Algorithm Development for Incorporating Soil Physical Properties of each Different Soil Class in a Landslide Prediction Model (SHALSTAB)

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Abstract. The Shallow Stability Model (SHALSTAB) identifies shallow landslide susceptible areas, combining a steady state runoff model that estimates the topographically induced spatial variation in pore pressures with an infinite slope model for shallow landslides. Although the landslides present a strong topographic control, the variability of the soil properties significantly modifies the model results. Thus, the aim of this study was to develop an algorithm for incorporating soil physical properties for each different soil class in the SHALSTAB model, in order to analyze the influence of these parameters in landslides triggering. This approach allowed the model to have a better performance when compared with SHALSTAB results with constant values of soil properties (simple method). It contributed to a more effective prediction in shallow landslide susceptible areas.
Key words: mathematical modeling, landslides, digital elevation model, SHALSTAB model.

1. Introduction

Landslides are common processes along the mountainous landscape of the Brazilian coast, especially during intense summer rainfalls (Ploey & Cruz, 1979; Fernandes *et al.*, 1994; Lacerda, 1997; Smyth & Royle 2000). These catastrophic phenomena are reported almost every year for causing loss of lives and serious damage to roads, bridges, and properties. This is especially true in major cities such as Rio de Janeiro, Santos, Petrópolis and Salvador. Unregulated peri-urban land development has given rise to complex urban structures, which predominantly spread towards the steep hillslopes inside and around the city. This urbanization, especially the slums, includes lack of basic infrastructure services and a rapid densification of informal settlements. The spatial segregation in the cities is characterized by the convergence of numerous intervening social, economic, cultural and environmental variables aggravated by the lack of appropriate public policies and the stigmatization of social minority groups in the urban space (Wacquant & Wilson, 1989; Paim *et al.*, 1999; Santos *et al.*, 2006).

The structure and dynamics of informal urban growth and land use change natural conditions and slope stability by the extensive use of cuts, deforestation, changes in drainage conditions, accumulation of garbage in deposits, among others (Dietrich *et al.*, 1993; Moeyersons, 2003). Many studies have shown that, in this region, topography plays an important role in controlling the location of landslide scars (Barata, 1969). Thus, it is necessary to establish tools for regulating and directing the development of urban land use in order to minimize an imminent urban crisis caused by landslides. Much of disaster policy still emphasizes the impact of nature, and this has led to the dominance of technical intervention focused on predicting the hazard or modifying its impact.

Process-based models are increasing the focus on erosion and landslide studies and hazard assessments because they allow for spatially explicit examination of the potential effects of changes in the governing hydrological and geomorphologic processes. For this reason, a variety of models have been developed and applied in studies of erosive processes (*e.g.*, Moore *et al.*, 1988) to locate saturation zones (*e.g.*, Beven & Kirkby, 1979; O'Loughlin, 1986, Dietrich *et al.*, 1992; Terlien, 1997) and evaluate areas of a landscape shaped by different geomorphologic processes (*e.g.*, Dietrich *et al.*, 1993). These models have been more and more used in environmental studies, since, besides making an understanding of the environmental changes deriving from inappropriate soil management possible, they can also be used to predict future landscape alterations.

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Several different methods and techniques for landslide susceptible mapping have been proposed or tested to identify potentially unstable slopes such as: (a) use of a critical slope angle to designate areas of high hazard (Cruz, 1974; Gao, 1993; Zhou *et al.*, 2002), (b) analyses that combine morphological aspects, vegetation, land use, lithology and geotechnical information (Montgomery *et al.*, 1991, Carrara, 1983; Carrara *et al.*, 1991; Gao, 1993; Larsen & Torres-Sanchez, 1998); and (c) an approach which combines a topographically-driven hydrological model with slope stability models to predict areas of high hazard (*e.g.*, Okimura & Ichikawa, 1985; Dietrich *et al.*, 1992; van Asch *et al.*, 1993; Wu & Sidle, 1995; Pack *et al.*, 1998; Iverson, 2000).

The Shalstab (Shallow Stability*)* model has been used to predict areas subject to shallow landsliding in both urban and rural settings in temperate regions of the western United States (Dietrich *et al.*, 1993, 1995, 2001; Montgomery & Dietrich, 1994; Montgomery *et al.*, 1998) and in tropical Brazil (Guimarães *et al.*, 2003a; Fernandes *et al.*, 2004; Gomes *et al.*, 2005). This approach is based on coupling a hydrological model and slope stability models (Montgomery & Dietrich, 1994; Dietrich & Montgomery, 1998).

The scope of this paper is to identify the landslide susceptible areas of the city of Salvador using the SHALSTAB model, and additionally, to examine the geotechnical properties for different soil classes in the model because, usually, SHALSTAB works with a unique set of soil property over the entire basin. The primary goal is to study spatial geotechnical factors for soil classes that conjointly influence the landslides occurrence. The second goal is to create an algorithm to incorporate spatial distribution of soil properties in the SHALSTAB model. The third goal is to compare these SHALSTAB results with results assuming constant values for the soil properties (simple method).

2. Study Area

The municipality of Salvador is located between the coordinates 12°47' and 13°30' south latitude and 38°18' and 39°30' west longitude in an area of 316 km^2. The study area is located in the northeastern portion of the municipality in a surface of about 9 km^2 that includes most of the district named *Subúrbio Ferroviário de Salvador* (Fig. 1).

The climate in the study area is mostly conditioned by the action of Tropical Unstable Lines (TUL), with the predominance of east winds that reach the coast of Bahia and cause rain, mainly in the summer. The climate of the area is classified as Tropical Humid (TU), with average annual temperature around 24° Celsius and annual precipitation index varying from 1200 to 2000 mm (Magalhães, 1993).

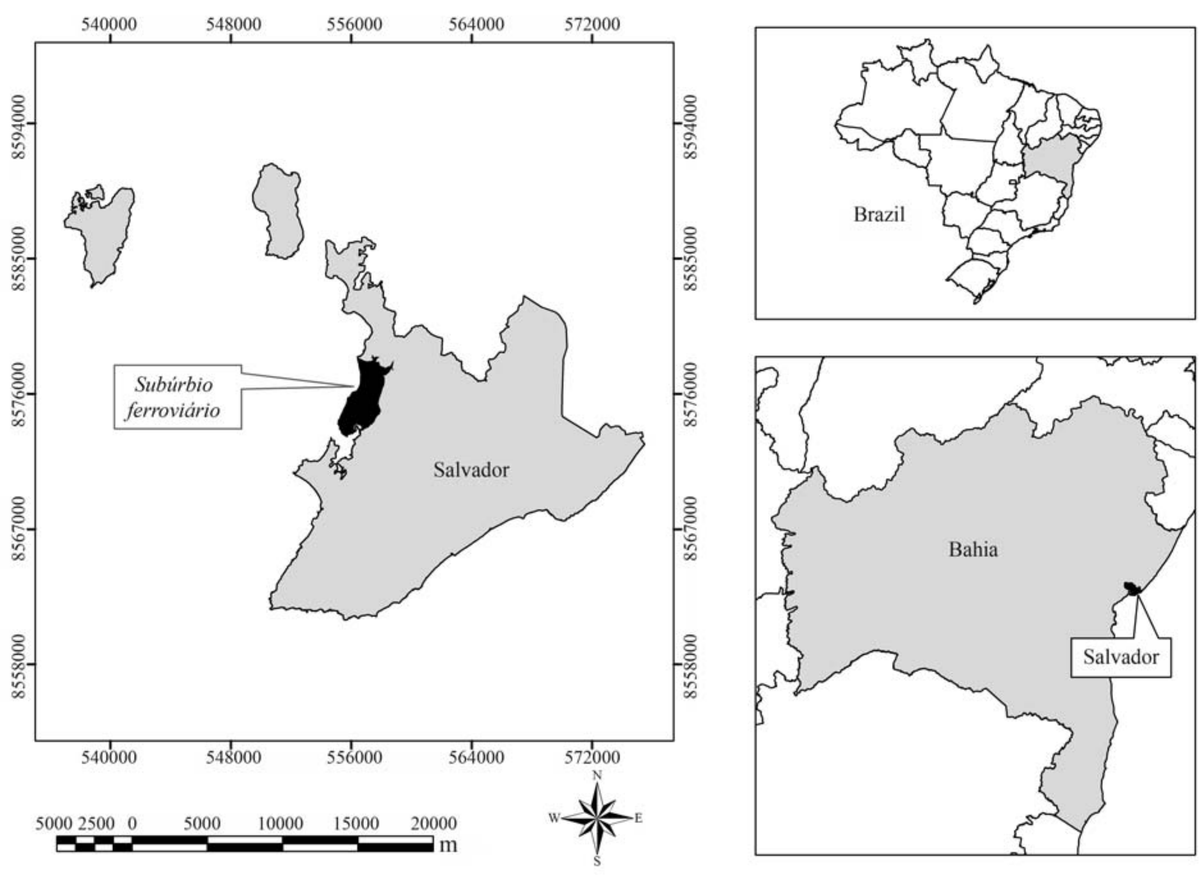

Figure 1 - Location map of the Subúrbio Ferroviário de Salvador.

Geologically, the city of Salvador is mainly represented by: (a) Crystalline Embasement formed by high degree, highly fractured metamorphic rocks (Tricart & Silva, 1968); (b) Recôncavo sedimentary basin terrains, which are abandoned rifts resulting from South Atlantic opening evolution, continental separation between the African and South American (Macdonald *et al.*, 2003), formed predominantly by siltites, shales and sandstones of the Marfim and Pojuca Group in the study area (Geohidro, 1993); and (c) Barreiras Group derived from Tertiary sediments composed of sandstones and conglomerate deposits (Viana *et al.*, 1971; Rossetti & Góes, 2001).

The low strength of the sandy layers of the Barreiras Group sediments results in soil erosion (Viana *et al.*, 1971; Geohidro, 1993). The natural geodynamics presents high susceptibility to landslides due to the pedologic characteristics (intense weathering and vertical variation of the soil profile texture) and extreme climatic events with concentrated rainfall (Peixoto, 1968; Magalhães, 1993). One can observe some spatial erosion patterns in morphology as: (a) the relief has convex hills with high desiccation, occasionally tabular rate; (b) interfluves are generally convex and the fluvial incision gives the concave features; (c) concave shaped slopes are the preferable zones for convergent flux, and they are more susceptible to landslides (Peixoto, 1968). The landslides and gully erosion are commonly triggered or accelerated by human occupation.

The soil occupation in *Subúrbio Ferroviário* occurred in 1875 and is one of the oldest in Salvador (Serpa & Garcia, 1999). However, only from 1950 to 1970 did a large population growth occur, through invasion, with the development of a complex urban structure with predominantly informal urban growth (Brito, 1997). In 1968 the first transference of poor population occurred, due to a governmental policy to withdraw slums from the richer areas of the city. As a result, the *Subúrbio Ferroviário* suffered a dense occupation by popular houses without any planning or environmental adjustment.

Despite Salvador's modernization, concerning urban investments in infrastructure, the city still grows without appropriate planning, mainly in the suburbs. In the *Subúrbio Ferroviário de Salvador*, the slope destabilization caused by deforestation and concentration of informal settlements intensified several environmental and social problems. This is one of the areas in the municipality of Salvador with the highest proportion of landslide victims. As the population increases, the number of houses multiplies and the slums expand intensively on the slopes disregarding its risk factors. The lack of state investments in infrastructure such as waste disposal systems, drainage systems, among others, is clear. Table 1 shows the occurrence and the increment of accidents caused by landslides in Salvador from 1971 to 1999, as well as a considerable social-economic loss.

Table 1 - Mass movement consequences in Salvador between 1971 and 1999 (Source: Augusto Filho & Wole, 1996; Codesal, 2002).

Year	Consequences
1971	104 deaths approximately and thousands of injuries and homeless
1989	109 deaths approximately and many properties damaged
1992	11 deaths approximately, many injuries and properties damaged
1993	5 deaths and many properties damaged
1994	4 deaths, many injuries and more than 150 properties damaged
1995	59 deaths approximately, 48 injuries and more than 500 homeless
1996	29 deaths approximately, many injuries and homeless
1997	10 deaths, approximately 150 homeless and many injuries
1998	3 deaths, many homeless and properties damaged
1999	3 deaths, 50 homeless and many properties damaged

3. SHALSTAB Model

The soil thickness reflects a direct relation between local pedogenesis and erosion (transport) or sedimentation (deposition) and also has a strong interrelation with slope. The relief concave portions (hollows), besides constituting places of high water table, since they represent convergent sites, are also places where the transport material causes sediment accumulation, and consequently, the increase in soil thickness, especially when on unchanneled valleys (Dietrich & Montgomery, 1998).

Dietrich & Montgomery (1998) developed a process-based mathematical model (SHALSTAB model) for the topographic control of shallow landslides. This model results from the combination of a slope stability model with a hydrological model and determines the shallow landslide susceptible areas for each cell (pixel) of the grid (region of interest). Its performance depends basically on both the DEM resolution and the soil physical parameters data.

The slope stability model is based on the concept of an infinite constant slope with constant soil thickness that defines the shear stress on the shear plane (Carson & Kirkby, 1972). The total shear strength at failure is given by Eq. (1):

$$\tau = C' + (\sigma - u)\tan\phi' \quad (1)$$

where τ is the shear strength (kN/m^2), σ is the normal stress (kN/m^2), u is the pore pressure (kN/m^2), C' is the net apparent cohesion attributable to soil cohesion and root reinforcement (kN/m^2) and ϕ' is the effective internal friction angle (degrees).

Figure 2 shows the soil block within the regolith so the value of weight (P) has to be determined indirectly. An approach is to work with the equivalent rectangle ABDF instead of parallelogram ACEF.

Thus, the soil thickness is expressed by Eq. (2):

$$e = z \cos\theta \tag{2}$$

P can be expressed by Eq. (3):

$$P = L \rho_s g z \cos\theta \tag{3}$$

where ρ_s corresponds to bulk density of the soil (kg/m^3), L is the block length (m) and g is the gravitational acceleration (m/s^2).

The lateral root strength model shows that greater root strength is more required for the lateral than the infinite-slope model that provides an only one-dimensional model.

Substituting P (Eq. 3) and dropping L, because it is not relevant in an infinite slope analysis, the shear stress (τ) and normal stress (σ) can be expressed by:

$$\tau = \rho_s g z \cos\theta \sin\theta \tag{4}$$

$$\sigma = \rho_s g z \cos^2\theta \tag{5}$$

Pore-water pressure (u) on the slide plane (Fig. 2), where ρ_w is the bulk density of water (kg/m^3) and h is the thickness of the saturated soil above the impermeable layer (m) is given by:

$$u = \rho_w g h z \cos^2\theta \tag{6}$$

Under this assumption, Eq. (1) can be expressed by:

$$\rho_s = gz \cos\theta \sin\theta = C' + (\rho_s gz \cos^2\theta - \rho_w gz \cos^2\theta) \tan\phi \tag{7}$$

According to Montgomery & Dietrich (1994), by solving Eq. (7) considering the ratio h/z, the slope stability model can be represented by Eq. (8):

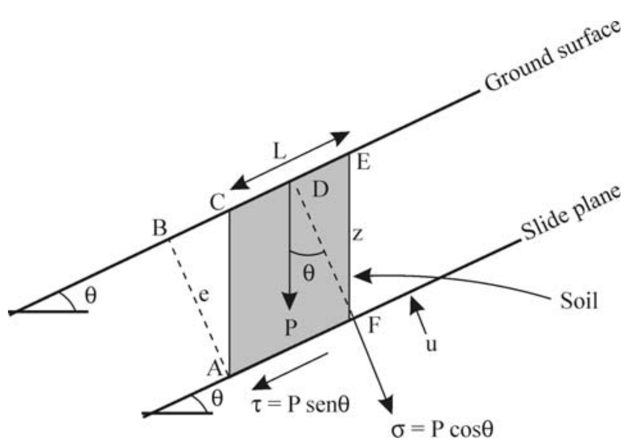

Figure 2 - Stresses acting on a slope of a translational landslide (Adapted from Guimarães *et al.*, 2003b).

$$\frac{h}{z} = \frac{C'}{\rho_w gz \cos^2\theta \tan\phi} + \frac{\rho_s}{\rho_w}\left(1 - \frac{\tan\theta}{\tan\phi}\right) \tag{8}$$

The hydrological model used by SHALSTAB is based on the methodology developed by O'Loughlin (1986), which maps the spatial saturation pattern from the analysis of the upward contribution area, soil transmissivity and local slope, considering that the subsurface flow is parallel to hillslope. Thus, soil saturation condition in equilibrium can be represented as a function of a local wetness (W), as showed in Eq. (9).

$$W = \frac{Q}{T}\frac{a}{b\sin\theta} \tag{9}$$

where a is the upwards contribution area (m^2), b is the length across which flow is accounted for (m), T is the soil transmissivity (m^2/day), Q is the rainfall intensity (mm) and θ is the local slope (degrees).

Montgomery & Dietrich (1994) adopted a simplifying assumption that the saturated conductivity of the soil is constant along the soil profile. Thus, local wetness can be expressed by the ratio h/z when $W < 1$, so:

$$\frac{h}{z} = \frac{Q}{T}\frac{a}{b\sin\theta} \tag{10}$$

This way, combining the infinite stability slope model with the hydrological model, which corresponds respectively to Eqs. (8) and (10), one can predict the critical ratio of the steady-state rainfall to the transmissivity necessary to trigger landslide (Q/T) (Eq. 11):

$$\frac{Q}{T} = \frac{\sin\theta}{(a/b)}\left(\left(\frac{C'}{\rho_w gz \cos^2\theta \tan\phi}\right) + \left(\frac{\rho_s}{\rho_w}\right)\left(1 - \frac{\tan\theta}{\tan\phi}\right)\right) \tag{11}$$

4. Methodology

The input data for the shallow landslide susceptible areas prediction model (SHALSTAB) are: slope and contribution area obtained for the study area from the resulting Digital Elevation Model (DEM) and the soil parameters.

4.1. Terrain attribute data

A 1-m grid DEM was built from digital contour coverage from a 1:5,000 scale topographic map (Fig. 3) and interpolated using the Topogrid module of ARC/INFO. This procedure employs an algorithm developed by Hutchinson (1989) to create hydrologically sound DEM. The algorithm was designed to produce accurate DEM's with reasonable drainage properties from comparatively low-detail and low-accuracy elevation and streamline data sets. The procedure couples a drainage enforcement algorithm that removes spurious sinks and pits, with a finite difference interpolation technique based on the minimization of a terrain specific, rotation invariant roughness penalty (Hutchinson, 1989). The interpolation algorithm was designed to

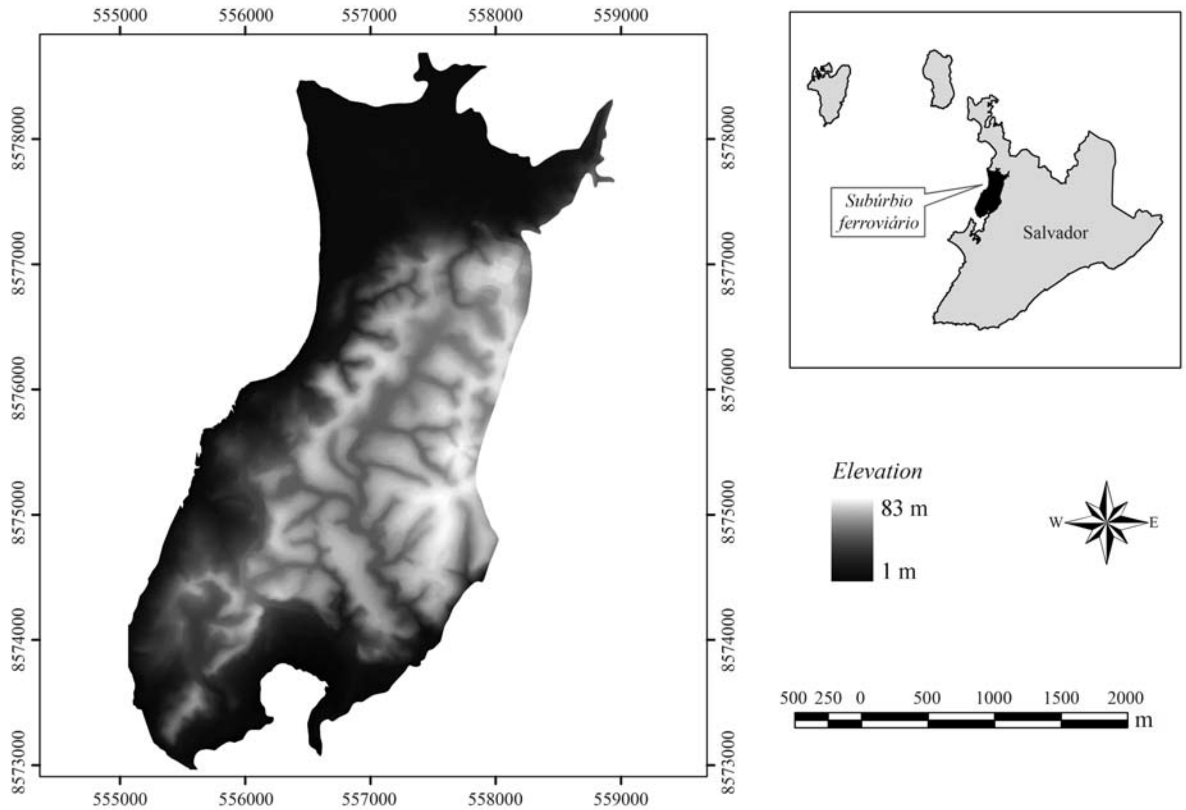

Figure 3 - 1-m grid Digital Elevation Model built from digital contour coverage from a 1:5,000 scale topographic map.

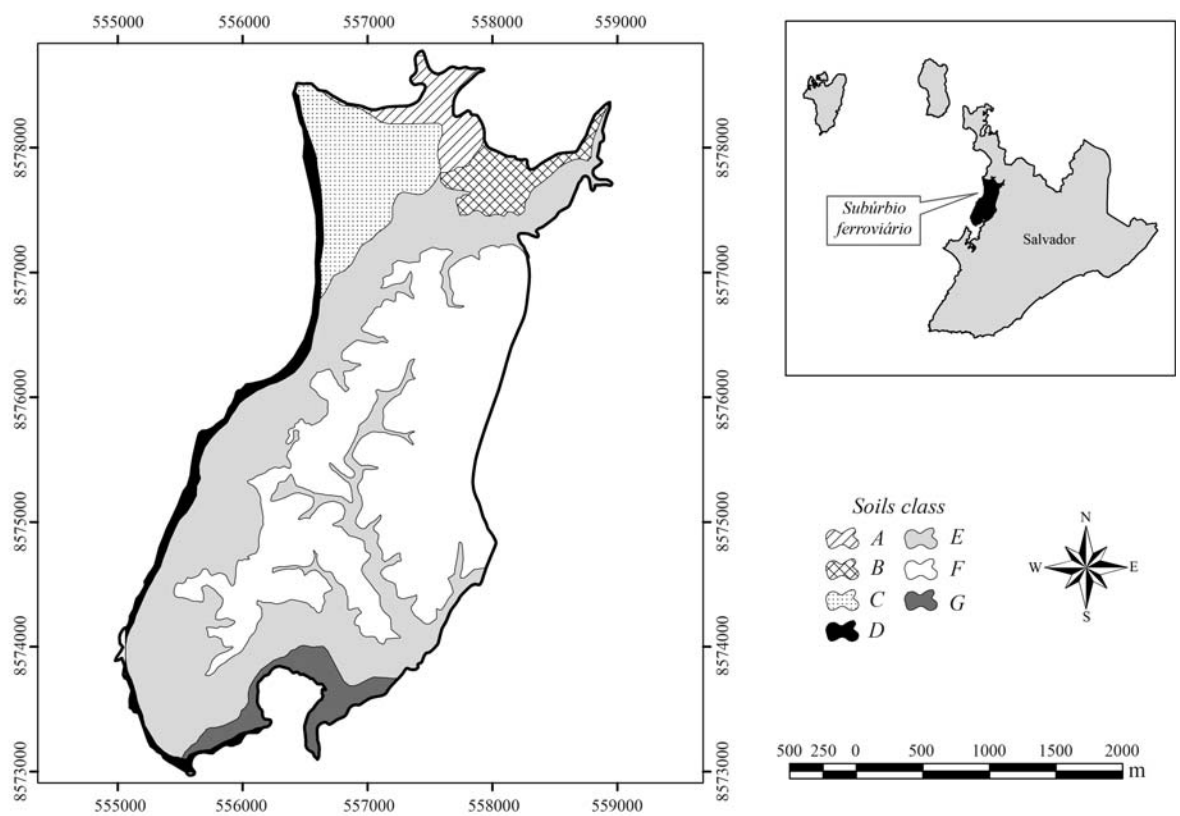

Figure 4 - Soil classes defined for the *Subúrbio Ferroviário de Salvador* (Source: Geohidro, 1993).

have the computation efficiency of local methods (*e.g.* Inverse Distance Weighted) and the continuity in the interpolated surface generated by global methods (*e.g.* Kriging interpolator). In addition, the location and flow direction of the major stream in the valley were digitized and used as extra input for the interpolation procedure.

4.2. Geotechnical properties data

The *Subúrbio Ferroviário* soil map presents seven classes (Geohidro, 1993) (Table 2 and Fig. 4). Classes A, B, C, D and G were grouped as only one class due to the fact that they are located in a gentle relief and, therefore, have the same potential to landslide (Table 3 and Fig. 5).

The geotechnical properties estimate for soil classes (friction angle, cohesion and bulk density) was based on the geotechnical essays developed by Menezes (1987) for three kinds of soils in the Recife urban area with the same characteristics of *Subúrbio Ferroviário de Salvador*.

Table 3 shows the correspondence between the three kinds of slope soils of the Recife urban area with the three kinds defined for *Subúrbio Ferroviário de Salvador* and their respective values of friction angle, cohesion and bulk density.

4.3. Algorithm approach

An algorithm in ARC/INFO Macro Language (AML) was implemented in the SHALSTAB model in order to input cohesion, friction angle and soil density values.

For comparison purposes the SHALSTAB model was also applied disregarding the soil cohesion (simple method) and considering constant values for the friction angle (45°) and soil density (1.700 kg/m^3) (Dietrich & Montgomery, 1998). The b value, which is the cell size (pixel), is also constant for the whole area and equal to 1 m.

Table 3 - Soil parameters (Menezes, 1987).

Soil types	ϕ (degrees)	*C* (kN/m^2)	ρ (kg/m^3)
A	25	1	1500
B	28	10	1500
C	31	7	1500

Notes: ϕ = Friction angle, C' = Cohesion and ρ = Bulk density.

5. Results

The shallow landslide susceptible area, expressed by the ratio *Q/T*, is demonstrated in Figs. 6 and 7. The bedrocks outcrops are located in the class named unconditionally unstable, as well as the areas where the most abrupt interfluves are found. They are characterized, thus, as landslide susceptible areas, even not being completely saturated. The class named unconditionally stable refers to the areas with low slopes.

The frequency distribution of the shallow landslide susceptibility was observed, both from the algorithm developed and from the simple method, in order to evaluate the spatial variation of the soil physical properties. By analyzing Table 4, one can notice that, for the two simulations carried out, the class considered unconditionally unstable is rather superior than the unconditionally stable one. It reached 92,49% in the simulation by the simple method and 97% in the simulation by the algorithm.

Regarding the other susceptibility classes, the comparison between the two simulations has shown that the al-

Table 2 - Degree of landslide potential obtained after crossing soil classes and local slope.

Soil class	Characteristics	Slope classes (%)					
		0 to 5	5 to 15	15 to 25	25 to 35	35 to 45	45 to 50
A	Composed of fine sand, silt, clay and organic matter. Come up on flood surface	B	M	A			
B	Alluvial deposit composed of fine sand, silty and clayey, low support capacity	B	M	A			
C	Expansive clay, from the alteration of shale, sensitive to humidity variation	B	M	M/A	A		
D	Beach deposit, composed of fine to medium-sized, light gray sand, occurs on the coast	B	M	A			
E	Sandy-silty-clayey, clayey layers, presents good cohesion.	B	B	M	M/A	A	
F	Originates from the Barreiras group. Composed of thick sand and red-gray clay	B	B	B	M	M/A	A
G	Composed of fine to middle-sized sand and organic matter	B	M	A			

Notes: B represents a low degree of landslide potential, M represents a median degree of landslide potential, M/A a median to high level of landslide potential and A represents a high degree of landslide potential (Source: Geohidro, 1993).

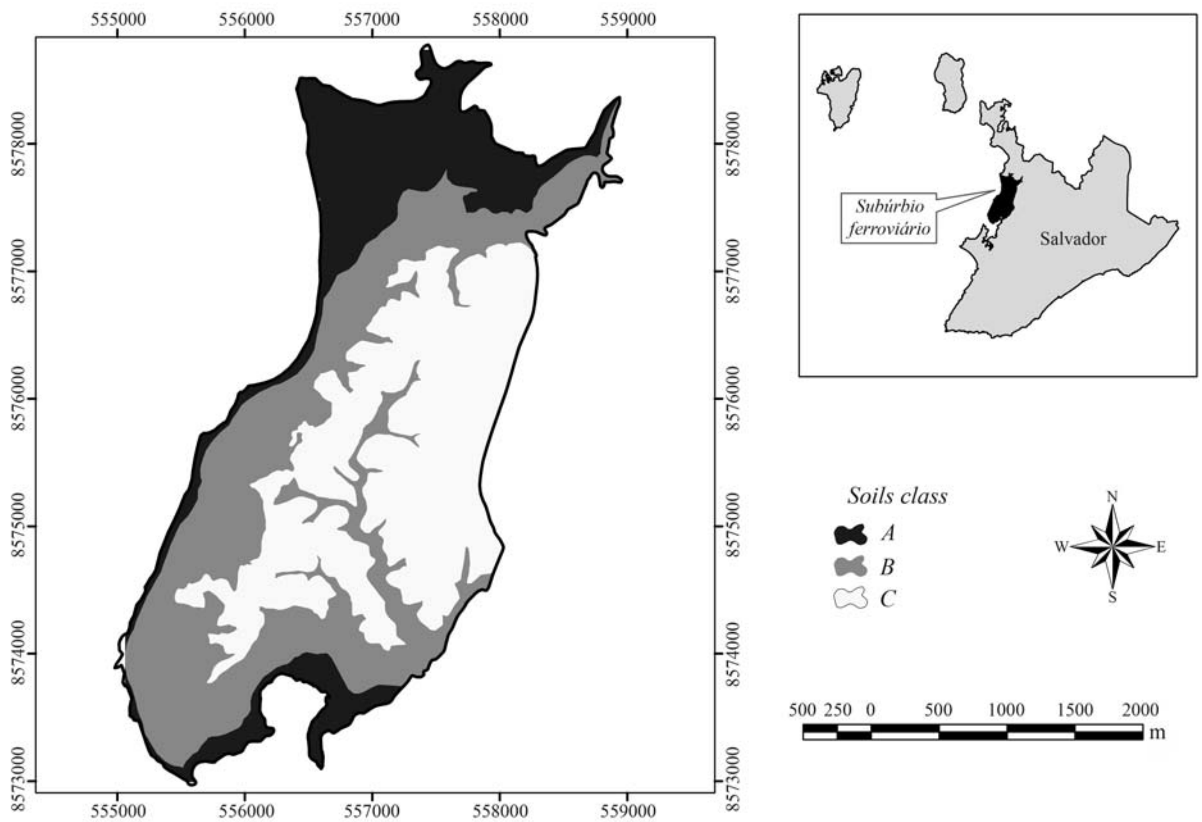

Figure 5 - Soils Map considering the three classes.

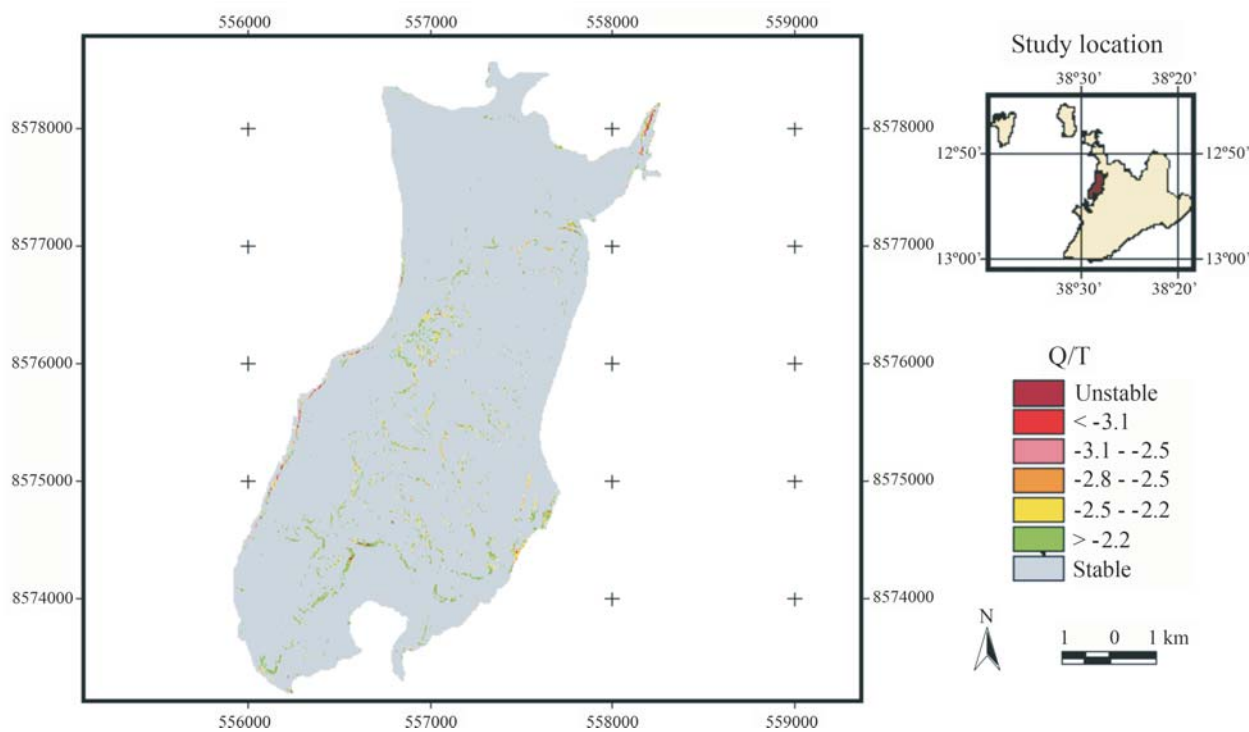

Figure 6 - Shallow landslide susceptibility map expressed by the ratio *Q/T* from the algorithm developed which considers the spatial variation of the soil properties.

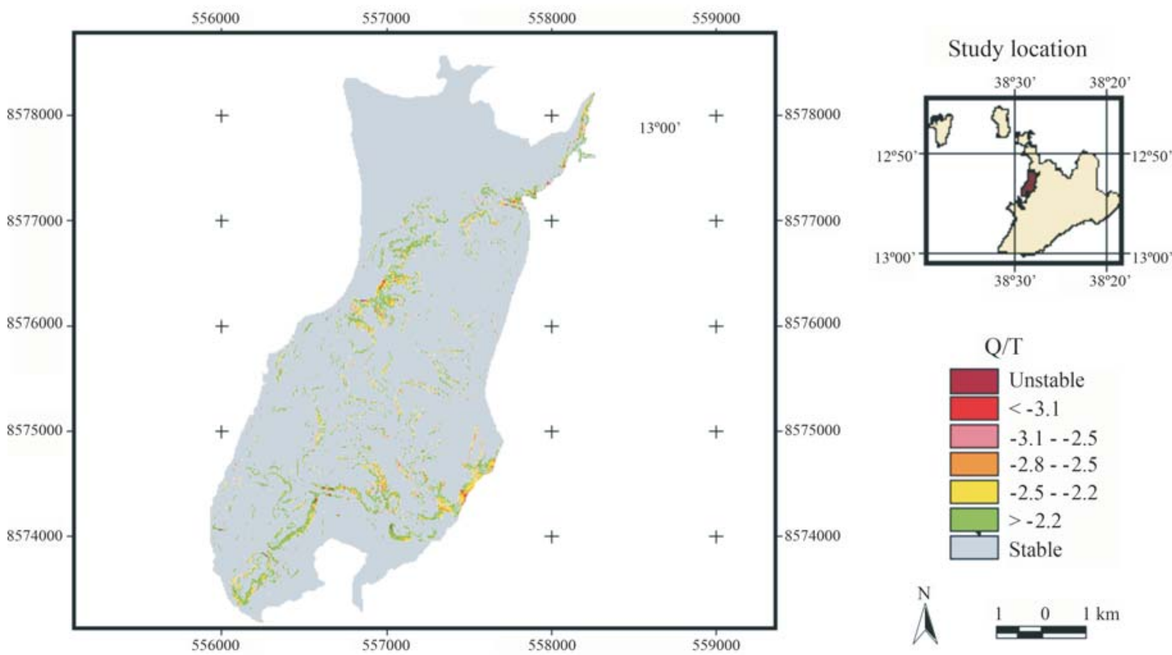

Figure 7 - Shallow landslide susceptibility map expressed by the ratio *Q/T* from the model that does not incorporate the spatial variability of soil properties.

gorithm simulation has identified less susceptible cells than the one that used the simple method. This behavior occurs due to the spatial variation of soil physical properties, and also because of the cohesion considered in the algorithm simulation. The latter decreases the slope instability since it makes the soil more cohesive and, consequently, decreases the percentage of unstable areas.

6. Conclusions

The mathematical modeling based on physical laws and GIS-based analysis constitutes a tool of great potential in identifying landslide susceptible areas by decreasing the subjectivity of the model and allowing for a rapid and efficient characterization over relatively large areas.

Regarding the simulations made to identify shallow landslide susceptible areas, it was observed that there was a high percentage for the class considered unconditionally stable in the study area, both in the simulation concerning the spatial variation of soil physical properties and in the simple method simulation.

It was also observed that there was an overestimate in the frequency potential for the unconditionally stable class in the simulation made by the algorithm in relation to the simple method.

Regarding the unconditionally unstable class, a slight difference between both simulations made was observed. The simulation in which there was spatial variation of soil physical properties presented a lower instability percentage. It happened because this simulation considered the influence of the cohesion in the landslide triggering.

Based on the results obtained, it was noticed that the SHALSTAB written in Avenue language was rather effec-

Table 4 - Frequency distributions of the susceptibility classes to shallow landslide in the Subúrbio Ferroviário de Salvador (Salvador, BA).

Stability classes	Log *Q/T* (algorithm)	Log *Q/T* (%)	Log *Q/T* (simple model)	Log *Q/T* (%)
Unstable	3959	0.04	4559	0.05
< -3.1	6287	0.07	5412	0.06
-3.1 - -2.8	7380	0.08	12403	0.13
-2.8 - -2.5	19412	0.21	51198	0.55
-2.5 - -2.2	55050	0.59	165057	1.78
> -2.2	185491	2.00	456142	4.93
Stable	8978884	97.00	8562166	92.49

tive and viable for using in planning cities of slope contention, besides being a user-friendly tool.

From the simulations made, it was observed that the result for the model, incorporating the soil physical properties, when compared to the results obtained with the simple method, has presented significant differences. It contributes to a more effective prediction in shallow landslide susceptible areas. This shows that better results may be obtained if the model is applied to areas where more data on relevant soil properties is available.

References

Augusto Filho, O. & Wolle, C.M. (1996) Landslide risk map: A methodological proposal and its application to the municipality of Ilhabela, SP. Solos e Rochas, v. 19:1, p. 45-62 (in Portuguese).

Barata, F.E. (1969) Landslides in the tropical region of Rio de Janeiro. Proc. 7th Int. Confer. on Soil Mech. and Found.Eng., Mexico. ISSMFE, London, pp. 507-516.

Beven, K.J. & Kirkby, M.J. (1979) A physically based, variable contributing area model of basin hydrology. Bulletin of Hydrological Sciences, v. 24:1, p. 43-69.

Brito, C.C.T. (1997) Lack of the urban land in Salvador and its consequences in the future reproduction of the urban space. Dissertação de Mestrado, Instituto de Geociências, Universidade Federal da Bahia, Salvador, 130 pp. (in Portuguese)

Carrara, A. (1983) A multivariate model for landslide hazard evaluation. Mathematical Geology. 15:3, p. 403-426.

Carrara, A.C.; Detti, R.; Guzzetti, F.; Pasqui, V. & Reichenbach, P. (1991) GIS techniques and statistical models in evaluating landslide hazard. Earth Surface Processes and Landforms, v. 16:5, p. 427-445.

Carson, M.A. & Kirkby, M.J. (1972) Hillslope Form and Process. Cambridge University Press, Cambridge, 475 pp.

Codesal (2002) Most serious accidents occurred by rains in Salvador between 1993 and 2002 - Relatório Técnico. 10 pp.

Cruz, O. (1974) Serra do Mar and Offshore in the Caraguatatuba-SP Area. Série Teses e Monografias, Instituto de Geografia, Universidade de São Paulo, São Paulo, 181 pp. (in Portuguese).

Dietrich, W E.; Bellugi, D. & Real de Asua, R. (2001) Validation of the shallow landslide model, SHALSTAB, for forest management. In: Wigmosta, M.S. & Burges, S.J. (eds), Land Use and Watersheds: Human Influence on Hydrology and Geomorphology in Urban and Forest Areas. Water Science and Application Monograph, Proc. American Geophysical Union, v. 2, p. 195-227.

Dietrich, W.E. & Montgomery, D.R. (1998) SHALSTAB: A digital terrain model for mapping shallow landslide potencial. National Council of the Paper Industry for Air and Stream Improvement (NCASI), Technical Report, 29 pp.

Dietrich, W.E.; Reiss, R.; Hsu, M.-L. & Montgomery, D.R. (1995) A process- based model for colluvium soil depth and shallow landsliding using digital elevation data. Hydrological Processes, v. 9, p. 383-400.

Dietrich, W.E.; Wilson, C.J.; Montgomery, D.R. & Mckean, J. (1993) Analysis of erosion thresholds, channel networks and landscape morphology using a digital terrain model. The Journal of Geology, v. 101, p. 259-278.

Dietrich, W.E.; Wilson, C.J.; Montgomery, D.R.; Mckean, J. & Bauer, R. (1992) Erosion thresholds and land surface-morphology. Geology, v. 20:8, p. 675-679.

Fernandes, N.F.; Guimarães, R.F.; Gomes, R.A.T.; Vieira, B.C.; Montgomery, D.R. & Greenberg, H. (2004) Topographic controls of landslides in Rio de Janeiro: field evidences and modeling. Catena, v. 55:2, p. 163-181.

Gao, J. (1993) Identification of topographic settings conducive to landsliding from DEM in Nelson County, VA, USA. Earth Surface Processes and Landforms, v. 18:7, p. 579- 591.

Geohidro (1993) Managing Plan of Draining and Stabilization of Soil Slopes in Salvador. Geohidro, Salvador, 233 p (in Portuguese).

Gomes, R.A.T.; Guimarães, R.F.; Carvalho Júnior, O.A. & Fernandes, N.F. (2005) Analysis of a landslides model prediction (Shalstab) in different cartographic scales. Revista Solos e Rochas, v. 28:1, p. 85-97 (in Portuguese).

Guimarães, R.F.; Montgomery, D.R.; Greenberg, H.M.; Fernandes, N.F.; Gomes, R.A.T. & Carvalho Júnior, O.A. (2003a) Parameterization of soil properties for a model of topographic controls on shallow landsliding: Application to Rio de Janeiro. Engineering Geology, v. 69:1-2, p. 99-108.

Guimarães, R.F.; Fernandes, N.F.; Gomes, R.A. T. & Carvalho Júnior, O.A. (2003b) Theoretical reviews of landslides model prediction shallow stability (Shalstab). Espaço & Geografia, v.6:2, p.133-150 (in Portuguese).

Hutchinson, M.F. (1989) A new procedure for gridding elevation and stream linedata with automatic removal of spurious pits. Journal of Hydrology, v. 106, p. 211-232.

Iverson, R.M. (2000) Landslide triggering by rain infiltration. Water Resources Research, v. 36:7, p. 1897-1910.

Lacerda, W.A. (1997) Stability of natural slopes along the tropical coast of Brazil. Proc. Symp. Recent Developments in Soil and Pavement Mechanics, A.A. Balkema, Rotterdam, pp. 17-39.

Larsen, M.C. & Torres-Sanchez, A.J. (1998) The frequency and distribution of recent landslides in three montane tropical regions of Puerto Rico. Geomorphology, v. 24:4, p. 309-331.

Macdonald, D.; Gomez-Perez, I.; Franzese, J.; Spalletti, L.; Lawver, L.; Gahagan, L.; Dalziel, I.; Thomas, C.; Trewin, N.; Hole, M. & Paton, D. (2003) Mesozoic break-up of SW Gondwana: implications for regional hydrocarbon potential of the southern South Atlantic. Marine and Petroleum Geology, v. 20:3-4, p. 287-308.

Magalhães, M.A.C. (1993) Mass Movement and Soil Occupation in Engenho Velho da Federação Neighbor. Salvador - Bahia. Dissertação de Mestrado, Instituto de Geociências, Universidade Federal da Bahia, Salvador, 129 pp. (in Portuguese)

Menezes, V.G. (1987) The rainfall and landslides in hillslopes in the Recife urban area. Proc. 50 Congresso Brasileiro de Geologia de Engenharia, São Paulo, v. 2, p. 347-358.

Moeyersons, J. (2003) The topographic thresholds of hillslope incisions in southwestern Rwanda. Catena, v. 50:2-4, p. 381-400 (in Portuguese).

Montgomery, D.R. & Dietrich, W.E. (1994) A physically based model for the topographic control on shallow landsliding. Water Resources Research, v. 30:4, p. 1153-1171.

Montgomery, D.R.; Sullivan, K. & Greenberg, M.H. (1998) Regional test of a model for shallow landsliding. Hydrological Processes, v. 12:6, p. 943-955.

Montgomery, D.R.; Wright, R.H. & Booth, T. (1991) Debris flow hazard mitigation for colluvium-filled swales. Bulletin Association Engineering Geology, v. 28, p. 303-323.

Moore, I.D.; O'Loughlin, E.M. & Burch, G.J. (1988) A counter-based topographic model for hydrological and ecological applications. Earth Surface and Processes and Landforms, v. 13, p. 305-320.

Okimura, T. & Ichikawa, R. (1985) A prediction method for surface failures by movements of infiltrated water in a surface soil layer. Natural Disaster Science, 7:1, p. 41-51.

O'Loughlin, E.M. (1986) Prediction of surface saturation zones in natural catchments by topographic analysis. Water Resources Research, 22:5, p. 794-804.

Pack, R.T.; Tarboton, D.G. & Goodwin, C.N. (1998) Terrain stability mapping with SINMAP, technical description and users guide for version 1.00. Report Number 4114-0, Terratech Consulting Ltd., Salmon Arm, Canada, 68 pp.

Paim, J.S.; Costa, M.C.N.; Mascarenhas, J.C.S. & Silva, L.M.V. (1999) The distribution of violence: mortality due to external causes in Salvador, Brazil. Revista Panamericana de Salud Publica, v. 6:5, p. 321-332.

Peixoto, C.S. (1968) The Physics Factors Conditioning the Problems in Salvador City. Tese de Doutorado, Faculdade de Filosofia, Universidade Federal da Bahia, Salvador, 186 pp (in Portuguese).

Ploey, J. & Cruz, O. (1979) Landslides in the Serra do Mar, Brazil. Catena, v. 6:2, p. 111-122.

Rossetti, D.F. & Góes, A.M. (2001) Imagine upper Tertiary to Quaternary deposits from northern Brazil applying ground penetrating radar. Revista Brasileira de Geociências, v. 31:2, p. 195-202.

Santos, S.M.; Barcellos C. & Carvalho M.S. (2006) Ecological analysis of the distribution and socio-spatial context of homicides in Porto Alegre, Brazil. Health & Place, v. 12:1, p. 38-47.

Serpa, A. & Garcia, A. (1999) The tourist potential of the subúrbio ferroviário de Salvador from inhabitants' point of view. Lima, L.C. (ed) Da Cidade ao Campo: A Diversidade do Saber - Fazer Turístico. FUNECE/UEC, Fortaleza, pp. 237-246 (in Portuguese).

Smyth, C.G. & Royle, S.A. (2000) Urban landslide hazards: incidence and causative factors in Niterói, Rio de Janeiro State, Brazil. Applied Geography, v. 20:2, p. 95-118.

Terlien, M.T.J. (1997) Hydrological landslide triggering in ash-covered slopes of Manizales (Columbia). Geomorphology, v. 20:1-2, p. 165-175.

Tricart, J. & Silva, T.C. (1968) Studies on Geomorphology in Bahia and Sergipe. Fundação de Desenvolvimento Científico da Bahia Press, Salvador, 189 pp. (in Portuguese).

Van Asch, T.; Kuipers, B. & Van Der Zanden, D.J. (1993) An information system for large scale quantitative hazard analyses of landslide. Zeitschrift für Geomorphologie, v. 87, p. 133-140.

Viana, C.F.; Gama Junior, E.G.; Simões, I.A.; Moura, J.A.; Fonseca, J.R. & Alves, R.J. (1971) Stratigraphic review in the Recôncavo/Tucano basin. Boletim Técnico Petrobrás, 14:3-4, p. 157-192 (in Portuguese).

Wacquant, L. & Wilson, W.J. (1989) The cost of racial and class exclusion in the inner city. Annals of the American Academy of Political and Social Science, v. 50:1, p. 8-25.

Wu, W. & Sidle, R.C. (1995) A distributed slope stability model for steep forested basins. Water Resources Research, 31:8, p. 2097-2110.

Zhou, C.H.; Lee, C.F.; Li, J. & Xu, Z.W. (2002) On the spatial relationship between landslides and causative factors on Lantau Island, Hong Kong. Geomorphology, v. 43:3-4, p. 197-207.