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Alert scenarios for the Metropolitan Region of Recife-PE based on monitoring of rainfall and soil humidity – a case study

Roberto Quental Coutinho[1#], Bruno Diego de Morais[1], Rodolfo Moreda Mendes[2], Marcio Roberto Magalhães de Andrade[2]

Case Study

Keywords
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Moisture monitoring
Barreiras Formation
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Abstract

In Brazil, landslides are frequent, causing deaths and property damage, and occur under the influence of natural and/or anthropic conditions. Rain acts as the main non-anthropic agent in triggering this phenomenon. Because of this, the prediction of landslides becomes an essential tool for managing high-risk areas. The Metropolitan Region of Recife (MRR) has a large history with numerous cases of mass movements over the years. Currently, research points out improvements in the quality of forecasts by including hydrological information, such as soil moisture, in warning systems. Given the importance of measuring soil moisture in situ, a network of equipment consisting of rain gauges and capacitive moisture sensors was installed in the MRR, to monitor rainfall and soil moisture in an integrated manner. The objective of this article is to understand the hydrological conditions of the soil in two high-risk areas of the MRR, built over the Barreiras Formation to set the foundations for the development of a Landslide Early Warning System (LEWS) that integrates rain and humidity. The data showed that the variation in soil moisture is very dependent on rainfall and presents sudden variations in moisture with increasing hourly rainfall. The data also revealed that the monitored soils remained wet for approximately six months in the year 2022, highlighting the potential for moderate rainfall during this period to trigger landslides.

1. Introduction

In Brazil, landslides are one of the most frequent hazards, resulting in significant economic and social losses, such as deaths, injured victims, and property destruction (Dias et al., 2021). Rain acts as the main non-anthropic agent in triggering this phenomenon, as it is related to the dynamics of surface and subsurface waters (Augusto Filho et al., 2018).

The Metropolitan Region of Recife (MRR) does not differ from the national scenario and has a large history with numerous cases of mass movements over the years (Bandeira & Coutinho, 2015). According to Macedo & Sandre (2022), between 1988 and 2022, in the city of Recife, 173 deaths caused by landslides were registered.

Due to this background, Bandeira & Coutinho (2015) and Coutinho & Delfino (2022) developed critical precipitation thresholds for several towns in the MRR, to predict landslides, aiming to warn the population residing in high-risk areas. However, many authors point out that, due to simplifications, such as not considering the hydrogeological processes involved in the slope rupture process, those systems that consider only precipitation can generate false alarms (Toll et al., 2011; Abraham et al., 2021).

In the current scenario, research has shown that the quality of forecasts improves when including soil hydrological information (Wicki et al., 2020). According to Pirone et al. (2015), rainwater infiltration is considered a critical factor in the occurrence of landslides, as it reduces matrix suction in soils, which consequently decreases their shear strength resistance. Thus, monitoring soil moisture is an important variable for predicting landslides (Bovolenta et al., 2020).

To monitor the risk of landslides, National Early Warning and Monitoring Centre of Natural Disaster - CEMADEN with technical support from the Group of Geotechnical Engineering of Disasters and Plains - GEGEP installed a network of equipment in the MRR. This network includes rain gauges and capacitive moisture sensors that monitor rainfall and soil moisture in an integrated manner. Therefore, this study aims to understand the hydrological conditions of the soil in two high-risk areas in the MRR during the year 2022. This year was marked by exceptionally intense rains, resulting in landslides and floods (Marengo et al., 2023). In addition,

[#]Corresponding author. E-mail address: roberto.coutinho@ufpe.br
[1]Universidade Federal de Pernambuco, Programa de Pós-graduação em Engenharia Civil, Recife, PE, Brasil.
[2]Centro Nacional de Monitoramento e Alertas de Desastres Naturais, Coordenação Geral de Pesquisa e Desenvolvimento, São José dos Campos, SP, Brasil.

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the article aims to set the foundations for the development of an early warning system for landslides, which takes into account both rainfall and soil moisture.

2. Description of the study areas

In this article, the study areas cover occupied hillside territories located in the cities of Recife and Jaboatão dos Guararapes, in the State of Pernambuco (PE), Northeastern Brazil, as shown in Figure 1. Area 1 is located in the North zone of Recife and has an approximate area of 25 km^2. Area 2 is located in the south of Recife and part of Jaboatão dos Guararapes municipality, and has an area of approximately 21 km^2. Both areas have a relief characterized by a sharp division between the plain and the hills.

These areas are urban territories, densely occupied, with the construction of houses on slopes that are susceptible to landslides, thus generating a serious socio-environmental problem that requires a series of actions by the public authorities and society (Coutinho et al., 2017). In the field, irregular occupations, steep slopes, cuts, and landfills carried out without technical criteria, waste accumulation, disposal of wastewater and other factors which induce the occurrence of landslides can be identified. Figure 2 illustrates the scenarios found in the study areas and shows the negative impact of anthropic intervention.

3. Climatic aspects

The climate of the city of Recife is characterized as coastal tropical, being strongly influenced by the humid air masses of the Atlantic Ocean and by the Intertropical Convergence Zone. This results in a climate that is generally humid, hot, and influenced by the proximity to the coast. According to Mendonça & Danni-Oliveira (2007), the city has an annual rainfall of about 2500 mm and an average temperature of 26.1 ºC. The wettest period occurs between March and August, with a monthly average of over 200 mm, while the driest season lasts from October to February.

For this paper, data from two automatic rain gauges were analyzed. Data were collected between 2019 and 2022. The rain gauges used were the RG-01, installed in the neighborhood Dois Unidos (Area 1), and the RG-02, installed in the neighborhood Ibura (Area 2). Figure 3 shows the accumulated monthly rainfall. In both areas, it is observed that the rainiest period occurs between March and August,

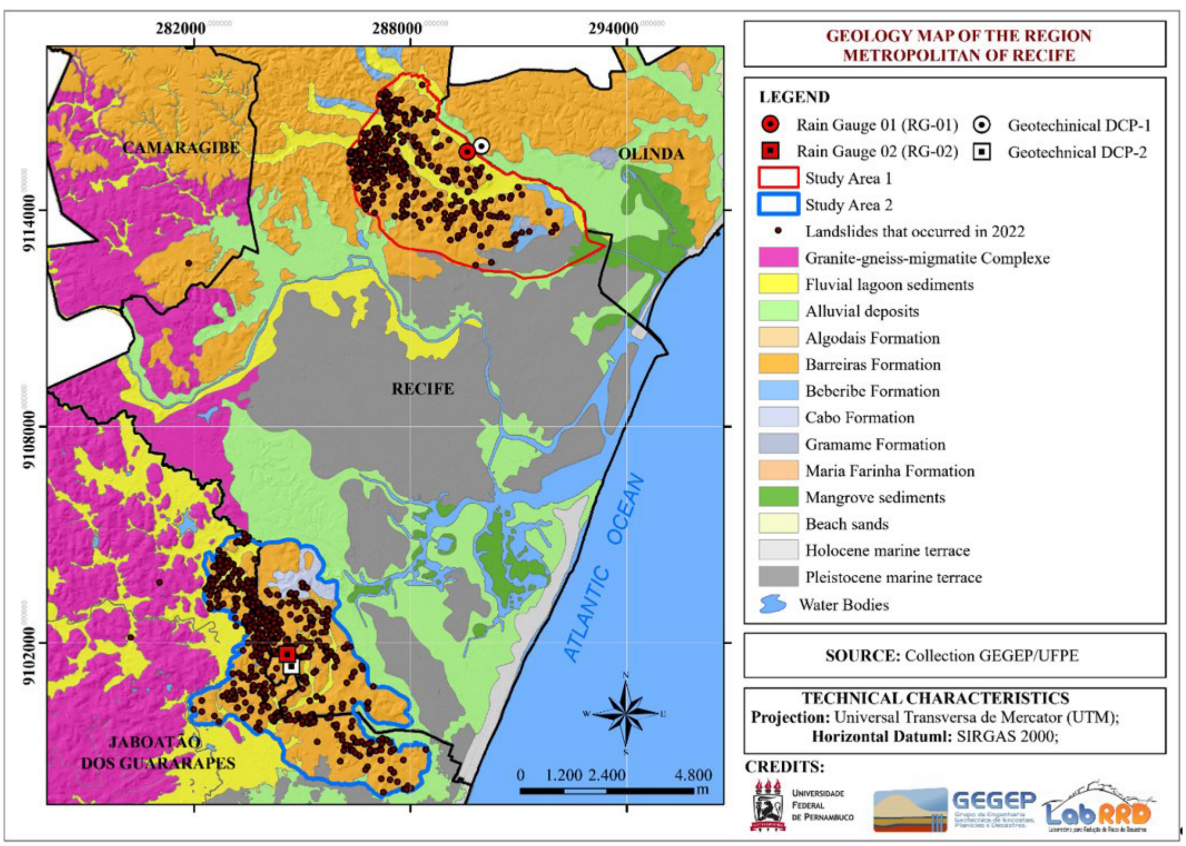

Figure 1. Location of the study areas, rain gauges, Geotechnical DCP, the spatial distribution of geological units in the MRR, and landslides that occurred in the study area in 2022.

Figure 2. Scenarios identified in the study areas: a) steep slopes; b) waste material accumulation on the slopes; c) wastewater discharge on the slope.

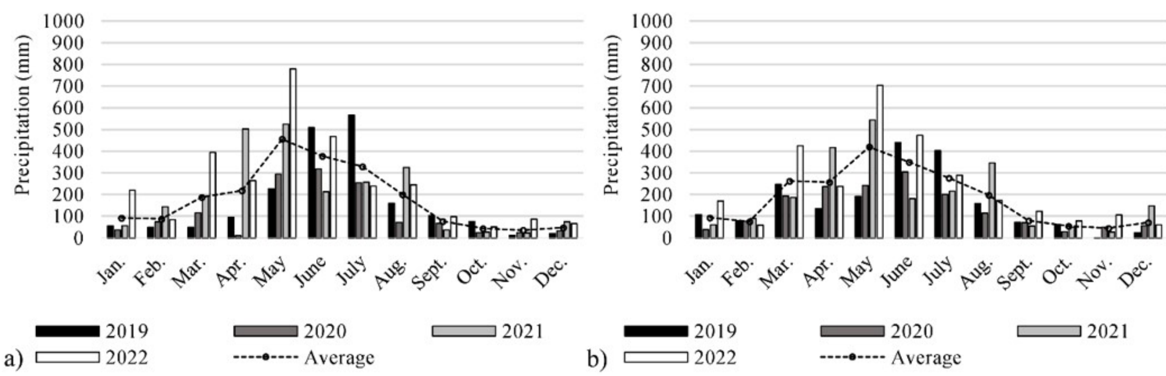

Figure 3. Precipitation recorded monthly between the years 2019 and 2022: a) RG-01 rain gauge; b) RG-02 rain gauge.

with monthly averages equal to or greater than 200 mm. In the analyzed period, May 2022 was the month with the highest monthly rainfall, 780 mm at RG-01 and 703 mm at RG-02.

4. Geological characterization

When analyzing the map in Figure 1, it is observed that the MRR has a complex geology, with several different geological units. However, the two studied areas are mostly located on the Barreiras Formation. This geological unit has continental expression, of great occurrence on the Brazilian coast, being commonly found in the slope areas of the MRR (Bandeira & Coutinho, 2015; Coutinho et al., 2019).

This geological formation has vivid colors, ranging from red and yellow to white, depending on the degree of iron oxidation (Bandeira & Coutinho, 2015). It is lithologically composed of poorly consolidated sand-clay sediments, specifically quartz sands, interspersed with rhythmic strata of fine sand and/or clay (Coutinho & Severo, 2009). Due to these characteristics, the soils of this formation are susceptible to gravitational mass movements and erosion processes (Coutinho et al., 2006).

5. Landslides in the study areas

In the MRR, the main triggering factors for landslides are geology, anthropic action, relief, and precipitation (Coutinho et al., 2019). Currently, the cities of Recife and Jaboatão dos Guararapes occupy the 6th and 10th place, respectively, among the cities with the highest number of deaths caused by landslides in Brazil, between 1988 and 2022 (Macedo & Sandre, 2022). Studies carried out by Bandeira & Coutinho (2015) revealed that 75% and 85% of landslides in these cities, respectively, are directly related to rain.

Between late May and early June of 2022, due to atmospheric disturbances coming from the east, exceptionally heavy rains were recorded in the states of Pernambuco, Alagoas, and Paraíba, causing landslides and flooding (Marengo et al., 2023). In Recife, on May 28, 2022, has accumulated 204 mm, being classified as extreme rain on the scale proposed by Guedes & Silva (2020). Figure 4a and Figure 4b, show that landslides in both areas are closely related to high levels of precipitation.

Most landslides in the MRR are shallow and their failure surfaces are translational (planar) and parallel to

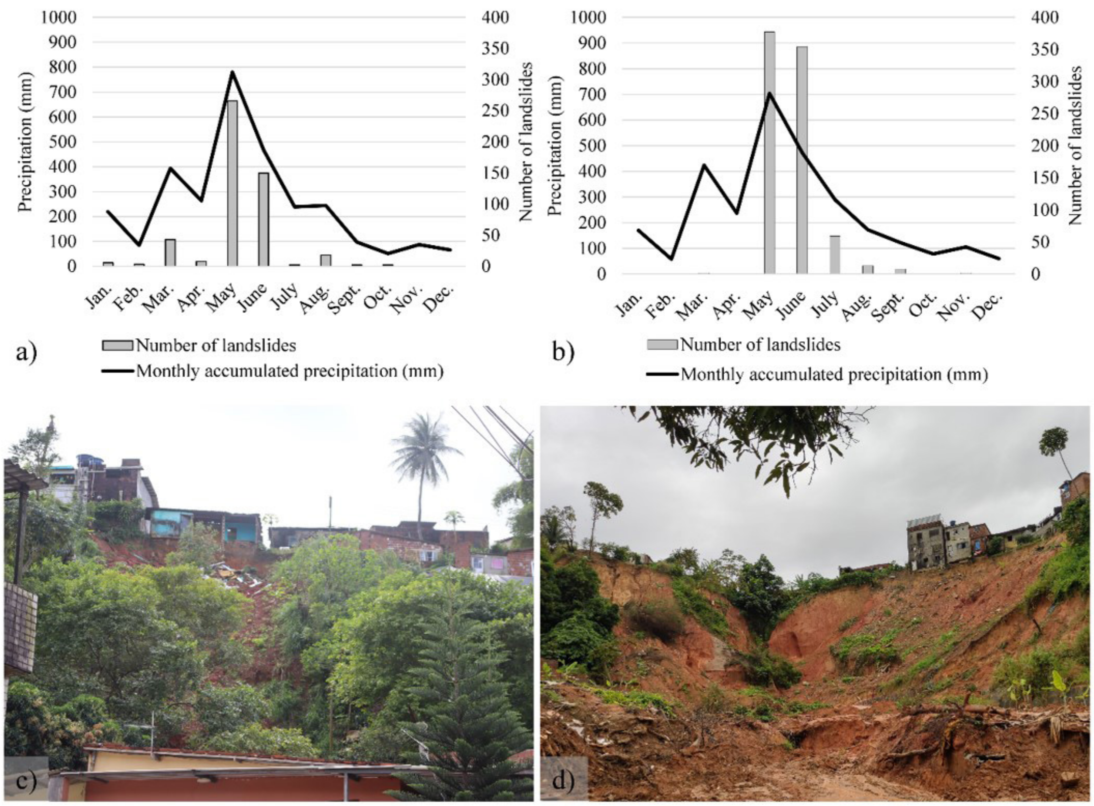

Figure 4. Landslides and monthly rainfall during 2022 in: a) Area 1; b) Area 2. Landslides that occurred on May 28, 2022: c) Córrego do Jenipapo – Area 1; d) Monte Verde – Area 2.

the slope (Gusmão Filho et al., 1997). Figure 4 shows two cases of landslides that occurred in the study areas on May 28, 2022. Figure 4c shows the planar landslide in Córrego do Jenipapo, located in Area 1, which caused fatalities and injuries. Figure 4d shows the landslide at Ave. Chapada do Araripe (Monte Verde), located in Area 2, on the border of Recife and Jaboatão dos Guararapes, which also resulted in fatalities.

Figure 5 presents the proposal for critical rainfall thresholds developed by Coutinho & Delfino (2022) for Area 1. The events were divided into three groups: (i) localized 1 to 3 landslides); (ii) sparse (4 to 9 landslides); and (iii) generalized (above 9 landslides). It is observed in Figure 5 that the dot representing the accidents that occurred in 2022 in Area 1 is outside the trends established by those authors. This discrepancy highlights the need to consider extreme weather events caused by climate change in engineering design and to integrate risk and disaster management strategies.

6. Geotechnical data collection platform

To improve the CEMADEN disaster monitoring and alert system, a geotechnical data collection platform (Geotechnical DCP) network was created in 2019 on MRR. These platforms aim to improve the understanding of rainwater infiltration dynamics into the soil, adding environmental parameters to the system. Each Geotechnical DCP incorporates several devices, including a rain gauge to measure the amount of rainfall, capacitive moisture sensors to determine the in-situ volumetric water content of soil (%), a data logger for collecting and transmitting data, and a photovoltaic panel to provide energy to the system.

Through the collected data, the aim is to predict and identify the conditions in which the maximum moisture values are reached, which indicates soil saturation, the most unfavorable situation for the stability of slopes. At each Geotechnical DCP, moisture sensors were installed every 0.5 m deep, covering a range of 0.5 to 3.0 m. This resulted in a total of 6 moisture sensors per platform. Figure 6 illustrates the equipment that makes up a Geotechnical DCP and shows the arrangement of moisture sensors installed in an access tube implanted in the ground.

7. Methodological aspects

To analyze the effect of rainwater infiltration into the soil, five stages of work were carried out in two study areas in the MRR affected by landslides in 2022. These stages were:

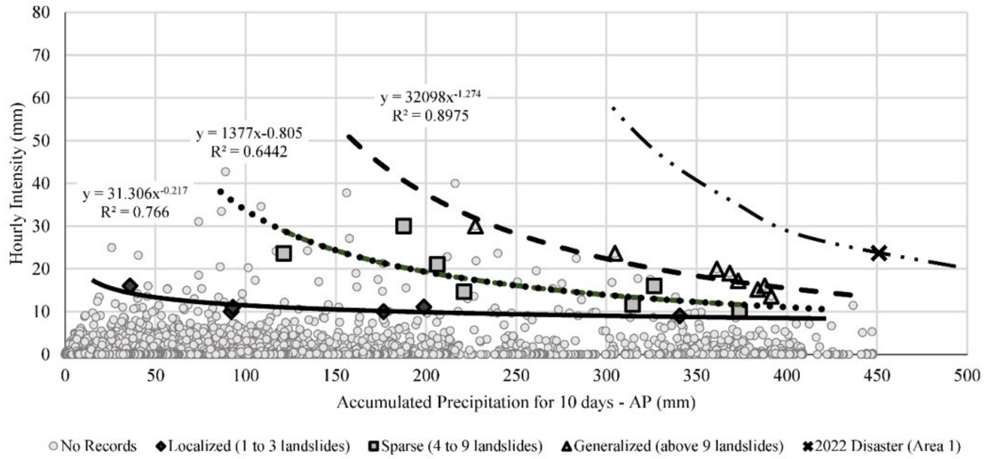

Figure 5. Correlation between hourly intensity by accumulated precipitation for 10 days [adapted from Coutinho & Delfino (2022)].

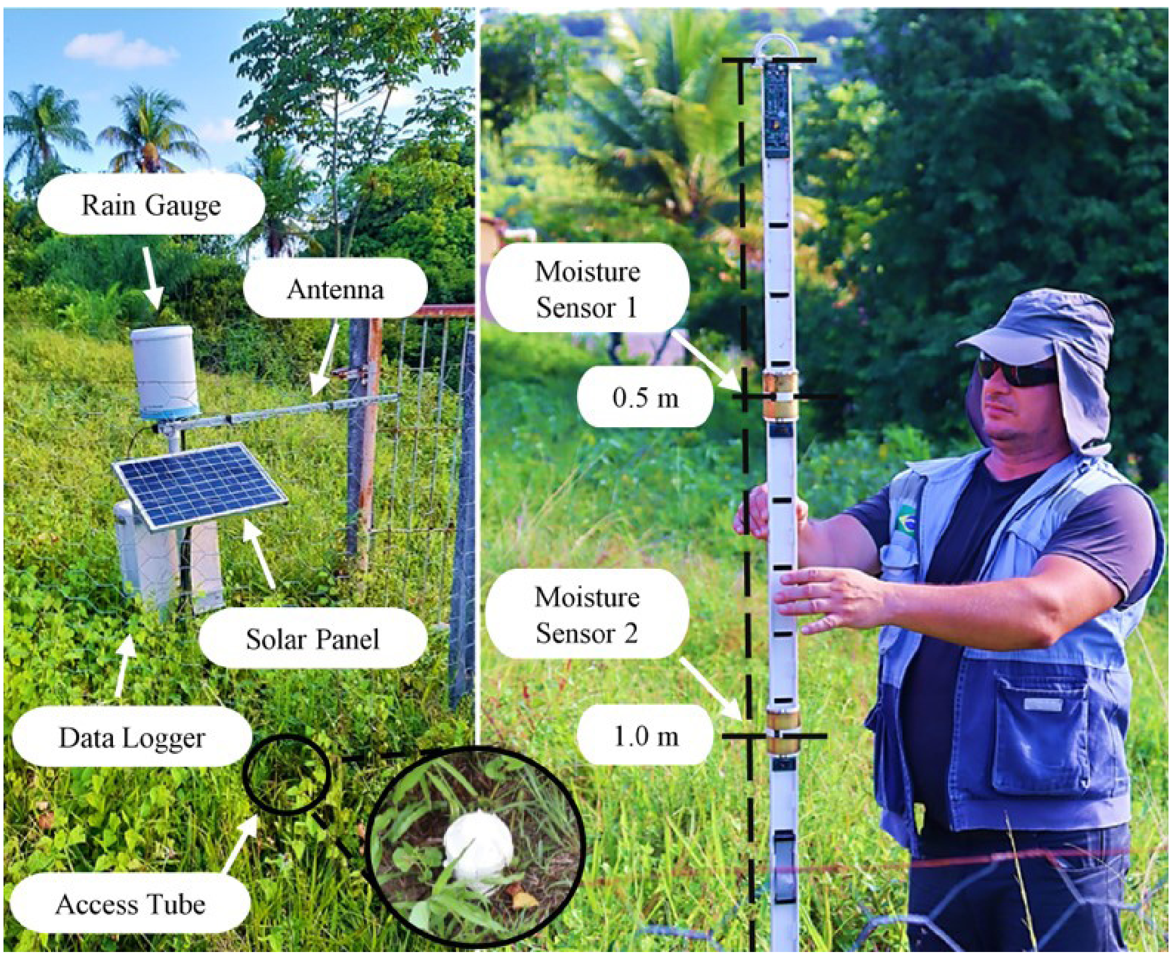

Figure 6. Composition of Geotechnical DCPs and arrangement of moisture sensors.

a) Selection of two Geotechnical DCPs installed near or within the study areas to analyze the variation of soil moisture in response to rainfall.

Geotechnical DCP-1 and Geotechnical DCP-2 were selected, as shown in the map in Figure 1. Geotechnical DCP-1 is close to Area 1, while Geotechnical DCP-2 is located within Area 2. Both the Geotechnical DCPs are located in the Barreiras Formation.

b) Geotechnical studies performed on the soils of the areas monitored by the Geotechnical DCPs.

Soil characterization tests were made: Determination of the liquid limit of the soil (ABNT, 2016a), Determination of the plasticity limit (ABNT, 2016b); and Granulometric analysis (ABNT, 2016c).

c) Gathering of the soil moisture data during the year 2022.

The data collected by Geotechnical DCP-1 covered the interval between January 1 to December 31, 2022. The data collected by the Geotechnical DCP-2 cover the interval between January 1 to December 4, 2022, due to sensor reading failures.

d) Correlation of moisture data with the precipitation information and occurrences of landslides within the study areas.

The data on landslide occurrences for the year 2022 were made available in digital spreadsheet format by the Local Civil Defense of Recife and Jaboatão dos Guararapes, containing the addresses and dates of occurrences. These occurrences were then related to rainfall and humidity data.

e) Data analysis, relating the results found with literature information available.

This step aims to provide a clearer understanding of the effects of infiltration of rainwater and soil moisture on slopes, contributing to the understanding of failure mechanisms and providing useful information for predicting future landslides.

8. Geotechnical characterization

To obtain detailed information about the soil profiles monitored by the Geotechnical DCPs, soil characterization tests were carried out, for which six (06) disturbed samples were collected at each 0.5 m depth in both analyzed areas. The geotechnical characterization, including USCS (Unified Soil Classification System) classification, Atterberg limits, and the granulometry of the soils are shown in Table 1.

The results reveal that the Geotechnical DCP-1 soil profile is predominantly clayey (48-55%) and is classified as low plasticity silt soil according to the USCS, showing an increase in silt fraction with the depth. The soil profile of Geotechnical DCP-2 is sandier (65-78%) and is classified as silty-clayey sand with little plasticity, again it is observed an increase in the silt fraction with depth.

9. Monitoring of Geotechnical DCP

The following results are related to the behavior of moisture sensors with changes induced by rainfall during the year 2022 in two different area.

9.1 Monitoring with the Geotechnical DCP-1

Figure 7a shows the graph of the average daily soil moisture measured by the Geotechnical DCP-1 and the daily precipitation recorded by the RG-01 during the year 2022. The data interval covers January 1 to December 31, 2022, and is divided into five smaller periods. The division criteria were the identification of relatively constant moisture values, to elucidate how the rainwater infiltration alters soil moisture. Table 2 presents the average volumetric soil moisture (%) and the corresponding standard deviation values for each period.

The first period occurred between January 1 to March 5, 2022, lasting 64 days. Since it is part of the driest season, the average moisture values for Period 1 are the lowest, as shown in Table 2. The data reveal that the lowest humidity situations occur at the most superficial depths, specifically between 0.5-1.5 m deep, in response to increased evapotranspiration that occurs in drier periods (Crawford et al., 2019).

The rains of March increased soil moisture levels, thus establishing the second period, characterized by soil wetting (from March 6 to May 22, 2022). The data in Table 2 show

Table 1. Geotechnical characterization of soils monitored by Geotechnical DCP.

Geotechnical DCP	Sample Depth (m)	USCS Classification	Atterberg Limits			Soil Granulometry		
			LL (%)	*PL* (%)	*PI* (%)	Clay (%)	Silt (%)	Sand (%)
Geotechnical DCP-1	0.5	ML	36	27	9	55	3	42
	1.0	CL	47	27	20	54	4	42
	1.5	ML	45	28	17	52	6	42
	2.0	ML	46	32	14	48	8	44
	2.5	MH	51	32	19	49	8	43
	3.0	ML	48	33	15	53	12	35
Geotechnical DCP-2	0.5	SC	20	12	8	20	2	78
	1.0	SM-SC	20	15	5	19	3	78
	1.5	SM-SC	23	19	4	24	4	72
	2.0	SM-SC	25	20	5	23	12	65
	2.5	SM-SC	22	18	4	14	14	72
	3.0	SM-SC	24	16	8	12	21	67

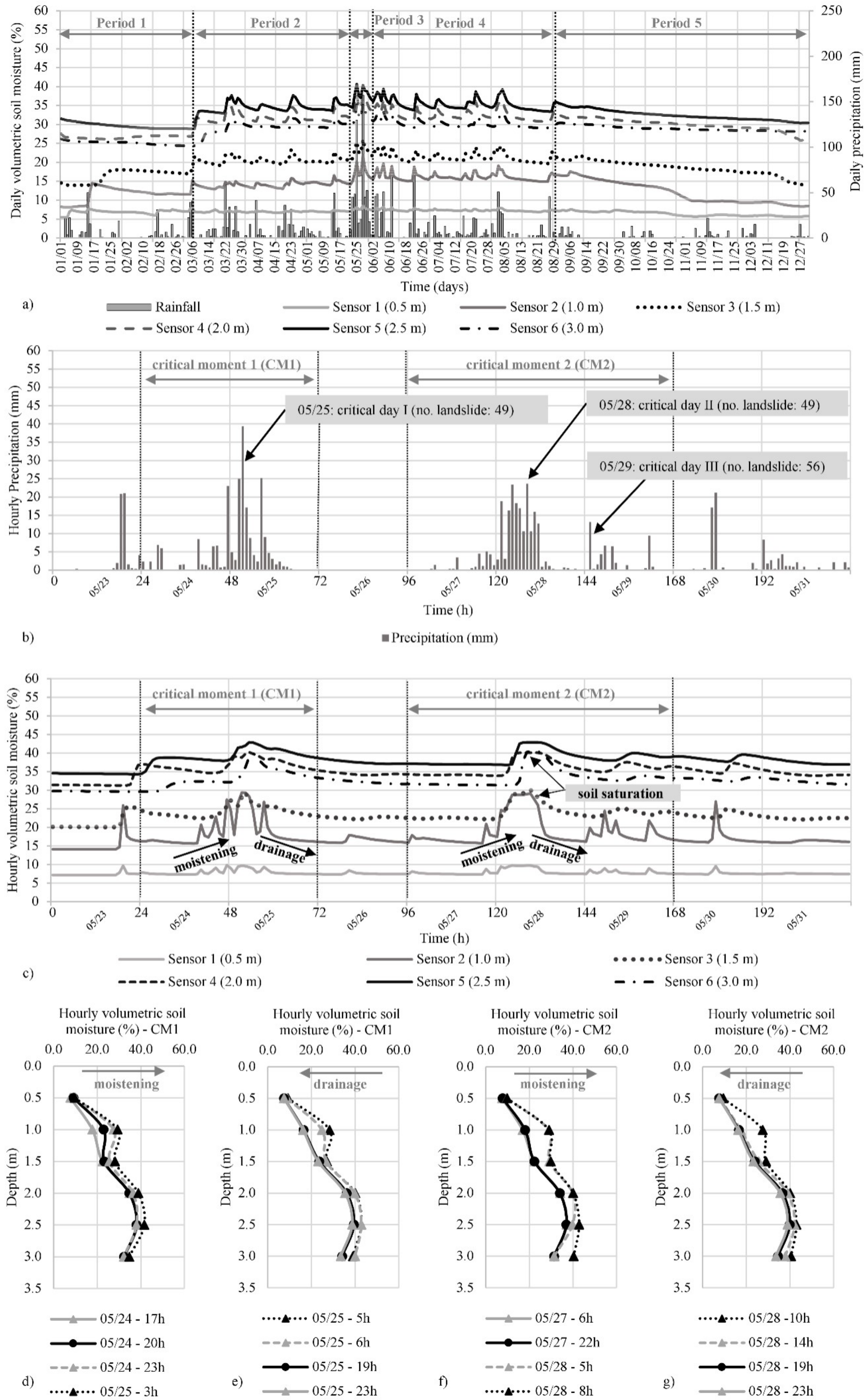

Figure 7. Monitoring data from Area 1: a) rainfall data and the average daily moisture between January 1 to December 31, 2022; b) period 3 hourly precipitation data; c) period 3 hourly average moisture data; d) wetting moisture profile – CM1; e) drainage moisture profile – CM1; f) wetting moisture profile – CM2; g) drainage moisture profile – CM2.

Table 2. Average moisture and standard deviation of the periods in Area 1.

	Sensor 1	Sensor 2	Sensor 3	Sensor 4	Sensor 5	Sensor 6
Period 1	6.89% (0.50)	11.52% (1.87)	16.44% (1.65)	26.65% (0.34)	29.64% (0.75)	25.11% (0.46)
Period 2	6.99% (0.20)	14.13% (0.71)	20.49% (0.88)	31.71% (1.22)	34.44% (1.50)	29.17% (1.59)
Period 3	7.80% (0.35)	17.88% (2.04)	23.53% (1.48)	35.43% (1.87)	38.21% (1.85)	32.74% (1.82)
Period 4	7.33% (0.26)	16.14% (1.00)	21.35% (1.16)	32.59% (1.44)	35.38% (1.46)	30.25% (1.07)
Period 5	6.39% (0.59)	11.98% (2.90)	18.45% (1.89)	29.91% (1.58)	32.42% (1.32)	28.90% (0.63)

Unit: Average volumetric soil moisture (%);
Note: The values presented in parentheses correspond to the standard deviation.

that in Period 2 there was an increase in the average moisture values at all monitored depths, compared to Period 1. In this period, it can be noticed that the humidity at all depths was more sensitive to rain as shown in Figure 7a.

In the third period, lasting eight days (from May 23 to May 30, 2022), an accumulated rainfall of 515 mm was recorded, resulting in the highest peaks of soil moisture, indicating probable soil saturation. According to the data in Table 2, in Period 3 there was an increase in the average moisture in all sensors, about Period 2. The data also show that the deeper layers (1.5-3.0 m) tend to retain the water infiltrated through the profile for a longer time.

The fourth period lasted 93 days (from May 31 to August 31, 2022) and represents the transition from the rainy season to the drier season. During this period, the average moisture values decreased about Period 3 due to the reduction in the amount of rain. The data in Table 2 show that in this period average moisture values are slightly higher than those recorded in Period 2. This shows that the soils in Area 1 remained wet for 179 days.

The fifth period occurred between September 1 to December 31, 2022, lasting 122 days and illustrates the variation in humidity during the return of the driest period. During this period, the data in Table 2 shows that there was a reduction in average moisture compared to Period 4, mainly between 0.5-1.5 m. While in the deeper layers, the humidity decreases more slowly, as shown in Figure 7a.

The Period 3 recorded a large number of landslides. In Area 1, between May 25 and May 31, 262 landslides were registered, according to data provided by Recife's Civil Defense. Thus, for a better understanding of this period, more detailed analyses were carried out, considering precipitation and the average humidity on an hourly scale, as shown in Figures 7b and 7c.

Figure 7b shows two periods of intense precipitation: the first between May 24 and May 25, 2022, and the second between May 27 and May 29, 2022. These two periods were identified as Critical Moments (CM). In general, there is a rapid increase in humidity, followed by drainage due to the cessation of rainfalls. During times of greater precipitation, the formation of 'plateaus' is observed, indicated by arrows, which suggest a possible saturation of the soil.

During the Critical Moment 1 (CM1), 225 mm of rain in 48 h, were recorded, with an hourly peak precipitation registering 40 mm at 3 a.m. on May 25. Moisture profiles during wetting and draining in CM1 are shown in Figures 7d and 7e, respectively. These graphs show that rainwater infiltration occurs faster in surface layers between 0.5 and 1.5 m deep. The percentage change in moisture during wetting, in ascending order of depth, were: 27%, 65%, 25%, 12%, 9%, and 7%.

During Critical Moment 2 (CM2), 254 mm of rain accumulated in 48 h, with the peak hourly precipitation at 8 a.m. on 05/28, registering 24 mm. The CM2 moisture profiles are shown in Figures 7f and 7g. The graphs show a progressive increase in hourly humidity, mainly between 0.5 and 1.5 m depth. The percentage change in humidity during wetting, between 6 a.m. on May 27 and 8 a.m. on May 28, 2022, in ascending order of depth, were: 29%, 72%, 33%, 18%, 16%, and 28%.

9.2 Monitoring with the Geotechnical DCP-2

Figure 8a shows the graph of the average daily soil moisture measured by the Geotechnical DCP-02 and the daily precipitation recorded at RG-02. The analysis interval starts on January 01 and ends on December 4, 2022, being divided into five smaller periods, using the same division criteria applied in Area 1. Table 3 presents the average volumetric soil moisture (%) and the corresponding standard deviation values for each period.

The first period occurred between January 01 and March 4, 2022, lasting 63 days, and is inserted in the driest season. The average values of moisture in period 1 are the lowest, as shown in Table 3. The lowest humidity situations occur at the most superficial depths, specifically between 0.5-1.5 m deep, due to the greater susceptibility of these layers to evapotranspiration. On the other hand, the two deeper sensors registered practically constant moisture values.

In early March, the rain increased soil moisture levels and this humidity remained high due to the increase in rainfall between March 5 and May 22, 2022, thus establishing the second period. The data in Table 3 show that in Period 2 there was an increase in the average moisture values at all monitored depths about Period 1.

In the third period, lasting six days (from May 23 to May 28, 2022), an accumulated rainfall of 497 mm was registered, resulting in the highest soil moisture peaks. Thus, according to the data in Table 3, in Period 3 there was an

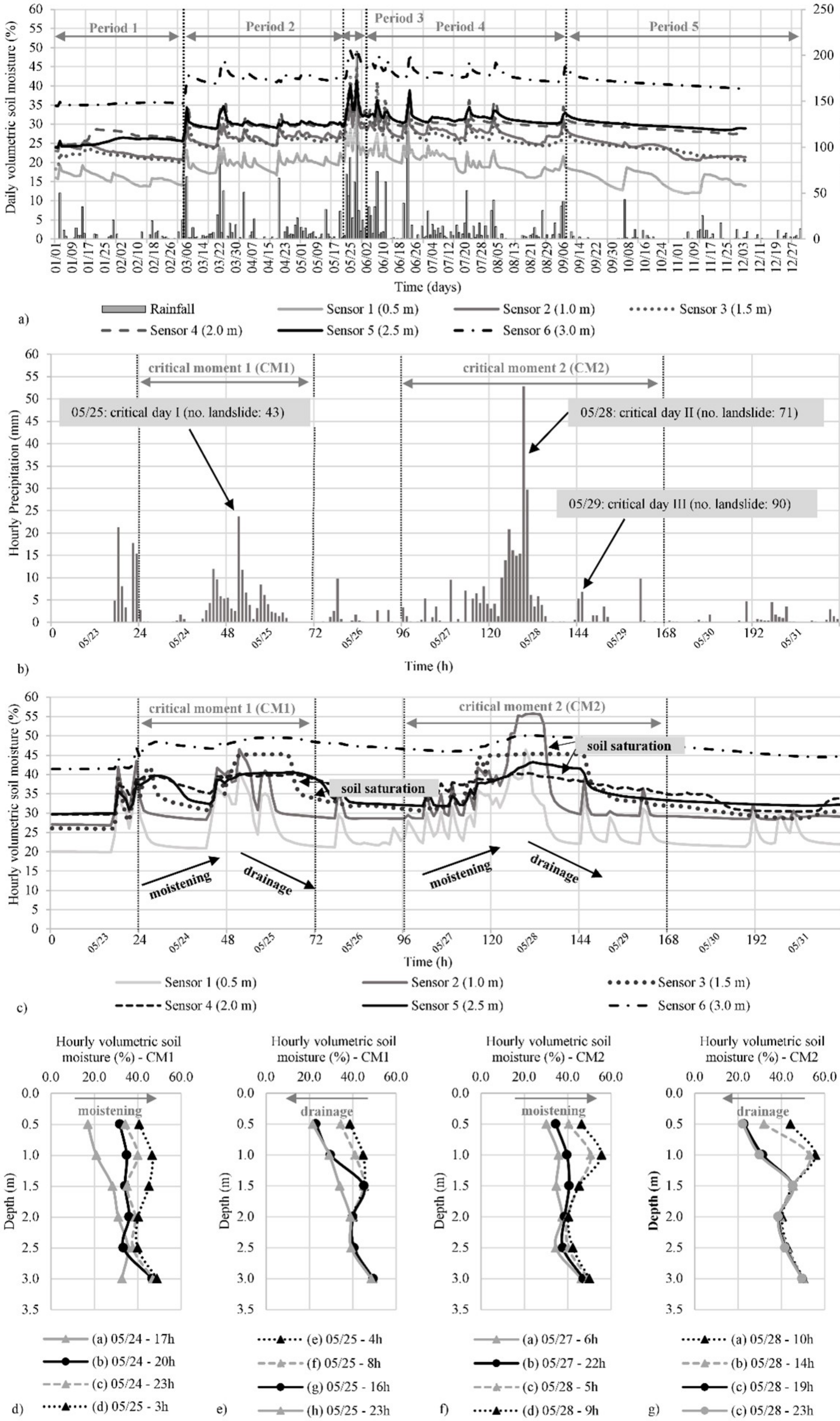

Figure 8. Monitoring data from Area 1: a) rainfall data and average daily moisture between January 01 and December 04, 2022; b) period 3 hourly precipitation data; c) period 3 hourly average moisture data; d) wetting moisture profile – CM1; e) drainage moisture profile – CM1; f) wetting moisture profile – CM2; g) drainage moisture profile – CM2.

Table 3. Average moisture and standard deviation of the periods in Area 2.

	Sensor 1	Sensor 2	Sensor 3	Sensor 4	Sensor 5	Sensor 6
Period 1	15.93% (1.33)	22.71% (1.34)	21.53% (1.06)	26.72% (1.28)	25.46% (0.81)	35.31% (0.28)
Period 2	19.62% (1.56)	26.37% (1.33)	26.21% (1.87)	29.94% (1.52)	30.09% (1.06)	42.03% (1.20)
Period 3	27.21% (2.86)	34.08% (4.41)	36.55% (5.28)	37.39% (1.94)	36.33% (3.36)	47.09% (2.30)
Period 4	20.27% (2.62)	27.90% (1.78)	27.35% (3.02)	31.01% (1.92)	31.61% (1.33)	43.17% (1.62)
Period 5	15.41% (2.06)	23.66% (2.10)	23.45% (1.69)	28.78% (1.01)	29.70% (0.97)	40.70% (1.16)

Unit: Average volumetric soil moisture (%);
Note: The values presented in parentheses correspond to the standard deviation.

increase in average moisture in all sensors, compared to Period 2. However, it was in this period that the highest standard deviations were identified, indicating that the monitored soil is permeable and has a low water holding capacity.

The fourth period lasted 101 days (from May 29 to September 6, 2022), and represents the transition from the rainy season to the drier season. During this period, the average moisture values decreased about Period 3 due to the reduction in the amount of rain. The data in Table 3 show that despite the loss of moisture, Period 4 values are still slightly higher than those recorded in Period 2. This indicates that the soils in Area 2 remained wet for 186 days.

The fifth period occurred between October 09 and December 4, 2022, lasting 89 days. During this period, there was a reduction in average humidity compared to Period 4, mainly between 0.5-1.5 m depth, due to the return of the drier season (Table 3). The graph in Figure 8a illustrates how the decrease in moisture was slow and proportional to depth, especially in the last two sensors, where the average daily moisture values remained relatively high.

Due to the high volume of rainfall and rapid changes in humidity, Period 3 saw a large number of landslides. In Area 2, between May 25 and May 31, 336 landslides were registered, according to data provided by the Local Civil Defenses of Recife and Jaboatão dos Guararapes. Thus, analyses were also carried out considering precipitation and average moisture on an hourly scale, as shown in Figures 8b and 8c. Two Critical Moments (CM) were established: CM1 between May 24 and May 25, 2022, and CM2 between May 27 and May 29, 2022. At the two critical moments, the formation of 'plateaus' indicating soil saturation is highlighted in Figure 8c by arrows.

During the CM1, 90 mm of rain accumulated in 48 h, with the peak hourly precipitation at 3 a.m. on May 25, registering 23 mm. The CM1 moisture profiles are shown in Figures 8d and 8e. These graphs show a progressive increase in hourly humidity, mainly between 0.5 and 2.0 m depth, as the volume of rain increases. The percentage variation of increase in humidity, between 5 p.m. on May 24, 2022 and at 3 a.m. on May 25, 2022, in ascending order of depth were: 94%, 64%, 46%, 13%, 22%, 4%.

In the CM2, an accumulated 298 mm of rain was recorded in 72 hours. The hourly precipitation peak occurred at 9 a.m. on May 28, registering 53 mm. Moisture profiles during the CM2 wetting and draining are shown in Figures 8f and 8g, respectively. These graphs show the increase in hourly humidity, mainly between 0.5 and 2.0 m depth, as the volume of rain increases. The increase in moisture between 6 a.m. on May 27 and 9 a.m. on May 28 was in ascending order of depth: 54%, 55%, 30%, 8%, 22%, and 8%.

10. Discussion of the moisture monitoring results

The data from the Geotechnical DCP-1 and 2 showed consistent behavior in response to rainwater infiltration, with Figures 7 and 8, clearly showing changes in soil water content as a result of rainwater infiltration. The data showed that closer to surface, faster is the sensor response to rainwater infiltration and greater is the magnitude of volumetric water content increase. Similar results were described by Chávez et al. (2016), Crawford et al. (2019), and Bovolenta et al. (2020).

In her studies Pirone et al. (2015), observed a good agreement between the matric suction trend and the volumetric water content, both experiencing fluctuations that depend on the depth of the sensor, being more significant in superficial soils. The results collected from Geotechnical DCP-1 and 2, the deeper layers tend to present more constant values of moisture content and slower drainage in the long term.

The variation in humidity in the deeper layers is more significant during the wettest period of the year (between March and August). During this period the results show that there is variation in moisture at all moisture levels, and the deeper layers respond more pronouncedly to rainwater infiltration. Pirone et al. (2015) observed that the deeper layers were virtually unaffected by individual rainfall events, as these layers generally reflect average seasonal variations.

During period 3, the Geotechnical DCP-2 mostly showed average moisture values and standard deviations higher than the Geotechnical DCP-1, indicating greater permeability and low water retention capacity, especially in the most superficial layers. The different grain sizes of the monitored profiles can explain this behavior since the Geotechnical DCP-1 profile is clayey than the other. Crawford et al. (2019), observed that clayey soils retain moisture for longer times and do not allow large increases in moisture like coarse soils.

In both areas, the soils remained wet for approximately six months. These data revealed a high susceptibility to landslides in this area, since high moisture values indicate lower suctions, and consequently lower shear resistance. In both areas, the sharp increase in soil moisture occurs in response to large hourly rainfall. However, during the CM1 and CM2, even after the reduction of rainfall drainage does not occur immediately at deeper levels, thus explaining the occurrence of some cases of landslides a few hours after the peak of rain.

11. Conclusion

A network of equipment was installed to monitor rainfall and soil moisture in an integrated manner for the development of an early warning system for landslides in high-risk areas of the Metropolitan Region of Recife. The data collected show that soil moisture variation is largely dependent on hourly rainfall. The most superficial layers present greater variation in humidity due to the effects of evapotranspiration. However, during the wettest period, variation in moisture is observed at all levels. The data also reveal that the monitored soils remained wet for approximately six months, indicating that medium rainfall can trigger landslides. This information will allow the improvement of proposals for meteorological thresholds under development for this region.

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Declaration of interest

The authors have no conflicts of interest to declare. All co-authors have observed and affirmed the contents of the paper and there is no financial interest to report.

Authors' contributions

Roberto Quental Coutinho: conceptualization, data curation, formal analysis, funding acquisition, methodology, visualization, writing – original draft. Bruno Diego de Morais: conceptualization, data curation, formal analysis, methodology, writing – original draft. Rodolfo Moreda Mendes: conceptualization, formal analysis, funding acquisition, methodology, supervision, writing – review & editing. Marcio Roberto Magalhães de Andrade: conceptualization, funding acquisition, writing – review & editing.

Data availability

The datasets generated and analyzed in the course of the current study are available from the corresponding authors upon request. Data generated and analyzed in the course of the current study are available in the 'Mapa Interativo da Rede Observacional para Monitoramento de Risco de Desastres Naturais do CEMADEN' repository, http://www2.cemaden.gov.br/mapainterativo/.

List of symbols

CEMADEN	National Early Warning and Monitoring Centre of Natural Disaster
CL	Low plasticity clay
CM	Critical moment
DCP	Data collection platform
GEGEP	Group of Geotechnical Engineering of Disasters and Plains
LL	Liquid limit
MH	High plasticity silt
ML	Low plasticity silt
PI	Plasticity index
PL	Plastic limit
RG	Rain gauges
MRR	Metropolitan Region of Recife
SC	Clayey sands
SM-SC	Silty-clayey sand
UFPE	Federal University of Pernambuco
USCS	Unified Soil Classification System

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