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Development of a soil moisture forecasting method for a landslide early warning system (LEWS): Pilot cases in coastal regions of Brazil

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ABSTRACT

Climate change has increased the frequency of extreme weather events and, consequently, the number of occurrences of natural disasters. In Brazil, among these disasters, floods, flash floods, and landslides account for the highest number of deaths, the latter being the most lethal. Bearing in mind the importance of monitoring areas susceptible to disasters, the REMADEN/REDEGEO project of the National Center for Monitoring and Natural Disaster Alerts (Cemaden) has promoted the installation of a network of soil moisture sensors in regions with a long history of landslides. This network was used in the present paper as a base to develop a system for moisture forecasting in those critical zones. The time series of rainfall and moisture were used in an inversion algorithm to obtain the geotechnical parameters of the soil. Then the geotechnical model was used in a forward calculation with the rainfall prediction to obtain the soil moisture forecast. The landslide events of March 2020 and May 2022 in Guarujá and Recife, respectively, were used as study cases for the developed system. The obtained results indicate that the proposed methodology has the potential to be used as an important tool in the decision-making process for issuing landslide alerts.

1. Introduction

Evidence of climate change has been observed in extreme events such as heatwaves, heavy precipitation, droughts, and tropical cyclones (IPCC. Intergovernmental Panel on Climate Change, 2023). Due to the nonlinearity in the occurrence of these episodes, the prediction of disasters is impaired, potentially increasing the impacts (Marengo et al., 2009). In Brazil, about 9 out of 100 inhabitants live in areas subject to disasters and approximately 3000 km^2 of the country's territory corresponds to areas susceptible to the disaster risk of climate events (Alvalá et al., 2019). Considering the projection of increase in extreme precipitation events, according to the Intergovernmental Panel on Climate Change (IPCC. Intergovernmental Panel on Climate Change, 2023), this number can increase if planning and management measures for disaster risk reduction are not implemented.

Floods, flash floods, and landslides are the natural disasters that cause the most deaths in Brazil (Marengo et al., 2023; De Assis Dias et al., 2018). Among these, landslides are the most common type and cause more deaths. A landslide is a nonlinear dynamic system that is affected by a variety of factors (Huang et al., 2023) as geological, geomorphological, climatic, and hydrological aspects, and vegetation characteristics or conditions, as well as land use and land cover (Tominaga et al., 2015). In addition, the irregular urban sprawl and the settlements in inappropriate locations, especially by the poor sector of the population, have increased the number of landslide events that cause human and material losses (Bortolozo et al., 2018, 2019). Thus, the landslide disaster risks arise from a combination of physical processes and social processes exposing certain groups in society to the potentially damaging effects thereof (Mendonça and Silva, 2020).

Specifically, the Brazilian coast has a higher occurrence of mass movements due to the steep terrain and high rainfall indices (Deborteli et al., 2017; Silva et al., 2021), associated with geological characteristics and anthropic interference on the environment. In this perspective, certain areas of the Northeast region of Brazil, mainly the states of

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Pernambuco, Sergipe, and Rio Grande do Norte, as well as the hillsides of the Serra do Mar and other rugged topography coastal zones of southeastern Brazil, are highly susceptible to disasters, especially landslides (Zachariah, 2022; Tominaga et al., 2015).

Therefore, it is possible to highlight the events that occurred in the Itajaí Valley in Santa Catarina in November 2008, where heavy rains caused floods and landslides resulting in 135 deaths, leaving thousands of people homeless (Marengo et al., 2009). In 2011, in turn, the mountainous region of Rio de Janeiro witnessed multiple floods and landslides resulting from extreme weather events (Cavalcante et al., 2020), considered the most devastating natural disaster ever to occur in the country, with more than 900 deaths and 300 people missing (De Assis Dias et al., 2018). In 2022, the cases of Recife, in Pernambuco (Marengo et al., 2023), and Petrópolis, in Rio de Janeiro (Alcântara et al., 2023; Bortolozo et al., 2022a), gained prominence due to the size of the impacts, the former reaching the number of 128 deaths by June 2022 (Barros, 2022) and the latter with more than 240 records in the same year (Puente et al., 2022).

In 2012, after a sequence of disaster events that occurred in Brazil, culminating with the tragedy in the mountainous region of Rio de Janeiro, some important actions were taken, such as the restructuring of the National Civil Defense System through the National Protection and Civil Defense Policy-PNPDEC (Law No. 12.608), currently named the National System for Protection and Civil Defense (SINPDEC, acronym in Portuguese) and creation of the Brazilian National Center for Monitoring and Early Warnings of Natural Disasters (Cemaden, acronym in Portuguese) as part of a national disaster risk management system (Di Gregorio et al., 2018). Thereafter, a continuous rainfall monitoring network was established in 2013 to support its natural disasters risk management in different risk areas in Brazil with over 1500 rain gauges installed in 2014. Since then, this network has continued to grow with the installation of new stations and maintenance of the existing ones (Meira et al., 2022) in municipalities susceptible to floods and landslides.

Cemaden is responsible for continuous monitoring and issuance of alerts based hydro meteorological and climate conditions, characterized as an Early Warning System (EWS) that operates in the national scope. With a more local coverage but using the global landslide hazard assessment for situational awareness (LHASA) framework, developed to indicate potential landslide activity in near real-time (Kirschbaum and Stanley, 2018), LHASA-Rio is a local alerting system that uses a decision tree approach has been developed for Rio de Janeiro municipality with local information about rainfall thresholds and landslide susceptibility (Kirschbaum et al., 2021).

In South America, Maragaño-Carmona et al. (2023) mention the increase in human losses due to extreme precipitation events and a lack of early warning systems. In some countries efforts to develop or implement early warning systems have been observed. Fustos-Toribio et al. (2022) evaluates the implementation of a Rainfall Induced Landslides Early Warning System (RILEWS) for Southern Andes based on logistic model and forced by geomorphological and atmospheric conditions in the southern Andes, in a way to generate Rainfall Induced Landslides probability zones. Guzzetti et al. (2020) relate a project to develop a LEWS for the Combeima valley, a mountainous area in Colombia. Rainfall and geophone data on a regional scale were used to alert once the dynamic thresholds are reached (Gamperl et al., 2021). For this, Huggel et al. (2010) developed a numerical model based on stochastic optimization that simulates the EWS to deal with the problem of missing data (precipitation, soil measurements, landslide records) and the uncertainties related to them. The Aburrá valley and the municipality of Medellín, Colombia, implemented an EWS (*Sistema de Alerta Temprana de Medellín y el Valle de Aburrá* - SIATA) to monitor real-time environmental variables (hydrological, meteorological, seismic and geotechnical) and forecast natural and anthropic phenomena in the region (Sapena et al., 2023). Other local LEWS have been mentioned in the literature by Piciullo et al. (2018), Pecoraro et al. (2019), and Guzzetti et al. (2020).

Aggravated by the effects of climate change, landslide disasters will continue to occur around the globe. Consequences have of greater impact on locals where levels of vulnerability and exposure are very high (Alcántara-Ayala and Garnica-Peña, 2022). The Landslide Early Warning Systems (LEWS) may be considered a non-structural passive mitigation measure (Piciullo et al., 2018; Basharat et al., 2021) and they are often a cost-effective mitigation measure to adopt (Calvello et al., 2020) and efforts for its implementation should be invested mainly in more vulnerable areas and developing countries such as those in South America.

LEWSs are specifically designed to monitor, forecast, and analyze conditions that could trigger one or more landslides and can be operationalized at different scales (Calvello et al., 2020) such as a hillside, a catchment, a municipality, a region, or an entire country (Piciullo et al., 2018). LEWS are based principally on empirical models (Piciullo et al., 2018; Pecoraro et al., 2019) and usually, is usually a mathematical model that forecasts landslide existence in specific areas (Basharat et al., 2021). Empirical models can be heuristic methods whose thresholds are defined without employing any rigorous mathematical or statistical criterion or can be correlation-based methods whose thresholds are defined considering one or more combinations of the monitored parameters (Pecoraro et al., 2019).

Most operational LEWS are based on rainfall exceedance thresholds only (Wicki et al., 2020; Basharat et al., 2021; Palau et al., 2023) considering that precipitation is the trigger factor in most cases (Marino et al., 2020) and rainfall thresholds usually do not consider the important role that soil moisture plays in slope stability (Palau et al., 2023). However, it is extremely difficult to define accurate critical threshold rainfall values that trigger landslides (Mendes et al., 2017, 2018). Soil hydrological information (e.g., soil moisture) when associated with the rainfall values has been demonstrated effective in improving the rainfall thresholds (Abrahm et al., 2021; Wicki et al., 2020) since the rainfall events that are needed to trigger landslides are dependent on the antecedent soil moisture conditions (Zhao et al., 2019; Segoni et al., 2018). However, the initial condition of soil moisture is not always available, and its prediction is necessary (Pan et al., 2003).

In this context, Marino et al. (2020) conducted shallow landslide forecasting simulations under various hydrometeorological settings and highlighted that when soil moisture was included as a parameter in their prediction models, the accuracy improved significantly. Abrahm et al. (2021) associated rainfall parameters with soil moisture data to define statistical rainfall thresholds and the results show that with a lower soil antecedent moisture, only severe rainfall events were able to trigger landslides. In Mendes and Filho (2015), climactic and geotechnical variables were real-time monitored by automatic rain gauges, moisture sensors, soil temperature and suction devices when landslides occurred, in January 2011, in three municipalities of São Paulo State, Brazil. The study found that soil temperature and moisture significantly influenced the triggering of shallow planar landslides in urban environments. However, the initial condition of soil moisture is not always available and its prediction is necessary (Pan et al., 2003).

However, the initial condition of soil moisture is not always available, and its prediction is necessary (Pan et al., 2003), which is normally not a trivial task. Moreover, soil moisture shows a high variability from daily to interannual timescales and is therefore difficult to measure (Michoud et al., 2013). While remote sensing methods have been relatively successful in measuring soil moisture (Uwihirwe et al., 2022), moisture estimates do not exceed a depth of 5 cm from the top soil surface and soil cover and topography as the main parameters that affect soil-moisture estimation (Ahmed et al., 2011). Thus, taking as an example the shallow landslides, the soil depth involved typically ranges 1–2 m below the surface and this zone is influenced by antecedent precipitation, soil texture, and vegetation (Marino et al., 2020). The limitations persist due to the coarse spatial resolution (Wicki et al., 2020) and data availability that must be in real-time (Palau et al., 2023) which is not always the case.

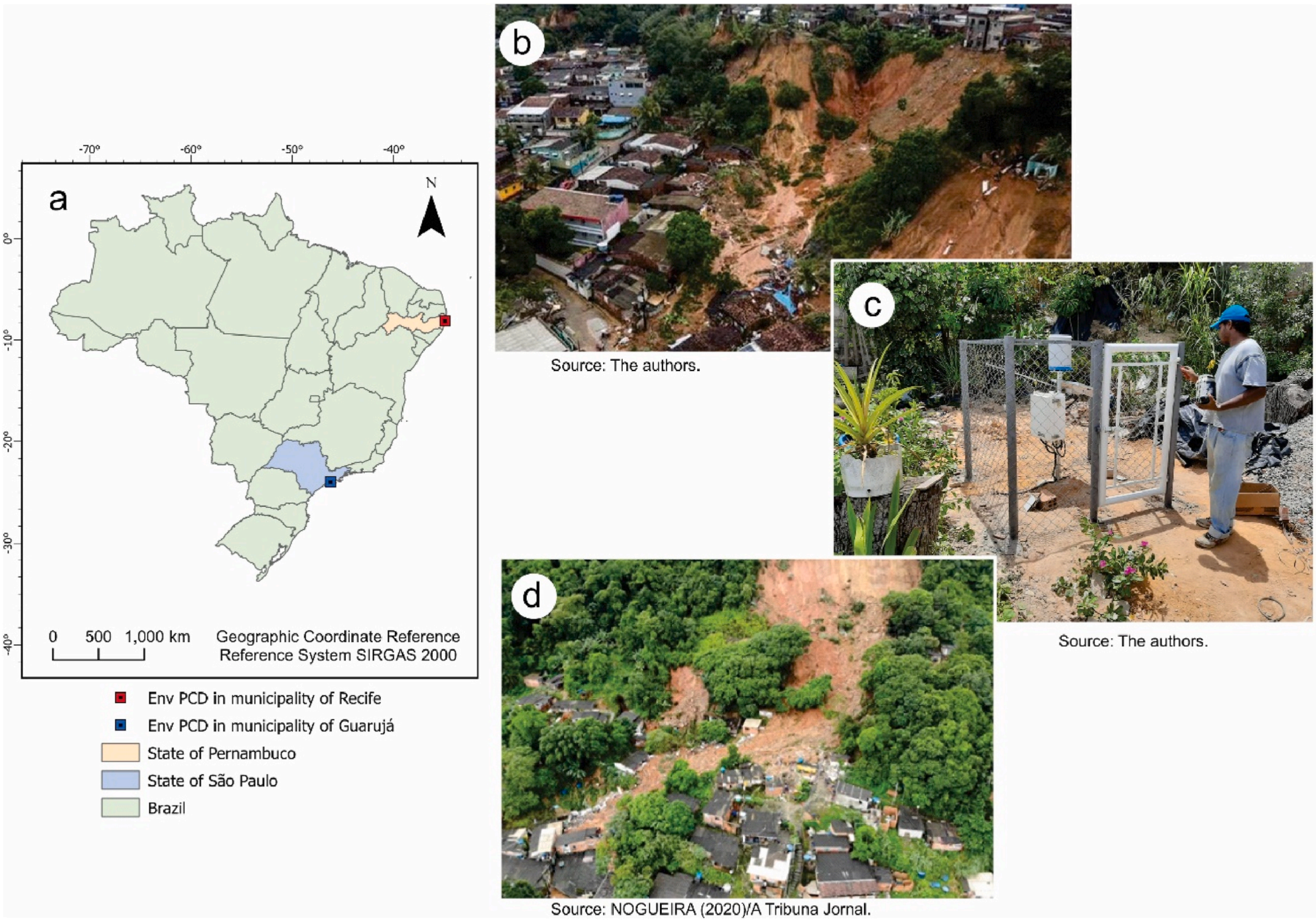

Fig. 1. Study areas and Env PCD. (a) Location of Env PCD in Recife (State of Pernambuco) and Guarujá (State of São Paulo) in Brazil; (b) Landslide in Recife registered on May 28, 2022; (c) Env PCD installed in Recife; and (d) Landslide in Guarujá, registered on March 03, 2020.

To this, the soil moisture variation observed by moisture sensors in rainfall events constitutes an essential instrument for the evaluation of landslide risk scenarios (Bortolozo et al., 2022b). With this in mind, the REMADEN/REDEGEO project was established, in which the Cemaden has been installing a network of soil moisture sensors in regions with a history of landslides. These Environmental Data Collection Platforms (Env PCDs, acronym in Portuguese, Plataforma de Coleta de Dados) are automatic devices that generate data on accumulated rainfall (mm) and volumetric soil moisture content (%) transmitted every 10 min to Cemaden's integrated and operational systems. The six moisture sensors are positioned every 50 cm depth, ranging from 0.5 m to 3 m. So far, about 105 Env PCDs have been installed as part of the project, in collaboration with the Civil Defenses of pilot cities and partner universities such as São Paulo State University (UNESP), in several regions including the Metropolitan Region of Recife in the State of Pernambuco, the Baixada Santista Region and the ABC Paulista Region in the State of São Paulo, the Serras Fluminenses Region in the State of Rio de Janeiro, and the municipalities of Blumenau in the State of Santa Catarina, and Salvador in the State of Bahia.

This research paper presents the development of a novel system aimed at predicting soil moisture conditions based on rainfall forecast data using advanced mathematical algorithms. The primary objective of this project is to establish an effective prototype tool for landslide prediction by producing a methodology capable of predicting soil saturation at specific Env PCDs (Environmental Variables Pre-Consolidation Devices) locations. Additionally, the study evaluates the potential applicability of the proposed methodology in enhancing the Cemaden LEWS by providing more precise alerts, thus aiding decision-making processes in the operation room.

2. Study areas description

Two cities were considered in this work to apply the proposed methodology (Fig. 1). One in the Southeast region (Guarujá) and another in the Northeast region (Recife) (Fig. 1a). The selection of these cities was based on their considerable geographical distance from each other (over 2100 km) and their distinct geological, geomorphological, social, and environmental contexts. This approach was aimed at representing the broad spectrum of scenarios in which Cemaden operates and the diverse contexts in which these stations function.

2.1. Guarujá, State of São Paulo

In March 2020, the Metropolitan Region of Baixada Santista (RMBS) registered a series of landslides and floods triggered by precipitation events. Among the nine cities that comprehend the RMBS, Guarujá was one of the three most affected along with the cities of Santos and São Vicente (De Freitas et al., 2022). For this reason, this region was designated as one of the target areas of application of the proposed methodology.

Guarujá is located in the State of São Paulo, has an area of 144 km^2 and 64 km of coastline (Roveri et al., 2020; IBGE. Instituto Brasileiro de Geografia e Estatística, 2021), with an estimated population of 324,977 inhabitants and a population density of 2026.80 inhabitants/km^2 (IBGE.

Instituto Brasileiro de Geografia e Estatística, 2021). The average annual temperature reaches 22 °C and the average precipitation is 3000 mm/year. Two well-defined seasons are identified annually, a rainy season from November to March, and a dry season from April to October (Roveri et al., 2020).

Despite the landscape full of high-end condominiums and buildings and is designated as a seaside resort, Guarujá has seen a significant increase in its housing contingent (290.752 inhabitants in 2010: IBGE. Instituto Brasileiro de Geografia e Estatística, 2021) resulting from its intense touristic activities and economic development, with accommodating settlements along the escarpment of the Serra do Mar (Ribeiro and Oliveira, 2015; Araki and Nunes, 2008). In addition, there is usually a growth of about 40% in population during the summer vacation period (rainy season), increasing the number of exposed to hazards of landslides (Araki and Nunes, 2008).

The area comprised by the city of Guarujá, despite containing traces of the Atlantic Plateau in relief units designated residual forms, corresponds mostly to the coastal plains, being still identified, to a lesser extent, as swamp plains, mangrove plains or those formed by marine sands, and littoral or continental sediments (Ross and Moroz, 1997).

The Guarujá municipality is characterized by crystalline rocks, specifically stromatitic migmatites and amphibolites, which are part of the Coastal Complex. The slopes in this area are deep and highly weathered, typically featuring shallow embankments of solum overlaying intensely altered rock, or saprolite. The bedrock in landslide-prone areas lies at depths between 5 and 10 m. Soil samples collected from a site where a PCD Geo was installed in Guarujá were analyzed for their granulometry. The results reveal a clayey-sandy solum, with the clay grain fraction increasing with depth until it reaches contact with the saprolite—up to 73% clay grains (Galvão, 2020).

Data collected from the Env PCD Vila Baiana site in Guarujá (Galvão, 2020) indicate variations in soil moisture at different depths. Specifically, the first layer, ranging from 0.3 to 0.8 m, has lower moisture levels (24.9%) compared to other layers. Throughout the entire thickness interval, from 2.8 to 3.2 m, the moisture level remains fairly constant. However, there is a significant increase in moisture around the 6th sensor level at the bottom of the probe (32.7%). Hydraulic conductivity tests carried out using a Guelph permeameter indicate that the soil has a low degree of permeability—specifically, 1.65×10^{-4} (Galvão, 2020). The matric potential is 2.14×10^{-1} cm/s, and the α parameter is 1.87×10^{-3} cm^{-1}.

Thus, above all, there is a predominance of a scenario characterized by the presence of residual forms comprising the Atlantic Forest as original vegetation, granitic rocks, and gneisses, in addition to high slopes and altitudes. Due to the recurrence of landslides in the area, Guarujá is one of the monitoring municipalities of Cemaden with a Env PCD on one of its hillsides. The Env PCD station, identified by the code 351870101G, is installed at latitude −23.97884° and longitude −46.239214°. On March 03, 2020 (Fig. 1d), a landslide event was recorded near this Env PCD, whose phenomenon is investigated in this work.

2.2. Recife, State of Pernambuco

The city of Recife, the capital of the state of Pernambuco, is located on an alluvial plain along the Atlantic Ocean coast, with many islands, peninsulas, and mangroves, with an average altitude of 4 m above sea level (Kobyama, 2022). The municipality covers an area of 218,843 km^2 with an essentially flat urban topography (71%) and slopes in adjacent areas present in hills and interfluve plateaus, where landslide events are concentrated (SANTOS et al., 2019). Its estimated population is 1,661, 017 people, and the demographic density is calculated at 7039.64 inhabitants/km^2 by the 2010 census, thus reaching the ninth position among the most populous municipalities in the country (IBGE. Instituto Brasileiro de Geografia e Estatística, 2021a).

The climate of Recife is defined as humid tropical, and despite its average annual temperature being evaluated at 26 °C (INMET. Instituto Nacional de Meteorologia, 2023), the region is characterized by high temperatures throughout the year with some reduction in the winter season. The annual average precipitation is around 2155,5 mm, occurring throughout the year but concentrated mainly from March to August (INMET. Instituto Nacional de Meteorologia, 2023). Recife ranks 16th among the most susceptible cities to climate change resulting from global warming according to IPCC. This is due to the lack of urban planning and infrastructure development in relation to rapid population growth and ongoing climate change (IPCC. et al., 2014).

Regarding its geomorphological characteristics, the municipality of Recife presents basically three landforms: hills, terraces, and plain, expressed by well-defined topographical features (Coutinho et al., 2020). The plain of the city of Recife, which extends through the sedimentary basins of Pernambuco and Paraíba, has a very heterogeneous relief, with the North region of the municipality characterized by hills and mountains resulting from the Barreiras Formation, by the Fluvio-lagoon Plain of the Beberibe River and by outcroppings of the Gramame Formation (Souza et al., 2017). Outcroppings of the Barreiras Formation can also be found in the West and South regions of the municipality. Soils of the Barreiras Formation present intense chemical alteration and are associated with most of the landslide occurrences (Fountoura et al., 2023). The south, besides on Barreiras Formation, the Alluvial Sediments, the Cabo Formation, and segments components of the Fluvio-lagoon System are found, elements that, due to a tectonic misalignment, distinguish themselves from the Recife plain (Souza et al., 2017).

The Recife metropolitan region is geologically divided between the granitoid complex (comprising granites and gneisses) and the sedimentary flysch ensemble of the Barreiras Formation, which overlies the granitoid batholith. Most landslides occur within the substrate of the Barreiras Formation's sedimentary deposits. The rupture planes are typically shallow, not exceeding 4 m in depth. At the top of the scars, rupture planes are between half a meter and 1 m deep, but they deepen to 3–4 m as the landslide progresses. The alternation between clayey and sandy layers in the Barreiras Formation negatively impacts slope stability. For instance, clayey slope tops are less susceptible to erosion due to the granulometric properties of clay. In contrast, sandy slope tops are more prone to erosion and landslide processes due to facilitated water infiltration (Morais, 2022). The sandy fraction is predominant, constituting 73% of the total composition. Of this, 29.4% is fine sand, 36.7% is medium sand, and the remaining 6.9% is coarse sand. The other fractions comprise 21.6% clay, 5.1% silt, and 0.3% gravel.

Morais (2022) analyzed 11 areas in the Recife region. The soils exhibited a wide variation in suction estimates, ranging from 2.5 kPa to 500 kPa. Volumetric moisture values between 25% and 30% suggest total suction below 10 kPa. The soils have a double porosity typical of sandy soils with a fine matrix (comprising both macro and micro pores), leading to bimodal retention curves. These curves indicate that significant variations in soil moisture result in only minor changes in suction, suggesting a very short time for the loss of suction and apparent cohesion in the pre-saturation period of the soils. Permeability tests using the Guelph permeameter revealed values at three depth intervals: 5.22×10^{-7} at 0–1 m, 2.61×10^{-7} at 1–2 m, and 1.08×10^{-7} at 2–3 m in clayey sand (Morais, 2022).

Due to their morphological and geological characteristics, combined with rainfall, tidal regimes, and unplanned urbanization, the city of Recife suffers constantly from landslides (Rodrigues et al., 2021). Additionally, the high population density, as well as the vulnerability of the most disadvantaged and less capable portion of the population, are aspects that compromise the potential for resilience in the face of physical-environmental disturbances (Da-silva-rosa et al., 2015). Station 261160611G, located at latitude −8.125° and longitude −34.954°, was used in this research.

Between the end of May and the beginning of June 2022, several landslides and floods were observed in the Metropolitan Region of

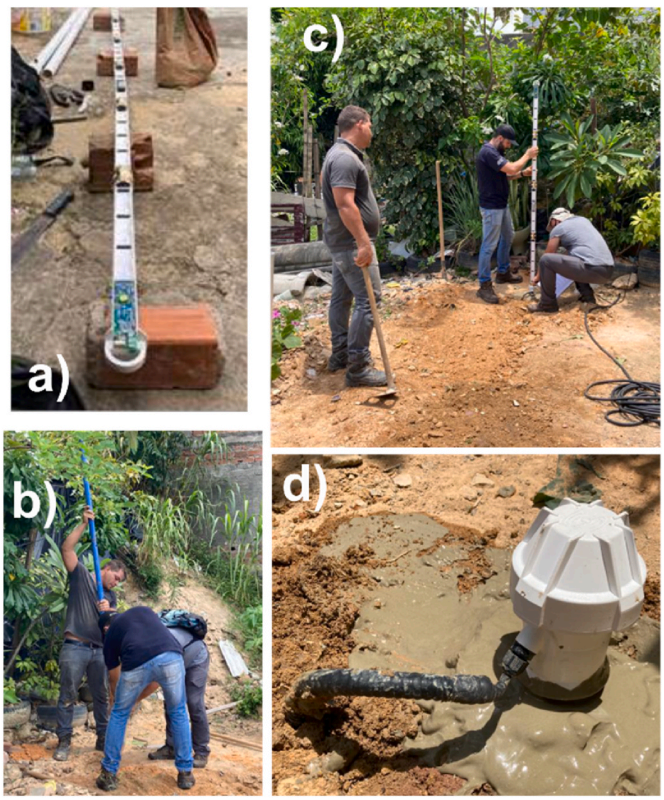

Fig. 2. Sequence of the probe installation process with six moisture sensors:(a) Moisture probe featuring six sensors placed every 50 cm along its 3-m depth; (b) Excavating soil to prepare for the insertion of the moisture probe; (c) Underground insertion of the probe; and (d) Completion of the moisture sensors installation, with bentonite coating on the surrounding surface of the probe.

Recife, affecting about 130,000 people, especially those located in geologically susceptible regions (Marengo et al., 2023). In particular, on May 28, 2022, the highest precipitation of the period was recorded, and fourteen municipalities in the Metropolitan Region declared a state of emergency (Marengo et al., 2023). This situation resulted in a landslide (Fig. 1b) near the Env PCD (Fig. 1c), which is the focus of investigation in this study.

Table 1
Parameters weighted in the SMmodel_GA_WEB program: Soil Water Balance Model.

Variables	Parameters	Description	Unit of measurement.
W_{max}	Field capacity/ hydraulic capacity	Relates to depth and porosity. Corresponds to the maximum amount of water that the soil layer can retain.	$[mm]$
ψ	Average matric potential at the wetting front	This expresses the energy of water retention by soil particles.	$[cm]$
K_s	Hydraulic conductivity of infiltration	The rate at which water permeates the soil in the vertical direction.	$[mm/h]$
k	Hydraulic conductivity of drainage	This refers to the ability of soil or rock to allow water to flow through it in a horizontal or lateral direction.	$[mm/h]$
m	Exponent of drainage	Parameter present in the empirical formulation for infiltration that reflects the nonlinearity of the process.	[1]
ET_{pt}	Potential evapotranspiration	This represents the process of water loss to the atmosphere, also known as evapotranspiration.	$[mm/day]$

1 Environmental Data Collection Platform (Env Pcd)

The Env PCD, installed by Cemaden (Fig. 2) in the cities of Guarujá and Recife, are composed of an automatic rain gauge and a probe containing six moisture sensors that measure the volumetric moisture content of the soil (Fig. 2a). The sensors are spaced 0.5 m apart, with the deepest sensor located at a depth of 3 m (3m). The sequence of the probe installation can be seen in Fig. 2b–d. The historical series used in this study included information on soil moisture measured by each sensor and accumulated precipitation data, collected at intervals of 10 min, during the period from January 1, 2020, to December 31, 2020, for Guarujá and from January 1, 2022 to June 13, 2022, for Recife.

The moisture sensors deployed in the Env PCD network aim to enhance our understanding of soil water content dynamics driven by rainfall. These sensors evaluate the extent of water infiltration by monitoring volumetric moisture variations at six different levels. One goal is to identify the conditions under which the soil reaches maximum moisture or full saturation.

The geotechnical network's moisture sensors focus on monitoring the unsaturated soil zones in slopes susceptible to landslides. These automatic devices provide rainfall measurements (in mm) and volumetric soil moisture data (in %), transmitting the information every 10 min to Cemaden's operation center. Each PCD station consists of four equipment kits: a photovoltaic energy subsystem, a data acquisition and transmission unit, soil moisture sensors, and a rain gauge.

The soil moisture sensors in the Env PCD network were developed using agricultural technology and adapted for monitoring factors that trigger landslides. Specifically, these sensors are capacitance-based EnviroScan model probes from the Australian company Sentek. These probes measure the volumetric water content present in the soil's intergranular pore spaces. The EnviroScan Moisture Probes come with a standard calibration equation developed by CSIRO, based on data from sand, silt, and silty clay samples. This standard equation has an R^2 value of 0.9737 for combined soil types (Sentek, 2011).

3. Soil water balance calculation

The "SMmodel_GA_WEB" program, developed in MATLAB (product of MathWorks Corporation) although compatible with GNU Octave, for the calculation of a continuous water balance model in order to simulate the temporal evolution of soil moisture. It was created by Brocca et al. (2008) and includes two formulations for the infiltration process: the Green-Ampt (Green and Ampt, 1911) and the Georgakakos and Baumer (1996) approaches. To calculate drainage, a gravitational estimate based on two equations is used, the first proposed by Georgakakos and Baumer (1996) and the second being a non-linear relation. The drainage calculation, in turn, was performed by a gravitational estimate, based on two equations, the first based on the proposal of Georgakakos and Baumer (1996), given by:

$$g(t) = a^{'}W(t) \tag{1}$$

where *a'* is related to the drainage response time and *W(t)* to the amount of water in the investigated soil layer. The second consists of a non-linear relationship described as follows:

$$g(t) = K_s \left[\frac{W(t)}{W_{max}}\right]^{3+(2/\lambda)} \tag{2}$$

where K_s refers to the saturation hydraulic conductivity, W_{max} to the maximum water retention capacity in the soil layer and corresponds to the pore size distribution index related to the structure of the soil layer.

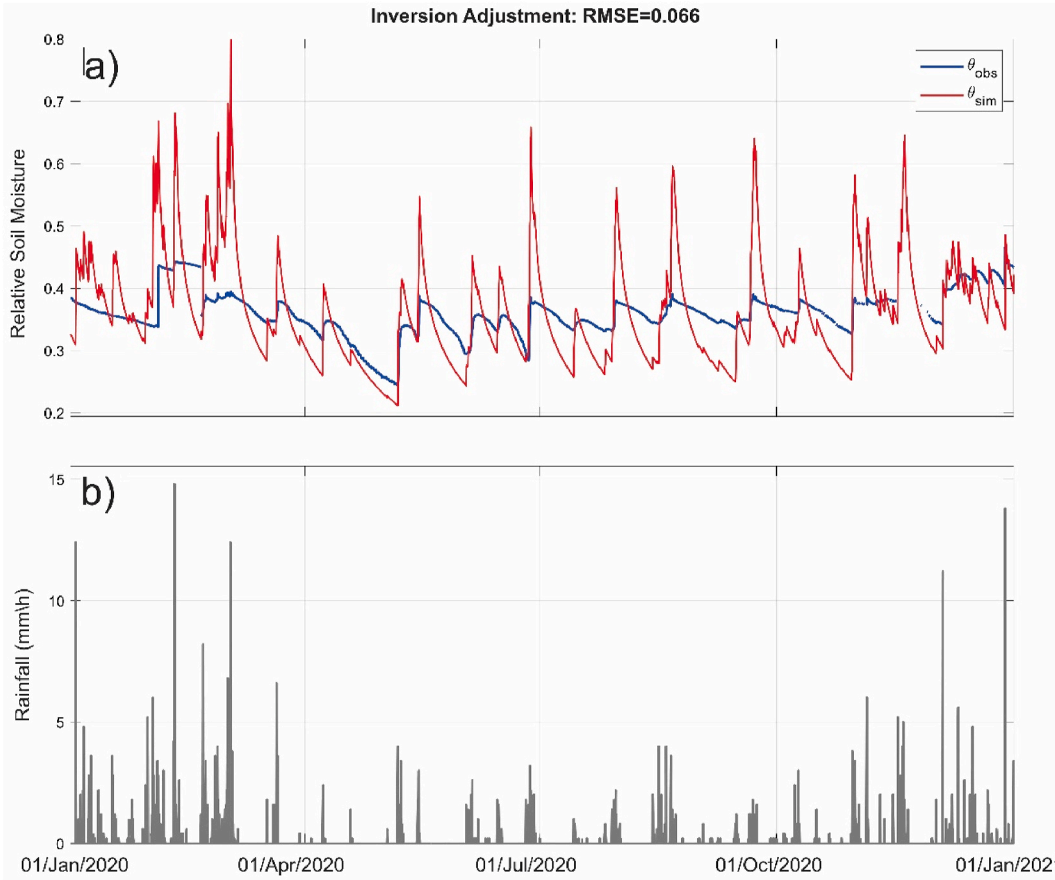

Fig. 3. Result of data inversion for Guarujá, complete interval, sensor 1. (a) Observed soil moisture data (Blue) and data calculated by data inversion (Red); (b) Accumulated rainfall in 10 min intervals given in mm/h.

Due to its open-source nature, the source code is accessible and can be used for various purposes. In the present study, certain functions were extracted from Brocca et al.'s (2008) main program and adjusted to be incorporated into the proposed methodology. The program was originally proposed for other types of study, but it is suitable for the one proposed in this work because it is a fast calculation program that can simulate well the soil response at the correct time. However, one of the limitations of the program is that it tends to exaggerate the maximum saturation values, reaching higher saturation values than the soil would reach. In the tests carried out, this characteristic was pronounced, but once known it is easily circumvented.

4. Data inversion

The SMmodel_GA_WEB software also allows the optimization of the geotechnical model using real rainfall, moisture, and temperature data as input. For moisture and rainfall, were used the Env PCDs data and the temperature was considered constant based on the average annual temperature in the study region.

In this way, it was possible to obtain the environmental parameters of the Env PCD places. For Guarujá, was considered the year of 2020 (01/01 to 12/31/2020), and for Recife only the first semester of 2022 (01/01 to 06/13/2022). Although seven geotechnical output parameters are needed, only six were optimized using the inversion algorithm, since the parameter "initial moisture condition" has the same value as the first observed data. The six adjustment parameters are described in Table 1.

The SMmodel_GA_WEB software assumes a homogeneous substrate, for this reason, 6 different models are needed for each PCD, one model for each sensor. The difference in depth is indirectly given by the Field capacity (W_{max}) property, which takes depth and porosity into account. So, for each PCD, 6 inversions are needed to obtain each set of parameters.

Initially, data were inverted for each month and then compared with the data obtained for the entire period. In general, the results were very close to each other (less than 1% variation), but in some months models that were very different from the others were highlighted. Was observed that this only happened in dry months, where periods of rain are not observed. This characteristic can be intuitively understood considering the intrinsic dependence of soil moisture on the infiltration of rainwater. During periods of drought, there is a significant reduction in the infiltration rate, which impairs the reading of the moisture sensor and compromises the accuracy of forecasting this parameter. It is essential to highlight that obtaining observed soil moisture data plays a crucial role in making reliable predictions. Therefore, the occurrence of water deficits has an impact on the accuracy of projections related to this factor.

Fig. 3 shows the results of the data inversion of sensor 1 throughout the year 2020 for Guarujá and in Fig. 4 the results for Recife (January 01, 2022–January 07, 2022) are presented. The adjustment of the inversion process yielded highly satisfactory results for both the Guarujá and Recife cases. The evaluation of the adjustments was primarily based on two key metrics: the Root Mean Square Error (RMSE) and the Nash-Sutcliffe (NS) coefficient. These criteria were utilized to determine the most appropriate adjustments for further assessment and analysis. The Nash-Sutcliffe coefficient, which can range from negative infinity to 1, served as a crucial indicator to gauge the level of agreement between the observed and calculated data. In the Guarujá case, the Nash-Sutcliffe coefficient was found to be −2.309, and the corresponding RMSE was calculated to be 0.066. As for the Recife case, the Nash-Sutcliffe coefficient was −1.666, and the RMSE was computed as 0.060.

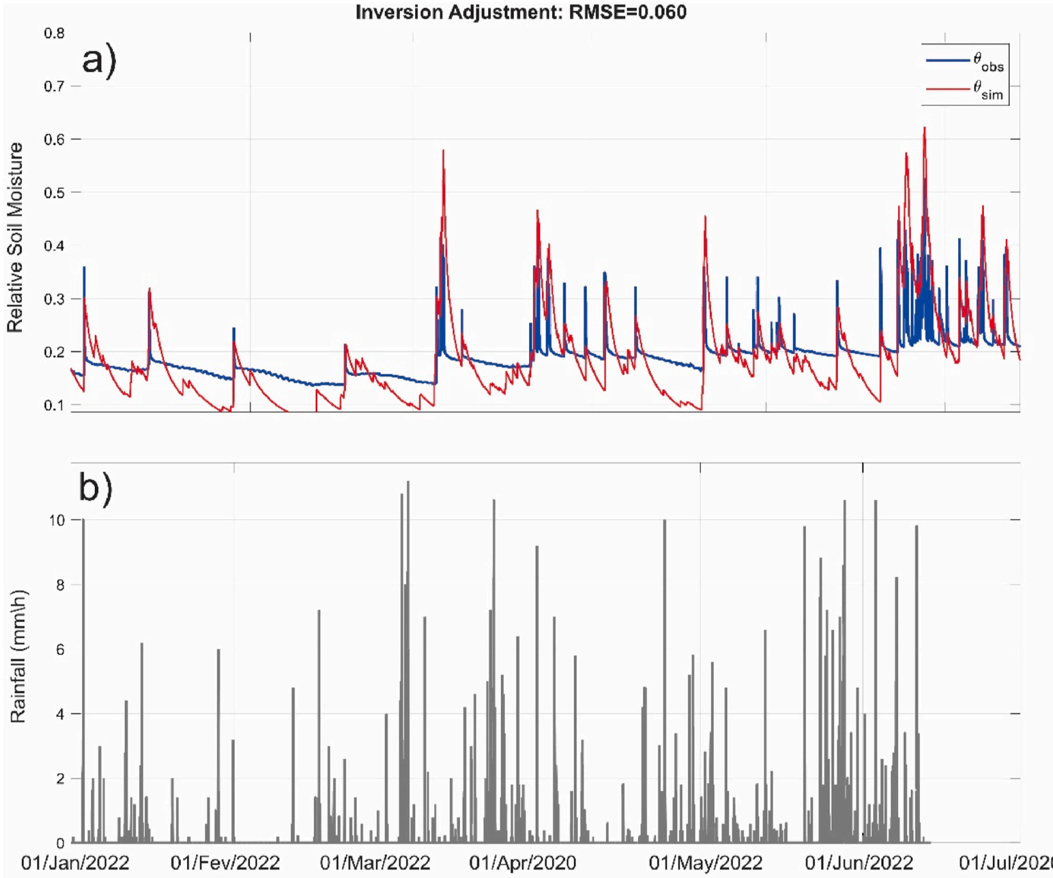

Fig. 4. Result of data inversion for Recife, complete interval, sensor 1. (a) Observed soil moisture data (Blue) and data calculated by data inversion (Red); (b) Accumulated rainfall in 10 min intervals given in mm/h.

Table 2
Landslide risk thresholds for Env PCD in Guarujá.

Degree of landslide risk based on soil moisture content for Guarujá			
Sensors	Depth (m)	High	Very High
1	0,5	36,1	37,7
2	1	35,5	38,5
3	1,5	35,6	39,4
4	2	28,9	32,4
5	2,5	38,5	42,9
6	3	35,3	40,2

Table 3
Landslide risk thresholds for Env PCD in Recife.

Degree of landslide risk based on soil moisture content for Recife			
Sensors	Depth (m)	High	Very High
1	0,5	30,91	41,80
2	1	36,42	46,11
3	1,5	32,27	38,86
4	2	33,20	36,93
5	2,5	34,37	38,81
6	3	44,58	47,38

5. Soil moisture forecast

After obtaining the parameters for each sensor of the PCDs, is possible to calculate the soil moisture response for any rainfall event using an adapted version of the forward calculation describe above. This capability allows to leverage weather forecast data to predict the moisture response based on current saturation conditions and the anticipated precipitation.

For the rainfall forecast the Global Forest System (GFS) model were used, once is one of the most used models in the Operational Room of Cemaden. The forecast precipitation is given in 3 h intervals, so to make these data compatible with the observed information of the Env PCD, the predicted rain in the 3h interval was equally distributed in 18 intervals of 10min accumulation.

To determine the risk level of soil saturation, the Cemaden's Operational Room employs a set of thresholds tailored for soil moisture sensors. These thresholds are customized for each location, considering the unique geological and geomorphological characteristics of the area. The defined thresholds are categorized as High and Very High, reflecting the varying degrees of moisture saturation. When the soil moisture sensors surpass these pre-established thresholds, the operational room operators promptly issue alerts to civil defense authorities. For Guarujá and Recife, the values are presented in Table 2 and Table 3, respectively.

The values presented in Tables 2 and 3 were derived empirically from the analysis of past landslide events. The methodology proceeded as follows: the lowest recorded moisture levels during dry periods served as the baseline. The maximum value was designated as the moisture level observed at the time of recorded landslide events. The range between these minimum and maximum values was divided into three equal segments, termed 'terciles.' Moisture levels falling within the first tercile above the baseline were categorized as 'Normal.' Those exceeding the first tercile but not surpassing the second were classified as 'High.' Finally, moisture levels exceeding the second tercile were designated as 'Very High.' These upper and lower thresholds define a spectrum of moisture values. Within this spectrum, the infiltration of rainwater effectively reduces matric suction, leading to a decrease in soil shear strength that peaks at saturation (the upper threshold).

In this study, we applied the developed methodology to analyze two

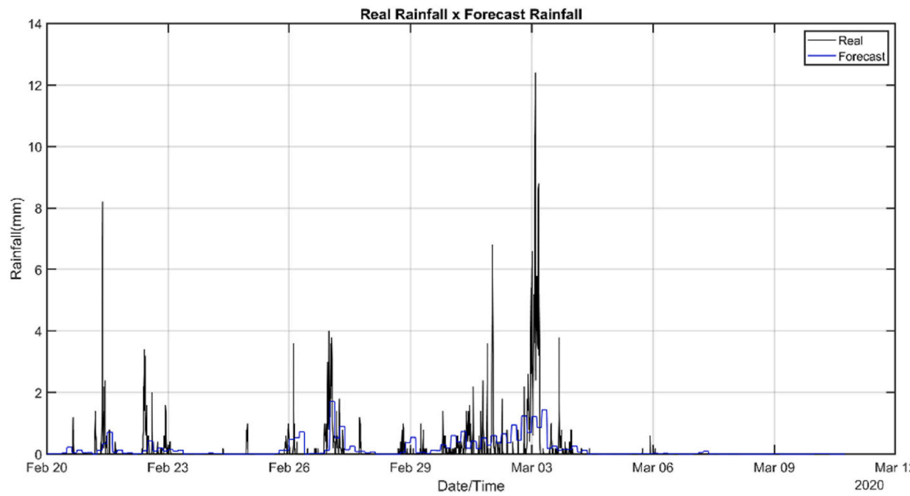

Fig. 5. Comparison between observed and predicted rainfall over time (February 20th to March 12th, 2020, in Guarujá).

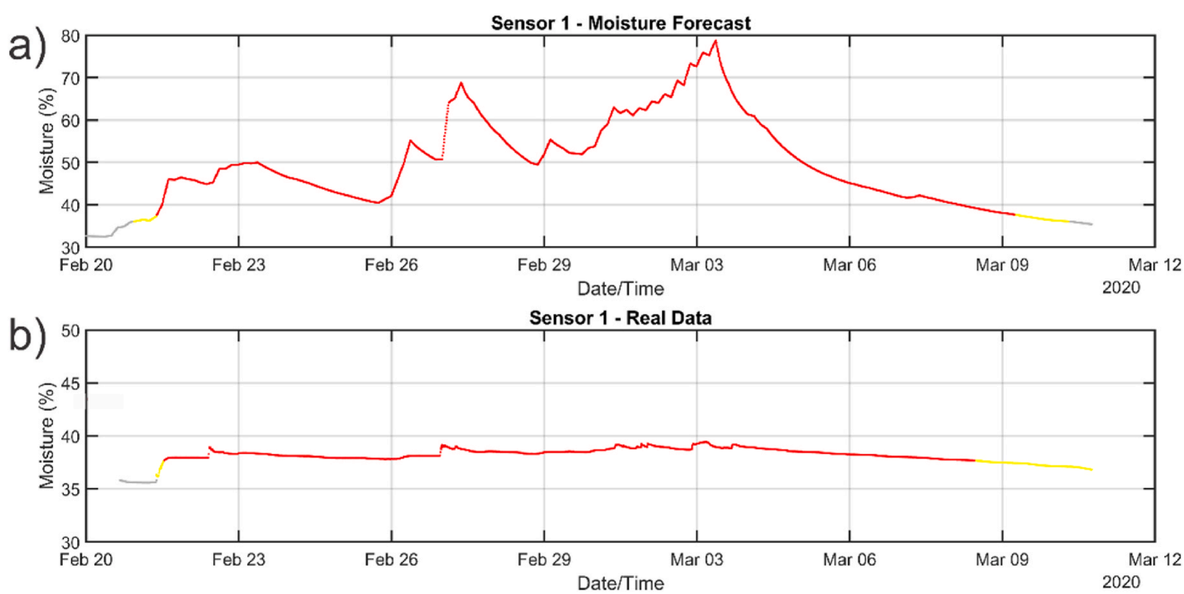

Fig. 6. Comparison between forecast and measurement of relative soil moisture (%) in Guarujá during the period from May 20th to June 1st, 2022, for sensor 01. (a): Model forecast. (b) In situ measurement. Moisture thresholds: red (very high), yellow (high), gray (normal).

critical periods of landslide events in the cities under study. The first period occurred from February 20 to March 12, 2020, for Guarujá, and the second period spanned from May 20 to June 1, 2022, for Recife.

Most of the landslides that occurred in Guarujá on the night of March 2nd to 3rd, 2020 were shallow translational landslides. In many of these sites, the rupture manifested right at the boundary between the solum and the saprolite, a pattern consistent with Selby's (1993) observations. The boundary between the solum and saprolite often served as the sliding plane. Depths to the failure plane predominantly ranged between 5 and 7 m, with the scars of the slides being considerably wider than they were deep. Notably, the landslide in the Morro do Macaco Molhado community measured 195 m in length and 113 m in width, resulting in 9 casualties. An even more devastating landslide occurred in the Morro de Barreira - João Guarda community, stretching 301 m long and 80 m wide and leading to 23 fatalities.

In Recife, the landslides transpired on soils stemming from sandy-clay sediments of the Barreiras Formation. These soils, which can be several tens of meters thick, are primarily composed of clayey sands and clayey-silty sands with consistent granulometric percentages (Andrade et al., 2023). The extent and width of these landslide scars are relatively modest. For instance, the largest landslides, which caused the most significant number of casualties—like the one on Milagres Street in the Jardim Monte Verde neighborhood, Recife (resulting in 20 deaths), and another in the Areeiro neighborhood in Camaragibe (leading to 6 deaths)—did not exceed 150 m in length and 70 m in width.

In the figures presented below, a comparison between moisture forecasts and the corresponding actual soil moisture data is provide. The top graph, labeled as "a," depicts the moisture forecasts, while the respective bottom graphs, labeled as "b," illustrate the observed soil moisture levels. To enhance clarity, the moisture values are categorized into distinct color-coded thresholds, representing different situations: normal, high, and very high moisture conditions. This color scheme facilitates a quick and intuitive understanding of the moisture variations during the analyzed period. Additionally, the graphs are further enriched with black dots, pinpointing moments in which landslides were recorded. These significant events provide crucial context and highlight the connection between soil moisture levels and landslide occurrences.

In Fig. 5, we have the rainfall measurement and the forecast obtained from de GFS model for the period of February 20th to March 12th, 2020, in Guarujá. Its possible to analyses that the model can not forecast the

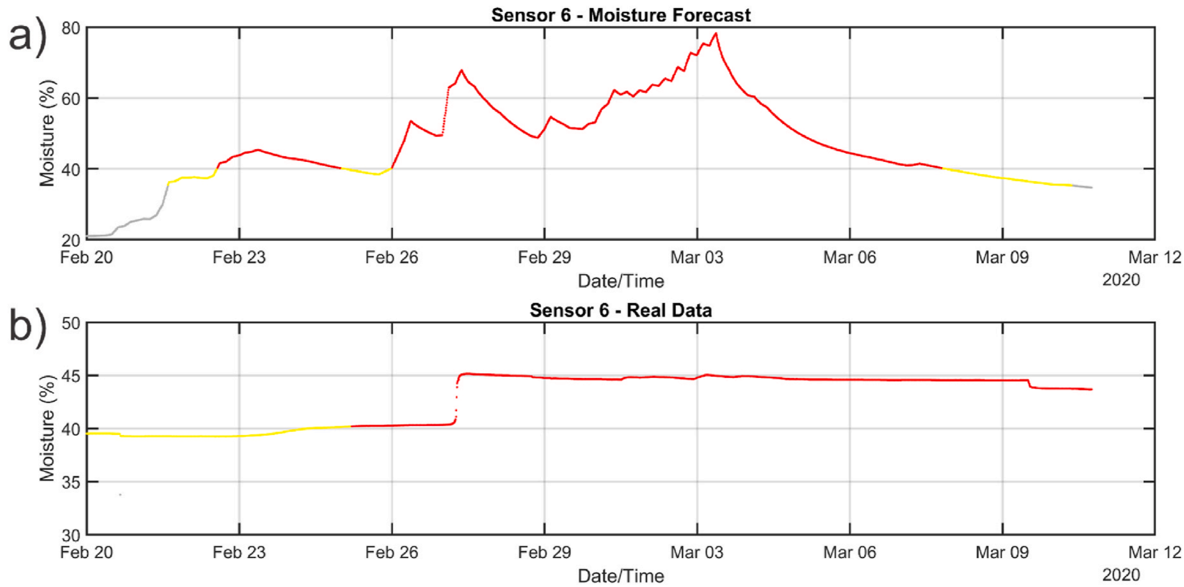

Fig. 7. Comparison between prediction and measurement of relative soil moisture (%) in Guarujá during the period from May 20th to June 1st, 2022, for sensor 06. (a) Model forecast. (b) In situ measurement. Moisture thresholds: red (very high), yellow (high), gray (normal).

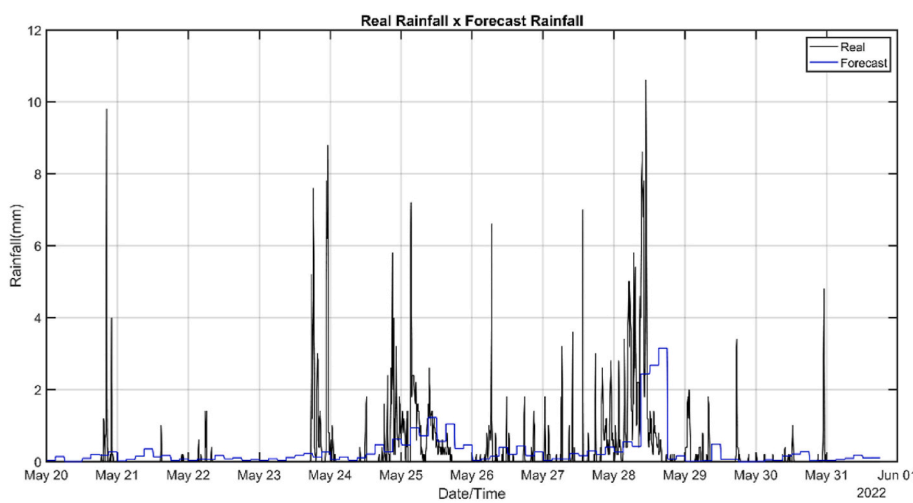

Fig. 8. Comparison between observed and predicted rainfall over time (May 20th to June 1st, 2022, in Recife/PE).

picks of rain, once the output is the accumulate rainfall in 3h. But it is very good to define the accumulate rainfall, once the measured value for the period was 457 mm and the forecast was 458 mm. In Fig. 6 we have the result of the prediction of soil moisture for sensor 1 (0.5 m deep). As previously explained, the direct calculation tends to extrapolate the saturation values, going above the normally borderline values of soils. In this case, it can be seen that the predicted values reach much higher values than those registered with the humidity sensors. However, in the case of this work, this is not a problem. Since the moment of variation is well registered and in the case of issuing alerts, values above those stipulated with the thresholds are already considered critical. In this case, the most important information is the moments of transition to high and very high thresholds and the return of higher thresholds to the normal situation (used to issue the end of the alert). In Fig. 7 we have the same analysis for sensor 6. The same observations are valid for this case, however at the end of the rainy season the forecast tends to values slightly lower than the measured ones. As it is a system with a very simple model, it is expected that in some situations it will not respond exceptionally.

In Fig. 8, we present the graph depicting the measured rainfall during the period from May 20th to June 1st, 2022, in Recife. In this particular case, the GFS (Global Forecast System) model did not achieve an optimal rainfall forecast. However, it should be noted that the accumulated rainfall during this period was exceptional, making it challenging for any meteorological model to predict with complete accuracy. The actual accumulated rainfall measured was 560 mm, while the forecasted value was 474 mm. Regarding the moisture forecast, some differences can be observed compared to the previous case. As the soil in this area is more sandy, it exhibits quicker responses to saturation and drainage. This characteristic is evident in Fig. 9, where sensor 1 displays very rapid responses to saturation and drainage. The moisture forecast cannot fully model such abrupt variations; however, it does identify periods of higher moisture levels. For sensor 6 (Fig. 10), the variations are smoother, and the forecasted results closely resemble the observed data, after accounting for the higher saturation values obtained with the model. Unlike the previous case, no instances of lower moisture values were observed in the forecasted data compared to the real case.

In Figs. 11 and 12, we have superimposed the occurrences of landslide events on March 3, 2020, in Guarujá, and on May 28, 2022, in Recife, onto the moisture forecast graphs specific to each study area and

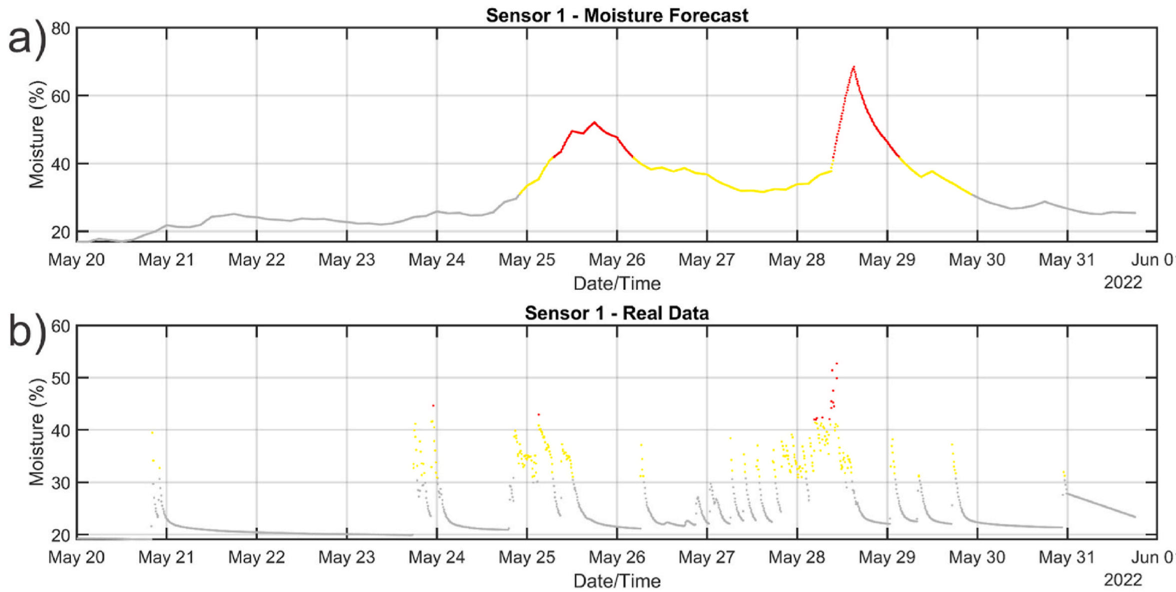

Fig. 9. Comparison between forecast and measurement of relative soil moisture (%) in Recife during the period from May 20 to June 1, 2022, for sensor 01. (a) Model forecast. (b) In situ measurement. Moisture thresholds: red (very high), yellow (high), gray (normal).

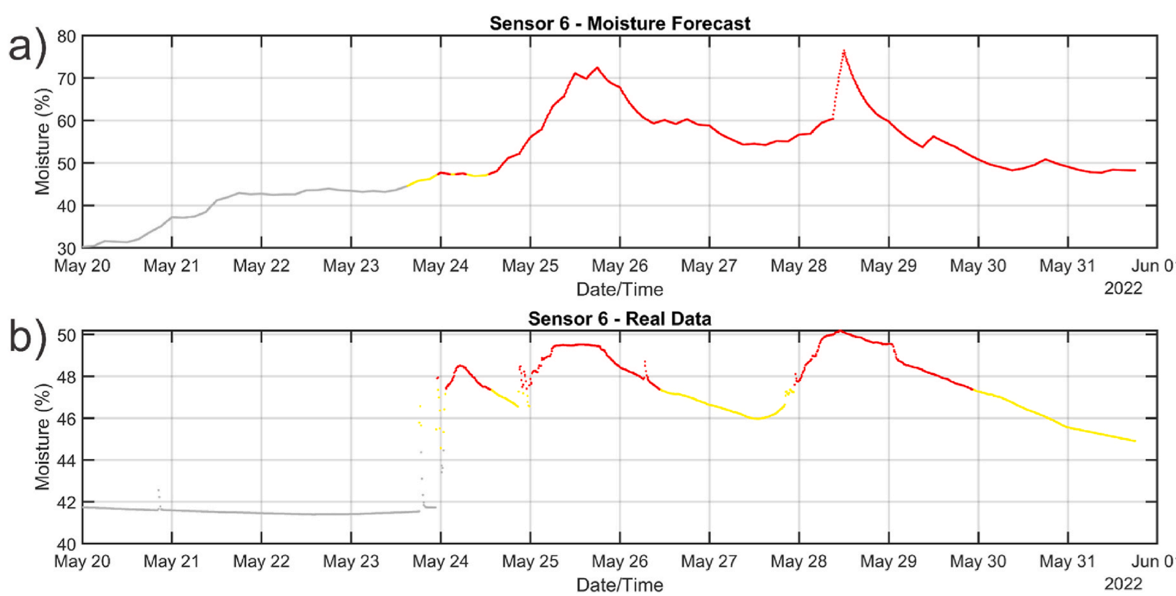

Fig. 10. Comparison between forecast and measurement of relative soil moisture (%) in Recife during the period from May 20 to June 1, 2022, for sensor 06. (a) Model forecast. (b): In situ measurement. Moisture thresholds: red (very high), yellow (high), gray (normal).

sensor. Notably, a consistent pattern emerges, as all landslide events were observed during periods of very high moisture levels, as indicated by the red curve on the graphs. These results demonstrate the significant application potential of the developed methodology in issuing landslide alerts. Despite the relative simplicity of the model, its robustness in real-case scenarios is evident. By leveraging soil moisture forecasts as a critical factor, we can effectively assess the potential for landslides and improve our landslide prediction and preparedness measures.

6. Conclusions

Based on the findings of this research, it is evident that the proposed methodology yields coherent and satisfactory results, showcasing its potential as a valuable supplementary tool for decision-making in Landslide Early Warning System (LAWS) issuances within the Cemaden's Operational Room. Despite the limitations arising from certain approximations made in the model, the developed program demonstrates its capability to integrate a comprehensive set of alert tools, effectively contributing to the prediction of landslide events and corresponding risk situations. It is essential to acknowledge that even more precise adjustments could be achieved by incorporating a greater number of parameters into the model and employing more refined mathematical formulations. The continuous enhancement of the model can lead to improved accuracy and reliability in landslide event forecasting.

Additionally, the set of geotechnical parameters already defined allows for working solely with precipitation data, assuming an initial saturation value, without relying on the moisture data from the Env

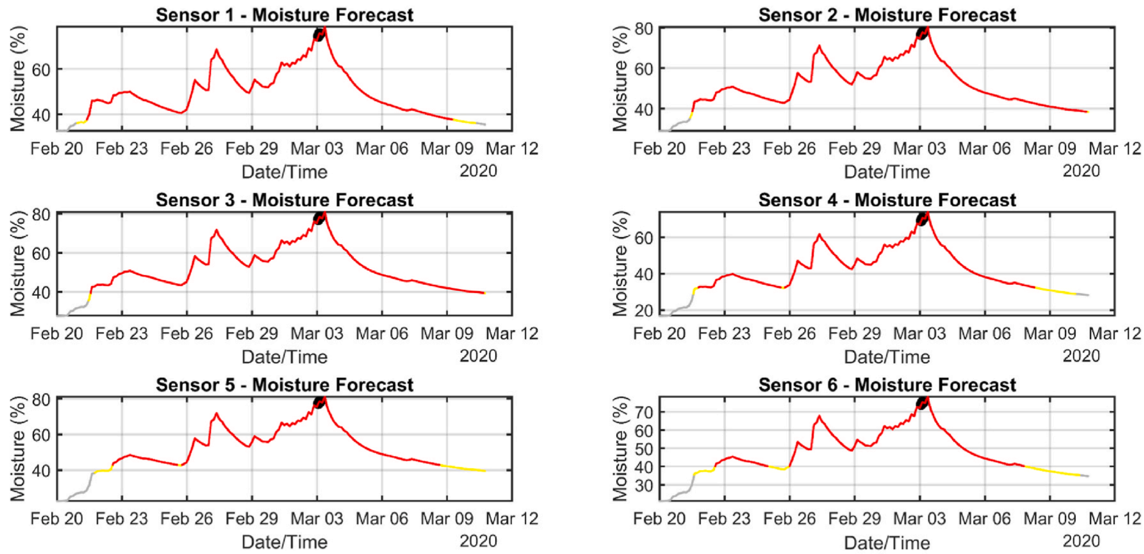

Fig. 11. Graphs of relative soil moisture (%) versus date, with moisture thresholds, for the period February 20 to March 12, 2020, covering all six sensors. Black dots: records of landslide events that occurred in Guarujá on March 3rd.

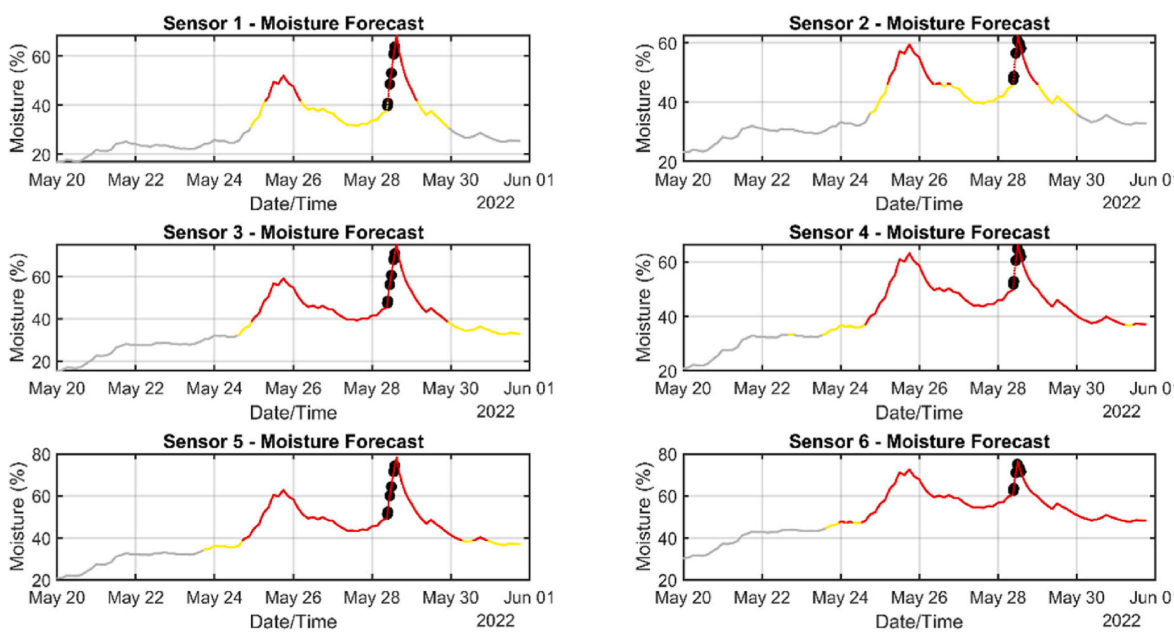

Fig. 12. Graphs of relative soil moisture (%) versus time, with moisture thresholds, for May 28, 2022, covering all six sensors. Black dots: records of landslide events that occurred in Recife on that date.

PCD. This feature proves to be valuable, especially during moments of signal loss from the PCD platform. Thus, the methodology can continue to generate estimated values even without the input of PCD data, rendering it a reliable and applicable alert instrument during emergency situations.

The methodology outlined in this study has been tested at two stations located approximately 2100 km apart, each with its own unique geological, geomorphological, social, and environmental characteristics. The promising results suggest that the approach could be a valuable tool for issuing alerts by Cemaden. Notably, the methodology has proven effective in two distinctly different contexts. Ultimately, we aim to implement this approach across all Environmental PCDs within Cemaden. This would include the five states currently equipped with these sensors and could extend to additional states that may install these sensors in the future.

In conclusion, this research highlights the potential of the proposed methodology as an effective tool in landslide risk management and decision-making processes. It showcases its adaptability, versatility, and applicability in real-time emergency scenarios, reinforcing its significance in contributing to the enhancement of landslide prediction and early warning systems, ultimately fostering greater resilience to natural hazards.

CRediT authorship contribution statement

Isadora Araújo Sousa: Writing – original draft, Validation, Project administration, Investigation, Formal analysis, Conceptualization. **Cassiano Antonio Bortolozo:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Tatiana Sussel Gonçalves Mendes:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Marcio Roberto Magalhães de Andrade:** Validation, Methodology, Formal analysis, Data curation, Conceptualization. **Giovanni Dolif Neto:** Methodology, Formal analysis, Data curation. **Daniel Metodiev:** Methodology, Formal analysis, Data curation. **Tristan Pryer:** Writing – review & editing, Software, Methodology. **Noel Howley:** Writing – review & editing, Software. **Silvio Jorge Coelho Simões:** Writing – review & editing, Methodology, Conceptualization. **Rodolfo Moreda Mendes:** Methodology, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Cassiano Antonio Bortolozo reports financial support was provided by National Council for Scientific and Technological Development. Isadora Araujo Sousa reports financial support was provided by National Council for Scientific and Technological Development. Daniel Metodiev reports financial support was provided by National Council for Scientific and Technological Development.

Data availability

The rainfall and soil moisture data are available in Cemaden's interactive map website.

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