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Papers

Geotechnical parametrization for shallow landslide modelling in Fradinhos, Vitória, Espírito Santo - Brazil

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Abstract

Vitória is prone to shallow landslides processes given its climatic and relief characteristics. The SHALSTAB model was used considering the soil's cohesion to assess the susceptibility to shallow landsliding at the Fradinhos watershed, located in the Central Massif of Vitória. The parametrization was done with soil samples collected on three separate places in the watershed and submitted to shearing, permeability and texture tests. The soil samples were close to Oxisols (either developed from colluvium or not) and Inceptisols, in association with slope angle. Almost 95% of the watershed was modelled in a lower instability class (log Q/T > 2.2), with flow lines ranging from straight to divergent and variable slope angle. There is a strong association of the unstable areas to the drainage lines, hollows and steeper slopes. The modelling with results in critical rainfall, which considers the saturated transmissivity in its formulation, has the most unstable zones (with shallow landslide initiation potential with rainfalls of 2.5 mm or less) related to drainage lines and steeper slopes. Closer to the Inceptisol soil sample, where the smallest values of saturated conductivity and soil thickness was found, the proneness to landslide initiation with lesser rainfalls is high. Close to the Oxisol developed from colluvium soil sample point, the critical rainfall for landslide initiation is elevated, with exception to areas with higher flow convergence and steeper slopes. The SHALSTAB model was an efficient tool to generate critical scenarios for shallow landslide susceptibility at the Fradinhos watershed, with greater proneness on hollows and steeper slopes.

INTRODUCTION

Modelling is one of the most important investigation tools in Physical Geography research, being used for simulations and process analysis of past, present and future landforms. The models are understood as simplifications of

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the observed reality, with the reduction from the real complexity to the synthesis of the relations judged most relevant for the process in study (FERNANDES, 2016). Landslide predictive modelling is used to map areas prone to the occurrence of such events. The maps (i.e. susceptibility, risk, inventory) are essential to aid the decision-making of local government and for land use planning.

Landslides are large magnitude processes that act on the terrestrial relief development. The shallow landslides are the most frequent among the mass wasting types (namely, shallow landslides, slumps, rockfalls, creeps and debris flows). The failure surfaces are usually planar and follow mechanical and/or hydrological soil discontinuities, as soil-soil or soil-rock contacts, with occurrence associated to intense rainfall periods (FERNANDES; AMARAL, 2011; GUIDICINI; NIEBLE, 1983).

Vitoria is the capital of the Espirito Santo state, located in Southeastern Brazil. Its territory (approximately 96 km²) splits into several islands and a continental part, with the presence of rocky massifs, mangroves, fluvial-marine and coastal plains, possessing high topographical amplitude and tropical-humid climate. The rocky massifs are steep and were more intensely occupied after the 1920s. Deforestation, slope geometry modifications and disorderly water and garbage disposal allowed those rocky massifs to be prone to erosive and landsliding processes (IBGE, 2019; MACHADO et al., 2018; VITÓRIA, 2013).

According to Bortoloti et al. (2015) the most common type of mass movement in Vitoria is the shallow landslide, with a predominance in younger soils and steeper slopes. The sliding process is induced, mainly, by destabilization activities in rock blocks and cuts made in talus and colluvium slopes for urbanization.

The SHALSTAB model (Shallow Landslide Stability) evaluates the topographical influence (via slope inclination and flow convergence) on the occurrence of shallow landslides through a combination of a slope stability model (based on the Infinity Slope Equation) and a steady-state hydrological model (MONTGOMERY; DIETRICH, 1994; O'LOUGHLIN, 1986). SHALSTAB model is one of the most used in the world (FERNANDES, 2016), with successful results in many countries (ARISTIZÁBAL et al., 2015; DIETRICH et al., 2001; GUIMARÃES et al., 2009; PRADHAN; KIM, 2015). In Brazil, SHALSTAB has been applied in multiple susceptibility assessments in watershed-scale studies (FERNANDES et al., 2001, 2004; GUIMARÃES et al., 2003; LISTO; VIEIRA, 2012; MARTINS et al., 2017; ZAIDAN; FERNANDES, 2009, 2015).

Silva et al. (2013) applied the SHALSTAB model on the island of Vitoria, despite using geotechnical data from the Quitite and Papagaio watersheds, both located on the Tijuca Massif (Rio de Janeiro, Brazil) (GUIMARÃES et al., 2003). The unstable areas are associated with the Central Massif of Vitoria and stable areas are associated to flat lands and flow-divergent areas.

Thus, the goal of this study was to calculate the shallow landslides susceptibilities on the Fradinhos watershed, part of the Central Massif of Vitoria, using the SHALSTAB model in its full formulation (considering soil cohesion) and local parametrization.

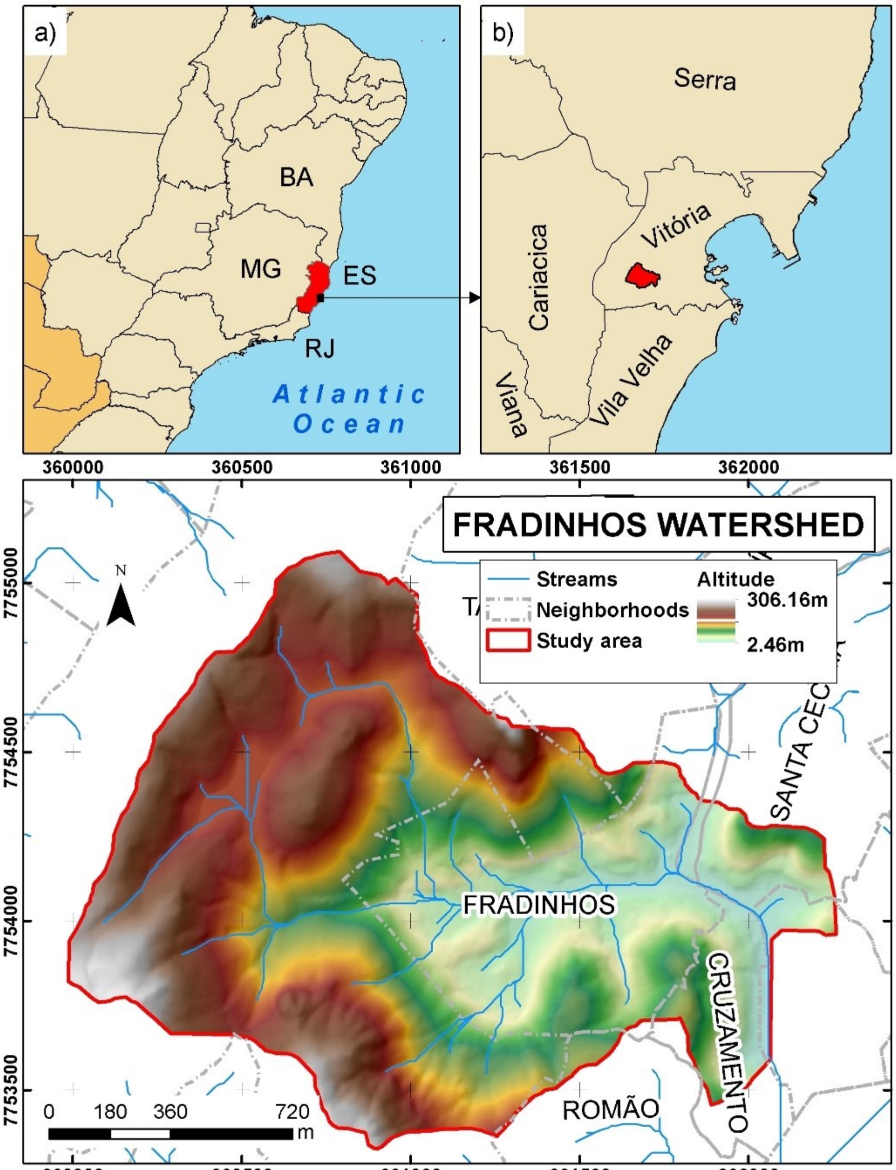
STUDY AREA

This study was conducted at the Fradinhos watershed (2.27 km²) located on Vitoria, capital of the Espirito Santo state. There are approximately 20.000 inhabitants in the watershed area, which accounts for a little over 5% of Vitoria's population (estimated on 360.00 inhabitants) (IBGE, 2019).

The climate in Vitoria is hot and humid, with a mean annual temperature of 25.3°C and mean annual precipitation of 1303.5mm. November, December and January are the rainiest months (with means of, respectively, 200 mm, 183.9 mm and 131.4 mm), while the driest months are June, July and August (registered means of 67.2 mm, 72 mm and 50 mm, respectively) (EFFGEN, 2018).

The Fradinhos watershed is set on the southeastern face of the Central Massif of Vitoria, with altitude ranging from 2 to 306 m above sea level (Figure 1).

Figure 1 – Fradinhos watershed location and altitude. a) Espirito Santo is marked in red with bordering states: Bahia to the north, Minas Gerais to the west, Rio de Janeiro to the south. b) Fradinhos watershed is marked in red on Vitoria, capital of Espirito Santo state, with bordering townships: Serra to the north, Cariacica to the west and Vila Velha to the south.



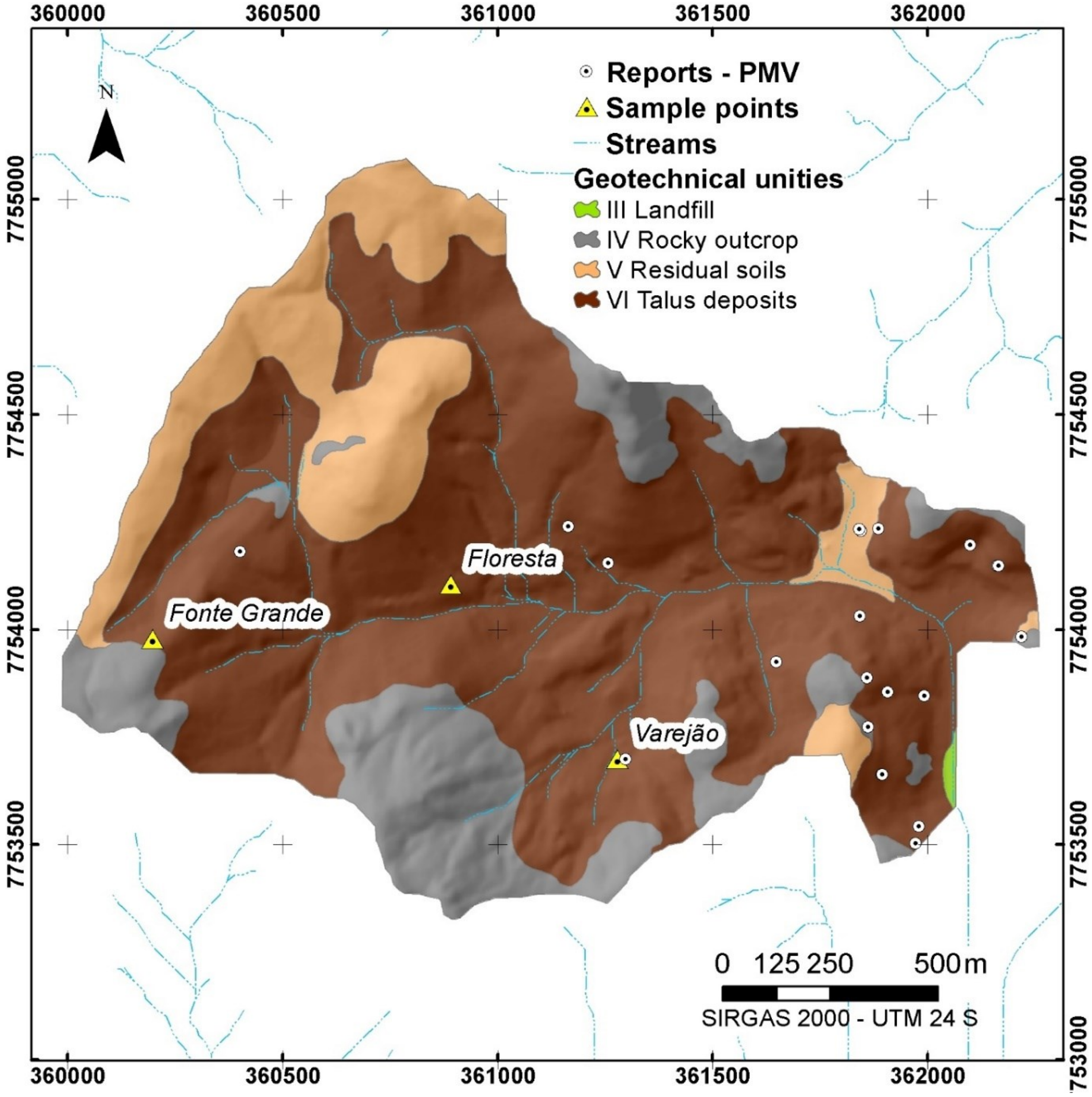
Sources: IBGE (2015b); IJSN (2019). Organized by the authors.

According to the Vitoria geological map (at the 1:100,000 scale), the Central Massif is set on the geological unit "Maciço Vitoria" (Vitoria Massif). This unit is part of the Espirito Santo's Intrusive Suite (542-488 Ma – Cambrian period) and features fine and medium-granulated granites (RADAMBRASIL, 1983; SGB, 2019).

The local geomorphological unit is comprised of Coastal Hills and Massifs (at the 1:250,000 scale). This unit is characterized by its depressed topography compared to the other units in the Morphostructural Domain of the Remobilized Folding Range, which presents folded and fractured structure. The hills and massifs have colluvial covers at the top, with angular and/or sub-rounded stonelines between the colluvium and the weathering mantle. Slopes covered by thin layers of colluvium expose boulders and rocky blocks (COELHO et al., 2012; RADAMBRASIL, 1983).

The geotechnical chart of Vitoria (at the 1:16,000 scale) shows that the study area presents Landfill, Rocky outcrop, Residual soil and Talus deposit (Figure 2).

Figure 2 – Geotechnical units in the Fradinhos watershed.



Source: Vitória (2014). Organized by the authors.

The Landfill unit associates to the watershed's outlet, where once there was a mangrove. This unit is prone to flooding and structural settlements. The Rocky outcrops unit is associated to thin soils and slopes steeper than 35%. This unit is prone to rock falls and slides, and thus there is an indication to use the areas with inclinations below 20%. The Residual soil unit presents soils with thickness up to 10m, in areas with slope inclination between 20-35%. The area is prone to shallow landsliding and erosional process, so the land use is free to areas with inclinations below 30%. The Talus deposit unit is composed by transported materials, and therefore the soils have heterogeneous texture, high porosity and permeability varying from medium to high. The areas with steepness between 5-45% have proneness to erosional process and mass wasting (VITÓRIA, 2014).

DATA AND METHODS

SHALSTAB model

The topographic control form of the SHALSTAB model, most commonly used, which considers soils as non-cohesive, is the following (MONTGOMERY; DIETRICH, 1994):

$$\log\left(\frac{Q}{T}\right) = \frac{\sin\theta}{a/b} + \frac{\rho_s}{\rho_w}\left(1 - \frac{\tan\theta}{\tan\varphi}\right) \quad (1)$$

Where Q/T is a hydrological ratio given by the net rainfall rate (Q) and the soil saturated transmissivity (T), θ is the local slope, a is the drained area upward to the cell contour b, ρ_s is the wet bulk density of the soil, ρ_w is the bulk density of water and φ is the soil internal friction angle.

The complete formulation of the SHALSTAB model, considering soil cohesion is the following (MONTGOMERY et al., 1998):

$$\log\left(\frac{Q}{T}\right) = \frac{\sin\theta}{a/b}\frac{C}{\rho_W g z \cos^2\theta \tan\varphi} + \frac{\rho_S}{\rho_W}\left(1 - \frac{\tan\theta}{\tan\varphi}\right) \quad (1)$$

Where g is the gravity acceleration and C is the soil cohesion.

The critical amount of rainfall needed to initiate a shallow landslide can be calculated through the equation:

$$Q = \frac{T}{a/b}\sin\theta\frac{C}{\rho_W g z \cos^2\theta \tan\varphi} + \frac{\rho_S}{\rho_W}\left(1 - \frac{\tan\theta}{\tan\varphi}\right) \quad (3)$$

SHALSTAB calculates a critical hydrological situation for slope stability by not considering the temporal and depth variation of the hydrological process (i.e., pore-pressure), which, in turn, controls the occurrence of shallow landslides (FERNANDES, 2016; GUIMARÃES et al., 2003). More details on the theoretical development of the SHALSTAB model can be found on Melo and Kobiyama (2018), Montgomery et al. (1998), and Montgomery and Dietrich (1994).

Physical parameters of the soil

To obtain the soil's wet bulk density (ρ_s), internal friction angle (φ) and cohesion (C), a direct shear test was performed, following the D3080:2012 standard (ASTM, 2012). Undeformed samples in cubic format (with edges sized 30 cm) were collected in the study area, following the Brazilian standard NBR 9604:2016 (ABNT, 2016), to execute the test.

The variable load permeability tests, to obtain the saturated hydraulic conductivity (k_{sat}) and calculate the soil transmissivity (T), were conducted by the Brazilian standard NBR 14,545:2000 (ABNT, 2000). The samples were cylindric-shaped and undeformed, measuring 15 cm in diameter and 13 cm in height.

Three locations were selected for soil sampling, considering land use (Table 1). Soil surveys were carried out, with morphologic analysis for soil profiling in field, according to the methodology proposed by the Brazilian Institute of Geography and Statistics (IBGE, 2015a).

Table 1. Name, coordinates and landuse from the sampling locations

Name	X (m)	Y (m)	Land use
Floresta	360891	7754105	Brazilian Atlantic Forest (Mata Atlântica)
Fonte Grande	360197.4	7753978.5	Pasture
Varejão	361277.9	7753698.1	Urban area

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The Floresta sample was collected in the Fonte Grande State Park, a conservation unit located on the Central Massif of Vitoria, with typical slope vegetation part of the Brazilian Atlantic Forest (Mata Atlântica). The geotechnical unit identified for this sample point is Talus Deposit (Figure 2).

The Fonte Grande sample was collected in a landslide scar on the western sector of the watershed (Figure 3a). The landcover is pasture, with rocky boulders at the site. The geotechnical unit identified is Talus Deposit, but close to the Rocky outcrop unit (Figure 2).

The Varejão profile was opened in an urban area, close to a landslide scar (Figure 3b), on the southeastern sector of the Fradinhos watershed. The landslide scar presents a number of rock blocks and construction rubble. The geotechnical unit identified is Talus Deposit (Figure 2).

The failure plan depth (z) estimate was performed through the soil granulometric analysis, following the methodologies by Ruiz (2005) and IBGE (2015a), considering that the failure plan is on the contact of the soil layers.

Figure 3 – Shallow landslide scars at the sampling points: a) Fonte Grande and b) Varejão.

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Geoprocessing operations

Geoprocessing and mapping operations were performed using the softwares ArcMap™ 10.3 (ESRI, 2014) and Surfer® 14 (GOLDEN SOFTWARE, 2017).

Neighborhood, town and state limits vector data were obtained at "Portal de Mapas" (IBGE, 2015b) and at the Integrated System of Geospatial Data of the Espirito Santo State – also known as GEOBASES (IJSN, 2019).

The spatialization of the soil's physical parameters were done through the interpolation method Inverse Distance to a Power, weighted for 2, thus becoming the Inverse Distance Squared. This method uses the distance between known data points to assess the influence over unsampled points, given that the greater the distance, the lesser the influence. Because the Inverse Square of the Distance is a geometric method and the calculation is performed based on Euclidian distances (i.e., iterations of the Pythagorean theorem), the interpolation's measure of uncertainty is not calculated as well as factors related to the formation and evolution of the soils (GOLDEN SOFTWARE, 2017; MICHEL; KOBIYAMA, 2015; YAMAMOTO;

Figure 4a). The samples were collected in layers depths ranging from 0-30 cm, 30-70 cm, +70 cm and +80 cm. At the 30-70 cm layer there were thick roots and bioturbation done by termites and ants.

At the Fonte Grande profile there were five layers, with total depth surpassing 128 cm. The first layer, between 0-30 cm depth, presents bioturbation activity by worms and termites. At the Varejão profile there were seven layers, with total depth surpassing 115 cm. Figure 5 shows the granulometric distributions from the sampled profiles, with its layers and depths.

LANDIM, 2013).

The digital elevation model (DEM), with spatial resolution of 3m, was built from contour line equidistant each 5m and elevation points (IJSN, 2019). The DEM was then used to derive the products needed for the modelling, such as slope angle, hillshade and contributing area.

The contributing area, with infinite direction flow, were calculated through the TauDEM package (TARBOTON, 1997). The SHALSTAB model were executed with the Raster Calculator tool. Vitoria City Hall provided the shapefiles and the technical reports of surveys of landslides occurrences, which were used to validate the shallow landslide susceptibility modelling (PROJETO MAPENCO, 2018).

RESULTS AND DISCUSSION

Textural analysis to attain the soil depth of failure (z)

At the Floresta profile, three layers with approximately 1m of depth were identified (

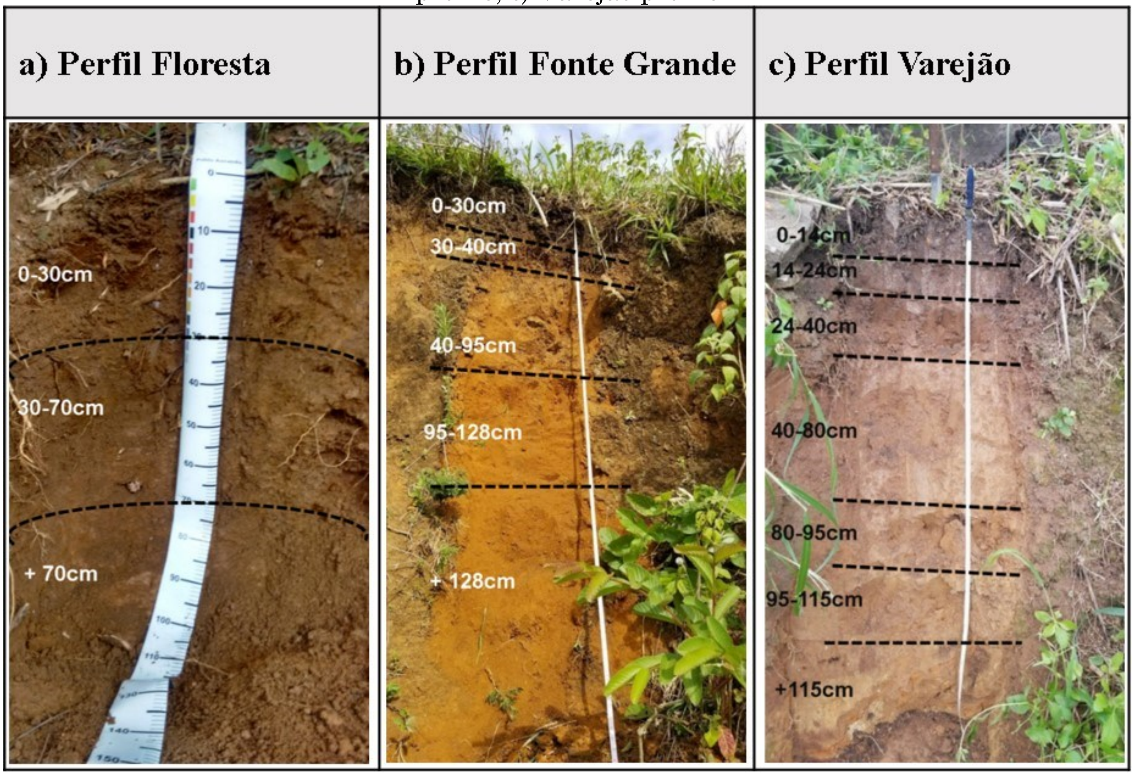
According to the IBGE (2015a) classification, the layers from the Floresta profile are sandy clay, sandy clay loam, very clayey and clayey, respectively.

The Fonte Grande profile presents sandy clay loam textures in the layers C1 and C2 (up to 40 cm depth), clay loam (layer C3, 40-95 cm depth), clayey (C4, 95-128 cm depth) and clay loam (C5, over 128 cm depth) (IBGE, 2015a).

The Varejão profile has a prevalence of the sandy texture (Figure 5), with the highest concentration of sand in the 95-115 cm depth layer (68.9%) and the lowest in the 24-40 cm depth layer (44.7%). The clay fraction tends to decrease as the depth increases, excepting the 24-40 cm depth layer (41.2%). The higher concentration of sand and the lower concentration of clay indicate the possibility that there can be parent material at the colluvium deposit and at the rocky blocks at the analyzed slope. Thus, the textures are, according to IBGE (2015a): sandy clay loam (0-14 cm), sandy loam (14-24 cm), clay (24-40 cm) and sandy loam (from 40 cm and over 115 cm depth).

Rainfall infiltration occurs easily in the permeable layers (e.g. sandy layers) and the water accumulates close to the more impermeable layers (e.g. layers with higher concentration of clay or bedrock). Such behavior promotes the formation of subsurface flow and saturation of shallower horizons, which could cause the soil to lose cohesion and trigger landslides (CARSON; KIRKBY, 1975; COELHO NETTO, 2008; FERNANDES et al., 1994; SELBY, 1993).

Figure 4 – Sampled profiles with identification and its depths: a) Floresta profile; b) Fonte Grande profile; c) Varejão profile



Source: Effgen (2018). Organized by the authors.

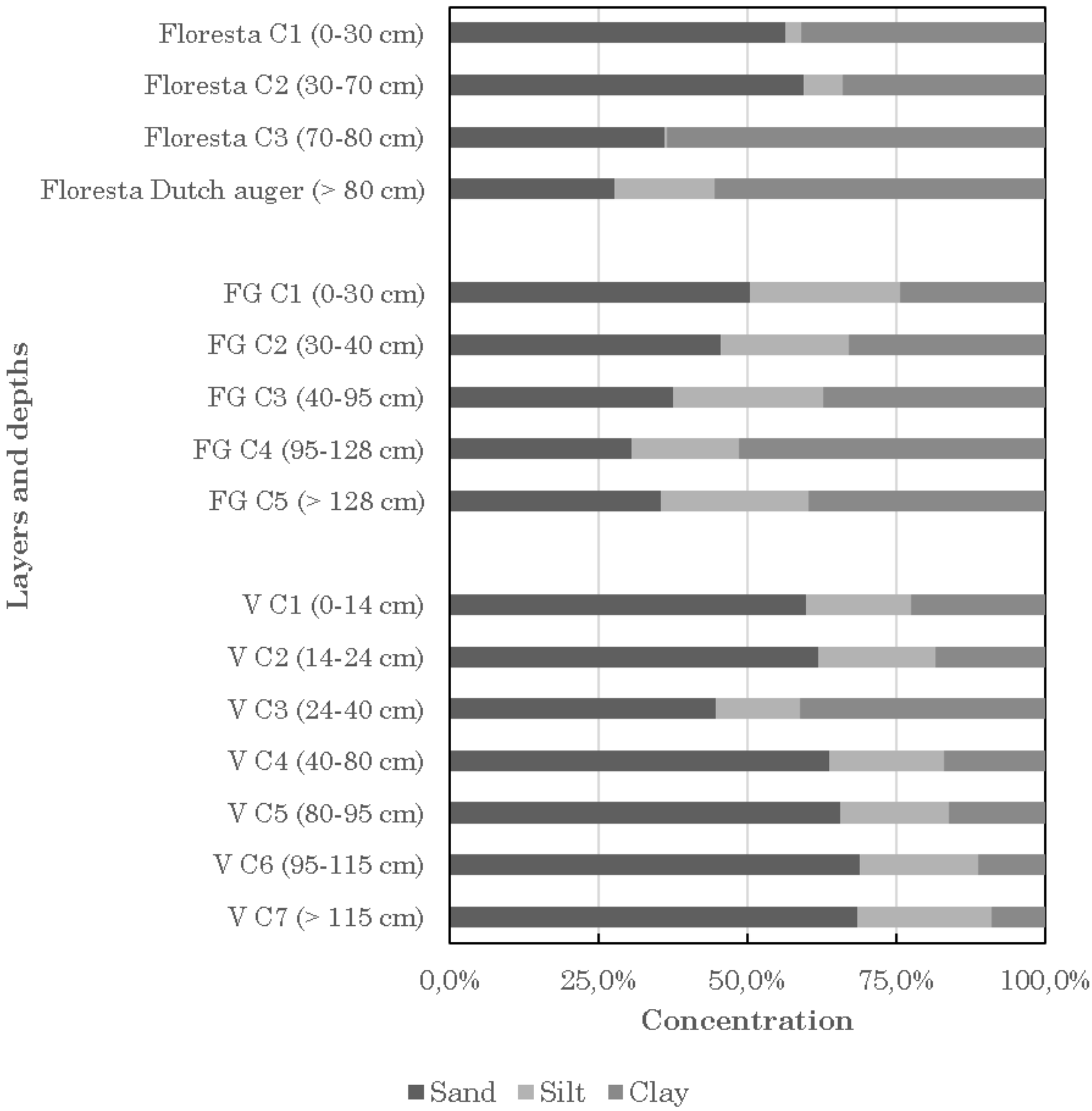
The alternation between layers with different mechanical and/or hydrological behaviors can form impermeable fronts in the soil. The failure surface in both investigated shallow landslide cases (Figure 3), for instance, occurred on the soil-soil contact.

Therefore, for the SHALSTAB model, the *z* value was defined as the limit of the layer where an abrupt texture change occurs – 70 cm for the Floresta sample point, 95 cm for the Fonte Grande sample point and 24 cm for the Varejão sample point.

From the morphological characterization carried out on the sampled profiles, three classes of soil were identified. The Floresta profile is a soil developed from a colluvium deposit, divided in deposition layers with an incipient pedogenesis. The Fonte Grande profile has morphological characteristics of a yellow Oxisol and the Varejão profile presents typical characteristics of a Haplic Inceptisol.

The Bw diagnostic horizon, representative of the Oxisols, is highly thick – a striking characteristic of the class. This is due to the deep weathering mantle originated from the decomposition of rocks, mainly younger gneissic and granitic rocks. The relevant past and present pluviometric index, as well as the physical and chemical characteristics of the rocks (e.g., banded structure and easily weathered minerals), are preponderant factors for the advance of the weathering front which imprints these soils with chemical characteristics such as low nutrient contents, high acidity (pH around 4.5) and low mineral reserve. These soils, typically, have good permeability, good drainage, low friability and erodibility (when clayey) due to the high stability of aggregates.

Figure 5 – Granulometric distributions from the Floresta, Fonte Grande (FG) and Varejão (V) profiles



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The study area's Haplic Inceptsols are spatially isolated or in association with shallow Oxisols and presents in their diagnostic horizon Bi 4% or more of primary alterable minerals with lesser resistance to weathering, besides having 5% or more of the horizon volume with the original rock structure. These soils present, majorly, bad physical characteristics (e.g., lower depths and higher disintegration) and high susceptibility to erosion due to physical conditions, rugged relief, low fertility and high acidity.

As mentioned before, colluvial soils present good depth but low pedogenesis degree, having a weak A horizon, over layers with fine fractions (silt and clay) with tendency to increase, indicating a podsolization process due to the textural gradient observed between layers.

Geotechnical parameters

Table 2 presents the values for saturated hydraulic conductivity, cohesion, internal friction angle, wet bulk density of the soil and failure depth obtained for each sampled location.

Table 2. Geotechnical parameters of the sampled locations, according to the International System of Units

Name	Saturated hydraulic conductivity (Ksat) (cm/s)	Cohesion (C) (kgf/cm²)	Internal friction angle (φ) (º)	Wet bulk density of the soil (ρs) (kg/m³)	Failure depth (z) (m)
Floresta	3.6×10^{-4}	0.18	30.58	1610	0.7
Fonte Grande	1.52×10^{-4}	0.058	27.52	1500	0.95
Varejão	2.78×10^{-5}	0.196	24.77	1790	0.24

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The hydraulic conductivity represents the easiness of water absorption through empty spaces in the soil, according to NBR 6502 (ABNT, 1995). In the analyzed watershed, the Floresta sample has the highest hydraulic conductivity, while Varejão sample has the lowest. The values were influenced by each profile's texture and the depth in which each undisturbed sampled was taken. Floresta was sampled at 60 cm (sandy clay loam layer) and Fonte Grande at 40 cm (clay loam layer). Varejão had its sample taken at the landslide scar, around 10 m away from where the samples for texture and direct shear tests were taken, in 60 cm depth and, therefore, its permeability is the lowest.

Cohesion is the soil's resistance to shearing stress, regardless of the normal stress (ABNT, 1995; GUIDICINI; NIEBLE, 1983). The highest cohesion value was measured at the Varejão sample, while the lowest was from the Fonte Grande sample (respectively, 0.196 kgf/cm² and 0.058 kgf/cm²).

The soil's resistance to shearing stress can be expressed by the Coulomb equation ($\tau = c + \sigma_n \tan\varphi$). In this equation, the c and φ parameters represent, respectively, cohesion and internal friction angle between the soil's particles. Those parameters are intrinsic characteristics of the soil, being determined by its properties and attributes, such as texture, structure, organic matter content, density, mineralogy and water content (ROCHA et al., 2002).

The samples' internal friction angle values ranged from 30.58° (Floresta sample) to 24.77° (Varejão). Such values can be justified by the textures from each sample (clays and cover soils, according to the consulted literature, have typical internal friction angles between 20-35°) and by the land cover (i.e., presence of thick and thin roots at Floresta and Fonte Grande, while Varejão has urban use and exposed soil) (GUIDICINI; NIEBLE, 1983; SELBY, 1993).

The bulk density is related to the resistance, morphology, soil genesis, as well as permeability, infiltration, compactness, root development and weathering behaviors (IBGE, 2015a; SELBY, 1993). The highest soil bulk density was recorded at the Varejão sample location, with 1,790 kg/m³, while the lowest was from the Fonte Grande sample location, with 1,500 kg/m³. Such values are in agreement with the texture and cohesion values found.

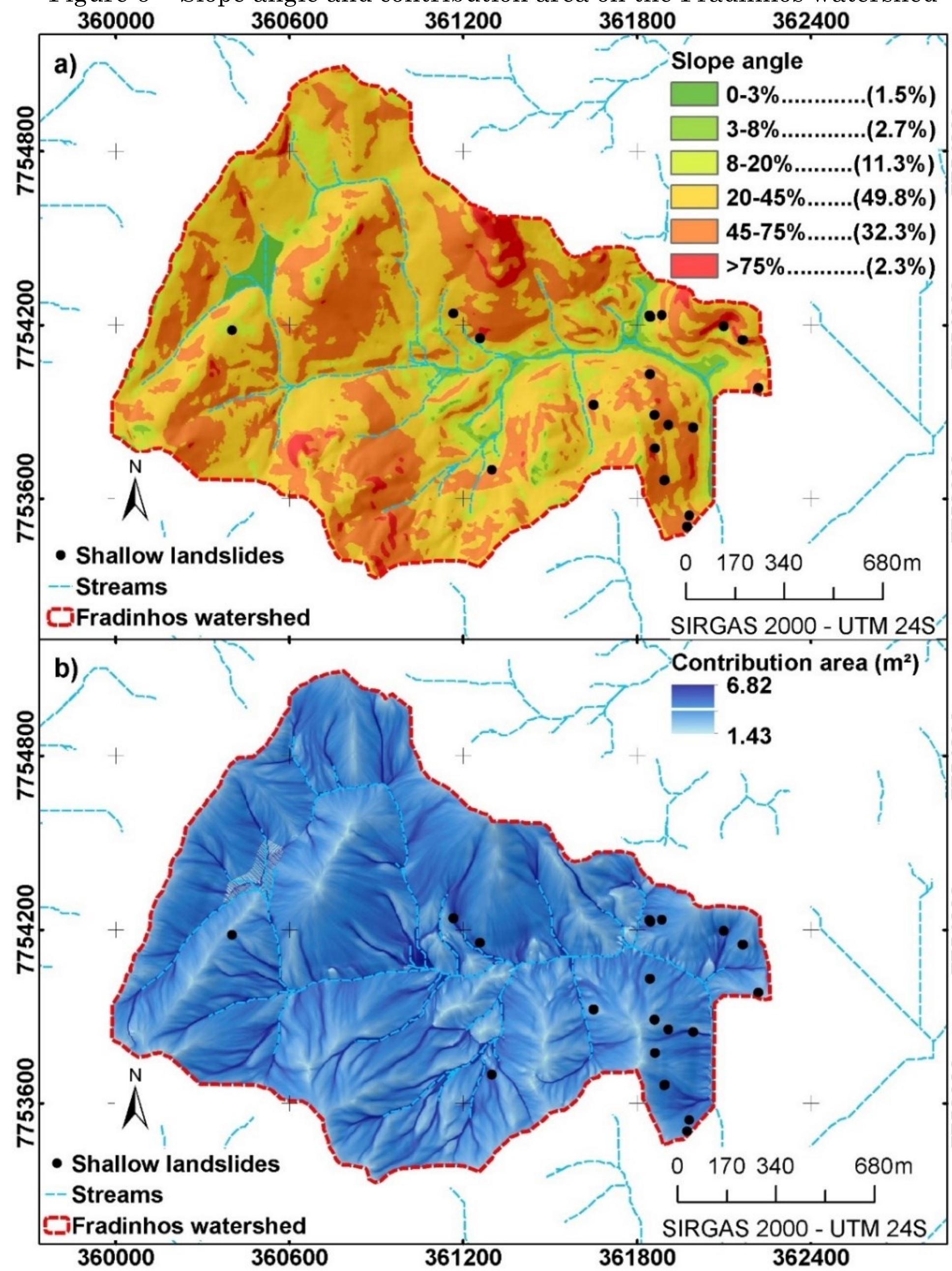
The values for geotechnical parametrization obtained for the Fradinhos watershed are befitting the ones found in the consulted literature (CARSON; KIRKBY, 1975; DE PLOEY; CRUZ, 1979; GUIDICINI; NIEBLE, 1983; GUIMARÃES et al., 2003; LACERDA, 2007; SELBY, 1993; VIEIRA; FERNANDES, 2004).

Shallow landslide susceptibility modelling

Figure 6 shows the slope angle and contribution area of the study watershed. The flatter surfaces, with slope angle reaching 8%, are associated to valley bottoms, with great flow convergence. Slope gradients superior to 45% are associated to convex slopes and middle and upper thirds of the hillsides.

There is a strong relationship between the soil classes and the relief of the area of study, mainly regarding the slope gradient. As stated by Lepsch (2002), relief is the factor that promotes easily noticeable differences on the soil, mostly by color variation in relatively small distances caused by imbalances on the distribution over the terrain of rainfall, sunlight and heat and erosion. Relief is a factor acting directly over the soil's water regime, increasing or decreasing the water content and influencing the time of formation of different soils, with local action, on a slope scale, since that landforms exert a decisive role on the exposure of original materials, on the intensity and direction of water flow on the profile, causing changes on the pedogenetic processes (CAMPOS, 2012).

Figure 6 – Slope angle and contribution area on the Fradinhos watershed



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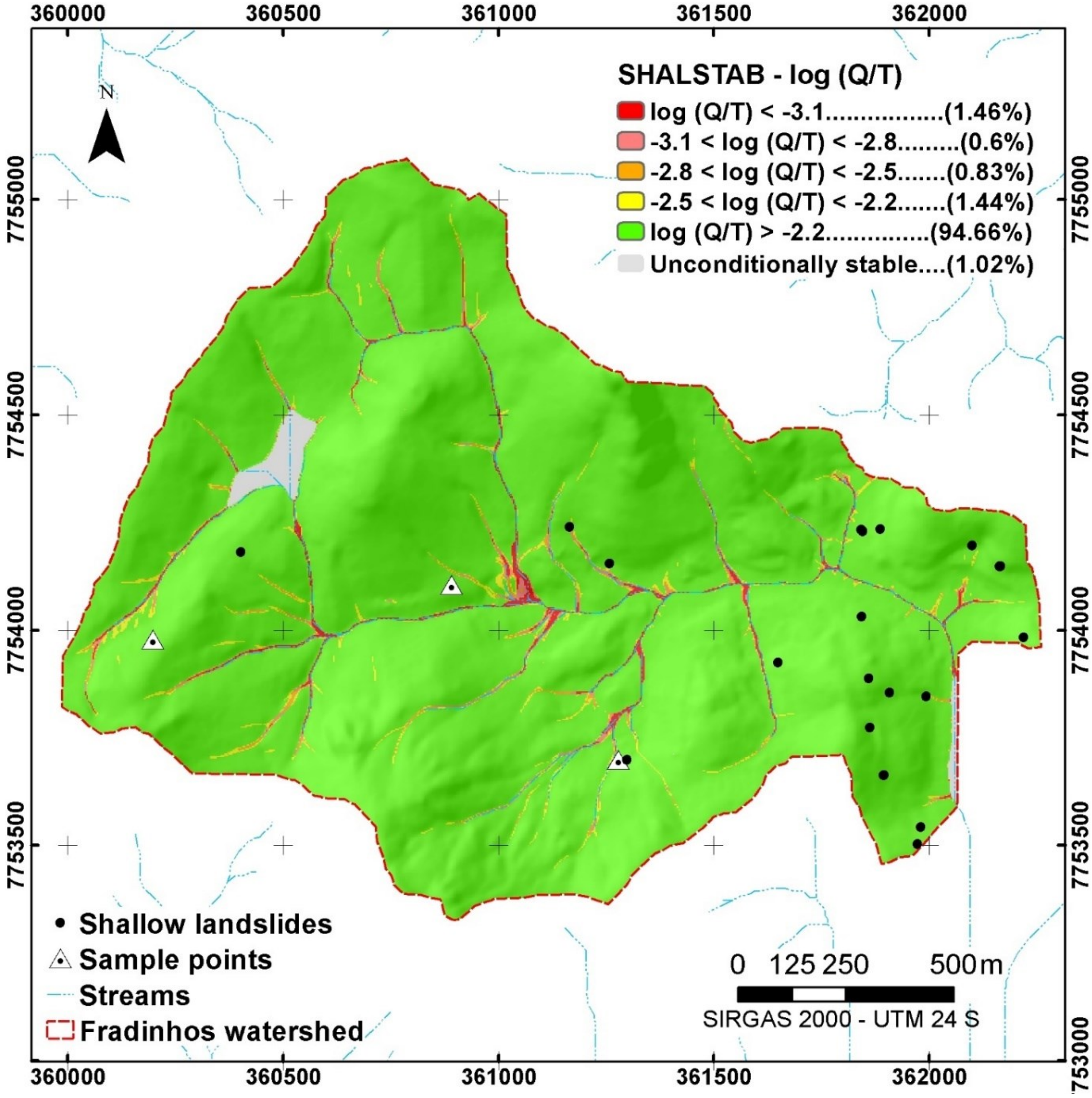
At Fradinhos watershed, the yellow Oxisols are on less inclined slopes, while the Inceptsols are on steeper slopes. The relationship between relief and class soils have been previously observed (CAMPOS et al., 2011; DEMATTE et al., 1996), and on areas with greater inclination, given the intensity of erosional processes, younger soils are present (Inceptsols), usually poorly developed, and on areas with gentler slopes, the soils are more developed (Oxisols).

The susceptibility to shallow landslide model for Fradinhos watershed is presented in Figure 7, resulting from the equation (2) and divided in classes of log (Q/T).

Almost all of Fradinhos watershed was classified as log (Q/T) > -2.2 (94.66%). Two sites are unconditionally stable (at the west and east ends of the watershed), i.e. even in saturated condition there is no susceptibility to shallow landslides. Those are flat areas, with linear slopes, that occupy 1.02% of the watershed.

The most unstable areas (with log (Q/T) values ranging from <-3.1 and <-2.8) are almost 2% of the watershed area and are conditioned to the highest flow convergence areas (hollows) and steeper slope gradient.

Figure 7 – Susceptibility to shallow landslides at Fradinhos watershed, with results in log (Q/T) and frequency of each class.



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The clustering of unstable areas in high flow convergence and steep slopes zones is expected from the SHALSTAB model, given that it prioritizes those areas in its formulations. This occurs because these zones (i.e. high flow convergence and steep slopes) have its pore-pressure rapidly increased during rainfall events, causing its soils to become less cohesive and prone to failures (FERNANDES et al., 2001, 2004; GOMES et al., 2013; GUIMARÃES et al., 2003; MONTGOMERY; DIETRICH, 1994).

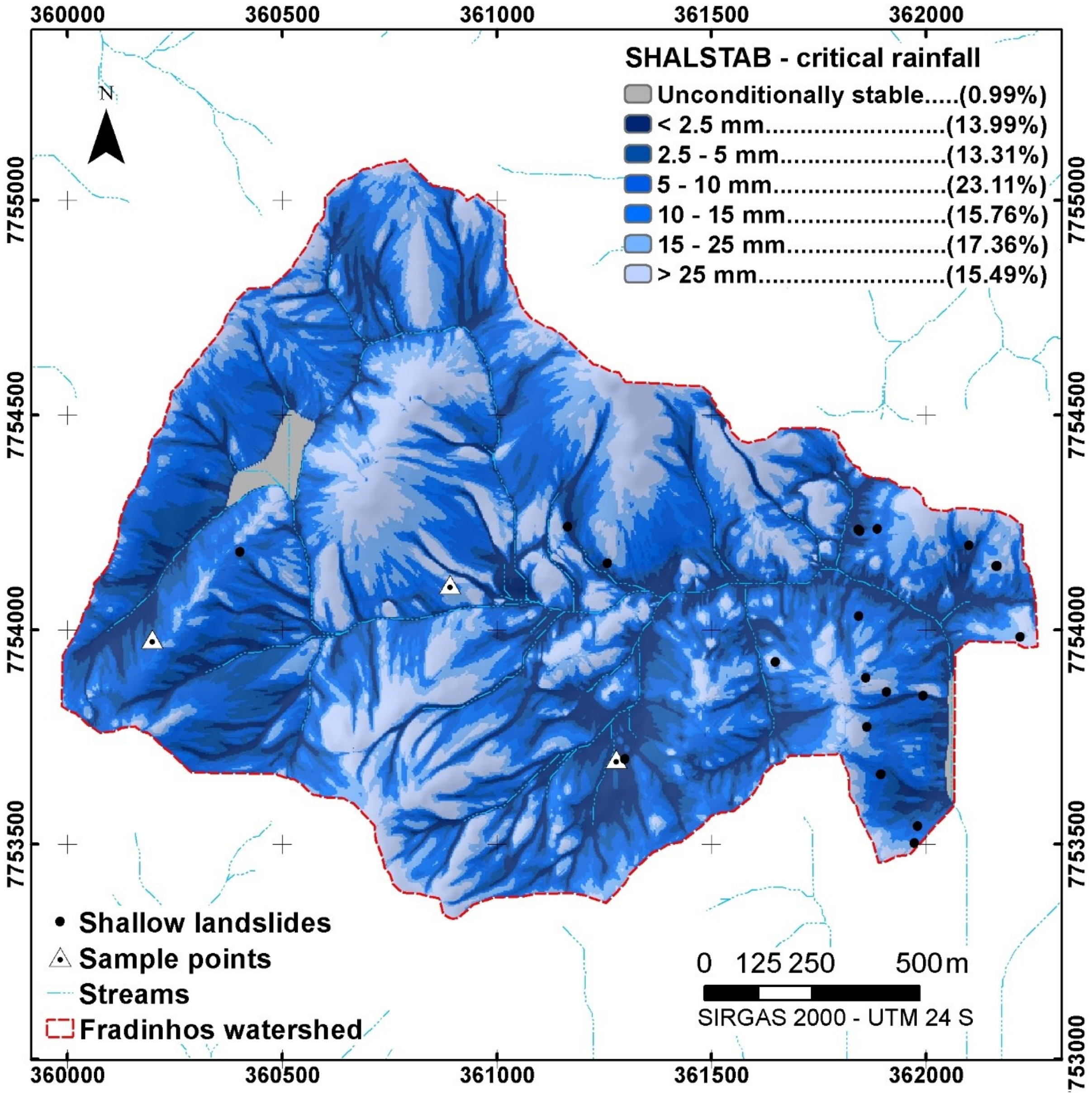
The medium instability areas, with log Q/T values ranging between -2.8 and -2.2, represent transition zones between high and low instability and occupy 2.27% of the watershed.

Of the 21 shallow landslides reports registered by the Vitoria Civil Defense on the Fradinhos watershed, 20 were modelled on the class log Q/T > -2.2 – which is considered the less unstable class. One report had its class modeled in the range -2.5 < log Q/T < -2.2 – considered a class of medium instability (LISTO; VIEIRA, 2012; ZAIDAN; FERNANDES, 2009, 2015).

Zaidan and Fernandes (2009) noted that the SHALSTAB model is more effective when used in areas with well differentiated geotechnical characteristics (such as soil-rock contacts), losing part of its predictive ability in thick soils, gentler inclination slopes and rocky outcrops. Melo and Kobiyama (2018), in a review about the SHALSTAB model, pointed that the use of the complete parametrization is related to higher frequency of stable classes since soil cohesion (*C*) is linked to the shear resistance.

Figure 8 shows the modeled result for critical daily rainfall needed for the triggering of shallow landslides at Fradinhos watershed, with class frequencies. The critical daily rainfall classification follows the one by Effgen (2018).

Figure 8 – Shallow landslide susceptibility at Fradinhos watershed, with results in critical rainfall needed for triggering and class frequency



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The unconditionally stable class is equivalent to the previous modelling, restricted to flat areas and linear slopes. Even in critical condition of saturation, there is no prediction of landslides.

The zones requiring the least daily rainfall to trigger a landslide are associated to hollows and on lower thirds, i.e. areas that concentrate subsurface flows.

The areas requiring more precipitation to trigger landslides are summits, convex and upper third slopes, which are more prone to flow dispersion and less capable of generating subsurface flows.

The most prevalent class in the Fradinhos watershed (23.11%) is the 5-10 mm of daily rainfall needed to trigger shallow landslides, followed the intervals 15-25 mm (17.36%) and 10-15 mm (15.76%). The rainfall intervals with the largest quantities of reports registered are the 5-10 mm and 15-25 mm, with 7 and 5 reports each.

The lesser than 2.5 mm of critical rainfall class had two reports registered, while the 2.5-5 mm class had three records of shallow landslides. Both the 10-15 mm and greater than 25 mm classes had two records each. The unconditionally stable areas had no register of landslides.

The climate normal (measured between 1961-2015) has 62.5% of its days without rainfall records in Vitoria, with a trend of decreasing frequency as the rainfall volume increases (Table 3) (EFFGEN, 2018).

Table 3. Daily rainfall frequency classes in Vitoria (climate normal 1961-2015)

Daily rainfall	Frequency (%)
0 mm	62.5
0.1 - 2.5 mm	16.1
2.5 – 5 mm	5.8
5 – 10 mm	5.9
10 – 15 mm	2.9
15 – 25 mm	3.1
> 25 mm	3.6
Total	100

Source: adapted from Effgen (2018).

By considering the hydraulic transmissivity in the susceptibility modelling, the result presented at

is altered in relation to the previous (

). The predominance of a unique instability class (log Q/T < -2.2) gives place to a great variability of classes of daily critical rainfall needed to trigger shallow landslides.

Close to the Varejão sample location (the one with the smaller permeability among the sampled), the critical daily rainfall needed to trigger landslides is the lowest (up to 10 mm/day), i.e., this relief section is prone to the formation of saturation zones.

Around the Floresta sample location, the minimum rainfall required to trigger landslides is above 10 mm/day. This relates to the great permeability of the soils in this area. The high convergence flow areas and steeper slopes around the Floresta point are an exception, requiring less than 2.5 mm/day to trigger landslides. The summits and convex zones, that disperses flow, need rainfall volumes over 25 mm per day to trigger landslides.

CONCLUSIONS

The Fradinhos watershed has different levels of susceptibility to shallow landslides, as previously shown. The zones with greater flow convergence and steeper slopes present greater proneness to landsliding than flat and convex areas.

The SHALSTAB model was an effective tool for generating critical scenarios, even with the limitation of not considering the temporal change of the soil's pore-pressure characteristics. Therefore, adopting transient models is a promising avenue for shallow landslides researches.

The spatialization linking soil and relief is fundamental to environmental and locational planning in an area, since the allocation of infrastructure without previous knowledge of terrain features can trigger serious problems related to mass wasting, the onset of erosional process, water loss due to accelerated surficial flow and the sedimentation of water courses.

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