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Landslide Susceptibility Evaluation on Agricultural Terraces by the Application of Physically Based Mathematical Models

Avaliação de Suscetibilidade a Movimentos de Vertente em Terraços Agrícolas pela Aplicação de Modelos Matemáticos de Base Física

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Abstract: *This paper focuses on the evaluation of landslide susceptibility in agricultural terraces, in the Douro Region, with earth embankments, using two physically based models: SHAllow Landslide STABility model and Stability INdex MAPping. The applied models combine an infinite slope stability model with a steady state hydrological model. Both susceptibility models use the following soil properties parameters: cohesion, friction angle, soil specific weight and thickness. The SINMAP also uses the root cohesion. Besides the different mathematical formulas applied on each susceptibility modelling, the definition of the contribution areas in the hydrological model is based on different algorithms. The SHALSTAB uses the Multiple Flow Directions (MFD) and the SINMAP uses the Deterministic-Infinity (D∞). The results validation is made with the inventory of past landslides, done through the contingency table method. This procedure shows that SHALSTAB classifies 77% of the landslides on the susceptibility areas, while SINMAP reaches 90%. Simultaneously, the SINMAP model presents a very high False Positive Rate (83%) against significantly lower values of False Positive Rate (67%) for SHALSTAB. The relation between True Positive Rate and False Positive Rate is better for SHALSTAB (1,14) then for SINMAP (1,09) showing a better balance between prediction capability and delineation of unstable area.*

Keywords*: SINMAP; SHALSTAB; Landslides; Agriculture Terraces*

Resumo: O artigo efetua a avaliação da suscetibilidade a deslizamentos, em terraços com talude em terra, no vale do Douro. São aplicados modelos matemáticos de base física: SHAllow Landslide STABility model e Stability INdex MAPping. Os modelos aplicados combinam os conceitos de talude infinito e, fluxo hidrológico em estado estacionário. Ambos os modelos, de suscetibilidade, utilizam as seguintes propriedades do solo: coesão, ângulo de atrito, peso específico do solo e espessura do solo. O SINMAP aplica ainda a coesão das raízes. Uma das principais diferenças entre os modelos refere-se à definição das áreas contributivas. O SHALSTAB utiliza o fluxo de direções múltiplas (MFD) e o SINMAP utiliza o fluxo de direções infinitas (D∞). A validação dos resultados foi realizada com base no inventário de deslizamentos, seguindo o método da matriz de contingência. Dos resultados obtidos, o SHALSTAB classifica corretamente 77% dos deslizamentos e o SINMAP 90% de deslizamentos. Contrariamente, o índice de falsos positivos do SHALSTAB é significativamente mais elevado (67%) enquanto o SINMAP apresenta (83%). No que se refere à relação entre os Índices de Verdadeiros Positivos e de Falsos Positivos o SHALSTAB apresenta um melhor balanço entre a predição dos deslizamentos e a dimensão das áreas definidas como instáveis com 1,14, relativamente a 1,09 apresentado pelo SINMAP.

Palavras-chave: SINMAP; SHALSTAB; Movimentos de Vertente; Terraços Agrícolas

1. INTRODUCTION

At of north of Portugal, landslides are predominant natural processes, mainly triggered by rainfall episodes (PEREIRA et al., 2010). In Douro Demarcated Region (DDR) - one of the world oldest regulated and demarcated wine region - these episodes are triggered for slope movements too, that affects the dry stone walls or earth embankments that supports agricultural terraces. The riser instability is related with shallow translation landslides.

Several mathematical models have been applied on the susceptibility analysis to landslides occurrence: - dLSAM (Shallow LandSlide Analysis Model), from Wu and Sidle (1995); - TRIGRS (Transient Rainfall Infiltration and Grid-based Regional Slope-stability analysis), presented by Baum et al., (2002); - SHALSTAB (Shallow Landslide Stability), defined by Montgomery and Dietrich, (1994), and SINMAP (Stability Index Mapping) by Pack et al. (1998).

The SHALSTAB has been applied in several areas, namely in California (Dietrich et al., 1998), Brazil (Guimarães et al., 2003; Fernandes et al., 2004; Vieira, 2007), at Apennines (Meisina et al., 2007), or in Italy Campania Region (Sorbino et al., 2010). In Portugal, this model was used in Lisbon municipality (Vaconcelos, 2011), in Arruda dos Vinhos (Pinmenta, 2011), in Tibo watershed - Arcos de Valdevez (Teixeira, 2012; Teixeira et al., 2014), and North Lisbon region (Henriques, 2014).

The SINMAP has been studied by several researchers to evaluate landslides susceptibility in China (Lan et al., 2003, 2004), Italy (Tarolli and Tarboton, 2006), Germany (Terhorst and Kreja, 2009), and also in Brazil (Michel et al., 2014; Nery and Vieira, 2015).

The main objective of this study is to evaluate the predictive ability of SHALSTAB and SINMAP to model the landslides susceptibility, along the risers in agricultural terraces of Douro valley.

2. STUDY AREA: CARVALHAS ESTATE

The landslides susceptibility modeling was applied in a watershed located on Carvalhas Estate (São João da Pesqueira municipality), covering an area of approximately 15ha (**Figure 1A, B and D**).

The study area is geologically characterized by the Bateiras formation, the oldest stratigraphic unit of the Douro group (upper Proterozoic), an anticlinal formed during Variscan orogeny (Sousa, 1989). This formation is characterized by the presence of black shales and phyllites intercalated with metagreywackes. The tectonic framework is related with the reactivation of Variscan faults, with WNW-ESE direction. This fracturing network is important in the Pinhão area, marking the transition between Bateiras and Ervedosa do Douro formations, (**Figure 1C**).

The soils of this area are classified mainly as anthrosols, derived from the agricultural transformations of original leptosols and luvisols (IUSS, 2006). According to the classification of Folk (1954), its texture varies between muddy gravel (mG) and gravelly mud (gM), with silt and clay percentages ranging from 45% to 69%. The sand varies between 7% to 16% and the gravel contents between the 25% to the 40%.

The vineyard is dominant, with 6 ha on a total of 15ha, and cultivated over agricultural terraces with earthen embankments (**Figure 2**), although there are other types of land frame systems, namely the post-phylloxera terraces supported by dry stone shale walls (**Figure 2**). The platforms are predominantly horizontal, with 2,5 m or 3,5 m wide, where can be planted up to two vine rows. On a very small area of the river basin is used a recent frame system characterized by earthen embankment micro-terraces between two support structures with dry stone vertical walls. The vineyard in this case is organized into rows horizontally arranged with 0.88 m and 1.32 m of space between vines.

A total of 156 landslides were surveyed in the study area. The wide and the length of the scar varies from 1 m to 3 meters and are up to 1.5 m depth. Generally, the slipped materials are retained on the terrace platform below (**Figure 2**).

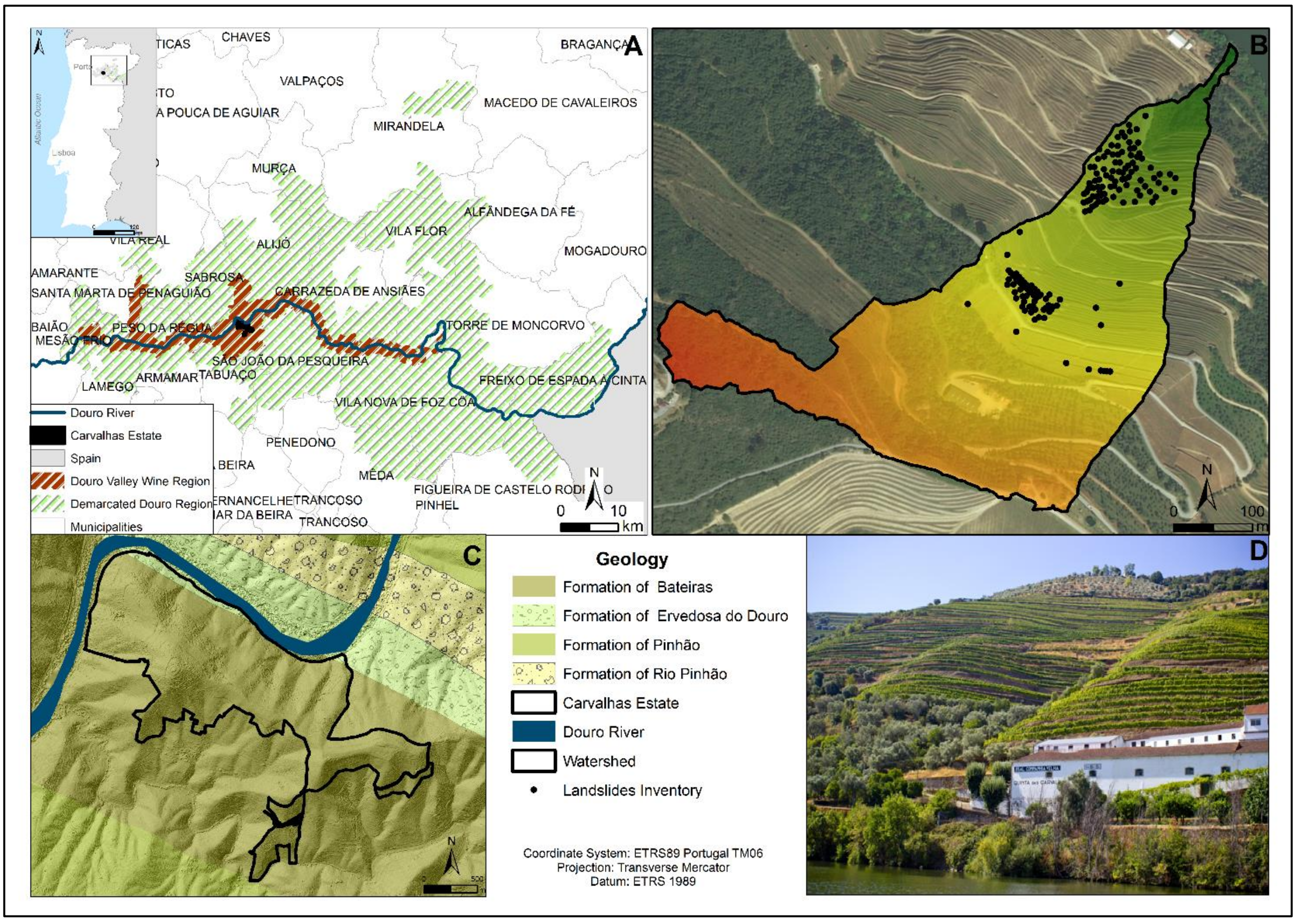


Figure 1: Study Area framework (A); Study watershed and landslides inventory (B); Geology of Carvalhas Estate (C); Overview of Carvalhas Estate.

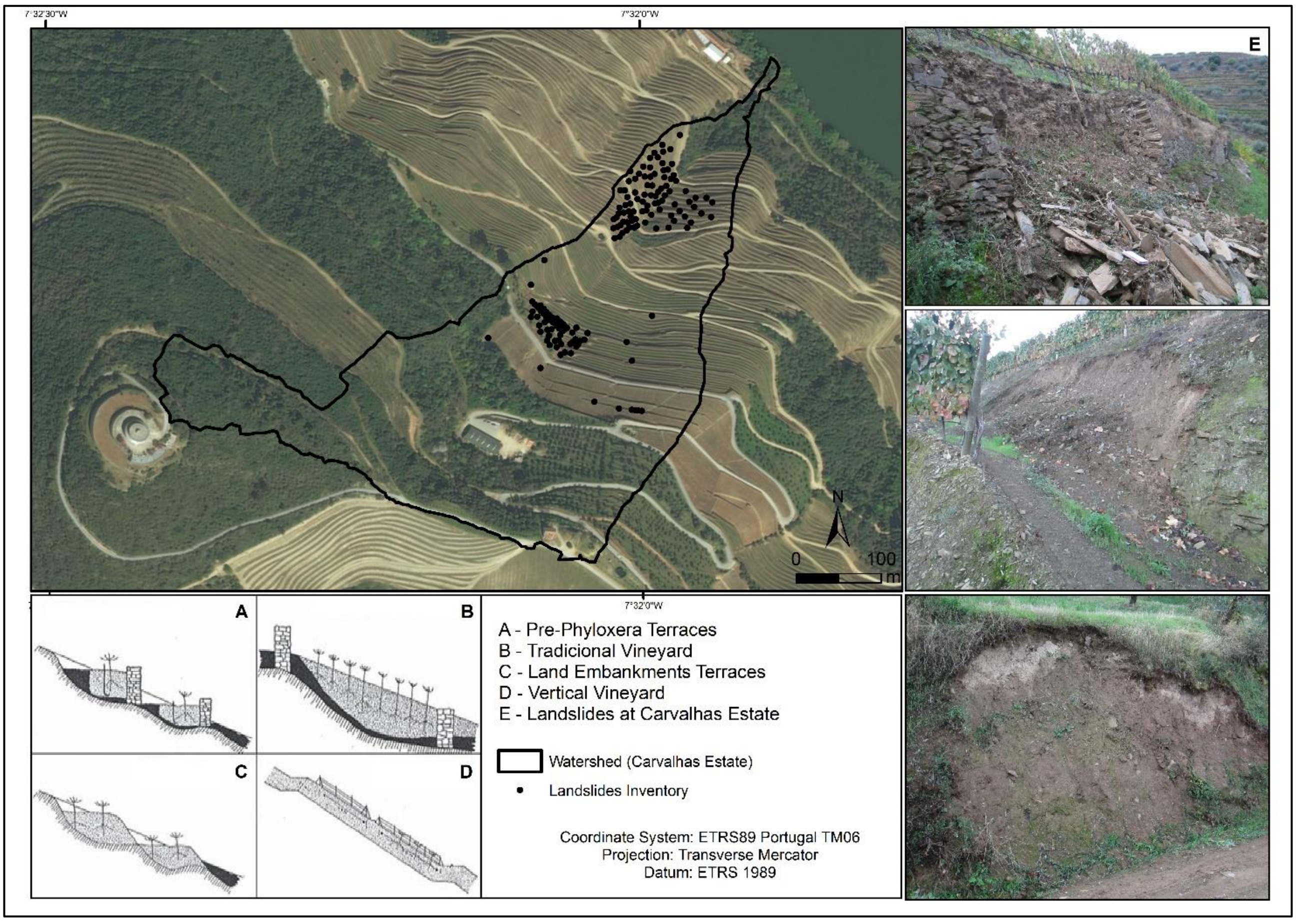


Figure 2: Landslides inventory at Carvalhas Estate and Types of terraces in the Douro Valley.

3. MATERIALS AND METHODS

The SHALSTAB, according to the theoretical approach (Montgomery, 1989, 1994, 1998; Dietrich et al., 1995), calculates the susceptibility to shallow translational landslides based on the combination of a hydrological model and a stability model. The latter is based on infinite slope concept, wherein the slope is considered homogeneous. This approach, defined by Labuz et al. (2012) outlines the relationship between soil and consolidated material as regards resistance to shearing (Selby, 1993), that has an effect on the ratio h/z (h - height of the water column, z - thickness of the soil).

The hydrologic model used on SHALSTAB, is based on the constant sub superficial runoff, defined by Beven and Kirkby (1979), and O'Loughlin (1986), and on the calculation of the contributing areas (a) – using the methodology of MFD (QUINN et al., 1991) in the water soil transmissivity (T) - and the slope (θ) (Montgomery, 1994).

The MFD hydrological model of SHALSTAB is based on the proportional distribution of the flow between pixels, namely the distribution weighted according to the slope of the neighboring cells along 3 main sections (**Figure 4**).

Through the combination of the two models (stability and hydrologic), the susceptibility modeling to landslides occurrence used the formulation (Eq. 1):

$$\mathbf{\frac{Qc}{T} = \frac{sen\theta}{a/b}\left[\frac{c'}{p_w g z \cos^2\theta \tan\phi} + \frac{p_s}{p_w}\left(1 - \frac{\tan\theta}{\tan\phi}\right)\right]} \qquad (\mathbf{Eq. 1})$$

Where:
Qc- Critical rainfall;
T- Transmissivity (m/s);
θ- Slope (◦);
b- Width of the ground unit (m);
a - Catchment area (m^2);
c'- Soil cohesion (N/m^2);
p_w- Specific weight of water (kN/m^3);
p_s- Specific weight of soil (kN/m^3);
φ- Internal friction angle (◦)

The SINMAP, is based on the association of stability model to the hydrological model (Beven, 1979; O´Loughlin, 1986), also supported on the infinite slope theory. The SINMAP stability model (IE) is established following the equation (2):

$$\boldsymbol{IE = \frac{C + \cos\theta\left[1 - \min\left(\frac{R}{T}\frac{a}{\sin\theta}, 1\right) r\right]\tan\phi}{\sin\theta}} \qquad (\mathbf{Eq. 2})$$

Where:
C= Cohesion (N/m2);
θ = Slope (◦);
R= Steady state recharge;
T= Soil Transmissivity (m2/hr);
ϕ= Internal friction angle (◦)
r= reason density (0.5)

The soil cohesion also incorporates the root cohesion. In this case, we considered the root cohesion equal to zero because they are very thin and without density enough to increase the soil cohesion, (Pack, 2005).

The SINMAP uses the methodology of D∞ (D-Infinity) to define the contributing areas, presented by Tarboton, (1997). The D∞ define infinite possibilities for the flow direction (Seibert, 2007). The definition of the contributing areas is based on the neighboring cells but don't specify three flow directions. Admits an infinite flow direction distribution.

The SINMAP stability classification, results from inputs of slope (topography), catchment area, and parameters which quantify the materials properties and hydrological conditions (through wetness parameter), (Pack, 2005). The topographic data is calculated automatically from DEM. The remaining parameters are introduced with maximum and minimum values, according the analysis performed in the study area.

The inventory of slope instability was made using several criteria (Seixas et al., 2006; Westen et al., 2006): a) presence of translational landslides; b) fallen and rebuilt stone walls; c) deformations and cracks on walls denouncing the pressure associated to the soil water saturation previous the landslides occurrence; d) inquiring of field workers and estate owners. In the earth embankment terraces is difficult to have a complete inventory because the majority of instability marks can be easily fixed and erased by the agricultural activity.

The Digital Elevation Model (DEM) used in our work as input for susceptibility modeling, resulted from aerial photographs with a 50-cm resolution, captured by a Cessna 402b aircraft with an aerial camera Intergraph DMC. The images were taken on July 23/2012 between 11:26 and 10h47 (UTC), with a longitudinal overlap of 60% and a lateral one of 30%. These images were processed in AGISOFT program that allowed the construction of a DTM with a pixel resolution of 1m, (Oliveira, 2014).

The soil sampling for cohesion measurement varies from average of 3877 N/cm3 on the landslide scars and 2900N/m3 near by the landslide on the not slipped materials with the same characteristics of the slipped materials. A saturated direct shear test performed on three landslides occurrences on the terraces showed similar values for cohesion and internal friction angle (φ) of 32º. The 6 specific soil weight (ps) sampling collected on the materials of the terrace riser on the friable materials, presents an average value about 16.7 kN/m3, (**Table 1**).

The average thickness of the soil (z) was estimated on the terrain in about 1,5m, following the premise that this value corresponds to the depth associated to the land remobilization process during agricultural terraces construction, observed during the terracing process along the field work. Note that the original material has a cohesion of 3877N/m3, a friction angle of 32º and, the mobilized material has a cohesion of 2900N/m3 and friction angle of 32º. It should be pointed out, that these mobilized materials correspond to a terrace with more than 10 years old, (**Table 1**).

The rainfall data (R) was obtained from the weather station located near S. Luiz estate (Adorigo), about 6km straight of the study area. The precipitation values, of 16.6 mm/day and 67.2 mm/day (recorded on October 5 and 7 of 2009 respectively), corresponds to the date of the most recent instability occurrences.

The hydraulic conductivity b was measured with a Guelph permeameter at 45 cm of depth. However, this depth did not occur in all experiments, since in some areas the rigid schist was very close to the surface and therefore some of the experiments were performed at 30 cm of depth, (**Figure 3**). Taking into account the recorded data, was used the average value of 0.00020 cm/min in order to calculate the transmissivity (T).

Cohesion, internal friction angle, soil thickness and specific weight of the soil are the parameters used with the SHALSTAB model (**Figure5)**. Beside those parameters SINMAP includes the T/R ratio, varying between 2.7 m2/h and 11.1m2/h. SINMAP also incorporates the roots cohesion, (Schmidt et al., 2001), in combination with the soil cohesion. However, since the roots of the vines are low density, very thin and small depth, has been assigned a zero value, (**Table 1**).

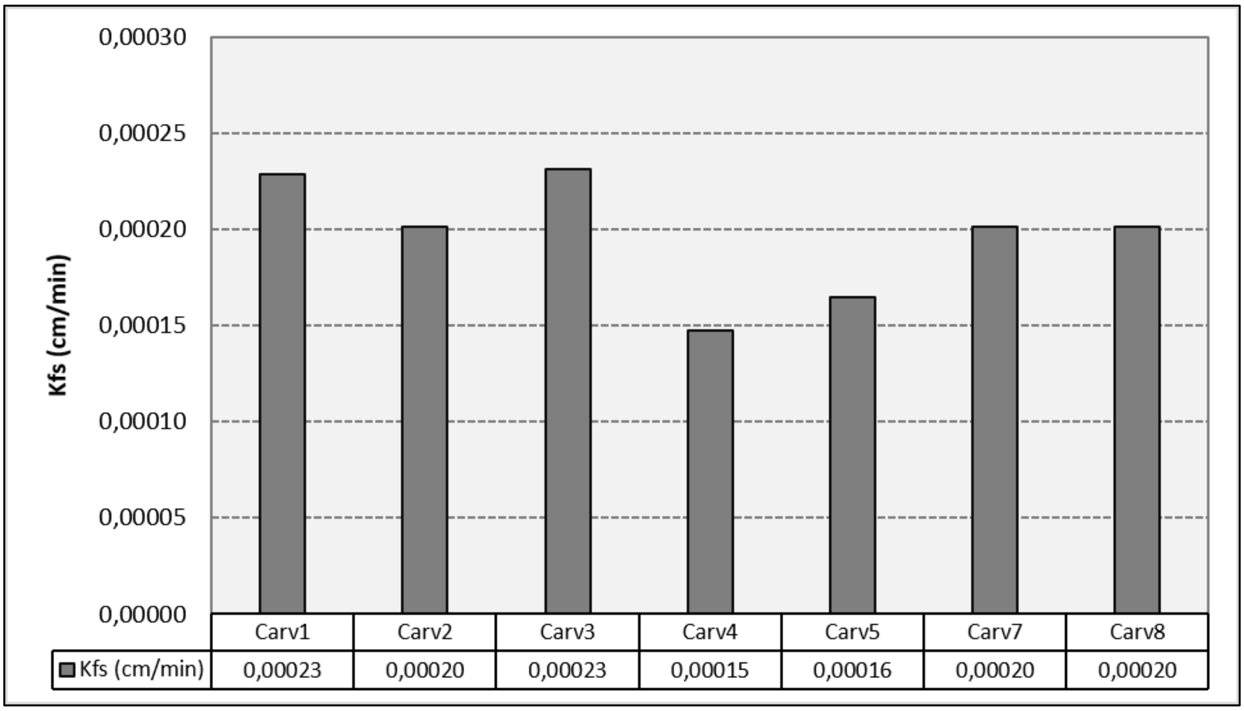


Figure 3: Saturated Hydraulic Conductivity

Table 1: Data used in SHALSTAB and SINMAP

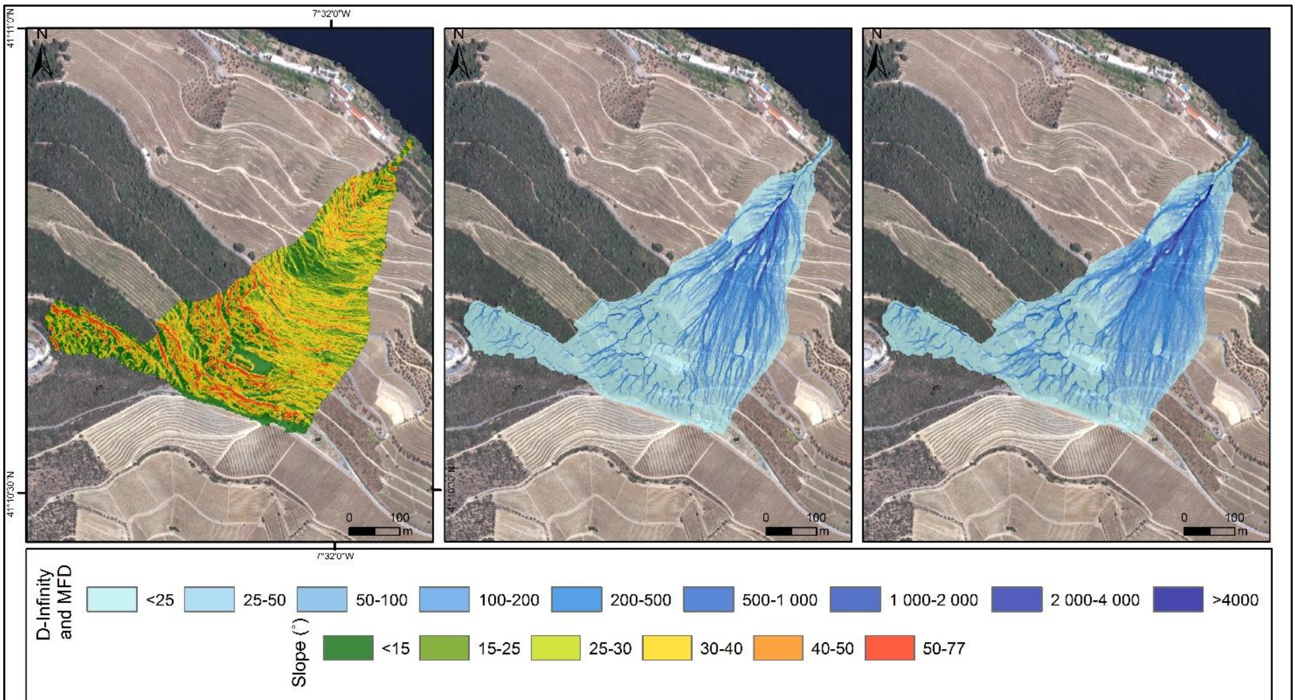
Models	**SINMAP**	**SHALSTAB**
Parameters	**Values**	**Values**
T/R min. and max.	2.7 and 11.1 m^2/h	
c' min. and max.	2900 and 3877 N/m^2	2900 N/m^2
φ min. and max.	32˚	32˚
Z min. and max.	2m	2m
ϱs min. and max.	16.7 KN/M^3	16.7 KN/M^3

4. RESULTS ANALYSIS AND DISCUSSION

According to the MFD, the most representative class are < 25m2, with 30.6%, followed by the classes of 100-200m2 (14.8%) and 50-100m2 (14.6%) (Fig. 4), with a total of 60% in the watershed area. Under 100 m2 the contributing areas occupy 57,7% of the watershed. According to the methodology of D∞, the class 0-25m2 is more representative in terms of area, with 49.55%, presenting the following classes a much smaller area, (Fig. 4), respectively 11.6% and 10.8% for a total of 72% of the watershed with contributing areas under 100m2. The greater area representation in first class reflects the importance of diffuse runoff on this contributing areas modelling, essentially in the upper part of the watershed. This reveals the importance the week drainage concentration effect in the first classes of contributing areas in the methodology of D∞, (Fig. 4).

In the SINMAP, the stable area (considering the 'stable' and the 'moderately stable' classes) occupies 15.5% of the watershed area and the unstable area ('Defended', 'Upper Threshold', 'Lower Threshold' and 'Quasi-stable' classes) represents 72,2%, (Fig. 5). Regarding the percentage of landslides by class, unstable classes represents 90.4% of the landslides inventory, against only 9.6% of the cases centred on the stable classes.

On the other hand, in the SHALSTAB, the class "Q / T log < -3.1" is the class that has the highest area in the watershed (24.02%), followed by "chronic unstable" class with 16.98% and "chronically stable" with 16.77%, (Fig. 5). In terms of slipped area by susceptibility classes, 37.18% of landslides occurred in class "chronically unstable" and 26.28% in the class log Q / T <-3.1, while the remaining classes have much lower values. In the case of SHALSTAB model, the values of log Q/T less than -2.5 are considered unstable and higher values are considered stable. The areas considered stable have a total of 23% of the landslides occurred. On the other hand, unstable areas have 77% of the landslides occurrence.



Class		0-25	25-50	50-100	100-200	200-500	500-1000	1000-2000	2000-4000	>4000
Area by Class (%)	D∞	49.55	11.58	10.83	9.35	8.91	3.88	2.42	1.52	1.96
	MFD	30.61	12.54	14.59	14.80	13.66	5.70	3.37	2.36	2.35

Coordinate System: ETRS 1989 Portugal TM06
Projection: Transverse Mercator
Datum: ETRS 1989

Figure 1: Slope and Contributing areas at Carvalhas Estate Watershed

The riser inclination is similar along all the river basin because they are build following predefined geometric rules. That fact could induce the representation of the unstable areas along all the terraced area. In fact, the spatial variation of the unstable area coincides with the higher inclination of the general topography, (Fig. 4). In those areas, the terraces are higher, leading to more instability of the terrace risers.

Notice that the susceptibility model presents the instability only in the areas with agricultural terraces. The terrace construction process has a huge influence on the soil characteristics. The soil properties used by both models are representative of the terraced areas, but not for the no terraced areas. The final results are only representative of the terraced areas. Even so, the hydrologic model is based on the total area of the watershed since the internal runoff along all the river basin is relevant for both models. Is not restricted to the terraced area.

The SINMAP has the highest TPR, (90% of correctly predicted slips), while the SHALSTAB has 77%, similar to other authors (i.e. Michel et al. 2014; Zizioli et al., 2013; Meisina and Scarabelli, 2007), a lower value than TPR for SINMAP but acceptable, since 77% of the landslides are correctly predicted. The SINMAP has a FPR of 83% and the SHALSTAB has 67%. So, to be able to predict 90% of the slides (more 13% than predicted in SHALSTAB), the SINMAP has to consider an unstable area 16% larger than the SHALSTAB, such as to other authors (i.e. Pradhan and Kim, 2015; Zizioli et al., 2013; Meisina and Scarabelli, 2007). The reliability of SHALSTAB is better (33%). Although the SHALSTAB has a better ACC, is still a relatively low value. However, considering that the entire watershed is located in an area of high instability with strong human intervention, is acceptable to have so large unstable areas in order to predict a significant quantity of landslides. Relative to PPV SHALSTAB has better results (PPV = 0.00298), yet very close to the values presented by SINMAP (PPV = 0.00283). Finally, it was elaborate the index TPR/FPR. According to Fawcett, (2006), a prediction model is acceptable when this ratio is greater than 1, situation that is seen in the analyzed models, but with better results obtained by SHALSTAB (1.14). However, the difference between the two models is residual (0.05 points), (Table 2).

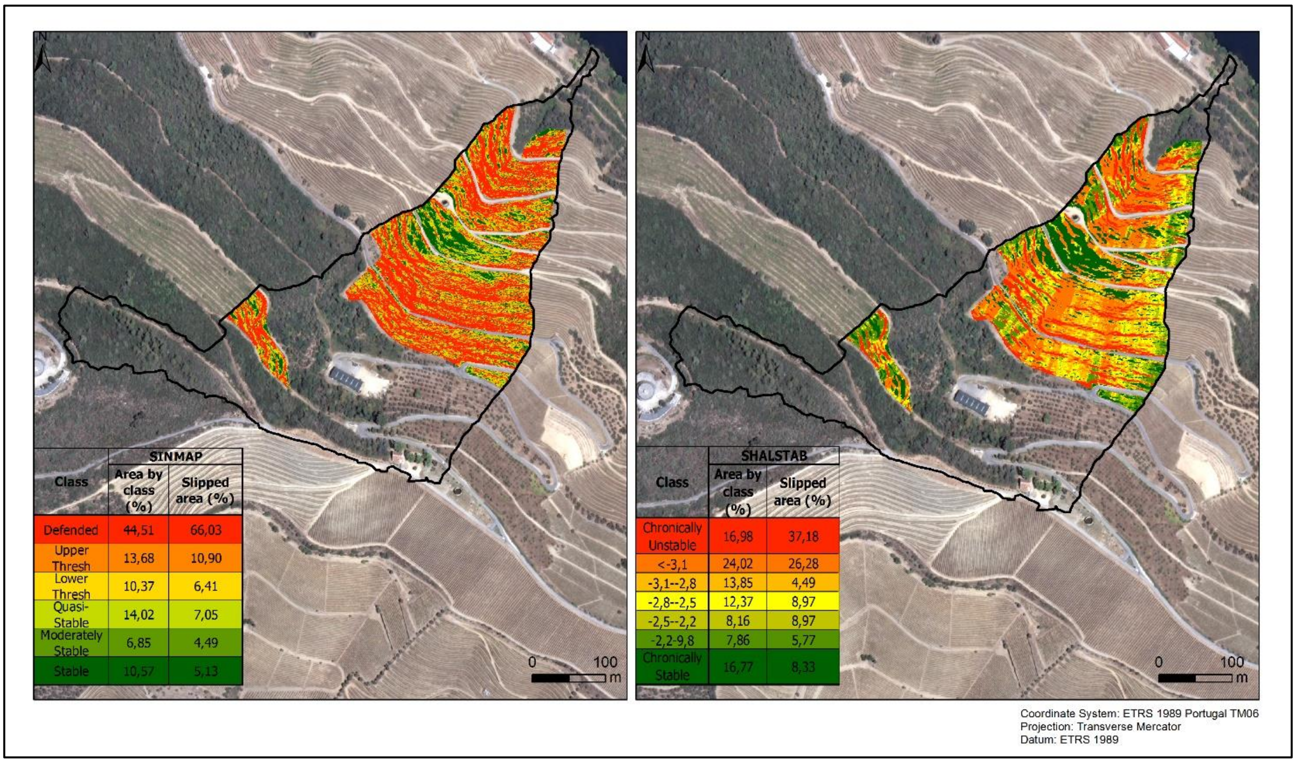


Figure 2: Susceptibility to landslide modelling with SINMAP and SHALSTB and contributing areas respectively.

Table 2 - Contingency matrix applied to the validation of susceptibility modeling in the Carvalhas basin. (TPR – true positive rates; FPR – false positive rates; ACC – accuracy; PPV – positive predicted value).

Modelling		TPR	FPR	Acc	PPV	TRP/FPR
SHALSTAB	**c' 2900 N/m2; ϕ 32°; z 2m; ϱs 16,7 KN/m3**	**0,77**	**0,67**	**0,33**	**0,00298**	**1,14**
SINMAP	**T/R min and max. 2,7 and 11,1 m2; c' min and max. 2900 and 3877 N/m2; ϕ min and max. 32°; z 2m**	**0,9**	**0,83**	**0,18**	**0,00283**	**1,09**

5. CONCLUSION

According to the main objective, which is to confront the predictive ability of SHALSTAB and SINMAP to model the landslides susceptibility, along the risers in agricultural terraces of Douro valley, the obtained results, SINMAP is able to predict great number of occurrences (90%) and SHALSTAB only 77%. However, the ability of SINMAP to predict so large number of landslides along the terrace risers is achieved by a huge enlarging of the area classified as unstable. This is reflected on the FPR that has a very high value for SINMAP (0,83) then SHALSTAB (0,67). So, we can refer that SHALSTAB has a better balance between the correctly predicted landslides and the dimension of the area classified as unstable. That is clearly represented by the TPR/FPR ratio, respectively 1,14 and 1,09 for SHALSTAB and SINMAP.

The main reason for the difference of predictive capacity of the two models is related with the construction methods of contributory areas. The D∞ of SINMAP model suggests a great influence of the terraces morphology, providing very small contributing area along a significant part of the watershed, giving greater importance to a diffuse internal flow. The MFD used in SHALSTAB allows an important degree of flow concentration, representing an internal flow based on preferential paths of the runoff. This way, the larger contributing areas defined by SHALSTAB develops a greater control in the definition of instability along the watershed. That, promotes a discrimination on the instability classification not so dependent from the stability model along the terraces risers as it seems to happen with SINMAP. The D∞ modelling considers the diffuse runoff as the main process of the soil saturation. Since the smaller areas of contributing area are very important in total area of the watershed, they represent the major part of the saturated areas along the platform of the terraces. That explains the importance given by the SINMAP susceptibility map to the terrace configuration and the great extension of the unstable areas. With so large unstable areas is understandable the high TPR (90%), the very high FPR (83%) and low ACC (18%).

Although the SHALSTAB only predicts 77% of landslides has a better TPR/FPR (1.14). Based on a hydrological model that identifies the main paths of internal runoff, it gives a greater importance to the hydrologic model to the unstable areas definition. SHALSTAB predict less 13% of landslides then SINMAP with a smaller area classified as unstable (less 16 %), that justifies a better ACC (0.33), FPR (0.67) and PPR (0.000298).

The main variances between the analyzed models can be related to the differences on the hydrological model. The secondary role played by the instability model is related with the 1m resolution of the DEM. It seems that is not good enough to represent the terraces configuration specially the smaller ones. This situation under represent the area occupied by the terraced area and under estimate the landslide stability along the terrace risers. With a more detailed DEM the representation of the morphology of the terraces will give to the models a more reliable susceptibility area, not much dependent of the hydrological model.

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