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GCL MODEL BY THE DETERMINATION OF THE CHARACTERISTICS IN THE BEGINNING ZONE OF THE DEBRIS FLOWS USING A GIS

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ABSTRACT

In recent years an increase in the prevalence of debris flows has been observed in various regions of the world. These events, which have caused a significant amount of damage to cities, infrastructure and ecosystems; emphasize the importance of developing early warning systems to alert residents of the danger in advance. A model to determine the probability of occurrence of a debris flow through the development of a geographic information system that combines a digital elevation model and a distributed hydrological model is described.

***Key words**: debris flow, geographic information system, digital elevation model*

INTRODUCTION

Natural disasters are a serious obstacle to human development and the fulfillment of the Millennium development goals such as poverty reduction. Natural disasters have resulted in annual economic losses ranging from 75,500 billion USD in the 1960s, 138,400 million in the 1970s, 213,900 million in the 1980s and 659,900 million in the 1990s, mostly in the developed world. However, the economic estimates fail to capture adequately the impact of disasters in the poorest countries, where in terms of human lives, means of subsistence and reconstruction of infrastructure the costs are higher. Currently, 85 percent of those exposed to earthquakes, tropical cyclones, floods and droughts, live in countries whose human development is medium or low. In absolute terms, it has been demonstrated that the economic cost of disasters has been increasing during the last decades.

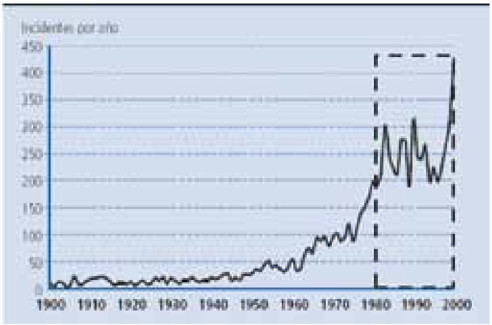


Fig 1 - Disasters registered by the EMDAT

The data base EMDAT offers a very precise view of the total losses by disasters with a suitable level of national detail. The period of time chosen is sufficient to represent the fluctuations of the most of natural disasters. Figure 1 shows the total number of disasters registered by the EMDAT between 1900 and 2000.

One of these natural disasters are the debris flows, which have increased in prevalence in recent years and in most regions of the world. For this reason, it is is important to study their behavior, in order to reduce the serious economic damage and loss of life caused by these natural hazards.

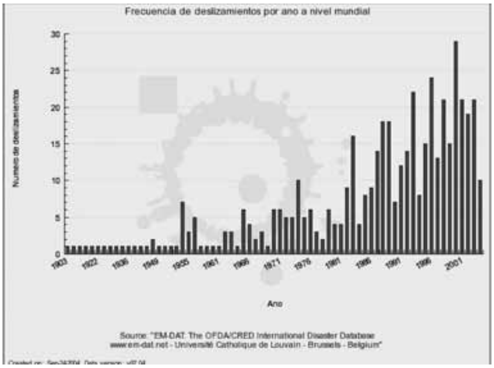


Fig. 2 - Landslide globally per year from 1903 to 2003

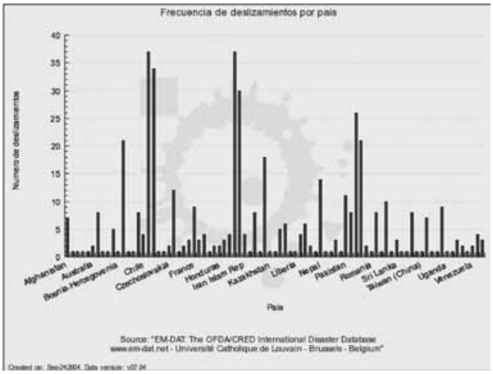


Fig. 3 - Landslides country from 1903 to 2003

DEBRIS FLOWS

Debris flows consist of a mixture of fine materials (sand, silt and clay), coarse material (gravel and rocks) and a variable amount of water. Debris flows move down slope under the action of gravity, usually in waves following the sudden collapse of the material in bank. The generally occur on slopes covered by unconsolidated rock and soil, especially where the vegetation cover has been removed by deforestation or forest fires. All debris flows have three fundamental elements: the generation area, the main path and deposit area.

These flows commonly traverse pre-existing drainage runoff channels that have a "V"-shaped or rectangular cross-section. Thick debris flows often form lateral ridges. Debris flows are deposited where the slope of the channel decreases or at the mountain front. Repeated occurrences of debris flows create landforms called debris fans. Some fluid debris flows are exceptionally long and can travel great distances from their generation area. Deposits of these flows of low viscosity extend outside areas of decreased confinement to form alluvial fans.

Debris flows occur in most climatic environments, from deserts to Alpine regions and from the Arctic to Mediterranean areas. These kinds of flows are potentially very destructive in mountainous regions, where the sudden appearance of water, usually from intense rainfall or snowmelt, can mobilize debris covering the slopes and can be incorporated into a coherent flow of debris.

Debris flows are rapid slope movements caused by hyperconcentrated flows of water and sediments, occurring in a wide variety of climates worldwide. They are particularly dangerous to life and property due to their high speeds and their houses, roads, bridges, trees and crops, as well as natural watershed areas and ecosystems along the length of the flow. Debris flows are generally associated with periods of high rainfall intensities or heavy rainfall-snowfall mixtures.

DEBRIS FLOWS AT WORLD LEVEL

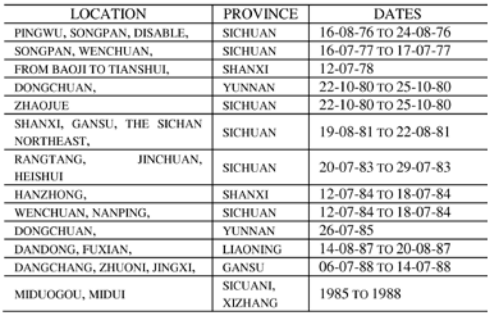
Debris flows disasters are not registered separately from landslide disasters in the EM-DAT database. Therefore, figure 2 presents the total number of landslides collated in the EM-DAT database.

Figure 2 shows that the reported incidence of landslides has increased for 100 years, from 1903 until 2003, and especially during the period from 1990 to 2002.

Figure 3 shows the countries that in 100 years have suffered the most frequent landslide disasters. The figure does not include recent landslide occurrences in other countries that have occurred since 2003.

DISASTERS ASSOCIATED WITH DEBRIS FLOWS

Debris flow disasters have occurred in numerous countries in recent years, including: United States, China, Japan, Italy, Taiwan, Central Asia, Germany, Switzerland, Russia, the Philippines, Ukraine, Canada, Brazil, Ecuador and Venezuela. Numerous debris flows have impacted the country of Mexico recent years, mainly in the Mexican trans-volcanic axis and coastal mountain ranges. Recent debris flows have occurred at Popocatepetl volcano, the volcano Pico de Orizaba, the volcano Nevado de Toluca, mountains of Puebla, in Acapulco, Gro., in the city of Tijuana, B.C. and in the coastal mountain of Chiapas and Oaxaca.



LOCATION	PROVINCE	DATES
PINGWU, SONGPAN, DISABLE,	SICHUAN	16-08-76 TO 24-08-76
SONGPAN, WENCHUAN,	SICHUAN	16-07-77 TO 17-07-77
FROM BAOJI TO TIANSHUI,	SHANXI	12-07-78
DONGCHUAN,	YUNNAN	22-10-80 TO 25-10-80
ZHAOJUE	SICHUAN	22-10-80 TO 25-10-80
SHANXI, GANSU, THE SICHAN NORTHEAST,	SICHUAN	19-08-81 TO 22-08-81
RANGTANG, JINCHUAN, HEISHUI	SICHUAN	20-07-83 TO 29-07-83
HANZHONG,	SHANXI	12-07-84 TO 18-07-84
WENCHUAN, NANPING,	SICHUAN	12-07-84 TO 18-07-84
DONGCHUAN,	YUNNAN	26-07-85
DANDONG, FUXIAN,	LIAONING	14-08-87 TO 20-08-87
DANGCHANG, ZHUONI, JINGXI,	GANSU	06-07-88 TO 14-07-88
MIDUOGOU, MIDUI	SICUANI, XIZHANG	1985 TO 1988

Tab. 1 - Regions affected by debris flows in China 1976-1988

UNITED STATES

Utah received national attention and in the spring of the year 1983 due to the floods, earth sliding and debris flow caused by severe snow storms in the region (Wieczorek *et alii*, 1987). The worst damages caused by the debris flows occurred in Davis County, in the opening of the Rudd stream. Some debris flows happened in at least 600 tributaries of the Colorado River in The Grand Canyon, between Lees Ferry and Surprise Canyon, Arizona (Melis *et alii*, 1994; griffiths *et alii*, 1996). Most of the flows occurred during convective summer storms with intensities of rain of the order of 40 mm/h.

More than 1.000 debris flows occurred on wooded slopes Madison County, Central Virginia, during an intense storm on the 27 of June of 1995 (Wieczorek *et alii*, 1996).

Numerous occurrences of debris flows have affected in the mountainous areas of southeastern of British Columbia in the last decade. In November of 1995 two debris flows appeared in Pierce Creek, in Valle Chilliwack, and in Hope Creek, with 50.000 m^3 of debris carried during two hours, near the city of Hope (Jacob *et alii*, 1997).

A series of debris flows appeared in several canyons 35 miles to the east of Portland, Oregon, on the days 7th and 8th of February of 1996, near the small localities of Dodson and Warrendale, destroying the interstate highway number 84 as well as the railroad and necessitating the evacuation of residents from the area (Powell *et alii*, 1996).

CHINA

The Liaoning province is located in the northeast region of China between 118°53' and 125°46' longitude and from 38°43' N to 43°26' N latitude, and is divided in four regions.

On July 28, 1981 an extreme precipitation event produced avalanches, rock sliding and debris flows in more than 100 ravines and slopes of the Laomao mountain in this province, resulting in damage to 115 villages in 6 counties and affecting 556.000 people, destroying 38.517 houses, 60.000 hectares of agricultural land and destroying 4, 9 kilometers of the Changchun-Dalian railroad line. Losses to the Chinese economy losses reached 547' 000.000 yean (Zhao *et alii*, 1992).

JAPAN

In Japan during twenty years, between 1967 and 1987, 4598 people were killed by natural disasters, of which 1257 passed away due to the debris flows, which corresponds to 27, 3% of the total (Takahashi, 1991). This high percentage results from the tendency of people tend to live in high risk zones, near the foot of mountains where this type of hazard is concentrated.

In 1990 the Mount Unzen volcano erupted, triggering 114 debris flows (lahars) that deposited nearly 8' 000.000 m^3 of debris that destroyed 1123 buildings. The number of refuges required by this event was greater than 11.000 in August of 1991 (Suwa & Yamakoshi, 1997).

ITALY

July 19, 1985 the failure of two dams in the Valley of the Stava River, in northeastern Italy caused a catastrophic debris flow, which destroyed 2 villages and killed 270 people (Berti *et alii*, 1997).

A debris flow also happened October 18, 1990 in Pomonte Creek, below Monte Capanne, Elbe Island, of Archipelago of Toscana, Italy, with approximately 34.000 m^3 of debris (Iotti & Simoni, 1997).

TAIWAN

During the last decade, several disasters produced by debris flows occurred in Taiwan, causing hundreds of deaths, injuries, and damage to houses, schools, highways, bridges and other public and private properties (Cheng *et alii*, 1997). In table 2 the characteristics of 6 of these disasters are summarizes.

SWITZERLAND

The debris flows are a common phenomenon in the Swiss Alps, as well as in other mountainous zones of the world. A tool important to understand the

LOCATION	DATE	IMPACTS
Tug-Men, Hualien, Taiwan	23-06-90	29 dead, 6 missing, 7 injured, 24 destroyed houses, 68 victims and important damage to highways.
Chun-Keng Kuo, Nantou, Taiwan	31-07-96 to 01-08-96	4 dead, substantial damages to houses, highways and other properties.
Er-Bu-Keng, Taiwán	31-07-96	5 dead, 10 houses and 3, 78 hectares of fruit destroyed, important streams damaged.
Feng-Chiu, Nantou, Taiwan	31-07-96 to 01-08-96	2 dead, 10 houses and 14 hectares of agriculture destroyed, serious damages in 18 highways, and rivers.
Tung-Fu, Nantou, Taiwán	31-07-96	2 dead, 18 destroyed or damaged houses.
Shen-Mu Village, Nantou, Taiwan	31-07-96 to 01-08-96	5 dead, 6 injured, 8 destroyed houses and bridges, important damage to 3 hectares of agriculture.

Tab. 2 - *Zones affected by debris flows in Taiwan*

Fig. 4 - *Location of the 3 debris flow observation stations in Switzerland*

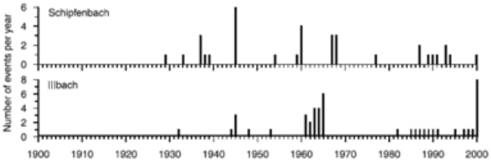


Fig. 5 - *Historical registries of debris flows during the XX Century in Schipfenbach and Illbach, Switzerland*

mechanics of this type of flows is the installation of observation stations that allow data collection in real time. This type of station has been installed in 3 river basins of Switzerland. These stations are equipped with ultrasonic video cameras, radars, geophones and instruments for measurement of precipitation. Figure 4 shows the locations of these stations.

Graph 5 shows the number of debris flow events per year that have been registered in two of these hydrological river basins of Switzerland.

In 2000 four important debris flows were observed in this area of Switzerland. These deposits varied in volume from 5.000 m^3 up to 35.000 m^3; average speeds ranged from 2, 0 m/s up to 5, 0 m/s, and maximum flow ranged between 20 m^3/s and 125 m^3/s.

CENTRAL ASIA

Central Asia is an area with a high level of debris flows risk; the most important areas include hills of Valle Fergana, Valle Zerafshan, and the Issyk-Kul river basin, the central and south part of Tdjikistan and also the hills of Kopetdag. In all these areas the destructive flows happen during the spring-summer period in small rivers and ephemeral channels (Salikhova & Liahovskata, 1992).

GERMANY

The village of Tramin in the south of Tyrolia was affected by a sudden debris flow on June 23, 1986, during a severe storm. The debris flow completely destroyed a new rest center and seriously damaged a wine cooperative, with the total damage amounting to 6 million dollars (Strunk, 1992).

RUSSIA

The areas in where greater amount of debris flows has appeared in this country are three regions: to the east of the Sayan mountains, the mountain to the Southeastern of Baikal Lake and the northeast of the Baikal region, with registries from 1871 to 1971 (Makarov & Agafonov, 1977).

THE PHILIPPINES

The eruption of Monte Pinatubo in June of 1991 deposited of 7 to 8 km^3 of pyroclastic material in slopes of the volcano. These pyroclastic deposits formed the sediment sources for the debris flows of volcano (lahars) of a frequent and great scale, that appear each season of rains causing great morphologic changes and massive devastation in the zone. To the date more than 400.000 people they have been moved and around 350 km^2 with territories of agricultural culture they are covered with material of lahars.

The number of dead in a series of debris flows that happened in the Philippines after six days of intense rains can surpass the hundred, said the authorities of the country, after 35 corpses were recovered and tens of people disappeared; in December of 2003, 300 people were evacuated towards safer zones after the soldiers got to the zone of disaster to rescue the victims cached under mud and debris.

THE UKRAINE

The combination of natural conditions in the mountains Carpathian, Crimean and along the rivers Dnieper and Dniester is favorable for the formation of the debris flows (Yablonskiy *et alii*, 1992).

CANADA

Howe Sound is a region prone to the presence of debris flows, which extends from the Horseshoe Bay (20 km to the northwest of Vancouver) to Squamish, in Canada, where they have appeared a great number of these events due to the type of ground, slopes in his valleys as well as the deforestation and fires in the zone.

BRAZIL

At the beginning of August of 2000 great debris flows took place caused by five days of torrential rains in the northeast of Brazil, causing 28 died and 90.000 abandoned. Bad weather caused the most serious damages in the states of Pernambuco and Halagaos, affecting to 46 localities.

ECUADOR

At least 36 died people died, 11 disappeared and 212 families damaged were the balance who left to the debris flows happened in Ecuador day 13 of June of 2001, affecting the provinces of Papallacta, Amazonia, Tungurahua and Zamora Chinchipe.

MEXICO

In this country, a great amount of debris flows have appeared in recent years, many of them in the Mexican trans-volcanic axis and coastal mountain ranges, such as the happened ones in Popocatepetl volcano, the volcano Pico of Orizaba, the Nevado de Toluca volcano, in the mountains of Puebla, in Acapulco, Gro., in the city of Tijuana, B.C. and in the coastal mountain range of Chiapas and Oaxaca, to only mention those that have produced important disasters in recent times.

VENEZUELA

Probably one of the disasters produced by the combination of diverse processes of removal in mass, including the debris flows, with greater dimensions in recent years, is due to the storm from the 14th to the 16th of December of 1999 in the coasts of Venezuela, particularly in slopes of the Mountain of Avila, at the north of Caracas, Venezuela. The severe storm from the 14th to the 16th of December of 1999 caused catastrophic sliding of earth and floods with debris flows throughout 40 kilometers on the coast of Caracas, between the Guaira and Naiguita, located in the coastal state of Vargas, Venezuela. The damages to the communications and the infrastructure of this zone were very high. In Vargas, more than 8.000 individual residences and 700 apartment buildings were destroyed completely (Salcedo, 2000).

The highways, and the telephone services, electricity, water and sewage systems severely were damaged. The total economic losses was calculated as 1, 79 Venezuelan pesos billion and preliminary estimations established that between 5.000 and 50.000 people they passed away (Brandes, 2000; Sancio & Districts, 2000; Salcedo 2000 and USAID; 2000). The estimation of the number of inhabitants of Vargas was approximately of 300.000 inhabitants before the catastrophe, which means that approximately 10% or more passed away by this event.

DEBRIS FLOWS INITIATION PROCCES

Knowledge of the mechanism in the debris flows initiation process is fundamental to the mitigation of risks associated with this type of hazards and a necessary requirement to implement measures to reduce the disastrous effects they produce. Understanding this process can provide a guide to classify hazardous areas and design protective structures. On the other hand, it also can increase the understanding of critical situations of these areas and serve as a criterion to send forecasts of hazardous events and people can be evacuated from those places of high risk (Honda *et alii,* 1997).

However, investigations related to debris flows until now, have essentially focused on the dynamics of debris flows, its deposit mechanism, numerical modeling and computer measurement features. The debris flows formation process is currently very poorly understood. This is the fundamental reason for this work, with the idea to help increase a little understanding of the debris flows initiation process.

TRIGGERING FACTORS OF THE DEBRIS FLOWS

The mass removal processes or field movements (which include debris flows) occur due to two fundamental causes (Terzaghi, 1950; Selby, 1993). External causes are all those that produce an increase in loads, but not in the strength of materials; internal forces are those which diminish the strength of materials without changing the loads. This way, we can say that mass removal processes are those movements of soil, debris and rocks that occur in a slope as a result of the direct influence of gravity and which can be triggered by internal or external factors.

The most important external type changes include geometric or weight changes facing slopes (as a result of erosion, undermining, incision of a river, artificial excavations, uploads and downloads), natural and artificial transitional loads that are exposed (earthquakes, explosions or use heavy machinery vibration) and changes to the hydrologic regime (intensity and duration of precipitation, etc.). The major internal changes relate to the transformation of materials from progressive movements (by lateral expansions, fissures, etc.), processes of weathering and erosion. Mass removal processes occur through a combination of factors, such as all contribute in different degrees to their instability.

However, according to the circumstances, some of these elements can be considered crucial, triggers as for example, the presence of extraordinary rainfall in permeable materials, reason why it is not only important to know the mechanisms and types of movements, but also the factors that cause and control such processes on defined spaces.

MODELS EMPLOYED TO DESCRIBE THE INITIATION DEBRIS FLOWS

Analysis of the initiation of the movement of a debris flow underlines that causal factors of this phase of the process are the location of the trigger area and the main triggering mechanism (hydrodynamic actions, geotechnical causes and mechanical equilibrium).

At one level of outcome is difficult to identify which of these mechanisms is the most likely makes the largest contribution; in any case, any of these types of mechanisms can include others, or rather, in the same event different trigger mechanisms can occur in different areas of the basin. In some studies concerning the trigger not cohesive debris followed by a flow of surface water flow conditions analysis focuses on the study of the instability of the accumulation of material that occurs below the saturation. A surface flow drained in a slope from intense rainfall, primarily saturated layers of debris, and then mobilizes them, thus causing the dispersion of solid particles of the full depth of surface runoff, which eventually becomes a flow of debris accumulation.

With the purpose of identifying mechanisms involving the solid material in a fluid, it is necessary to analyze the roles played by various forces acting on the genesis of the movement. Approaches developed to date are as follows: model of infinite slope stability, approximation of Shields, approach of Takahashi, and recent developments, (Lorenzini & Mazza, 2004).

GCL MODEL

The debris flows initiation process is influenced by many factors: morphological, geological, hydrological, plant coverage, topographic, and anthropogenic; it is necessary to establish a methodology that takes into account most of these aspects.

Some researchers have intended to understand the relationship between climate and geomorphologic processes, which trigger debris flows. These works have analyzed the physical properties of the failed slope, the effects of the angle of inclination and soil pore pressure, mechanical movement debris flows and the resulting deposits properties (Scott, 1972; Williams & Guy, 1973; Hollingsworth & Kovacs, 1981; Istok & Harward, 1983; Pierson & Costa, 1987; Montgomery & Dietrich, 1994; Wu & Sidle, 1995; Pack, 1995; Morgan *et alii*, 1997; Reid *et alii*, 1997; Griffiths *et alii*, 1997; Wieczorek *et alii*, 1997; Tognacca & Bezzola, 1997; Gregoretti, 2000; Iverson, 2000; Chen & Jan, 2004; Reid *et alii,* 2003; Savage & Baum, 2003).

Taking into consideration the prevailing factors and models for known debris flows startup as well as the analysis of the works of previous researchers, distributed hydrologic models and using digital elevation models in combination with the model of infinite slope stability and geographic information systems technology, it was developed a model to estimate the potential areas of startup in a debris flow.

DESCRIPTION OF THE GCL MODEL

The proposed model was realized by a computer program, which was developed using some sub-

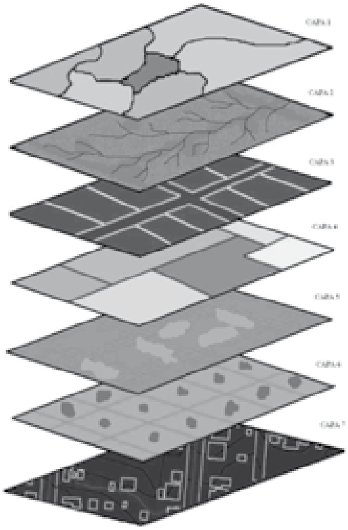


Fig. 6 - Themes or layers in the ‘zoinifluder’ project

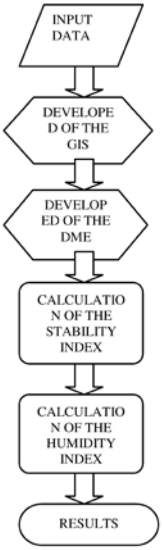


Fig. 7 - Flowchart of proposed model

routines proposed by Pack, using Arc View GIS 3.3 with Arc View Spatial Analyst extension program, and digital models of elevation. This model predicts the potential stability of a debris flow, uses an equation to the safety factor and Darcy’s law for flow-saturated within the ground, in order to estimate the distribution of pore pressures. The saturated flow refers to the flow where the pores are completely filled with water.

The theory underlying the proposed model was implemented in computerized form. The theory was incorporated in a library of routines of computation that can be called to perform computational tasks, including the calculation of stability and saturation rates (humidity index). In addition the library routines are also available for many basic tasks for the management of the mesh data in the digital elevation model (DEM), model including topographic fill mines, calculation of slopes, and determination of the directions of the flow and definition of drainage area to a specific point. These different routines were written in C programming language and are contained within a file (DLL) dynamic link library.

The spatial or geographical nature of the analysis carried out in the model, printed or on-screen maps are required to play some computer outputs. Instead of creating common routines to provide common geographical analysis skills, the model uses the of geographic information systems (GIS) software itself to handle these tasks.

GEOGRAPHIC INFORMATION SYSTEM

According to the requirements necessary for the determination of the initiation areas produced by debris flows in a mountainous region, it was selected the use of the software developed by ESRI to a geographical information system called Arc View GIS 3.3 due its versatility and features, (Shamsi, 2002).

In response to the main factors which triggered the debris flows it was proposed the topics listed below as an integral part of the project of Arc View GIS 3.3, called zoinifluder.apr, and presented in Figure 6.

Layer 1 - Topography of the area of study
Layer 2 - Surficial hydraulics dates
Layer 3 - Soil internal friction angle
Layer 4 - Soil density
Layer 5 Soil cohesion
Layer 6 Plants cover (the root of the trees force)
Layer 7 Subsurficial hydraulics dates

FLOWCHART OF THE GCL MODEL

In order to display graphically the proposed model it presents a diagram of flow in Figure 7.

RESULTS

The proposed GCL model derives its ranking of the ground stability from input as the topographic slope, specific catchment area and the quantification of the properties of the material (such as resistance) and climate (mainly hydrological parameters such as rain) parameters. Each of these parameters is outlined on a numerical grid in the study area. The primary production of this modeling approach is an index of stability, which is the numeric value which is classified or categorizes the stability of the ground in each location of the mesh within the study area. Topographic variables are automatically calculated from the digital elevation (DEM) model data. Other input parameters are recognized as uncertain, so in the model are specified in terms of upper limits and lower ranges that they can be taken.

FUTURE WORKS

It is necessary to apply the proposed model to a recent debris flow to validate this model, which will take place in a next stage of the investigation under way.

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