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Macrozonation Methodology for Landslide Hazard Determination

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ABSTRACT

This is a simple expert system designed to allow a fast, low cost "a priori" classification of landslide hazards in seismically active tropical areas. It has been created to guide decision making where further and more detailed geotechnical investigations should be performed.

The input consists of 5 factors. A combination of three of them (slope, lithology and soil humidity) define the "intrinsic landslide susceptibility indicator." Meanwhile, the "triggering indicator" results from a combination of rainfall and seismic intensity factors.

This system provides a data framework which can be adapted to local and regional trends. The zonation serves as a guide in determining the general trend and spatial distribution of potentially unstable slopes.

INTRODUCTION

Landslides are a common phenomenon in tropical areas. It is a highly significant process in the evolution of landscapes. At the same time, a rapid population growth, with its increasing socioeconomic problems, promotes a disordered settlement of hazard-prone areas. Slope instability and landslides have thus increased their impact in Central America and the Caribbean (DeGraff et al , 1989; Mora, 1989) The zonation of landslide hazards then becomes a very valuable tool for disaster mitigation and preparedness

A review of landslide hazard zonation was given by Varnes (1984), emphasizing the importance of local geologic, geomorphic, hydrologic and climatic conditions. Einstein (1988) developed a determination procedure consisting of five different levels: state-of-nature mapping, danger mapping, hazard mapping, risk assessment and landslide management. Hansen (1984) also proposed different mapping strategies.

At present, the existing geotechnical methodologies allow very detailed investigations on single local cases, upon which the processes are analyzed and quantified, resulting in physical models. However, these models are not useful when extrapolation and prediction in large areas are necessary. Models applicable to large areas are urgently needed for urban planning and hazard reduction (Mora 1991; Mora and Vahrson, 1992).

For this reason, a simple grid unit-based expert system was developed in order to determine landslide hazards on an "a priori" basis, where accurate quantitative field data is scarce. Its inputs are simple morphodynamic (geomorphic) indicators. The scale being used and the preciseness of the available data will influence the approximation to reality of the results.

These indicators are: the intrinsic landslide susceptibility (*SUSC*), determined from the combination of a slope factor (*Sr* = relative relief), a lithology factor (*Sl*) and a factor representing the relative soil humidity conditions (*Sh*) and the triggering factor (*TRIG*), determined from the combination of the factors *Ts* = seismic and *Tp* = precipitation (rainfall) intensities. Efforts are now being made to introduce the influence and effect of land use.

For each factor, an index of influence is determined by a reference value through a specific weight. By multiplying and summing these indexes through the following equations, a relative hazard level = *H* is determined:

$$H = SUSC * TRIG \qquad \text{Eq. 1}$$

$$H = (Sr * Sl * Sh) * (Ts + Tp) \qquad \text{Eq. 2}$$

Spatial distribution of these factors and indicators, alone or by their combination, can be mapped over any type of grid unit. Most Geographical Information Systems (GIS) can be applied to automatically process this kind of data. The results allow identification of the most susceptible and problematic areas, leading to appropriate decisions as to where detailed geotechnical field and laboratory studies should have priority.

Each value of the factors is located on a map and combined with the others over the grid units, according to the scale being used. We recommend the use of a scale of 1:50,000, since it is a standard land-use planning tool and because of its good topographic resolution over the geomorphic features. Input data can also be placed with sufficient accuracy. For other scales, the *Sr* parameter should be recalibrated after defining the unit area to be applied.

Field reconnaissance, analysis of aerial photographs and satellite images can help significantly to improve the diagnosis.

This straight-forward and inexpensive method is particularly suitable for applications in tropical areas with important seismic activity where rapid urban growth, extension of infrastructure facilities, lifeline distribution and productive activities are increasingly prone to growing losses caused by different kinds of landslides.

As an application example, we present the results on the 1:50,000 Tapantí quadrangle (approximately 500 km^2, part of the Caribbean watershed of Costa Rica, see location in Figure 1). The size of the grid unit is 1 km^2. The GIS we applied is IDRISI, a user friendly and low cost geographic information and image processing system developed by the Graduate School of Geography at Clark University.

DETERMINATION OF THE LANDSLIDE HAZARD

The Susceptibility Indicator *SUSC*

Included in this indicator are the factors representing the intrinsic properties of the landscape, mechanical quality of local materials and its "passive" behavior. The properties defining the condition of the slopes under analysis are the relief (*Sr*), their lithologic composition (*Sl*) and the soil humidity (*Sh*)

The slope factor *Sr* represents the natural rugosity of the landscape within a grid unit. It is defined by the maximum difference of elevation in an area of 1 km^2 (relative relief, Rr):

$$Rr = \frac{h_{max} - h_{min}}{km^2} \qquad \text{Eq. 3}$$

where:

Rr = slope value, relative relief (m/km^2)
h_{max} = maximum elevation within one grid unit (m)
h_{min} = minimum elevation within one grid unit (m)

An analysis of Rr values and its spatial distribution shows the influence of the lithologic/tectonic setting. Retrospective correlations indicate an exponential growth of landslide susceptibility (all other parameters kept constant) until high values ($Sr > 800$ m/km^2) are reached. In such cases there are usually massive rocks, more stable than soils, thus evolving into steeper slopes, unless fracture systems combine in the development of rock slides.

Relative relief values have been classified through statistical distributions in order to obtain the slope factor (*Sr*) and its relative weight, which can be used in automatic calculations. It is desirable to develop a

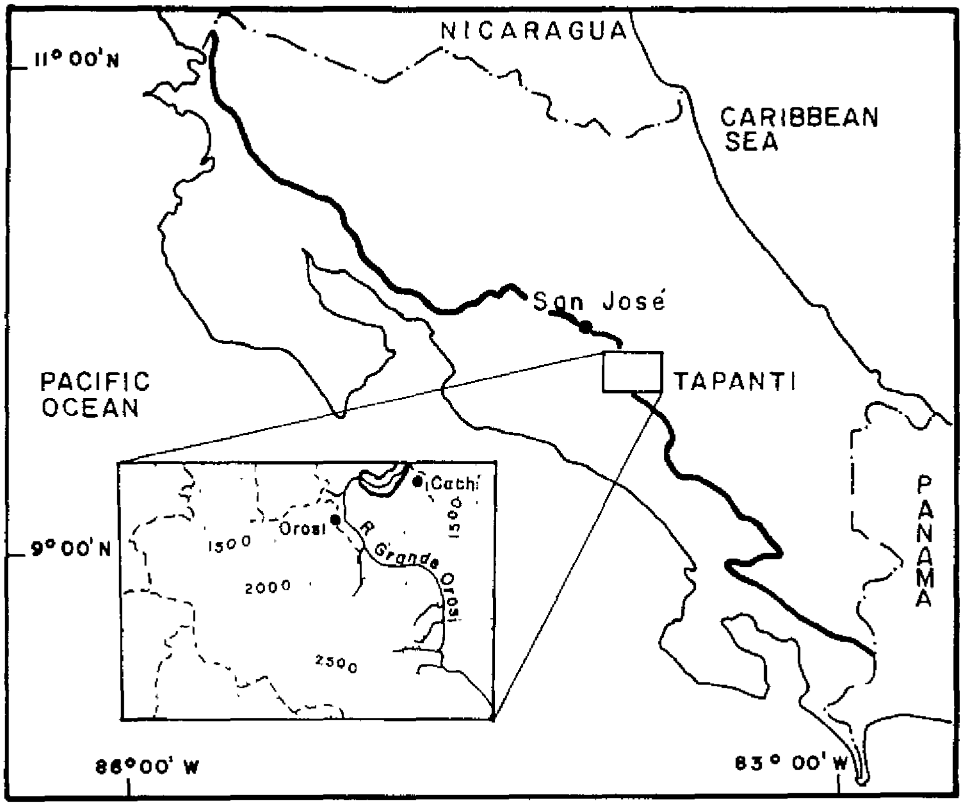

Figure 1 Location of the 1:50,000 Tapantí quadrangle in Costa Rica.

histogram of Rr values to define local trends. In general, for Costa Rica and Central America, Table 1 presents the common classes.

Note that for reliefs of less than 75 m/km^2, in cases of flat or nearly flat areas, the slope factor has a value of zero. This is the only factor reaching such a value, because even if the other factors indicate adverse conditions, the resulting landslide hazard is almost insignificant. In the Tapantí area, *Sr* varies between 0 and 4 units, since slope values range from 0 to 790 m/km^2 (Figure 2).

The lithologic factor *Sl* is probably the most relevant factor and at the same time the most difficult to assess. Ideally, detailed geotechnical information should be used. Where this information is unavailable, a general geologically-based description is to be applied. The description and comparisons must be developed with a good geotechnical judgment.

Several characteristics should be considered: volumetric weight, identification indexes, shear strength indicators, hydrothermal and/or weathering alteration degrees, spatial distribution and characteristics of discontinuities (bedding, joints), their relation with the slope geometry, drainage and pore pressure (negative or positive) conditions, behavior and position of the water table(s). Since these details are not always available, Table 2 shows a general classification of different lithologies and their assigned index (*Sl*). Obviously, *Sl* values need to be completed and adapted to local and regional conditions. The lithologies within the Tapantí quadrangle have been classified as medium, highly and very highly susceptible (*Sl* = 3; 4; 5). Figure 3 shows their distribution.

The relative soil moisture factor *Sh* parameter takes into account the average conditions of soil moisture. It quantifies the influence of accumulated humidity

Table 1 *Relative relief values (Rr), their classification and the resulting values of the slope factor (Sr)*

Slope Value Rr (m/km^2)	Classification	Slope Factor *Sr*
0–75	Very low	0
76–175	Low	1
176–300	Moderate	2
301–500	Medium	3
501–800	High	4
>800	Very high	5

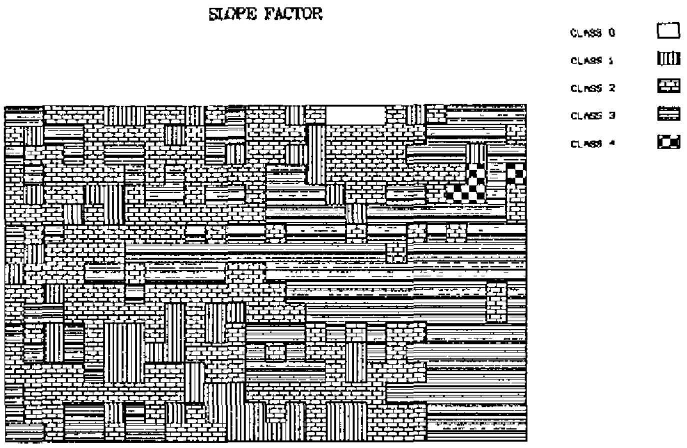

Figure 2. Distribution of the slope factor *Sr* (Tapantí).

throughout the year and can be regarded as a starting point from which heavy rainfalls might act as a destabilizing element. Adding more water increases pore pressures and thus the possibility of a failure. On the other hand, drier soils need heavier rainfalls to produce a rupture.

The best way to determine soil moisture contents is obviously through direct measurements *in situ*, followed by detailed water balances. However, since this information is usually not available, a simple methodology of a soil-water balance is applied, requiring only the average values of monthly precipitations. The following steps have to be taken:

1. Each monthly average precipitation value is assigned to an index value, as shown in Table 3. It has been found that the 125 mm limit value is representative for the average monthly potential evapotranspiration (PET) in Central America (Vahrson, 1991). It has also been shown that significant infiltration requires at least 40 mm of rainfall accumulated in ten days, corresponding to about 125 mm/month. In cases where enough information exists the limit of 125 mm of rainfall should be substituted with the average monthly potential evapotranspiration. For 100 stations in Costa Rica, the values of the potential evapotranspiration according to Hancock and Hargreaves (1977) are well correlated with the elevation, leading to the formula:

$$PET = 1721 - (0.177 * EL) \qquad \text{Eq. 4}$$

Table 2. *Classification of different lithologies and their susceptibilities, following examples of representative cases in Costa Rica and Central America.*

Lithology	Qualification	Factor *Sl*
Permeable compact alluvium; permeable limestone, slightly fissured intrusions, basalt, ignimbrite, gneiss, hornfels, low degree of weathering, low water table, clean-ruggose fractures, high shear resistance.	Low	1
Higher degree of weathering of above mentioned lithologies and of hard massive sedimentary rocks, lower shear resistance and shearable fractures.	Moderate	2
Considerably weathered sedimentary, intrusive, metamorphic, volcanic rocks, compacted sandy regolithic soils, considerable fracturing, fluctuating water tables	Medium	3
Considerably weathered, hydrothermally altered rocks of any kind, strongly fractured and fissured, clay filled; poorly compacted pyroclastic and fluvio-lacustrine soils, shallow water tables	High	4
Extremely altered rocks, low shear resistant alluvial, colluvial and residual soils, shallow water tables	Very high	5

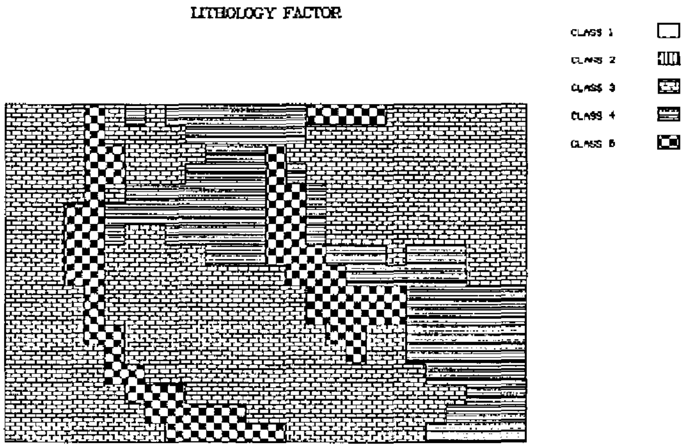

Figure 3. Distribution of the lithology factor *Sl* (Tapantí).

where:

PET = potential evapotranspiration (mm/year).
EL = elevation (m).

2. Once each month is evaluated, the total of all twelve monthly assigned values has to be calculated for each analyzed rain gage station. These total values range from 0 to 24.
3. The total is classified into five groups, as shown in Table 4.

For spatial interpolations and extrapolations of this factor, local and regional precipitation trends should be taken into account. It is also advisable to analyze the influence of the elevation on this factor. In the case of the Tapantí quadrangle, it covers a range from 2 to 5 units. Figure 4 shows the spacial distribution of these values in Tapantí.

The Triggering Indicator *TRIG*

This indicator represents the active external driving forces and their probability of occurrence as landslide triggers. It combines two factors: The one hundred-year seismic and rainfall intensity events.

Table 3. *Classification of average monthly values of rainfall.*

Average Monthly Precipitation (mm/month)	Assigned Value
<125	0
125–250	1
>250	2

The seismic intensity factor *Ts* is determined by analyzing landslides triggered by earthquakes to establish the influence of seismic intensities within similar lithologic, climatic and geomorphic conditions. Different sets of intensities (Modified Mercalli Scale) of approximately comparable seismic sources were correlated with parameters of landslide density and surface destruction (Mora and Mora, 1992; Mora et al., 1992).

Correlations with accelerations, different attenuation models and duration of different levels of strong motion have been attempted without an apparent success, most probably because of lack of sufficient and reliable data (Mora and Mora, 1992).

In Table 5, data from this analysis show several categories of influence, using values of 100-yr return periods related to historical records. It is important to notice that seismicity accounts for the most important and frequent landslide-triggering element, at least in Central America, and for this reason, its index of influence can reach a factor value of up to 10.

In the case of Tapantí, the one hundred-year seismic intensity trend shows moderate-medium values (VI

Table 4. *The Moisture Factor (Sh), resulting from the classification of accumulated values of average monthly precipitation indexes.*

Accumulated Value of Precipitation Indices	Qualification	Factor *Sh*
0–4	Very low	1
5–9	Low	2
10–14	Medium	3
15–19	High	4
20–24	Very high	5

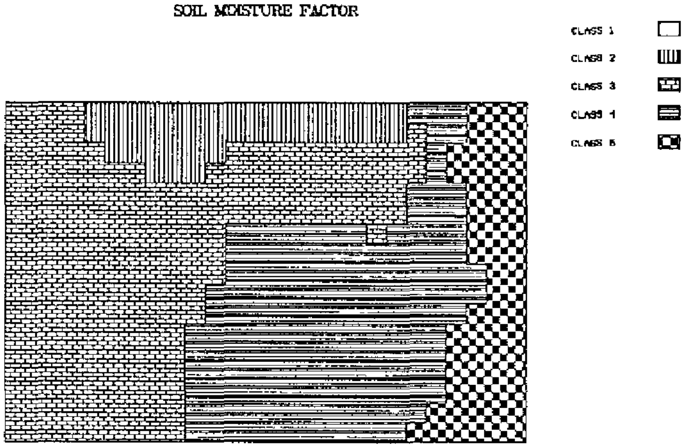

Figure 4. Distribution of the moisture factor *Sh* (Tapantí).

and VII on the Modified Mercalli Scale), giving *Ts* factor indexes of 4 and 5 (Figure 5).

The precipitation intensity factor *Tp* is in Costa Rica and Central America the second most important landslide triggering element. In other areas this factor might even be the most important.

Landslides in residual-regolithic soils on steep slopes are very commonly triggered by short but very intense (convective) rainfalls (Vahrson et al., 1987; Mora et al., 1988). Deeper-seated landslides (i.e. earth-rock slumps; Mora, 1991) are often triggered, reactivated and/or accelerated by less intense, but longer and volumetric (orographic) precipitations.

In order to cover both types of phenomena, a factor was developed based on the determination of the one hundred-year maximum values of daily (24 hr) precipitations, analyzing time series of ten years or more.

Table 5. *Determination of the seismic intensity factor as a trigger for landslide generation, using hundred year intensity values (Modified Mercalli Scale) based from observations in Costa Rica and Central America (Mora and Mora, 1992)*

Intensities (MM) *Tr* = 100 yr	Qualification	Factor *Ts*
III	Slight	1
IV	Very low	2
V	Low	3
VI	Moderate	4
VII	Medium	5
VIII	Considerable	6
IX	Important	7
X	Strong	8
XI	Very strong	9
XII	Extremely strong	10

Usually for all rainfall gages, daily precipitation values are available.

The Gumbel (1945) distribution shows generally a good correlation (Vahrson and Fallas, 1988) in Costa Rica. Table 6 shows the maximum values for 100-yr return periods and their correlated classes. In order to utilize stations with only short records ($n<10$ yr) to cover regions which otherwise have no information, in the same table (column 2) an auxiliary classification is given, based on the average of the yearly maximum values (duration: 1 day).

As in the case of the humidity (moisture) factor *Sh*, interpolations and extrapolations of these values must consider local and regional trends. Also, the relation between elevation and rainfall intensity indicates that in regions above 2,000 m in Costa Rica, *Tp* values of 1 or 2 are usually found. Rainfall intensity *Tp* values in Tapantí range from 2 to 4 (Figure 6).

Combination of Factors and Indicators

By a combination of the susceptibility and trigger indicators, the final landslide hazard can be estimated. The susceptibility indicator *SUSC* results from multiplying the slope, lithology and moisture factors:

$$SUSC = Sr * Sl * Sh \qquad \text{Eq. 5}$$

where:
SUSC = susceptibility indicator
Sr = slope factor (Table 1)
Sl = lithology factor (Table 2)
Sh = moisture factor (Table 4)

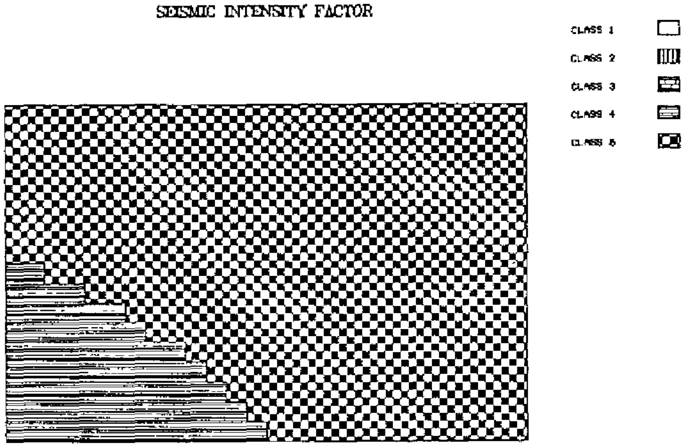

Figure 5. Distribution of the seismic intensity factor Ts (Tapantí).

The values of $SUSC$ range from 0 (possible when $Sr = 0$) up to 125 units. The susceptibility indicator of the Tapantí area is shown in Figure 7 and its values range from 0 to 64 units

The trigger indicator $TRIG$ is the total of the summation of the seismic and rainfall intensity factors:

$$TRIG = Ts + Tp \qquad \text{Eq. 6}$$

where:
$TRIG$ = triggering indicator
Ts = seismic intensity factor (Table 5)
Ts = precipitation intensity factor (Table 6)

The range of the trigger indicator $TRIG$ varies from 2 to 15 units, and in the Tapantí area it has been determined to be between 6 and 9 units (Figure 8)

The final degree of landslide hazard Hl is defined as the product of the susceptibility indicator $SUSC$, and the trigger indicator $TRIG$ as mentioned in Equation 1:

$$Hl = SUSC * TRIG$$

where:
Hl = total landslide hazard

Substituting Equation 5 and Equation 6 in Equation 1 as mentioned in Equation 2:

$$Hl = (Sr * Sl * Sh) * (Ts + Tp)$$

The extreme values of the total landslide hazard Hl vary between 0 (only in the case of very flat areas) and 1,875 units.

To determine the landslide hazard derived from either type of triggering factors, Equation 2 can be separated into the following components:

$$Hsl = Sr * Sl * Sh * Ts \qquad \text{Eq. 7}$$

where:
Hsl = hazard derived from landslides triggered by seismicity

$$Hpl = Sr * Sl * Sh * Tp \qquad \text{Eq. 8}$$

Table 6 *Precipitation intensity factor Tp resulting from the classification of maximum daily precipitations for a return period of 100 yr. An auxiliary classification in column 2 is based on the average yearly maximum values (duration 1 day), applicable only in cases of rain gages with short records*

Maximum Rainfall n>10 yr, Tr = 100 yr	Rainfall n<10 yr; Average	Qualification	Factor Tp
<100mm	<50mm	Very low	1
101–200 mm	51–90 mm	Low	2
201-300 mm	91–130 mm	Medium	3
301–400 mm	131–175 mm	High	4
>400 mm	>175 mm	Very high	5

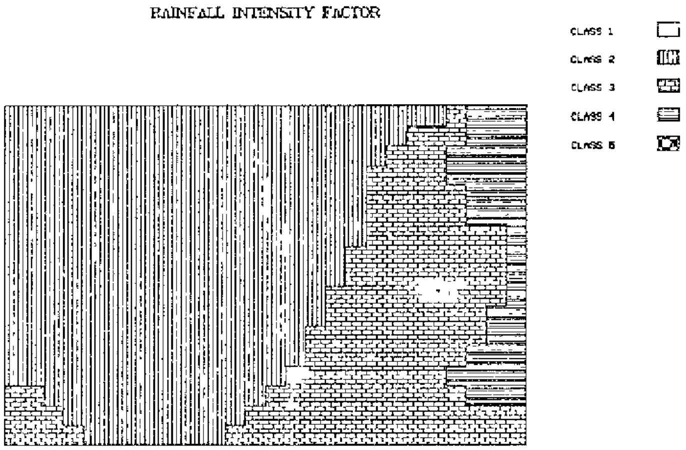

Figure 6. Distribution of the rainfall intensity factor *Tp* (Tapantí).

where:

Hpl = hazard derived from landslides triggered by rainfalls

The values of *Hsl* and *Hpl* range from 0 to 1,250 and 0 to 625 units, respectively.

Classification of the Hazard

According to the results obtained by combining all of the above mentioned parameters through Equation 2, the value of the landslide hazard indicator *Hl* may be classified and evaluated for each particular site as shown in Table 7.

In the example of the Tapantí area (Figure 9), the total landslide hazard *Hl* ranges between Very Low (1) and High (5), with a clear predominance of medium landslide hazard. Anomalies are normally due to the influence of human activities (land use, road and pipeline construction, etc.), deficiencies and insufficiencies of the available data.

CONCLUSION

This macrozonation methodology for landslide hazard determination is capable of showing those areas with a significant degree of potential slope instability. Decisions establishing appropriate priorities to perform more detailed geotechnical site studies, especially where future urban development, infrastructure expansion, lifelines and productive activities can be made.

The most important advantages of this methodology are its inexpensive application, the need for only simple parameters derived from available information, and where detailed geotechnical data is scarce,

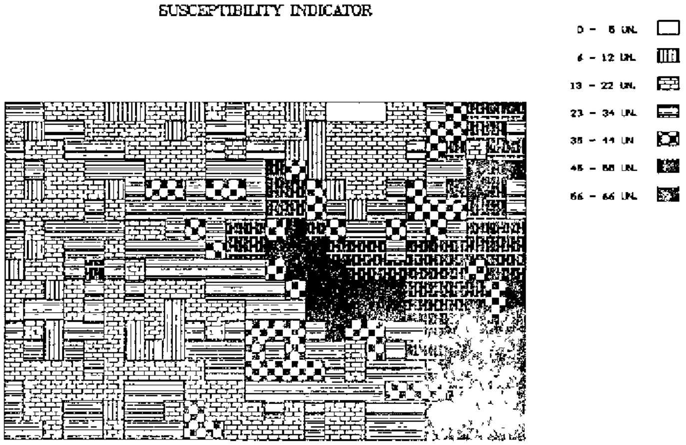

Figure 7. The susceptibility indicator *SUSC* (Tapantí)

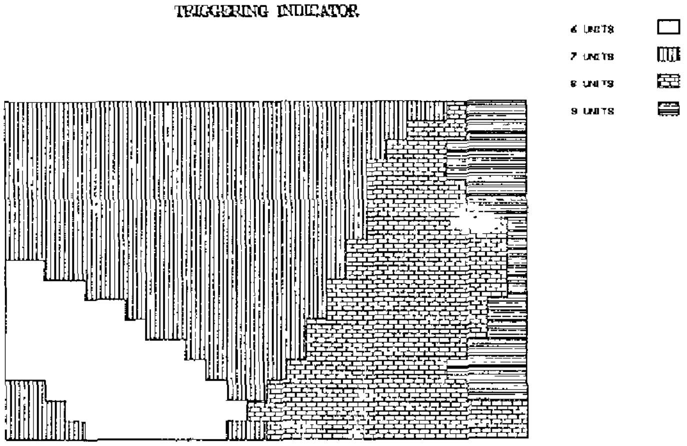

Figure 8. The triggering indicator *TRIG* (Tapantí).

rapid determinations and faster processing when a geographical information system is used.

However, in the determination of some factors, such as the lithologic, humidity susceptibilities and the rainfall intensity trigger factors, it is important to include experienced opinions and judgment as well as to account for the influence of local and regional elements. There is still the need to include a way to determine the influence of land use, especially when inappropriate use (agricultural misuse of soils, overgrazing, deforestation, road and pipeline construction, arbitrary urban development, etc.) is practiced.

This system should not be utilized as a prediction methodology nor as a way to forecast the type of landslides that might occur. It is intended only to be a guide in determining the general trend and spatial distribution of potentially unstable slopes.

Future development of this methodology should include a definition of the most appropriate grid units, in-depth statistical analysis, improvement of the lithological susceptibility determination and its widespread application in order to demonstrate its advantages and weaknesses under different natural and anthropic conditions.

Table 7 *Classification of the landslide hazard Hl parametric values, as derived from Equation 2.*

Value from Equation 2 *Hl*	Class	Classification of Hazard of Landslide Potential
<6	I	Negligible
7–32	II	Low
33–162	III	Moderate
163–512	IV	Medium
513–1250	V	High
>1250	VI	Very high

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