Combined analysis of landslide susceptibility and soil water dynamics in a metropolitan area, northeast Brazil

Cristiane Ribeiro de Melo[1#] iD, Paulo Abadie Guedes[2] iD, Samuel França Amorim[3] iD,

Fellipe Henrique Borba Alves[4] iD, José Almir Cirilo[5] iD

Case Study

Abstract
Landslide susceptibility and water balance in the soil, in the community of Lagoa Encantada, Recife Metropolitan Area, Brazil, were assessed using the computational models SINMAP and HYDRUS-1D. The SINMAP input parameters were the physical and hydrodynamic characteristics of the soil, evidence of landslides and the DEM; and for the HYDRUS-1D model, the hydraulic parameters of the soil. For both programs, simulations were also carried out, based on the rain recorded in the area. The soil was classified using the Unified Soil Classification System (USCS). To assess infiltration processes that cause landslides, HYDRUS-1D was used, under the same scenarios simulated by the SINMAP model and also in the evaluation of the infiltrated volume, in real landslides. The SINMAP results (susceptibility maps) show a 71% increase in the susceptible area ($SI < 1$; SI = stability index) between the two precipitation scenarios, and are consistent with evidence of landslides. The HYDRUS-1D results complement SINMAP results and suggest that infiltration values for simulated scenarios were similar to those of real landslides. It is concluded that it is possible to map areas of greater instability and to predict possible landslides in different precipitation scenarios, by quantitatively assessing the infiltrated volume that contributes to the destabilization of the soil.

1. Introduction

In Brazil, the most frequent mass movements are the shallow rotational and translational landslides, triggered by the decrease in the shear resistance of surface soils subjected to intense rains (Sausen & Lacruz, 2015). The critical rainfall volumes that trigger mass movements vary with the soil infiltration regime, the dynamics of groundwater in the massif, the type of material and the instability under study (Gusmão Filho et al., 1997). Landslides related to human interference occur with much less rainfall than natural landslides (Santos, 2012). In the city of Recife, the highest incidence of landslides is observed in the Barreiras Formation. This formation consists of sandy-clayey sediments, poorly consolidated: it is environmentally unstable (Silva et al., 2010). The sandy material has a high content of feldspars, which, under the hot and humid weather, favor landslides (CONDEPE/FIDEM, 2019).

The area chosen for study was the Lagoa Encantada community, with an area of approximately 6 km², located in the Recife Metropolitan Area (RMA), in the Ibura neighborhood, 15 km from downtown Recife. In this place, the relief is steep, unstable and with several human interventions: it has many areas of risk.

For disaster prevention, important information must be generated and updated to determine various levels of threat; indeed, the reliability of the process is limited by factors such as the availability and quality of the data (Dragićević et al., 2015). The minimum database for the preparation of landslide forecasts are: maps of susceptibility or risk of landslides (to indicate which areas are exposed to the problem), previous levels of groundwater in the soil, intensity and duration of rain that are needed to trigger processes and meteorological data and forecasts (Baum & Godt, 2010).

There are computational models that allow assessing the propensity for landslides due to previous precipitation events of known magnitudes and soil characteristics, such as: TRIGRS (Baum et al., 2009), SHALSTAB (Dietrich & Montgomery, 1998), SINMAP (Pack et al., 2005), among others. However, few have the characteristic of a free and

#Corresponding author. E-mail address: cristiane.melo@cprm.gov.br
[1]Serviço Geológico do Brasil, Recife, PE, Brasil.
[2]Instituto Federal de Educação Ciência e Tecnologia de Pernambuco, Recife, PE, Brasil.
[3]Universidade Federal de Pernambuco, Recife, PE, Brasil.
[4]Agência Pernambucana de Águas e Clima, Recife, PE, Brasil.
[5]Universidade Federal de Pernambuco, Centro Acadêmico do Agreste, Caruaru, PE, Brasil.

open source program, for broad access to the scientific community and management institutions that are interested in studying areas susceptible to landslides.

The use of physical models to assess the spatial susceptibility of superficial landslides has proved to be very promising, starting from an analysis of distributed slope stability (Baum & Godt, 2010). The TRIGRS is an open-source program designed for physically-based modeling of the timing and distribution of shallow landslides, caused by rainfall (Alvioli & Baum, 2016). SHALSTAB and SINMAP are also open-source programs. Both combine a hydrological model with an infinite slope stability model for predicting landslide occurrence (Michel et al., 2014). Zizioli et al. (2013) compared the stability models TRIGRS, SHALSTAB, SINMAP and SLIP. The research demonstrates that the four physically based models, although they use different hydrological models, present a close performance regarding prediction of shallow landslide areas. However, according to Witt (2005), SINMAP has the advantage of being able to use transmissivity and recharge values in the calculation so that the precipitation limits can be tested. This characteristic was important when choosing SINMAP for this study.

Combined assessments between susceptibility assessment models are observed in the literature (e.g. Pradhan & Kim, 2016); and methods that assess susceptibility using relief, soil properties and infiltration (e.g. Baum et al., 2010). An alternative is to evaluate the results of susceptibility models and infiltration models in a combined way, aiming to better evaluate the sliding processes. An example is Silva & Zuquette (2013) who calculated the three-dimensional safety factor (3D) and related the results to the wetting depths using HYDRUS-1D.

In this work, the proposed methodology aims to use, in a combined way, a model that is based on geotechnical and climatological information, the accumulation of water in situations of intense precipitation (water balance in the soil) and high resolution digital models of the terrain, in an area not yet studied. The assessment of landslide susceptibility and water balance in the soil were simulated using the following two free access computational models: SINMAP, which computes and maps areas of potential slope instability based on digital elevation data and locations of observed landslides, and HYDRUS-1D, which analyzes the movement of water and solute in porous unsaturated, partially saturated or fully saturated media. It was also decided to use input data that are exclusively public and accessible free of charge. Based on these tools, a general methodology was proposed that aimed at zoning areas by level of susceptibility and understanding the accumulation of water, in the soil, in situations favorable to earth movements caused by the action of rain. Therefore, our objective was to contribute to the techniques of assessing susceptibility to landslides, providing a method of combined analysis, which uses exclusively free software and open data, and which can be useful for future risk analyses and for the creation of warning systems in the studied community.

2. Characterization of the area

The term Barreiras Formation is used to name little or unconsolidated sediments, with varied colors, lithologically varying between clay and conglomerates, with irregular and very indistinct sedimentary structures. It can occur in a discordant way on the crystalline basement or on cretaceous and tertiary sedimentary units. The Lagoa Encantada community was built on this geological unit. According to Pfaltzgraff (2007), covering the crystalline basement and the Cretaceous sedimentary units, the formation is characterized by deposits of coarse sand, interspersed with rhythmic strata of fine sand and/or very friable and easily erodible clay. When subjected to precipitation, water infiltrates the sandy layer and finds the clay layer, which is impermeable. Water accumulates in the sandy area, which becomes more fragile due to poor cohesion, increasing the risk of landslides.

As usual in these occupations, in Lagoa Encantada the decrease in natural vegetation caused by human action, for the construction of houses, is observed everywhere. This behavior of the population results in the exposure of the soil to intense rains, which weakens its resistance to shear and increases the active stresses. Souza et al. (2012) classified the accumulated precipitation intensity in 24 hours for Recife as: heavy rain with values between 18.6 mm and 55.3 mm; and very heavy rain above 55.3 mm.

According to the records provided by the Civil Defense Coordination of Recife (CODECIR), 2,141 requests were met in the 2013-2017 period. There were 65 landslides, 04 damaged walls, 1,755 new plastic sheeting placed and 317 existing plastic sheeting were replaced. Throughout the community, the photointerpretation of high-resolution satellite images and field visits confirmed the existence of scars from past landslides; these certainly were the motivation for the construction of restraint walls and application of plastic tarpaulins, as documented during a field visit. The orthophoto and slope map for this region, where the community is located (Figure 1), shows a hill region with high slopes. The slope classification follows the SiBCS - Brazilian Soil Classification System (EMBRAPA, 2018). Bandeira (2010) showed that in the Southern Area of Recife metropolitan area, in the Barreiras Formation, 69% of slope instability was recorded, with accumulated rainfall values greater than 60 mm in 72 hours. From the total unstable areas in the mentioned area, 75% of the landslides occurred in the Lagoa Encantada community. The majority of landslides in the area occurred until the beginning of 2016, when they declined. Preventive actions implemented by the institutions in charge and awareness raising work with the community have contributed to the reduction of disasters.

3. Materials and methods

An overview of the work structure is presented next. Initially, the type of soil was evaluated, in order to determine
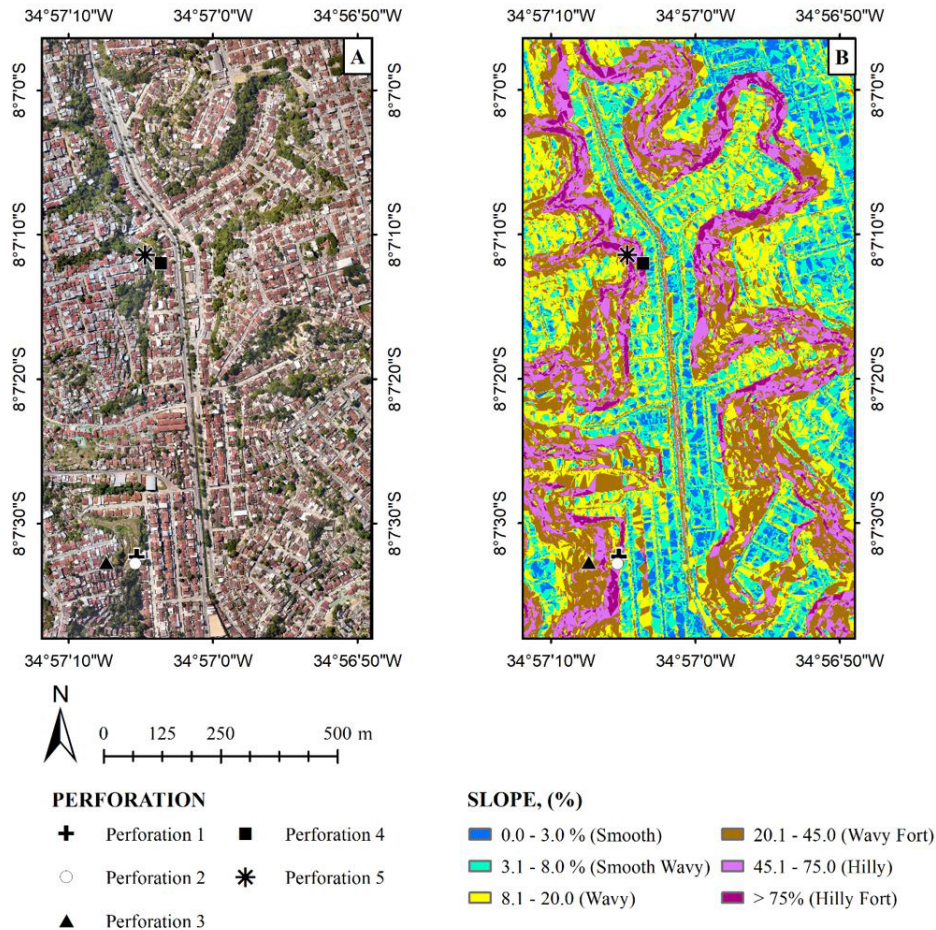
Figure 1. (A) orthophoto, and (B) slope map of Lagoa Encantada.

its physical and hydrodynamic characteristics. In addition, precipitation data, data on previous landslides and the terrain elevation model were also obtained. With this information, the area's behavior regarding landslides was evaluated for two different scenarios: one representing the situation of little rain and the other, the situation of a lot of rain (winter) in the region. The combined assessment was carried out using two separate open source programs: SINMAP and HYDRUS. The assessment carried out by SINMAP determines the map of susceptibility to landslides in the area. It considers rain, but it does not model the infiltration over time. The assessment carried out by HYDRUS complements the previous one, providing data of infiltration over time.

The work structure is depicted in Figure 2. The soil type was determined by prospection with manual auger, and classification by the Unified Soil Classification System (USCS) (steps 1 and 2; items A and B). The rain records used in the study make up item C.

The susceptibility analysis is as follows. The records of landslides that occurred at the site (item D) were used to calibrate the SINMAP model (step 3). This work also used high quality images of the terrain, produced by LIDAR (item E). The cited data (items A to E) were used as input

to the SINMAP model, for the assessment of susceptibility to landslides in two scenarios (item F). SINMAP can work with only a single type of soil.

The infiltration analysis was performed with the HYDRUS-1D model (step 4) from the hydraulic parameters of the soil (item B) and the rainfall data (item C). The soil water balance (step 4) was simulated with precipitation (item C) and infiltration data (HYDRUS-1D), for two situations (item G).

The combined evaluation between the analysis of the models (steps 3 and 4) allows to verify the areas susceptible to landslide, and to evaluate the accumulation of water in the soil in such situations. Unlike SINMAP, HYDRUS-1D can handle more than a type of soil.

3.1 SINMAP model

The computational model denominated "Stability INdex MAPping" (SINMAP) is a deterministic mathematical model that enables the classification of areas that are susceptible to shallow translational landslides; it is configured and manipulated in a GIS environment. SINMAP is related to hydrological factors, as well as factors related to soil fragility, precipitation, soil type and relief as input parameters. The
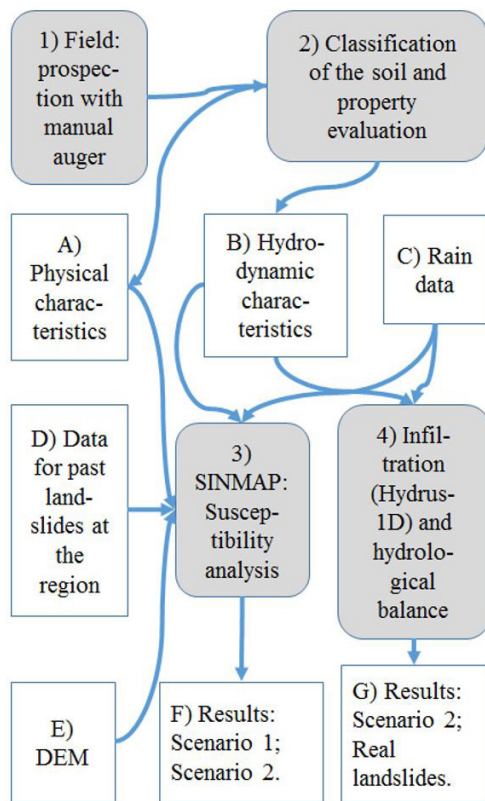
Figure 2. Work structure overview.

Table 1. Slope stability classes (Menon-Júnior, 2016).

SI range	Suggested classes	Possible influences of non-modeled factors
SI > 1.5	Stable	Significant destabilizing factors are required for instability
1.5 > *SI* > 1.25	Moderately stable	Moderate destabilizing factors are required for instability
1.25 > *SI* > 1.0	Little stable	Destabilizing factors are required for instability
1.0 > *SI* > 0.5	Little unstable	Destabilizing factors are not required for instability
0.5 > *SI* > 0.0	Moderately unstable	Stabilizing factors may be responsible for stability
0.0 > *SI*	Unstable	Stability factors are required for stability

model was applied in a region that experiences shallow translational and rotational landslides.

The accuracy of the program results is strongly dependent on the quality of the digital elevation model (DEM) that is used (Pack et al., 2005). The validation of the model depends on the verification of the spatial coincidence between the previously mapped slip scars, and the areas designated as unstable by the model. The results are presented based on the stability index (*SI*), or safety factor, which is the probability that an area be considered stable, assuming uniform distributions of the parameters, in the uncertainty ranges. This probabilistic result is of great importance for usage in future risk analyzes. The safety factor presented here does not correspond to the safety factor calculated by limit equilibrium models like the slice methods; they just have the same name.

The *SI* can vary from 0 (most unstable situation) to 1.5 (most stable situation). SINMAP is simulated for 6 *SI* classes, as shown in Table 1. One advantage of the model is that it is not restricted to a specific program and operating system. Rather, it presents the option of being used on the MapWindow platform (open source GIS software). More information about SINMAP can be obtained in USU (2017).

3.1.1 SINMAP input parameters

The DEM used in the model is one of the products of the Pernambuco Three-Dimensional Program (PE3D),

which provides products generated through Light Detection and Raging (LiDAR) technology. The DEM provided by PE3D is generated after classification of point clouds with a density of approximately 1 point/m^2, removal of elevation points related to treetops and buildings, and finally the surface interpolation through kriging. The matrix file used has a spatial resolution of 1m, and an altimetric accuracy greater than 25 cm. For more information about the PE3D program, see Governo do Estado de Pernambuco (2017). For DEM validation, see Governo do Estado de Pernambuco (2018).

Another input for SINMAP was a set of records from highly susceptible points, including past landslides occurred in the community, with and without victims. These records were used in the calibration and validation of the SINMAP model. This information was provided by the Coordination of Civil Defense of Recife (CODECIR), from 2013 to 2017. The location of Lagoa Encantada has rainfall monitored by the Ibura and Alto da Bela Vista automatic stations, which are operated by the Pernambuco Water and Climate Agency (APAC, 2017).

The physical parameters of the soil and its hydrodynamic characteristics were obtained from Santana (2006), who analyzed the same type of soil in nearby areas (2 km). Ebel et al. (2018) suggested that estimates of unsaturated hydraulic parameters, based on field data *in situ*, in contrast to laboratory measurements, can lead to a more accurate simulation of the hydrological response to rain. However, it was not possible to carry out more specific experiments due to financial cost, poor accessibility, and the lack of security in the community.

The identification of the type of soil in Lagoa Encantada was made based on the prospecting test with a manual auger, carried out *in situ* and later in laboratory tests to characterize the deformed samples according to the USCS classification. With the soil defined, the parameters presented by Santana (2006) were used, which identified the same type of soil in the UR2 community, located approximately 2 km from the area

studied here. In the study, Santana (2006) collected deformed samples for characterization tests, granulometry tests with sedimentation, Atterberg limits and densities; undisturbed samples for direct shear tests; permeability tests "Tri-Flex" and *in situ* permeability "Guelph".

For the Barreiras Formation, in Recife, studies showed that the humidity profiles, both in winter and summer, differ only over the first three meters of depth, delimiting the potential landslide surface in the studied area (Gusmão-Filho et al., 1997). Normally, depending on the intercalations of draining sandy layers and impermeable clay layers, as well as the characteristic of the superficial layer, in most cases very deep water tables and fringes of variable surface moistening are founded. Such information served as the basis for determining the average rupture depth, which was visually estimated as 2 m, in the field.

3.1.2 Physical parameters of the soil and hydrodynamic characteristics

The field estimations took place in September 2017, just after the rainy season for the region. During the previous 10 days, as well as in the work day there were no rains of significant volume, which could interfere with the results. The daily rainfall recorded were considered according to Souza et al. (2012) dry day (rainfall < 2.2 mm) or very light rain (2.2 mm ≤ rainfall < 4.2 mm). For recognition of the soil profile, five perforations were made with manual auger, at different levels of elevation, in two locations in the community: Point 1, where there is no record of landslides; and Point 2, where there is a record of a landslide, which occurred on 06/28/2011. The locations for the perforation points are depicted in Figure 1. The coordinates and depths reached in each one of the perforations are presented in Table 2.

At Point 1, the depths reached by prospecting for the three levels were up to 8.9 m, and for the two levels of Point 2, up to 7.50m. The subsoil profile for each perforation can be seen in Figure 3.

In the holes made, samples were taken at every meter of depth, or visual change of layer, to be subsequently subjected to laboratory analysis. The deformed samples were sieved and the granulometric classification was performed for use by USCS. No tests were carried out to determine the percentage of clay and silt particles. The Atteberg limits (liquid limit

and plastic limit) were determined using a prepared sample with prior drying.

According to the Unified Soil Classification System, the particle size and boundary analyzes showed variations for the samples between clayey sand (SC), low plasticity clay (CL) and silty sand (SM). However, it was observed that the predominant soil in the sampling is of the SC (clayey sand) type. This type was considered to be characteristic of the whole local soil profile. The parameters used for the soil
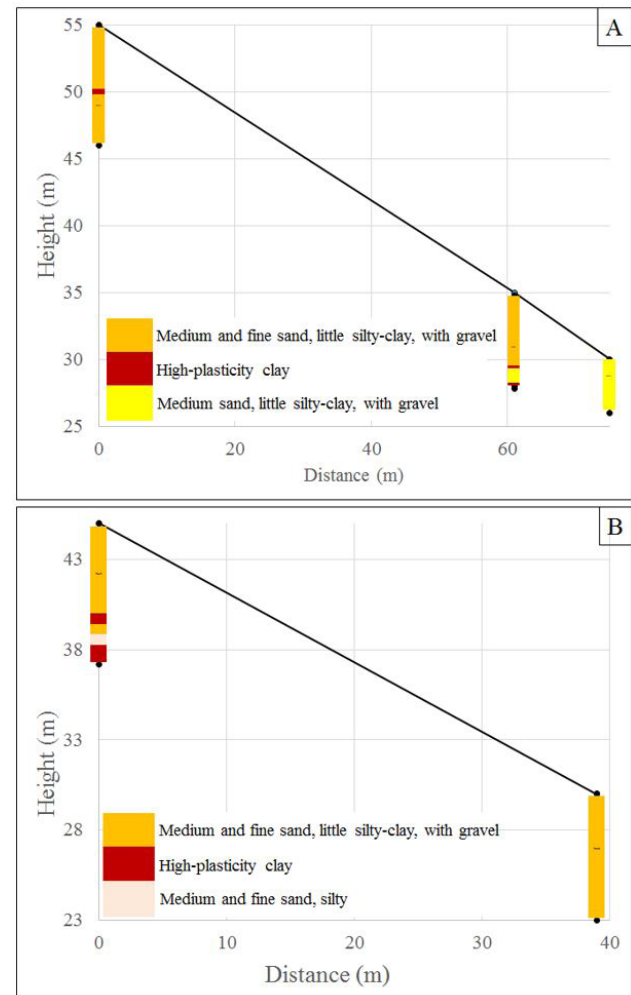
Figure 3. Sub-soil profile: (A) point 1: perforations 1 to 3; (B) point 2: perforations 4 and 5.

Table 2. Perforation points made in Lagoa Encantada.

Point	Perforation	Coordinate		Altitude (meters)	Depth reached (meters)
		Latitude	Longitude		
1	1	8º 7' 32,32"	34º 57' 5,29"	30.00	3.70
	2	8º 7' 32,80"	34º 57' 5,40"	35.00	7.05
	3	8º 7' 32,70"	34º 57' 7,40"	55.00	8.90
2	4	8º 7' 12,00"	34º 57' 3,60"	30.00	7.00
	5	8º 7' 11,40"	34º 57' 4,70"	45.00	7.50

type SC, considered as the only soil for entering parameters in SINMAP, were presented by Santana (2006), who studied and identified the soil from the UR2 Community, located approximately 2 km from Lagoa Encantada, within an area of the Barreiras Formation. The basic soil parameters that were used in the model are shown in Table 3.

The dimensionless cohesion, or the contribution of cohesion to stability slope, necessary for the model, unlike the classic cohesion of soil mechanics, is the ratio between the cohesive strength of the soil and the root zone in relation to the weight of a saturated layer of soil, as shown in Equation 1.

$$C = \frac{(Cr + Cs)}{(h \cdot \rho_s \cdot g)} \tag{1}$$

Where the symbols and units used in SINMAP are: C = dimensionless cohesion; Cr = root cohesion (N/m²); Cs = soil cohesion (N/m²); h = perpendicular thickness of the soil (m); ρ_s = density of wet soil (kg/m³); and g = acceleration of gravity (m/s²). For use into the model, Cr was considered null, due to homogenization and considering the worst scenario of complete removal of vegetation, and h as 2 m depth.

The soil hydrodynamic characteristics in Lagoa Encantada were performed by correlation, as performed for the physical characteristics. The transmissivity value ($T = 0.1526$ m²/h) is the product between the hydraulic conductivity determined for the SC soil ($k = 0.07632$ m/h) (presented by Santana, 2006), and the depth of the soil susceptible to sliding (h = 2 m) determined visually in the area. The T/R ratio, transmissivity over groundwater recharge (incident rain) that was used by the program, depends on the recharge capable of causing slippage, as considered in the analysis. Two scenarios were evaluated for soil recharge: scenario 1, for rains occurring in a period of low precipitation; and scenario 2, for a rainy season with high rainfall.

3.1.3 Hydrological data

For the simulation of scenario 1 (low rain incidence), the precipitated volume in November, recorded by the Data

Table 3. Physical soil parameters for entry into the SINMAP model.

Parameter	Value
Type of soil	SC (clayey sand)
Soil density (ρ_s)	2,670 kg/m³
Internal friction angle (ϕ)	29° (min) and 36.1° (max)
Cohesion (C_s)	0 kPa (min) and 8.88 kPa (max)
Dimensionless cohesion	0 (min) and 0.17 (max)

Collection Platform (PCD), "Alto da Bela Vista", was used as the groundwater recharge value. Considering that the month of November had the lowest daily rainfall in the available data series, with values close to zero, it was decided to use, in the referred Scenario 1, the monthly total precipitated occurred in the month, as the maximum and minimum recharge. The situation of daily maximum rains, in the studied region, occurs on average in the rainiest quarter, between the months of May and July, with June being normally the most critical month. For scenario 2, the highest rainfall that occurred in 48 consecutive hours was used, in all rain series recorded in the PCD. The evaluated scenarios, their respective recharges and the T/R values are shown in Table 4.

3.2 HYDRUS-1D model

The prediction of a landslide event depends on the pore water pressure, a consequence of the incident rain that is deterministically quantified by the Richards Equation (van Genuchten, 1980). The water balance in the soil was simulated trying to determine the accumulation of water in a situation that could slide, assisting in the assessment of risk areas and situations, based on the joint analysis of the relief and the infiltration of water in the soil. The HYDRUS-1D software (Šimunek et al., 2013), which aims simulating the one-dimensional movement of water, was selected. The model numerically solves the Richards equation for variable water flow, offering the option of four analytical hydraulic models that describe water retention in the soil, as a function of hydraulic conductivity. More information at PC-progress (2019).

HYDRUS-1D (version 4.17) was used by Feltrin et al. (2013) to simulate the dynamic of water in the soil, in an area under vegetation cover in a native field. Feltrin et al. (2013) compared the simulated results with results obtained in field measurements; they concluded that the results presented by the program are compatible with the drainage obtained in a lysimeter. Zhang et al. (2017) applied the SINMAP model to Zhouqu County, successfully identifying areas susceptible to landslides, and determined the saturated hydraulic conductivity for use in the model, using the HYDRUS-1D software. Therefore, it is reasonable to assume that HYDRUS-1D can be used to adequately simulate infiltration in the studied region. It is also an open source program, hence it was chosen.

In this work, the HYDRUS-1D model was used to reproduce the water balance in the soil in the same simulated situation for the use of SINMAP, in the winter period, making possible a joint evaluation of the results. In a second analysis,

Table 4. Groundwater recharge considered for precipitation and T/R ratio scenarios.

Scenarios	Recharge (mm)		Period of the occurrence		T/R	
	Maximum	Minimum	Maximum	Minimum	Maximum	Minimum
Scenario 1	20.31	9.09	November/2016	November/2015	12,090	5,411
Scenario 2	120.59	57.73	June 03 and 04, 2016	June 28 and 29, 2017	127	61

the model was used to simulate the water balance in real situations of landslide in the Lagoa Encantada area.

The analysis of water accumulation in the soil was carried out by hydrological balance. This decision aimed to better represent the accumulation of water in the soil and maintain consistency in relation to the analysis using SINMAP. This analysis considered Scenario 2 SINMAP, which includes the maximum rainfall observed throughout the series, over a period of 48 hours. The maximum rain occurred between 3 and 6 April, 2016.

Unfortunately, because the free version of the program was initially thought for use in agriculture, it disregards topography. The disregard of the slope of the terrain, which would contribute to the decrease of infiltration and increased runoff, brings, as a consequence, an overestimated simulation for the infiltration.

3.2.1 HYDRUS-1D input parameters

To determine the water balance in the soil of Lagoa Encantada, the standard module of the HYDRUS-1D program was used to calculate the infiltration of water, in a profile of two layers of the soil. Groundwater recharge estimation was not considered in our calculations because, during prospecting, the presence of groundwater was not found. It was assumed, for the model, that the water table was located far below the bottom of the soil domain, and therefore it would not affect the flow processes, in the adopted soil profile. As no specific tests were performed to determine the parameters necessary for the model, it was decided to use the hydraulic parameters of the soils provided by the program, which are very approximate averages for the different texture classes (PC-progress, 2020).

Soil was reclassified as required by the model, and it was necessary to adapt and use the United States Department of Agriculture (USDA) soil texture classification system. Considering that the soil found during prospection was classified by the USCS as SC (clayey sand) type, the Loamy Sand soil option in the soil catalog was used as the best alternative to represent the studied area. It is important to note that in the area under study, as the topsoil is subjected to transformations caused by weather, sun exposure and other agents, a thin impermeable or semi-permeable layer is formed above the ground. Thus, in order to better represent the real soil conditions, the soil was considered as being divided into two layers: 1) an initial layer of Sandy Clay Loam soil from 0 to 12 cm deep; and 2) a second layer from 13 cm to 200 cm thickness of Loamy Sand soil. The depth of the two layers representing the soil profile totalized 2 m of the rupture surface, the same depth considered for SINMAP. The analytical hydraulic model, chosen at HYDRUS to assess infiltration in the pilot area, was that of van Genuchten (1980). The flow of water that penetrates through the soil surface increases, as the pressure of the surface water layer increases. According to the program manual, this flow into

the soil stabilizes when the depth of the surface water layer reaches 3 cm (Šimunek et al., 2013).

3.2.2 Rain period used in the simulation

To assess the water balance in the soil, all simulations, from January 1th to September 30th, of each year were evaluated. This means that the simulated period corresponded to 250 consecutive days of observation. The assessment begins in the dry period, passing through the most humid quarter, which occurs between the months of May to June, until the recession of rains in September. Unfortunately, in the Lagoa Encantada and its surroundings (up to a maximum of 7 km), there were no PCD or rain gauges with hourly precipitation records, with a series prior to May 2015. In order to observe the gradual accumulation of water in the soil, prior to the landslide events that occurred in 2015, a significant series of data was needed. Thus, the infiltration analysis was performed on a daily basis (accumulated for 24 hours), using data from the CPRM/Recife rainfall station, monitored by the Geological Service of Brazil (SGB). It belongs to the National Hydrometeorological Network, located 11 km from the studied area. The data series that was used for the referred study can be accessed at the National Water Agency (ANA, 2019).

4. Results

4.1 SINMAP simulation and scenario assessment

The results show the SINMAP susceptibility classes for the simulation of the two proposed scenarios: scenario 1 - groundwater recharge for one month, during the summer, where the monthly total precipitation is low; and scenario 2, for a maximum rain of 48 hours, which occurred during winter, for the entire series recorded by the PCD station "Alto da Bela Vista". The maps for stability and saturation index for scenarios 1 and 2 are in Figure 4.

The calculation was performed over a total area of 0.791 km^2 using DEM with a spatial resolution of 1 meter. However, the area effectively calculated by the model corresponded to 0.614km^2. In other words, an amount of 22.4% of the total area was classified by the program as "no data". Of all the susceptible points plotted, only 75 of them were presented on the area with calculated *SI* and the others on the area not calculated, classified as "no data". Thus, the results of this work consider only the 75 points with calculated *SI* by SINMAP.

When compared, the maps of scenarios 1 and 2 show that, in the situation of lower rainfall, the region that is in low humidity and has a stable or moderately stable factor of security is greater. In this case, the zones at the threshold of saturation and total saturation occupy very few areas. In scenario 1, even though the groundwater recharge is very
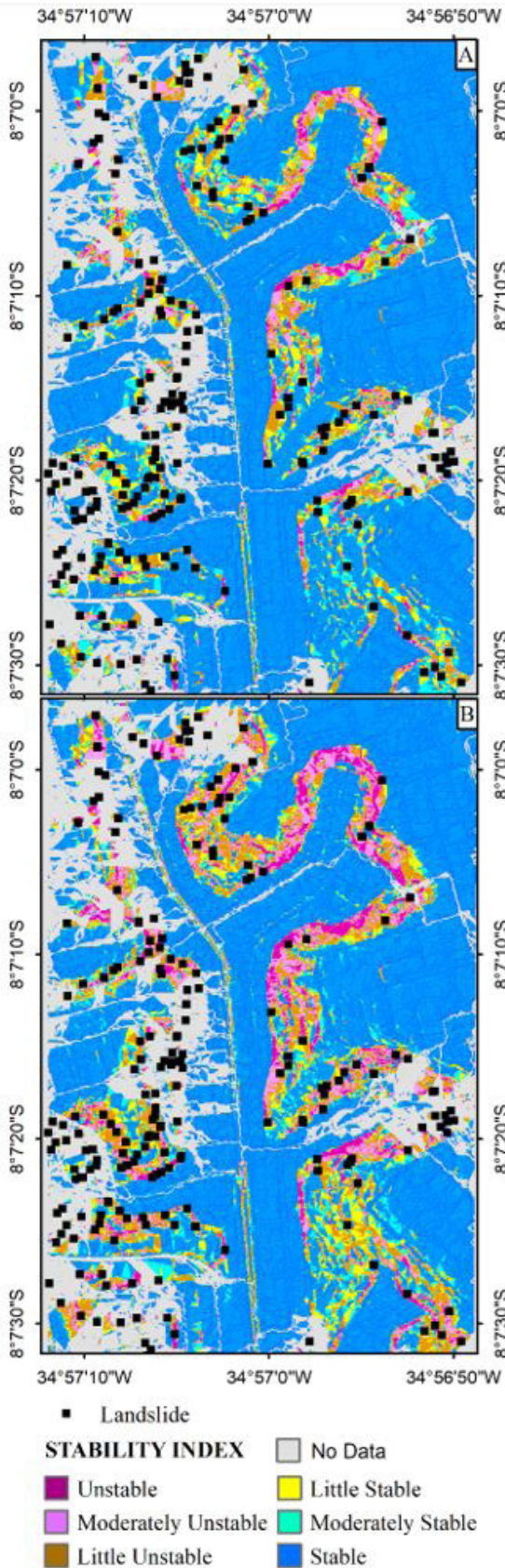
Figure 4. Stability and saturation index for (A) scenario 1 and (B) scenario 2.

low, there is instability on the slope, at the steepest points. With the simulation of increased recharge (scenario 2), and a significantly increased number of unstable zones, a smaller recharge was observed (Table 4), which is more diluted in time, in relation to the constant transmissivity. With the increase in precipitation in winter, there was a transformation from "moderately stable" and "little stable" classes, at steep places, to "little stable" and "little unstable" classes, respectively.

The graph that was generated from the validation model for the two scenarios can be seen in Figure 5. According to the results for the two scenarios, the slip points provided for the validation are distributed in the areas of least stability in the *SI* value and are located in a region with steeper slopes, with a contribution area of up to 100 m². In Figure 5, it was noted, for scenario 1, that a considerable part of the landslides
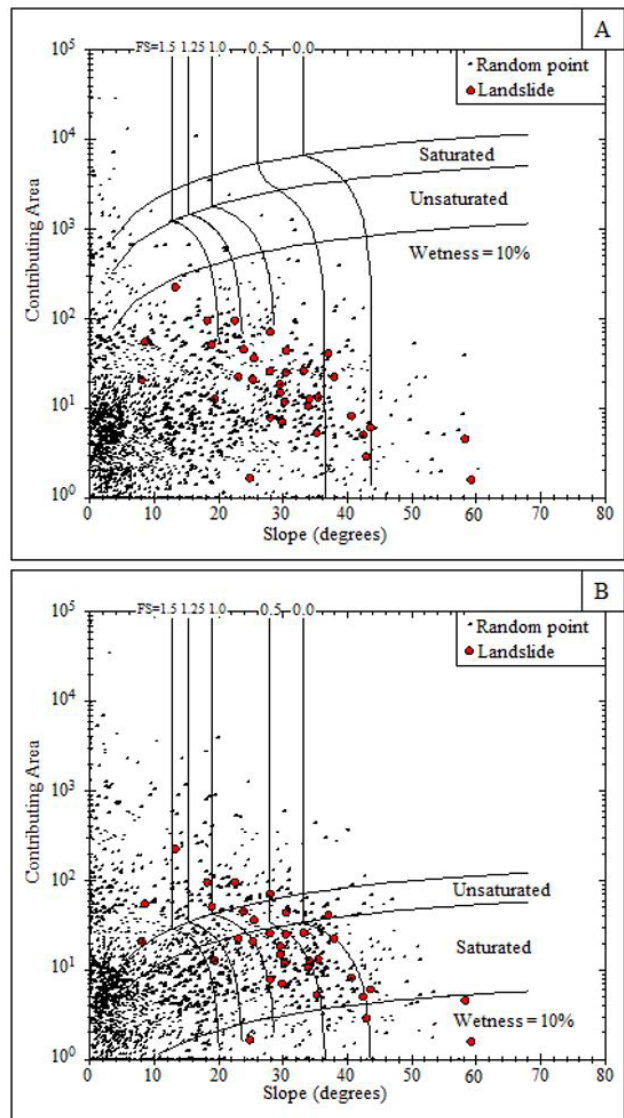

Figure 5. Results of the SINMAP validation model (sliding scars mapped by CODECIR in red and model calibration points) for (A) scenario 1 and (B) scenario 2.

occurred in slope intervals between 20º and 44º. The same is presented for scenario 2. For the low rainfall situation, most of the mapped risk points were in conditions of low humidity, and with a stability index (*SI*) below 1.25. However, in the situation of greater humidity, the mapped risk points were mostly in the zone with the highest saturation, with a stability index (*SI*) below 1.0. The evaluation of the two scenarios showed that, in case of landslide, this will not be caused only by rain, but also by the excessive slope of the terrain and other associated factors.

Following the same methodology presented here, simulations were carried out for maximum rainfall of 12 and 24 hours in the studied region. For these groundwater recharges, SINMAP predicted, as expected, that for the Lagoa Encantada community the most stable areas can be found in the flatter regions, regardless of the soil and hydraulic parameters used. The areas of greatest instability combined well with the steeper terrain, provided that it was in a certain range of slope of the terrain. For all recharge simulations, the results showed that massive precipitation is not necessarily required for the landslides to start; furthermore, the topographic factor is an important trigger for the occurrence of landslides.

Table 5 show the statistics of the areas simulated by SINMAP for each scenario, according to the risk class. In these tables, the following three terms are presented: 1) "#Landslides", which corresponds to the number of landslides inserted in each stability zone, based on the points susceptible to landslides supplied to the program by the user (total of 75 points); 2) "% of slides", which is the percentage distribution of the referred points; and 3) "LS Density (#/km^2)", which corresponds to the relationship between the number of landslide points and the respective area for each stability index.

The analysis of Table 5 show that, for Scenario 1 (little rain), 55% of the studied cases are in an unstable situation, with 41 landslide points reported in CODECIR's history (total of 75) that are inserted in such areas. With the increased precipitation for scenario 2, which presents the highest reload, there is an increase of percentage of landslide cases in the areas of instability to 77%, which corresponds to the insertion of 58 mapped points in an unstable area. Significant changes in the precipitation threshold showed

that SINMAP was particularly sensitive to changes in the amount of groundwater recharge, with an increase in the expected areas of instability. This is expected because the recharge rate certainly is one of the most important factors in triggering landslides.

4.2 Soil water balance using HYDRUS-1D

The accumulation of water in the soil in the days prior to landslides is an important destabilizing factor. In this way, the water balance in the soil was modeled in order to try to understand how the infiltrated water contributes to the risk of landslide in the region. The water balance was simulated for two situations: 1) scenario 2 simulated by SINMAP, where the maximum rain per 48 hours, of the whole series recorded in the community, was used as a groundwater recharge; 2) simulation of the volume of water accumulated on the ground in real landslide situations that occurred in 2014.

4.2.1 HYDRUS-1D simulation for real landslide situations

In the studied location, the rainiest quarter usually is between the months of May and July, a period in which, on average, 50% of the annual rainfall is concentrated. In 2014, when the total precipitous of 202.20cm was recorded, the landslides occurred on June 26 and July 12. During the mentioned winter months, the total precipitated corresponded to 42% of the annual precipitation. The volume infiltrated in 2014 was simulated by HYDRUS-1D. The rains that occurred during the year and the infiltrated volume are shown in Figure 6. Based on the results, the accumulated infiltration was calculated (Figure 6).

In the studied area, the landslides that occurred in winter are more common because this is a period of intense precipitation. Table 6 shows the numerical values involved in the water balance, on the day of the mentioned landslides. The soil types present in Lagoa Encantada were also studied by Schilirò et al. (2019), in another region. This study concluded that the soil types SC and CL were the most influenced by the rainfall events evaluated, and that they are very susceptible to landslides. It also showed that humidity conditions are an important triggering factor.

Table 5. SINMAP statistics for scenarios 1 (S1) and scenarios 2 (S2).

SI	*SI* > 1.5	1.5 > *SI* > 1.25	1.25 > *SI* > 1.0	1.0 > *SI* > 0.5	0.5 > *SI* > 0	0 > *SI*
#Landslides (S1)	14	6	14	19	16	6
% of slides (S1)	18.67	8	18.67	25.33	21.33	8
Area (km^2) (S1)	0.47	0.03	0.04	0.04	0.02	0.01
LS Density (#/km^2) (S1)	29.91	193.09	356.78	442.61	732.87	553.05
#Landslides (S2)	9	0	8	27	21	10
% of slides (S2)	12	0	10.67	36	28	13.33
Area (km^2) (S2)	0.43	0.03	0.04	0.06	0.04	0.02
LS Density (#/km^2) (S2)	21	0	202.22	431.52	573.35	570.48

Table 6. Water balance in the soil on the day of the landslides in 2014.

Landslide date	Precipitation on the day of the landslide (cm)	Accumulated from January 1 until the day of the landslide		
		Precipitation (cm)	Infiltration (cm)	Overland flow (cm)
06/26/2014	8.4	115.9	78.6	28.9
07/12/2014	0	129.2	87.1	42.1

Figure 6. (A) simulated soil water balance from 01/01/14 to 09/30/14; (B) accumulated infiltration for 2014.
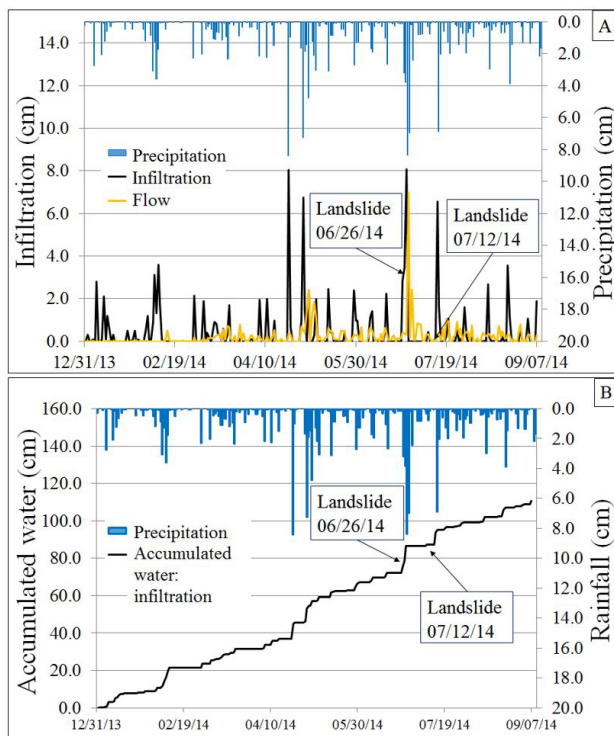

Figure 7. (A) simulated soil water balance for 01/01/16 to 09/30/16. (B) accumulated infiltration for 2016.

According to Table 6, the average infiltration in the soil, until the day of the registered landslides, would be close to 70% of the value of the accumulated precipitation until that day. This data assumes that the soil was subject to the same conditions established for the HYDRUS-1D simulation, but disregarding the influence of the slope, which is a limitation of the model for the open version. In the observed cases, the landslides occurred after the accumulated precipitation, between the first day of the year (see item 3.2.2) until the day of the landslide, was greater than 100 cm of rain. The exposed areas available for infiltration, and subject to urbanization, can be seen in Figure 1.

4.2.2 HYDRUS-1D simulation for Scenario 2 SINMAP for maximum 48h rain

In order to maintain consistency in relation to the analysis in item 3.2.2, it was decided to assess the hydrological balance, using the CPRM/Recife rain station. The year 2016, with a precipitated annual total of 139.40cm of rain, presented an anticipated rainier quarter, between the months of March and May. During the aforementioned months, the precipitated
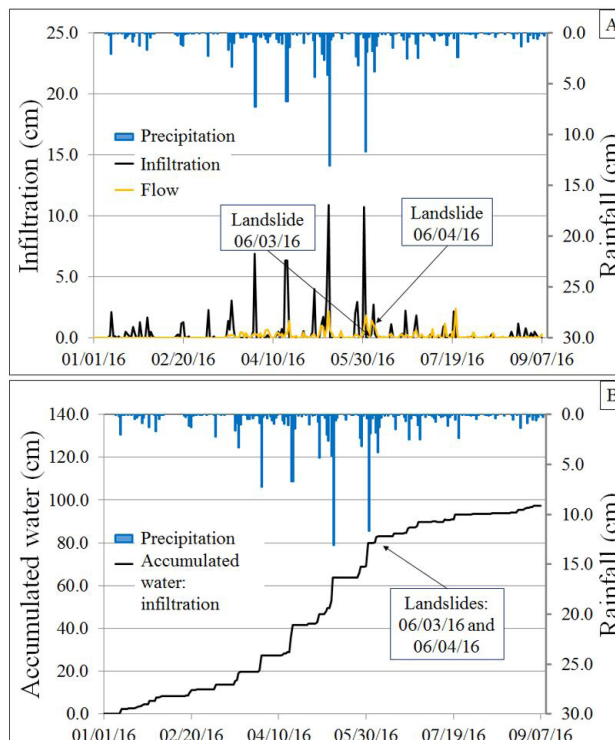
total corresponded to 64% of the annual total, that is, there was a high concentration of precipitation in the period. The rainfall and the infiltrated volume, simulated for scenario 2, is shown in Figure 7. Based on the results of the simulated infiltration, the water that was accumulated in the soil, for the year 2016, is also illustrated in the same figure.

According to Figure 7, a possible landslide that occurred during the critical situation of instability in Scenario 2 would happen after a period of great accumulated infiltration. The accumulation of water in the soil in the days preceding Scenario 2, in addition to the little rain recorded on the day of the event, would be the triggering agents for an eventual landslide. The hydric balance showed that the accumulated precipitation from January 1 to the day of the landslide (June 4, 2016) was 107.2 cm and the infiltration was of 80.1 cm. The simulated infiltrated volume corresponds to 75% of the total precipitated in the year. It is important to note that, unlike HYDRUS-1D, the SINMAP program does not consider the accumulated rain in the period before the landslide, but a punctual rain with a value that can be accumulated, or not. Another difference, which must be

considered, is the type of soil involved in the analysis. As previously mentioned, the types of soils used for the two programs are different, but have similarities in their general characteristics.

Considering the simulation for scenario 2, and comparing it with the values presented in real landslide situations for 2014 (Table 6), it is observed that the infiltration values for the referred scenario are similar to those of real landslide cases. In other words, the situation presented to SINMAP, added to the HYDRUS-1D infiltration calculation would result in an approximate representation of a real landslide in the Lagoa Encantada region, in Ibura.

5. Discussion

Using a more accurate DEM in order to improve the analysis by SINMAP of unstable areas, prevented the evaluation of 22.4% of the area provided, as well as of the sliding scars in these areas with "no data". These results are in agreement with Thiebes et al. (2016), who states that the quality of spatial resolution influences the accuracy of the results. However, increasing the quality of the DEM can result in areas with an uncalculated SI ("no data").

The analysis of the SINMAP data obtained showed an increase in susceptible areas from scenario 1 to scenario 2, but the "no data" area remained the same. This is also in accordance with Witt (2005) and Sulaiman et al. (2017), in the following aspects. Witt (2005) showed that SI was not calculated by SINMAP in some regions ("no data"). Sulaiman et al. (2017) tested different DEM resolutions and concluded that the coarser DEM reveals less area which is unstable and, even with 1 meter DEM, it may not be possible to overcome the problems.

According to Figures 2A and 2B, native vegetation is mainly in the steepest areas, which is expected, and did not present identifiable landslides. In Lagoa Encantada, for example, the banana tree is common: it facilitates infiltration and destabilization. According to McGuire et al. (2016), vegetation can increase or decrease stability. The apparent cohesion provided by the roots is a strong factor for stability, in relation to the other factors, which can also exert influence during events of extreme rain. However, according to Guoa et al. (2019), some types of roots can facilitate slipping, increasing infiltration during precipitation.

The HYDRUS results for the real landslide scenarios show the levels of infiltration that probably occurred to cause the landslide situation. The assessment of accumulated rain, with HYDRUS-1D, was based on Gusmão Filho (1990), who studied landslides in Barreiras Formation in Recife and emphasized the importance of evaluating concentrated rain. Chen et al. (2018) used a combined method of landslide susceptibility analysis, which employs soil moisture monitoring through sensors and a numerical simulation model. HYDRUS-2D was used to determine soil parameters and the model data was compared with field measurements. The results show that the combined analysis, using field humidity monitoring with sensors, can reliably predict the potential for future landslides, under heavy rain.

6. Conclusions

The Lagoa Encantada community, located in the area of Barreiras Formation hills, in the city of Recife, is vulnerable and prone to landslides and accidents. That is due to human interventions, the type of soil, high slopes, absence of natural vegetation, and intense rainfall.

This study aimed to contribute to the techniques of assessing susceptibility to landslides, providing a method of combined analysis, which uses exclusively free software and open data, and which can be useful for future risk analyzes and for the creation of warning systems in the studied community. The proposed method uses two analysis: one for landslide susceptibility, and another for hydric balance in the soil. To assess the susceptibility to landslides in the area, the computational model SINMAP was used. The simulation of the hydric balance of the soil in landslide situations was carried out through the HYDRUS-1D program.

As expected, the SINMAP susceptibility map showed an increase in areas susceptible to landslides, due to increased precipitation. The HYDRUS-1D model showed that the landslides occurred in situations of accumulated precipitation greater than 100 cm of rain and infiltration of approximately 70% of this precipitation.

When evaluating the infiltration in the superficial layer in real events, it was observed that landslides occurred when the accumulated infiltration, presented by the program, reached an average value of 82.9 cm, with a variation of more or less 4.3 cm. This information is not yet conclusive, as it was obtained with little data. However, the result is important and promising, as it suggests a practical strategy to better understand the causes of landslides due to infiltration, soil and relief. Thus, more research is necessary to evaluate if the observed or predicted infiltrations, at this level, can potentially work as relevant forecast data for landslides in the region. For instance, it is important to study past landslides in more detail, and see how infiltration may vary.

This work represents an important step in the creation of more accurate models for assessing slip susceptibility, as it allows to consider, in a combined way, important triggering factors for the Barreiras Formation. Future work may try to assess if the method can be used in other susceptible areas (possibly with different soil and relief), the influence of wastewater on the susceptibility to landslides, as well as to evaluate ways of dealing with the presence of uncalculated areas ("no data") in the susceptibility map.

Declaration of interest

The authors declare that there are no conflicting interests.

Authors' contributions

Cristiane Ribeiro de Melo: original draft preparation, investigation, validation, discussion of results, writing – reviewing and approval of the final version of the manuscript. Paulo Abadie Guedes: investigation, discussion of results, writing – reviewing and approval of the final version of the manuscript. Samuel França Amorim: original draft preparation, investigation, validation, discussion of results. Fellipe Henrique Borba Alves: validation, discussion of results and diagram creation. José Almir Cirilo: original draft preparation and discussion of results.

List of symbols

ANA	National Water Agency
APAC	Pernambuco Water and Climate Agency
CL	Low plasticity clay
CODECIR	Coordination of Civil Defense of Recife
CONDEPE/FIDEM	State Planning and Research Agency of Pernambuco
CPRM	Brazilian Geological Survey
DEM	Digital Elevation Model
LIDAR	Light Detection and Raging
PCD	Data Collection Platform
PE	Pernambuco
RMA	Recife Metropolitan Area
SC	Clayey sand
SHALSTAB	Shallow Landsliding Stability Model
SiBCS	Brazilian Soil Classification System
SINMAP	Stability Index Mapping
SM	Silty Sand
SLIP	Shallow Landslides Instability Prediction
TRIGRS	Transient Rainfall Infiltration and Grid-Based Regional Slope-Stability Model
UR2	Residential Unit 2
USCS	Unified Soil Classification System
USDA	United States Department of Agriculture
USGS	United States Geological Survey
C	Dimensionless cohesion
Cr	Root cohesion
Cs	Soil cohesion
g	Acceleration of gravity
h	Depth of the soil
ϕ	Internal friction angle
K	Hydraulic conductivity
R	Recharge
SI	Stability Index
ρ_s	Soil density
T	Transmissivity

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