conditions as well as homogeneous and constant permeability (Sidle & Ochiai, 2006).

3.5.2 Geotechnical aspects of physical methods

Geotechnical models of landslides triggered by rainfall generally assume a constant slope and an infinite length, and assume that the failure surface is parallel to the ground surface and that the failure length is much larger than the thickness of the displaced mass (Borga et al., 2002). These analyses based on shear stress (τ_f) on the slope should not exceed the shear strength (τ) of the material; therefore, the factor of safety (FS) of the slope can be defined in terms of effective stresses by means of the relationship between τ / τ_f (Brunsden & Prior, 1984).

Although the vast majority of models use soil properties to calculate the factor of safety based on stability analysis of infinite slopes, they differ in the method in which the pore pressure is calculated as discussed above. There are physical models as SINMAP (Pack et al., 1998); SHALSTAB (Montgomery & Dietrich, 1994), LISA (Hammond et al., 1992), which assume a static state, saturated flow parallel to the slope and use Darcy's Law to estimate spatial distribution of pore pressure, except for LISA, which requires only water table depth. The stability model of Iverson (2000), in contrast, considers transient unsaturated flow to estimate pore pressure response at depth.

One of the most recognized physical model is proposed by Montgomery & Dietrich (1994) and Montgomery et al. (1998), called SHALSTAB. This model employs a TOPOG hydrological model (O'Loughlin, 1986) to estimate the height of saturated portion of profile, which assumes that the dominant control of spatial distribution of landslides is given by topography, which define slope angle and subsurface flows converge. They define an index for analysis of soil saturation that is used to predict water table in terms of water flow in soil and rainfall intensity. The proposed stability model uses the Mohr-Coulomb criterion, which in order to be simple assumes cohesion equal to zero. In this way, the model combines a geotechnical model to define the hydrological model equation:

$$\frac{h}{z} = \frac{q}{T}\frac{a}{b\sin\beta}$$

In which: q is the subsurface flow rate per unit area of drainage with unitary width b, T is soil transmissivity, and h/z is the relationship between thickness of permeable soil and thickness of saturated soil. The hydrologic radio q/T captures the magnitude of the rainfall event, represented by q, in relation to the ability to direct subsurface flow downstream. For higher values of q in relation to T, it is most likely that the ground is saturated and unstable areas will become greater. In regards to the topographic index a/(bsinβ), it captures the essential effect of topography on surface flow. The difference between this radio with the ratio defined by the TOPMODEL, is that the latter uses Tanβ representing the slope angle of fault surface, rather than sinβ representing the total head gradient that causes subsurface flow (Montgomery et al., 1998).

According to the investigations of Montgomery & Dietrich (1994) and Montgomery et al.(1998) some researchers have shown that shallow landslides are tightly controlled by surface topography, which affects subsurface flow convergence, increasing soil saturation and reducing soil shear strength (Guimaraes et al., 2003; Pellenq et al., 2003; Rosso et al., 2006; Fernandez et al., 2004).

The SINMAP method corresponds to a computer program that predicts the potential for landslide stability, similar numerically to SHALTAB, due to it is using the same factor of safety equation and Darcy's Law for saturated flow (Morrissey et al., 2001). The difference is that SHALTAB ignores cohesion. With respect to the LISA method (for Level I Stability Analysis) this was developed by the United States Department of Agriculture (USDA), for soils with similar topography and geology. LISA follows a probabilistic approach based on a safety factor concept, considering the trees weight and vertical depth of saturated soil. The values for each parameter in the equation are defined by a probability distribution function (PSF) and the results are presented in a histogram showing the distribution of the factor of safety calculated using the Monte Carlo method.

Morrissey et al. (2001) compares three different methods SINMAP, LISA, and Iverson, They found that the method of Iverson is preferable since it considers the transient response and spatial pore pressure in the calculation of slope stability. The method SINMAP and LISA are similar and used probability distribution functions of certain parameters; however, LISA allows the use of distributed values for all parameters.

One of the first known methods was the **d**istributed **S**hallow **LA**ndslide **M**odel (dSLAM), developed by Wu & Sidle (1995), posteriorly modified as Integrated Dynamic Slope Stability Model (IDSSM) by Dhakal and Sidle (2003). The dSLAM is a dynamic and distributed physical model of stability, which uses an infinite slope stability analysis with a combined slope-parallel subsurface and saturated surface kinematic wave modeling approach (Takasao & Shiiba, 1988) and a continuous dynamic vegetation root strength model. It is assumed that the infiltration capacity of the soil is always in excess of the rainfall intensity, thus only subsurface flow and non-Hortonian overland flow occur. This model uses hourly rainfall hyetographs to simulate individual events or long strings of random rainfall events for long-term simulations.

Simoni et al. (2008) proposed a model for simulation of rainfall-induced shallow landslide triggering that called GEOtop-FS. The model combines the infinite slope stability analysis with the hydrological distributed model, GEOtop (Bertoldi & Rigon, 2004), which is spatially-distributed, finite-difference model. GEOtop simulates surface runoff and soil moisture redistribution, by solving the Richard´s equation numerically in 3D physically based. GEOtop simulates moisture content and pore pressure evolution resulting from infiltration and models subsurface saturated and unsaturated flows, surface runoff, channel flows, and turbulent fluxes across the soil-atmosphere interface. All the basin's cells are divided in channel and hillsides cells. The surface runoff on the hillsides is described as a succession of uniform motions and the subsurface flow is on the basis of Darcy's law. In both cases, the connectivity among the cells is defined by the D8 scheme, with eight drainage directions. The motion inside the channels is described by the parabolic solution of the De Saint Venant equations. The safety factor is computed with a probabilistic approach; in order to determine the likelihood of slope failures, soil parameters are assigned distributions instead of single deterministic values.

Not only slope angle is important, since slope shape (concavity and convexity) is a factor that controls the occurrence of shallow landslides (Talebi et al., 2008; Borga et al., 2002; Iida, 1999). Under these considerations, three basic hydro-geomorphological units are useful for evaluating the stability (1) divergent, (2) flat and (3) convergent. The divergent landforms are generally more stable in steep terrain, followed by flat and concave landforms or convergent, which are less stable (Berne et al., 2005). On the diverging or convex slopes, sub-surface flow is dispersed, which allows a subsurface water flow to be unfrequent and pore pressures to be typically much lower than on slopes with other landforms (Berne et al., 2005; Sidle & Ochiai, 2006). Talebi et al. (2008) examined the stability of 9 possible slope landforms, combining the longitudinal profile or curvature of the profile (concave, straight, and convex) and the perpendicular profile or curvature plane (convergent, parallel and divergent). These authors consider that the profile curvature controls the change of the mass flow rate of water down the slope, while the curvature plane defines the topographic convergence, which is a major control of subsurface flow concentration. The convex profiles are generally more stable than concave or flat profiles; with regards to curvature plane, stability increases when the plane changes from convergent to divergent, especially for convex profiles.

CHASM, **C**ombined **H**ydrological **A**nd **S**tability **M**odel, is a physically based two-dimensional combined soil-hydrology-slope stability model that allows simulation of changes in pore water pressures in response to individual rainfall events (Anderson 1990; Wilkinson et al., 2000). The procedure adopted to model the hydrological system is a forward explicit finite difference scheme. The slope is divided into a series of rectangular columns, each subdivided into regular cells. The hydrology model simulates flow over and through the discretized slope by moving water between adjacent cells. Vertical flow through each column within the unsaturated zone is calculated using Richards's equation and flow between columns is modeled in one dimension using the Darcy equation for saturated flow. The stability assessment techniques used in CHASM is Bishop's simplified circular method (Bishop, 1955). At each time step of the simulation, pore pressures, both negative and positive, are incorporated directly into the effective stress determination of the Mohr–Coulomb equation for soil shear strength. The Fredlund et al. (1978) criterion is used for the unsaturated portion. This provides input into the limit equilibrium technique for derivation of the minimum factor of safety (the ratio of restoring to destabilizing forces), with temporal variations arising from hydrodynamic responses and changes in the position of the critical slip surface (Wilkinson et al., 2002). This analysis involves a numerical search for the slip surface that minimizes the factor of safety.

Baum et al. (2002) develop a Fortran program called TRIGRS based on a model of transient one-dimensional vertical infiltration model with a simple slope stability, according to the developments of Iverson (2000), assuming saturated conditions or very close to saturation. This model found that results are very sensitive to initial conditions, particularly the static flow component and initial depth of the water table. This model has been subsequently used and modified by others (Lan et al., 2005; Salciarini et al., 2008; Godt et al., 2008). Some discussed aspects of the model proposed by Iverson are based on failure not considering slope flow direction, morphology and infiltration levels (Montgomery & Dietrich, 2002), and the model is only meaningful for short duration rainfall (Frattini et al., 2009). Iverson (2000) proposes to evaluate the factor of safety during a rainfall event, as a function of depth and time, reflecting the response of pore pressure. The method assumes that the slope is initially wet and the area of the basin is much greater than landslide thickness. Iverson (2000) considers that the factor of safety varies as a function of depth and time, so it divides the factor of safety into a static component (Fs0) and a component that varies with time (FS)'.

The main disadvantage of infinite slope models is that they do not have in mind the stresses produced by the sub surface flow and topography in different directions perpendicular to the slope. Some studies have shown that deviations from the flow parallel to slopes, especially in deeper soils significantly affect shear strength (Borga et al., 2002). Crosta & del Negro (2003) found that in addition to vertical infiltration of water convergence sub surface in longitudinal direction is also relevant, and that these effects are magnified in concave areas, where lateral flows are concentrated.

Table 3.1 Review of most of physically based models used by researchers.

MODEL	HYDROLOGY	STABILITY	D
SHASLTAB	Static state – TOPOG (O'Loughlin, 1986)	Infinite slope model in saturated conditions	3D
dSLAM	Kinematic Wave Groundwater (Takasao & Shiiba, 1988)	Infinite slope model in saturated conditions	3D
CHASM	Finite different scheme using the Richards's equation for vertical infiltration & Darcy equations for lateral flow.	Bishop's simplified circular method in unsaturated conditions	2D
Pradel & Raad	Transient vertical infiltration – Green & Ampt	Infinite slope model in unsaturated conditions	1D
GEOtop-FS	Finite different scheme using the Richards's equation for vertical infiltration & Darcy equations for lateral flow. GEOtop (Bertoldi et al., 2004)	Infinite slope model in saturated conditions	3D
TRIGRS	Transient vertical infiltration – Iverson (2000) & simple runoff-routing scheme	Infinite slope model in saturated conditions	3D

3.6. Landslide prediction and early warning systems

Early Warning Systems are defined by the UN/ISDR (2009) as the sets of capacities needed to generate and disseminate timely and meaningful warning information to enable individuals, communities and organizations threatened by a hazard to prepare and to act appropriately and in sufficient time to reduce the possibility or harm or loss.

In regards to the evacuation of people, local officials and decision makers are interested both in determining the time when landslides occur as well as in its probable location, when and where. Early warning systems for landslides provide a rapid means for monitoring and communicating information about threats to a vulnerable community. The alert systems are mainly used to protect lives, noting the possibility of occurrence of a landslide in advance, providing time for notification and evacuation of people (Larsen, 2008).

Arattano & Marchi (2008) classified early warning systems into two main classes: early warning systems and alert systems for the event. Early warning systems can predict the occurrence of an event before it takes place by monitoring the conditions precedent. Alert systems detect the event when it has already occurred and raises an alarm. Some other authors also distinguish the post-event warning systems which intend to detect that the event occurred and allowed to take appropriate action. The instruments and sensors for each type of system vary considerably. Because the early warning systems are based on empirical or physical relationships of rainfall versus the occurrence of the event, the instruments used are those normally applied to monitor hydrometeorological conditions such as rain gauges and radar.

In the cases where statistical analysis is impossible due to the lack of information, hydrological processes characteristic of the slope should be studied in detail to understand and explain the mechanisms responsible for the generation of landslides triggered by rainfall. Physically based models of the geotechnical and hydrological aspects have to be applied in such cases in order to find critical rainfall thresholds.

Local authorities can use these critical levels to develop early warning system for landslides to improve evacuation procedures.

An early warning system consists of three basic elements:

a) rain sensors and telemetry;
b) physical or statistical models for defining rainfall thresholds;
c) means of communication of warnings to authorities and community.

The Global Platform for the Promotion of Early Warning (UN-ISDR, PPEW) defines four key elements for an effective early warning system (UN, 2006):

a) previous knowledge of the risk;
b) monitoring and alerting;
c) dissemination of alerts and communication;
d) response capacity.

These systems have been widely used for events such as floods, tsunamis, and flash floods, thanks to numerical and physical models developed. However, early warning systems for landslides have only been developed and implemented in few countries.

In order to be effective, an early warning system for landslides should comprise a comprehensive network of rainfall stations in real time or distributed rainfall estimates via radar, and must be supported by a robust model for the definition of thresholds (Larsen, 2008).

Regarding the definition of critical rainfall thresholds as triggering factors of landslide, many intensity - duration thresholds have been used to indicate different levels of potential threat. In the case of the San Francisco Bay, a lower security threshold was defined, below which a landslide occurrence was unlikely and above which landsides were likely. In the same way, a higher or warning threshold was established, about which a great number of landslides usually occurred and left considerable economic and human losses (NOAA-USGS, 2005).

In many areas, early warning systems based on thresholds or statistical models are not possible due to the lack of reliable rainfall and events. In this case, physical models must be used. For the application of these physical models, it is required a detailed study on failure mechanisms triggered by rainfall (Terlien, 1998).

Nonetheless, early warning systems currently operating are mainly based on empirical models because the current understanding of failure mechanisms and conditions which lead to landslides are not sufficient to develop systems based on physical models (Anderson & Sitar, 1995).

The advantage of early warning systems based on rainfall thresholds is that rainfalls are relatively simple and inexpensive to measure over large areas. If rainfall data are spatially dense enough, the thresholds are able to allow good spatial resolution. Additionally, where data about soil properties and pore pressures in surface horizons are affordable, rainfall thresholds can be related to geological and geotechnical conditions, considerably improving the temporal prediction of shallow landslides (Keefer et al. in Reichenbach et al., 1998).

An important factor in these systems refers to standards or predefined messages. The NWS considers three messages or levels (forecasting, monitoring and warning). The forecast is used to indicate a threatening weather event which may develop due to the conditions monitored, providing information for those who need considerable time to prepare. A phenomenon is monitored when the risk of threatening has increased significantly, although its occurrence, location and time is still uncertain. The warning is generated when the threatening event is occurring, is imminent or has a very high probability of occurrence.

3.6.1. Conceptual models for landslide prediction

Jakob & Weatherly (2003) proposed discriminant functions for landslide occurrence (CSL) for the location of the North Shore mountains of Vancouver and based on antecedent rainfall and stream flow data or the non-occurrence (CSNL). The difference of the discriminant scores, ΔCS, for both groups is a measure of landslide susceptibility during a storm. Additionally, they define three threshold levels of alert: Warning

Threshold (LWT Landslide Warning Threshold) when ΔCS is -1; Conditional Threshold (CTLI Conditional Landslide Initiation Threshold) when CS is zero; and Imminent Threshold (ITI imminent Landslide Initiation Threshold) ΔCS corresponding to intensity greater than zero and greater than 4 mm/h. However, they consider that ITL cannot be used as a warning, due to the fact that landslide may occur while the threshold is exceeded.

Chien-Yuan et al. (2005) developed a model for early warning of debris flows using rainfall stations in real time. The pre-alert for landslide occurrence derives from critical rainfall thresholds of historical events, combined with rainfall patterns and geology.

Godt et al. (2006) combined a water balance model, which is defined as Antecedent Water Index (AWI) with a intensity-duration threshold (ID) using a decision tree to predict the conditions that can generate landslides as well as three alert levels: null, observation and alert. When the beginning of the storm is AWI ≤ -0.1, it is considered a null warning, even if the ID threshold is exceeded. For wet conditions between AWI -0.1 ≤≤ 0.02 and exceeded the critical threshold generates a level of observation. And if ≥ 0.02 AWI generated a level of pre-consultation or warning indicating that soil moisture conditions allow that an additional rainfall can trigger landslides, if an event exceeds the threshold level ID, alert is generated indicating the imminent possibility of the occurrence of numerous shallow landslides.

Recently, there have been developments to build early warning systems for landslides triggered by rainfalls; some of these studies have focused on the hydrological response of soils under the effect of infiltration. Most of them incorporate monitoring of pore pressures under saturated and unsaturated conditions. But there are still practical limitations for field measurement of pore pressure (Tohari et al., 2007). Those authors propose a conceptual methodology for the prediction of landslides based on moisture content, from which they can obtain the critical time for the occurrence of landslide.

Fan-Chieh et al. (2007) presented a decision support system for alert of landslides and flows based on monitoring real-time rainfall in Taiwan. The purpose of this system is to provide support and suggest to authorities the chance of occurrence in susceptible areas and, based on that, to determine whether a pre-evacuation is necessary. The system is made up of real-time monitoring of field stations rainfall, combined with monitoring current levels of thematic maps and historical information as critical thresholds, isohyets of landslides. This information is supported on a WebGIS platform in which experts make decisions on actions to undertake in the territory. The platform has three essential modules, the module of rainfall, the landslide module and the module of flows. Currently, the system has a radar system QPESUMS (Quantitative Precipitation Estimation and Segregation Using Multiple Sensors) which has not yet been fully integrated into the system.

Hong & Adler (2007) propose an early warning system for real-time landslides triggered by rainfalls and earthquakes, the two biggest triggers for such events. It involves three basic components: (1) a database of susceptibility to landslide, which includes geology, elevation, topography, soils, and coverage; (2) a system of precipitation estimates and satellite instruments on real time; and finally (3) a prediction system of acceleration at the surface after an earthquake. The susceptibility database would indicate where landslide will occur and triggering factor will indicate when. Susceptibility maps could be taken from the Shutle Radar Topography Mission of NASA (SRTM) and the soil database of FAO. With respect to real time systems, they proposed the Rainfall Measuring Mission, TRMM-Tropical (Tropical Rainfall Measuring Mission) which can be obtained in real time on NASA's page (http://trmm.gsfc.nasa.gov), and acceleration at surface through the Global Assessment Program for Earthquake Response (PAGER), which has developed a real-time map found at http://earthquake.usgs.gov/eqcenter/shakemap/. Preliminary results of these authors show that the system works well for landslides triggered by rainfalls in short periods of time (<6 h). Finally, they call for further work using forecasts (1 to 10 days) from numerical weather models that can generate alerts with higher response time to communities.

Setyo & Liao (2008), by using a model of vertical infiltration (Green-Ampt) and a model of stability of infinite slopes, suggest a relationship in terms of cumulative rainfall and intensity to predict landslide occurrence and time of occurrence, applied to different cases worldwide with good results. Setyo & Liao came up with the terms Normalized Cumulated Rain (NAR) and rainfall intensity Standard (NRI).

Guzzetti et al. (2008) proposes a global early warning system based on a comprehensive empirical threshold defined from a database of landslides around the world, and integrated measurements of rainfall from satellite data such as TRMM program.

Brunetti et al. (2009) developed a prototype early warning system for the Department of Civil Protection (DPC) of Italy, to predict the possible occurrence of landslides induced by rainfall throughout the country. The system is based on a set of empirical critical rainfall thresholds and zoning maps in hazard detail scale and risk of landslides. The early warning system compares rainfall measures obtained by weather radar and rain gauges and quantitative forecasts of rainfall result of meteorological models with empirical threshold defined in each of the regions and regional thresholds.

Cepeda et al. (2009a) proposes an early warning system based on susceptibility curves using thresholds associated with susceptibility level. This application allows following the evolution of a rainfall event and defining alerts based on the localized distribution of levels or categories of susceptibility.

3.6.2. Landslide early warning systems around the world

Few places in the world have implemented warning systems based on critical thresholds of rainfall. An early warning system was developed by NOAA and USGS in the Bay Area of San Francisco in the period of 1986 to 1995 as part of an exploratory program. This system was based on quantitative forecasts of rainfall (QPRF) and empirical critical thresholds of precipitation. It was supported by a network with more than 40 rainfall stations in real time.

Some other similar systems have been developed in Japan, China, Brazil, New Zealand and Hong Kong (Aleotti, 2004; Guzzetti et al., 2005; Cannon, 2005).

In Japan, a system for warning and evacuation was developed based on infiltration and surface flow. Certain amounts of rainfall accumulations within certain periods of concentration were identified and combined with models of static stability. To improve the accuracy of forecasts they combined rain gauges with measurements of ground radar and telemetry in real time (Guzzetti et al., 2005).

In the area of Yangtze in China, a system for monitoring landslides was implemented in 1991, which used more than 70 stations and 300 professionals. This network protects a population of over 300 thousand people and it has been predicted that by 2005 more than 217 landslides, which avoided economic losses estimated at $ 27 million (IEWP, 2005)

In Rio de Janeiro, GeoRio (Geotechnical Engineering Office in Rio de Janeiro) designed and implemented in 1996 a system composed of a network of 30 rainfall stations in real time and weather radar, called Rio Alert System. This system generates forecasts and warnings for landslides and floods for government agencies and the community during intense storms (NOAA-USGS, 2005).

In New Zealand, a system was developed for predicting in real time the occurrence of shallow landslides triggered by rainfall, according to weather forecasts generated by global and regional models. The global models of the United Kingdom Meteorological Office (UKMO) are combined with regional atmospheric models (New Zealand Limited Area Model, NZLAM) that allow predicting atmospheric variables such as precipitation and temperature for a cell of 12 km and 24 hours in advance. These regional atmospheric models feed forecasts models to predict soil moisture and high water table. At a higher resolution scale, hydrological models are used to estimate the static soil moisture at the local scale, and infinite stability models are used to determine the threshold of soil water that trigger landslides. This system generates probabilistic forecasting in time and space for landslide occurrence in different regions of New Zealand (Schmidt et al., 2008).

In Hong Kong, the Geotechnical Engineering Office (GEO) developed as an automated computer system called the Landslip Warning System (LWS) operating 24 hours 7 days a week. This system is based on forecasts of rainfall for short times and comprises 86 stations of rainfall. Additionally, it is powered by radar and satellite imagery to monitor variations and movement of rain cells. The LWS is programmed so that when defined thresholds are exceeded, alerts are generated to the public by national and local media like radio and television (Aleotti, 2004). The GEO classifies landslides with a volume greater than 50 m^3 as major incidents, which usually cause loss of life and suggest that an alert should be generated by landslides when 10 or more landslides are expected, based on the fact that 10% of the reported events are classified as major incidents. Dai & Lee (2001) found that major incidents with no fewer than 10 moves are discriminated using rainfall events under the 12-h and 24-h.

NOAA and the USGS developed an early warning system for flash floods and debris flows generated by rainfall in areas recently burned by wildfires associated to empirical intensity-duration thresholds. They contrast these types of events generated by the steady increase of material from the adjacent hills to the valleys by surface erosion of those triggered by rainfall infiltration (Cannon et al., 2005; NOAA-USGS, 2005; Restrepo et al., 2008).

Germany is developing the project Integrated Landslide Early Warning Systems (ILEWS), supported by a robust system for monitoring soil moisture and rainfall in real time using the physical model called CHASM on a web platform (Bell et al., 2009).