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Thresholds of Instability: Precipitation, Landslides, and Early Warning Systems in Brazil

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Abstract

Rainfall accumulation thresholds are crucial for issuing landslide warnings by identifying when soil saturation from rain could potentially trigger a landslide. Two essential types of thresholds are considered: environmental and operational. The environmental threshold indicates the minimum rainfall level required to potentially initiate a landslide. Conversely, the operational threshold is set lower to enable agencies to issue alerts before reaching environmental thresholds. Establishing these thresholds improves the accuracy of landslide predictions in terms of location and timing. This study introduces an innovative approach for determining these thresholds. Our approach employs cluster analysis and historical landslide data from the Metropolitan Region of Recife, Pernambuco State, Brazil. We applied our defined values to a significant landslide event in 2022, validating their robustness as the foundation for the operational threshold used by Cemaden, Brazil's National Center for Monitoring and Early Warning of Natural Disasters.

Keywords

Cluster Analysis, Landslides, Environmental Thresholds, Rainfall, Brazil

1. Introduction

In Brazil, from 2003 to 2018, the national civil defense identified 32,121 disasters, averaging around 2000 events per year. The northeast and south regions have the highest incidence of events, with extreme rainfall and drought being particularly frequent. The most lethal types of disasters in Brazil involve mass movements related to land use and occupation. These are exacerbated by soil degradation, a result of poor management in combination with natural conditions [1] and [2]. Variables contributing to soil erosion include intense localized rains, steep slopes, unprotected vegetation, clandestine settlements without adequate infrastructure, and pedological and lithological inconsistencies. Rainfall, in terms of both its intensity and accumulated volume, is a critical factor in triggering landslides.

Accumulated rainfall is a key variable in global landslide warning systems. These systems typically use threshold values to decide whether to issue alerts, and to classify these alerts by severity (low, medium, high). Thresholds are generally of two types: environmental and operational. The environmental threshold represents the minimum level of accumulated rainfall that makes a landslide possible. The operational threshold is set deliberately lower to trigger alerts more quickly, enabling a rapid response from relevant authorities to mitigate the impact and protect the community.

An early warning should facilitate the ability of individuals exposed to landslide hazards to take timely actions to prevent or mitigate their risk and prepare for effective responses. However, the specific location and intensity of rainfall events vary greatly and are difficult to predict. Among the operational factors that significantly influence the anticipation of landslide alerts are the accuracy of weather forecasts and the response capability in high-risk areas. These factors determine the choice of longer or shorter lead times and, in turn, impact the accuracy of alerts. Therefore, operational thresholds demonstrating higher probability of accuracy are used, based on empirically observed initiation thresholds. It is typical for operational rainfall indices in alert systems to be set slightly below the environmental threshold, generally around 10% to 20% lower, depending on the local context.

The Metropolitan Region of Recife (RMR) in Pernambuco State is notably vulnerable to landslides, primarily due to unregulated urban settlements on hillsides that have been developing since the 1940s, and specific geological conditions of the area [3]. Landslides in the RMR are more frequent between April and August, coinciding with the region's rainy season. The topographical attributes of the RMR contribute to high levels of precipitation, influenced by its tropical climate [4]. Additionally, unique soil conditions, varying between the southern and northern sectors of the Pernambuco Lineament [5], are conducive to landslides. During the first half of 2022, the region saw significant rainfall accumulation [6], and records from the State Coordination for Protection and Civil Defense of Pernambuco (CODECIPE) indicate multiple landslide occurrences.

The study [7] found a correlation between precipitation and landslides along the northern coast of São Paulo State, emphasizing the importance of considering the ratio of cumulative rainfall over 6 hours and 72 hours when setting threshold values. Similarly, were used multivariate analysis to develop environmental indicators that describe the relationship between rainfall and landslides in the Vale do Paraíba region in São Paulo State, highlighting the impact of three-day accumulated rainfall on landslides.

To define the thresholds outlined by these studies, it's crucial to identify levels of rainfall that do not trigger landslides, those that may cause minor landslides, and those that could initiate widespread landslides.

Typically, alert systems utilize threshold values to make decisions regarding the issuance or non-issuance of alerts. These systems also use these thresholds to categorize alerts into different levels of severity, such as low, medium, and high. This approach is exemplified in the studies conducted by [7] and [8] for the coastal region of São Paulo State. Additionally, similar methodologies have been employed in other research endeavors that leverage historical landslide data and rainfall accumulation to establish these threshold values for various regions across Brazil. This can be observed in the studies conducted by [9] [10], and [11]. However, Cluster Analysis provides a valuable alternative for setting thresholds. This technique is commonly used in a variety of geoscience disciplines, making it suitable for this study.

This research introduces a new approach to setting these thresholds by merging cluster analysis with historical landslide data for the Metropolitan Region of Recife in Pernambuco State, Brazil. These thresholds were then successfully applied to a major landslide event in 2021, confirming their effectiveness as operational guidelines in Cemaden's Operational Room, Brazil's National Center for Monitoring and Early Warning of Natural Disasters. The primary goal of using this innovative methodology is to enhance the accuracy and efficiency of landslide warning systems, thereby improving safety measures and disaster preparedness in landslide-prone areas.

2. Study Site

2.1. Location

The Recife Metropolitan Region (Recife RM), State of Pernambuco, is located in the Northeastern region of Brazil (**Figure 1(a)**). The Recife MR region is composed of 14 municipalities and correspond the fifth-largest metropolitan contingent in Brazil [12]. The coast of Northeast Brazil is commonly affected by natural hazards due to the presence of housing in areas susceptible to flooding and landslides [13]. Reference [14] estimated that 631,000 people are exposed in risk areas in the Recife MR in 11 of their 14 municipalities. Considering the municipalities of Recife (1.488.920 inhabitants) and Jaboatão de Guararapes (643.759 inhabitants) (**Figure 1(b)**), the population corresponds a 23.5% of the total population of the State of Pernambuco (9,058,155 inhabitants) according to latest 2022 census [15].

The climate of the region is influenced by several key factors, namely its geographical location, topography, land cover, and pressure systems in operation

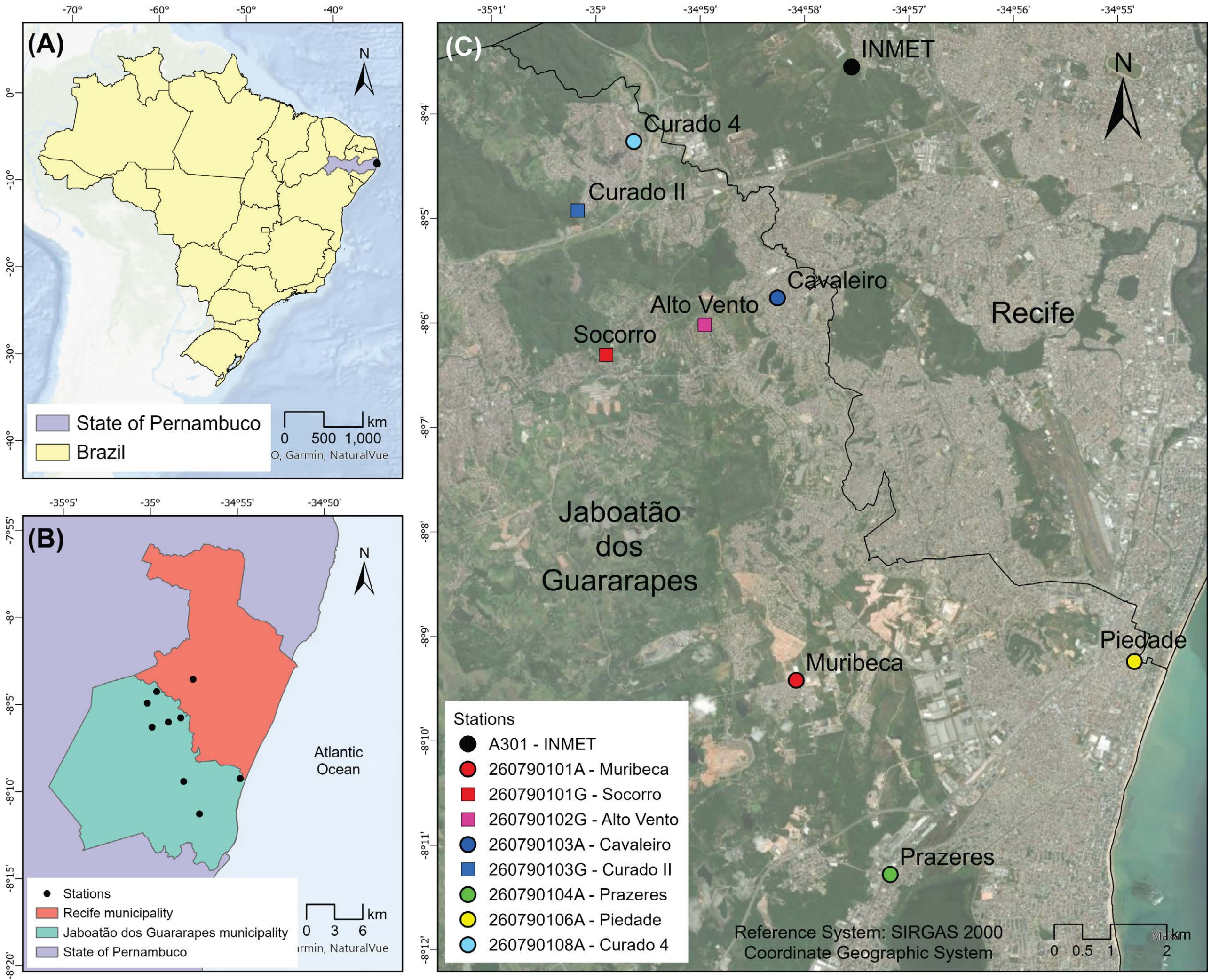

Figure 1. Study site location. (a) State of Pernambuco located in Brazil; (b) Recife and Jaboatão dos Guararapes, municipalities of the Recife RM, located in State of Pernambuco and rain gauges; (c) INMET and Cemaden's rain gauges used in this work.

[16]. It can be classified as a humid tropical climate, with average annual temperatures ranging from 20˚C to 28˚C. During the summer months, the mean temperature rises to approximately 30˚C. In terms of precipitation, the annual index exceeds 2000 mm [12]. The Recife Metropolitan Area experiences significant fluctuations in precipitation, particularly in areas with inadequate urban development and insufficient drainage infrastructure. As a result, this can lead to the occurrence of floods and landslides [12].

2.2. Geology and Geomorphology

The soil in the Recife area mainly consists of a mix of sand and clay, featuring minerals like kaolinites and illites that come from the underlying crystalline bedrock. Basic volcanic rocks in the region also undergo changes due to the presence of iron and magnesium minerals from the smectite and chlorite groups, leading to the formation of expansive clay soils [17]. The sandy-clay layers of the Barreiras Formation extend over large areas and can be found along the slopes surrounding plateau-like terrains marked by steep cliffs, some over 30 meters high [18]. Landslides are most common in areas where the Barreiras Formation is present [19]. This formation serves as a natural, unconfined water reservoir, affecting both the water flow and the stability of nearby slopes. Generally, these soils can be categorized as either clay-sands or clay-silty sands. They have a uniform grain size, vary from low to medium in plasticity, and are not highly compressible. Moreover, they lack cohesion [18] and are easily eroded, making them prone to erosion on slopes [20]. Variations in the deep water zones, combined with temporary water table rises in shallower layers due to rainfall, create conditions that favor landslides, especially at shallow depths.

Regarding the area's geomorphology, the Metropolitan Region of Recife is mainly composed of large coastal plateaus intersected by significant river valleys near the coast. In terms of tectonic features, the area is crisscrossed by ancient faults that were partially reactivated during the Cretaceous period but are now stable. According to [21], there are three main orientations of these faults: the east-west Pernambuco Lineament; northeast-southeast faults connected to the opening of the Atlantic Ocean, which led to staggered blocks forming towards the continental shelf; and northwest-southeast faults that contributed to the formation of a depression south of the Pernambuco Lineament, giving rise to the Cabo de Santo Agostinho Basin.

2.3. Landslide Events

In the eastern Northeast of Brazil, rainfall patterns are influenced by Wave Disturbances of the East. Maximum rainfall occurs between May and July, with an annual average exceeding 1500 mm [22]. Extreme weather events in this region are primarily due to the interaction between Wave Disturbances of the East and warmer sea temperatures. These conditions produce intense convective systems, resulting in heavy rainfall [23]. Such intense rain events lead to landslides, flash floods, and flooding, causing substantial harm to communities and exacerbating existing socio-environmental issues [24] [25].

Since colonial period in Brazil, human activities have made the Metropolitan Region of Recife (Recife MR) susceptible to geomorphological events. These activities include altering water courses, landfilling, deforestation, and hillside occupation [26]. Urbanization intensified in the 1960s, further escalating these problems [12].

The earliest recorded flood in the region dates back to 1632 [12]. The two most catastrophic floods occurred in 1966 (**Figure 2(a)**) and 1975. In the 1966 event, River Capibaribe overflowed, primarily causing flooding [27]. In contrast, the 1975 flood inundated 80% of Recife, displacing 60,000 people [12]. To mitigate such disasters, dam systems were implemented in the 1980s [12].

Between May 23 and 30, 2017, a series of floods, landslides, and property destruction affected 12 cities in the State of Pernambuco, resulting in numerous deaths. Jaboatão dos Guararapes was particularly hit, experiencing six landslides

[28]. Another significant event occurred from June 13 to 18, 2019 (**Figure 2(b)**), when heavy rains triggered over 150 landslides in Jaboatão dos Guararapes, causing one death and injuring four people [29].

At the end of May 2022 (**Figure 2(c)**), three weeks of continuous heavy rainfall led to landslides and floods, resulting in 130 deaths and displacing over 130,000 people in the Recife MR [27]. The southern part of Recife and the northern area of Jaboatão dos Guararapes were the most severely affected in both instances [30].

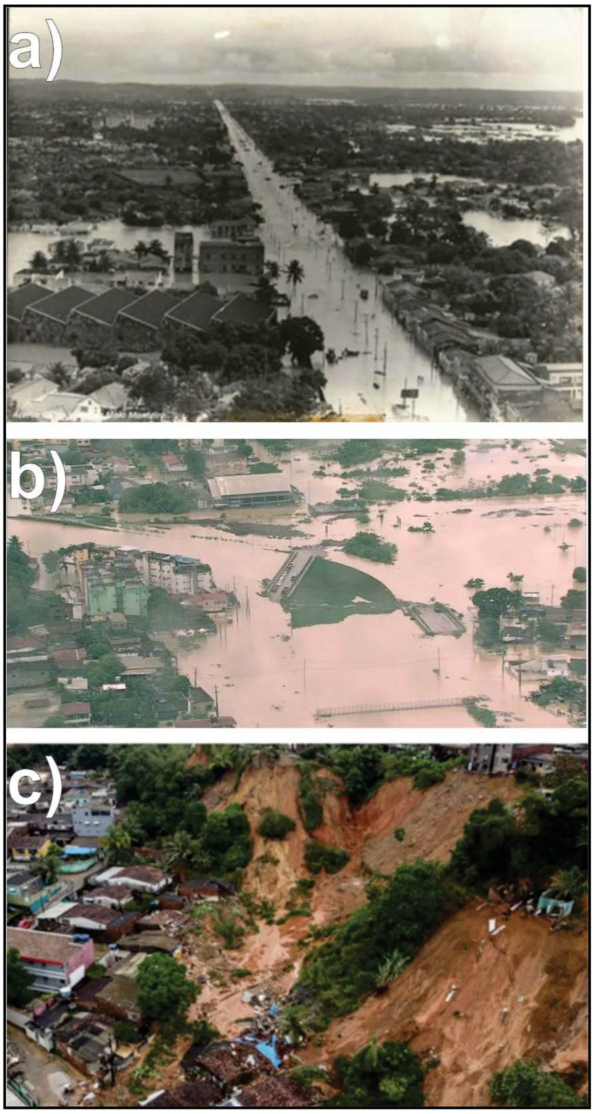

Figure 2. Records of the extreme events in the Recife. (a) Avenida Caxangá in Recife municipality taken over by the flood of 1966 (source: Acervo de Gisela Vieira de Melo; JC Online, 2016); (b) flood event with landslides in Jaboatão de Guararapes municipality in 2019 (source: Reprodução Globocop/TV Globo; CBN Recife, 2019); and (c) landslides in Jaboatão dos Guararapes municipality in 2022 (source: Diego Nigro/AFP; MetSul Meteorologia).

2.4. Climatology and Disasters in Recife Metropolitan Region

For the computation of climatological parameters, monthly precipitation data from 2005 to 2021 were used. This data was sourced from the historical meteorological database managed by the National Institute of Meteorology (INMET) for the Recife Station. Rainfall data, featuring a robust temporal resolution, were collected from both gauge and geotechnical stations operated by Cemaden. These records include measurements taken at 10-minute intervals for rainfall events and hourly intervals for other variables. Data collection in the region began with the establishment of the first station in 2014. Currently, the network consists of a total of nine stations: six gauge-only and three geotechnical stations. The spatial coordinates for all these stations are illustrated in **Figure 1**. Information regarding landslides was obtained from the Secretaria de Estado e Desenvolvimento Econômico (SEDEC) for the localities of Recife and Jaboatão dos Guararapes, spanning from 2014 to 2021, with the exception of the year 2020.

The average annual monthly precipitation for the period 2005-2021 is 2050.6 mm. The rainy season typically spans from April to August and accounts for 1443.9 mm of the total precipitation, while the dry period falls between October and December, contributing only 163.3 mm. June stands out as the month with the highest cumulative rainfall, registering 358.27 mm. Prevailing atmospheric systems affecting this precipitation pattern include the Intertropical Convergence Zone (ITCZ) and its seasonal movements, as well as the influence of Easterly Wave Disturbances (EWD) [31]. Additional factors like land and sea breezes, along with their respective intensities [32], and the role of frontal systems [33], also significantly influence regional rainfall patterns.

A comparative analysis was performed focusing on the monthly precipitation data for the year 2021, collected from both INMET and CEMADEN stations. During this year, a notably higher frequency of landslide incidents was observed in the metropolitan area of Recife. All stations demonstrated a consistent seasonal trend in precipitation, with peak accumulation occurring from May to August, and lower levels from September to March (**Figure 3**). Noteworthy are the contrasting values among the stations: Cavaleiro station (260790103A) consistently registers the lowest precipitation values, while Curado II station (260790103G) records the highest. This analysis is particularly significant, as subsequent cluster analyses will exclusively use data from CEMADEN stations along with climatological data from INMET stations.

To delve deeper into this, an inquiry examined the monthly precipitation patterns for 2021 in detail. This comprehensive review considered the relationship between the frequency of landslide incidents, monthly precipitation levels, and long-term climatological patterns from 2005 to 2021 (**Figure 4**). The objective was to understand the correlation between instances of above-average rainfall and the occurrence of landslides. The months with a notably higher incidence of landslides were April, May, June, and August. Except for June, all these months experienced rainfall levels exceeding the established climatic norms. It's crucial

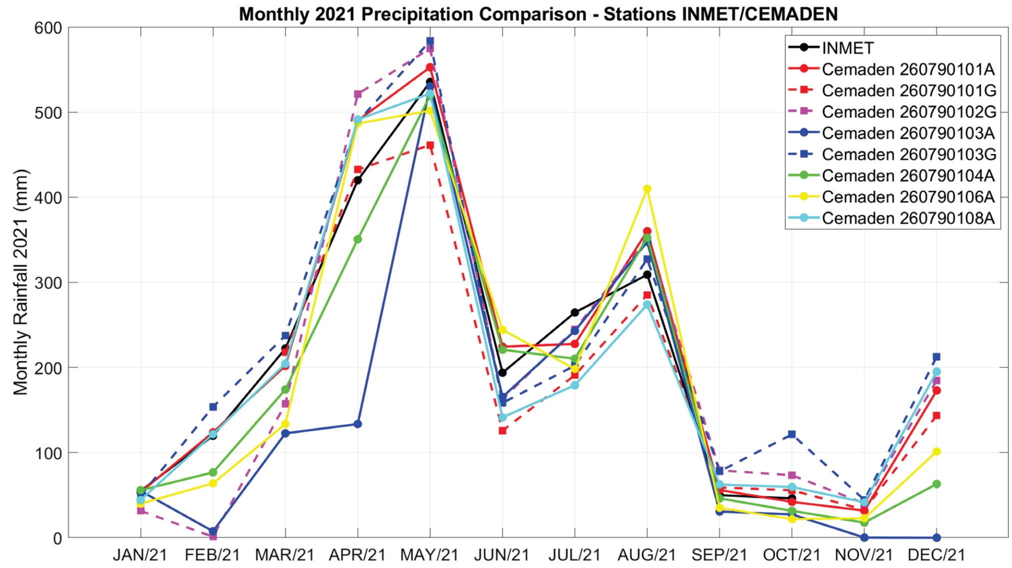

Figure 3. Comparison of monthly precipitation only for 2021 for INMET and CEMADEN stations.

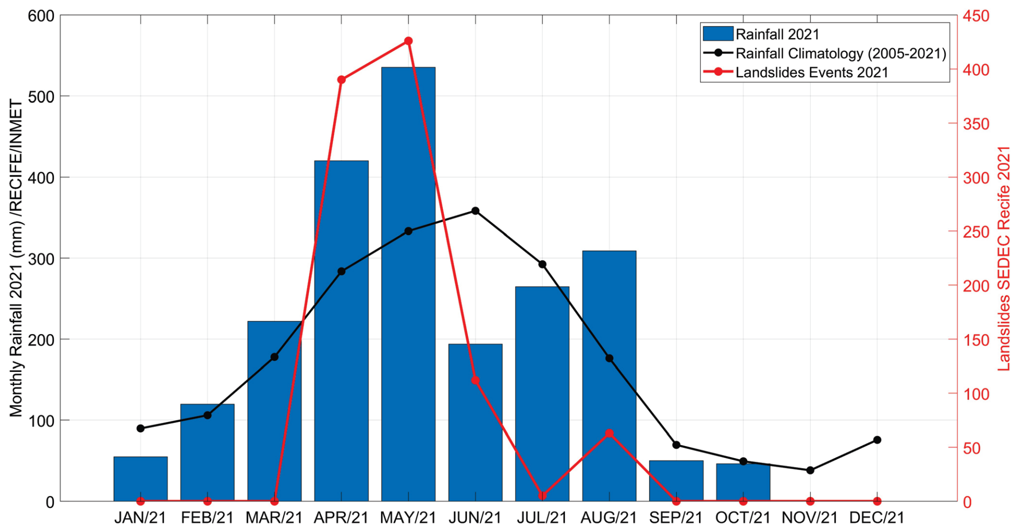

Figure 4. Precipitation (blue bars) and number of landslides (red line) for RMR in the year of 2021 (black line represents the precipitation climatology between 2005 and 2021).

to note that while June did not show significant deviations from the average rainfall, the preceding two months had substantial precipitation, making the terrain more susceptible to landslides due to increased saturation.

3. Cluster Analysis

Cluster Analysis is a multivariate statistical technique used for classification. It aims to create groups comprising elements that are similar within each group and different from elements in other groups [34]. In this study, it was employed for two distinct classifications:

1) Classification of landslide events, grouping them based on rainfall accumulation at different time scales (1 h, 3 h, 6 h, 24 h, 48 h, 72 h before the event) for

the closest stations.

2) Classification of precipitation data with various time accumulations (1 h, 3 h, 6 h, 24 h, 48 h, 72 h) specifically for the Socorro Station. This station was selected as it experiences the highest frequency of events within a 3 km radius, especially from April to August 2021—a period marked by a large number of landslides. The goal of this classification is to identify precipitation thresholds that correlate with the occurrence of landslides.

In Cluster Analysis, it is essential to have a metric capable of distinguishing between similar elements, often termed a "distance measure". The most widely adopted and intuitive measure for this purpose is the Euclidean distance [34]. Furthermore, a method must be chosen to group these elements based on calculated distances. Clustering methods are broadly categorized into two types: hierarchical and non-hierarchical. In hierarchical methods, a dendrogram visually reveals the step-by-step progression of group formation. Initially, all "n" elements form a single group, eventually culminating in "n" individual groups [34]. The Ward method [35] is the most commonly used hierarchical approach, as it minimizes within-cluster variance.

Conversely, non-hierarchical methods lack a visual representation of group formation and require the number of groups to be predetermined. The K-means algorithm is a notable non-hierarchical method. It functions iteratively, assigning data points to the nearest centroid (representing the cluster center) and then recalculating centroids based on the new clusters. This process continues until convergence, resulting in clusters with minimal within-cluster variance and maximal between-cluster variance [36] [37].

The optimal clustering method and the appropriate number of clusters can be determined through various metrics such as the Silhouette value, Calinski-Harabasz index, or Davies-Bouldin index [38]. For hierarchical methods, a dendrogram can be utilized to examine data point distribution and their inter-distances. These techniques provide valuable insights into the optimal number of clusters that best represent the underlying data structure [34].

This study explored both the Ward and K-means methods for classifications 1) and 2). The optimal number of clusters was determined following the methodology outlined by [34] and applied to both methods. Notably, for classification 1), the Ward Method yielded superior results, while for classification 2), both methods produced identical outcomes. As a result, subsequent analyses exclusively employed the Ward Method. A dedicated software application was developed specifically for this analysis [39].

4. Cluster Analysis for Rainfall Accumulation

Rainfall data from Cemaden stations are recorded at 10-minute intervals during rainy periods and hourly during rainless periods. To standardize the data to 10-minute intervals, we used the software "Analise_Pluviometros_Cemaden" [40]. This software not only aligns the data to consistent 10-minute intervals but also calculates rainfall accumulations for 1, 3, 6, 24, 48, and 72 hours for each data entry. In other words, for each 10-minute interval, cumulative rainfall values for the preceding 1, 3, 6, 24, 48, and 72 hours are available. Employing this dataset in Cluster Analysis allowed us to categorize rainfall events into three groups based on these specific accumulations. We conducted this analysis using rain gauge data from "Estação Socorro—260790102A", located in the city of Jaboatão dos Guararapes, one of the municipalities in the Metropolitan Region of Recife. This station was chosen due to its high number of recorded landslide events within a 3 km radius.

Figure 5 and **Figure 6** display graphs depicting the triggering 3-hour (**Figure 5**) and 6-hour (**Figure 6**) rainfall patterns, alongside antecedent rainfall for 48 and 72 hours. While our analysis covered all possible combinations of 1, 3, 6, 24, 48, and 72-hour rainfall accumulations, the cases presented here exhibited the strongest correlation between triggering and antecedent rainfall patterns.

In **Figure 5**, the graphs illustrate 3-hour triggering rainfall in relation to antecedent 48-hour (**Figure 5(a)**) and 72-hour (**Figure 5(b)**) rainfall. The three clusters represent groups characterized by lower intensity and accumulations (Group 1—blue), intermediate rainfall (Group 2—black), and higher intensity and accumulations (Group 3—red). Green stars denote values accumulated during landslide events recorded near the station in 2021. The graphical representation in **Figure 5** reveals that the distinction between clusters is most prominent in the 72-hour versus 3-hour case, where minimal overlap between clusters is observed.

In **Figure 6**, the same groups and events depicted in **Figure 5** are presented, but this time featuring 6-hour triggering rainfall. Here again, cluster separation is more distinct in the 72-hour antecedent rainfall case (**Figure 6(b)**) compared to the 48-hour antecedent rainfall case (**Figure 6(a)**). Notably, the combination of 72-hour antecedent rainfall and 6-hour triggering rainfall proved most effective, displaying the least overlap and the most distinct delineation among clusters. Consequently, this specific combination has been selected for defining both environmental and operational thresholds.

5. Environmental and Operational Thresholds

The main goal of this research is to define the environmental threshold and the operational threshold. According to [41], a rainfall threshold refers to the condition or amount of rainfall that is likely to initiate sediment-related disasters. In this context, the environmental threshold is the approximate minimum level of rainfall where the initiation of a landslide becomes possible. The operational threshold, conversely, is set lower than the environmental threshold and serves to trigger danger alerts issued by responsible authorities. When rainfall reaches the operational threshold, a warning can be disseminated to alert residents and emergency services about the potential for landslides, helping to minimize damage to property and save lives.

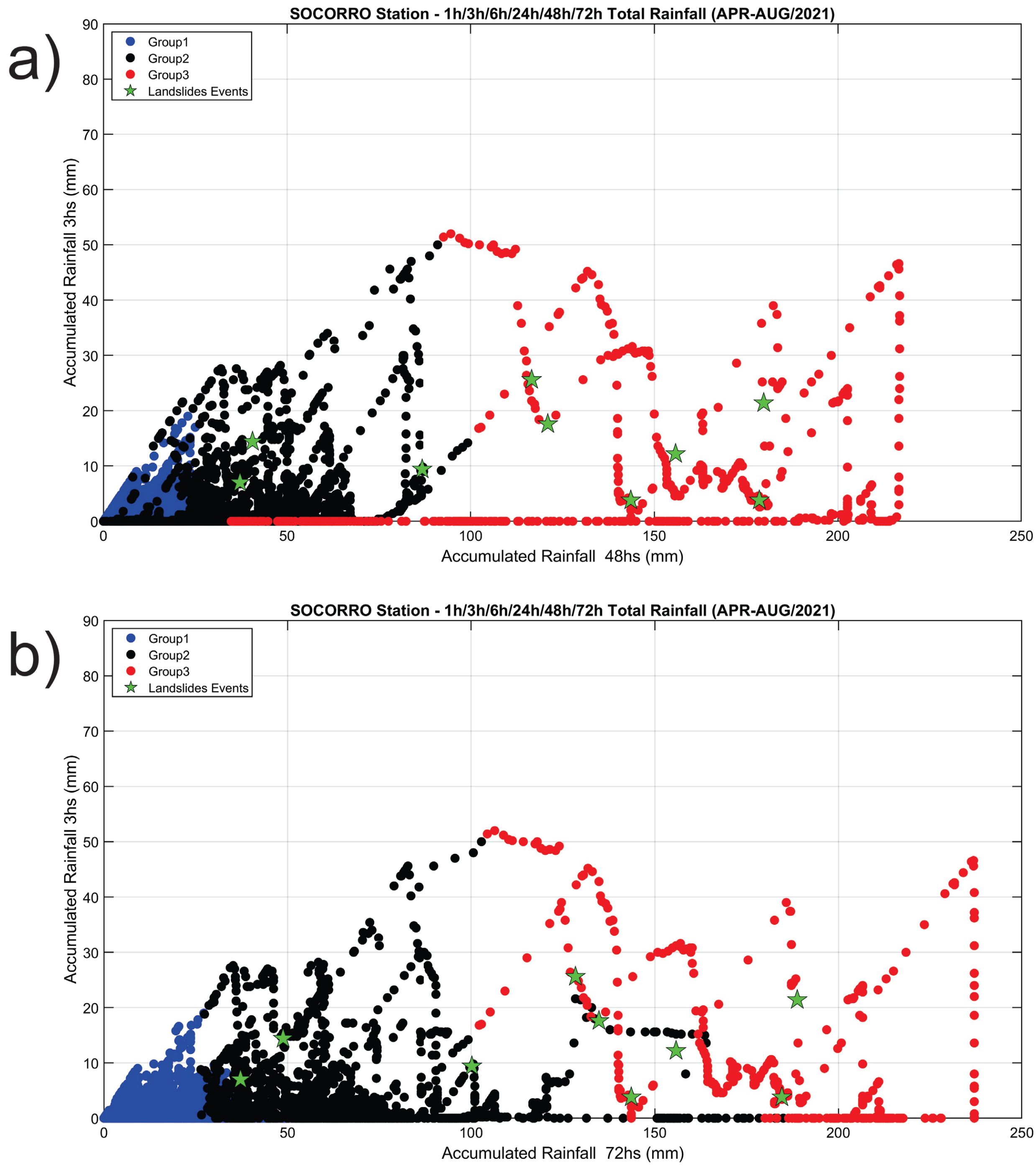

Figure 5. Cluster Analysis for Rainfall Data. Graphs depicting the 3-hour triggering rainfall in relation to the antecedent 48-hour rainfall (a) and 72-hour rainfall (b). The presented clusters denote the category of rainfall with lower intensity and accumulations (blue), intermediate rainfall (black), and the category with higher intensity and accumulations (red).

Reference [8] developed an empirical method based on the rainfall events of January 22/23, 1985, which caused widespread landslides along the Serra do Mar Mountain Range in the region of Cubatão (State of São Paulo). The method considers four days of accumulated rainfall as being effective in preparing the terrain for potential landslides by progressively reducing shear resistance and increasing active exogenous forces. Consequently, short-term (hourly) precipitation may act as a triggering factor. In this research, we employed a 72-hour period for antecedent rainfall and a 6-hour accumulation period for triggering rainfall, as described in the previous section.

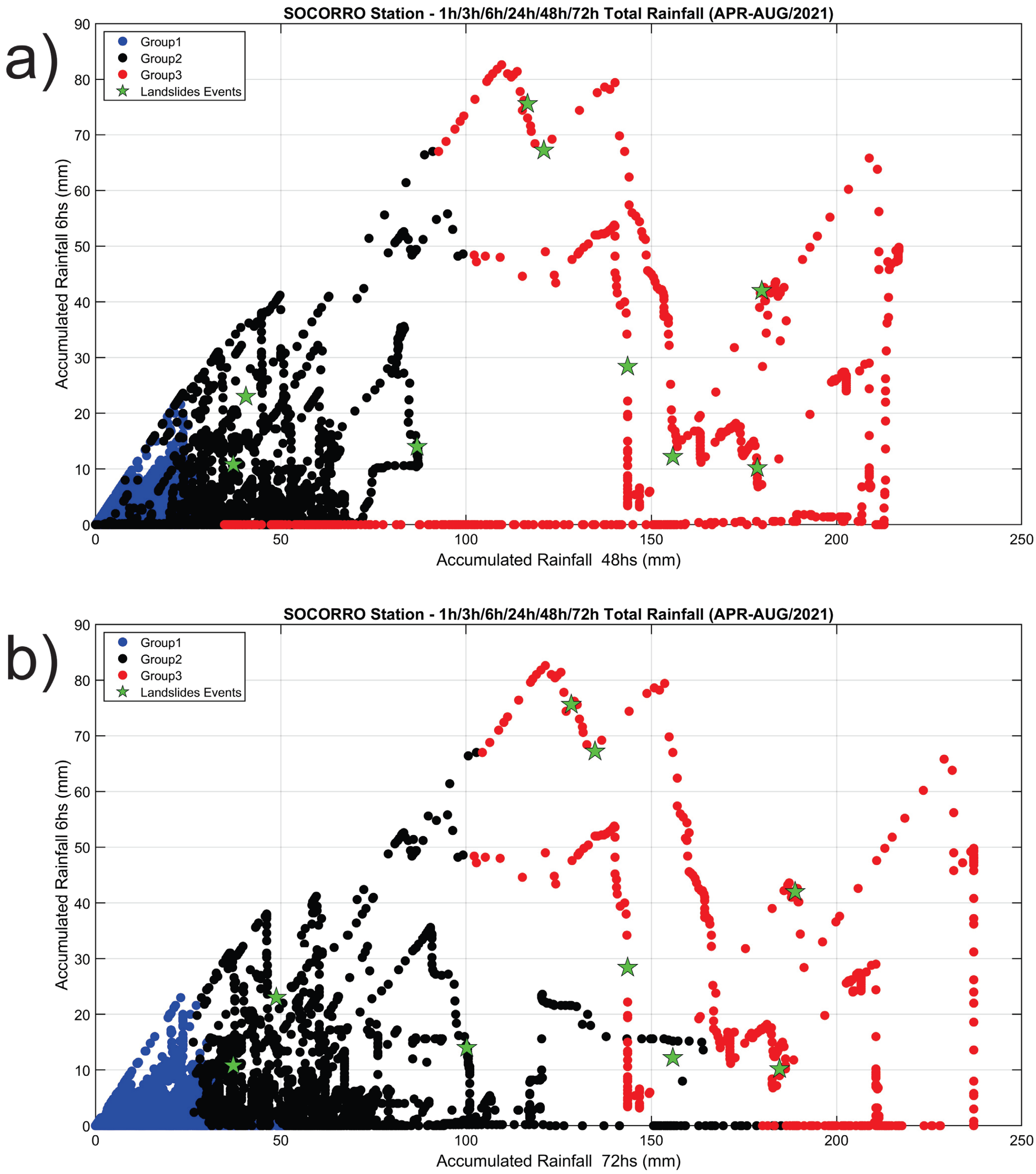

Figure 6. Cluster Analysis for Rainfall Data. Graphs depicting the 6-hour triggering rainfall in relation to the antecedent 48-hour rainfall (a) and 72-hour rainfall (b). The presented clusters denote the category of rainfall with lower intensity and accumulations (blue), intermediate rainfall (black), and the category with higher intensity and accumulations (red).

Figure 7 presents the environmental and operational thresholds based on clusters identified through cluster analysis. The environmental thresholds are depicted in Figure 7(a) and are represented by two distinct levels. For operational purposes, the thresholds usually need to be set lower to facilitate the triggering of alerts for civil defense actions aimed at mitigating landslide impacts. Thus, Figure 7(b) shows the operational thresholds, which in the Cemaden system

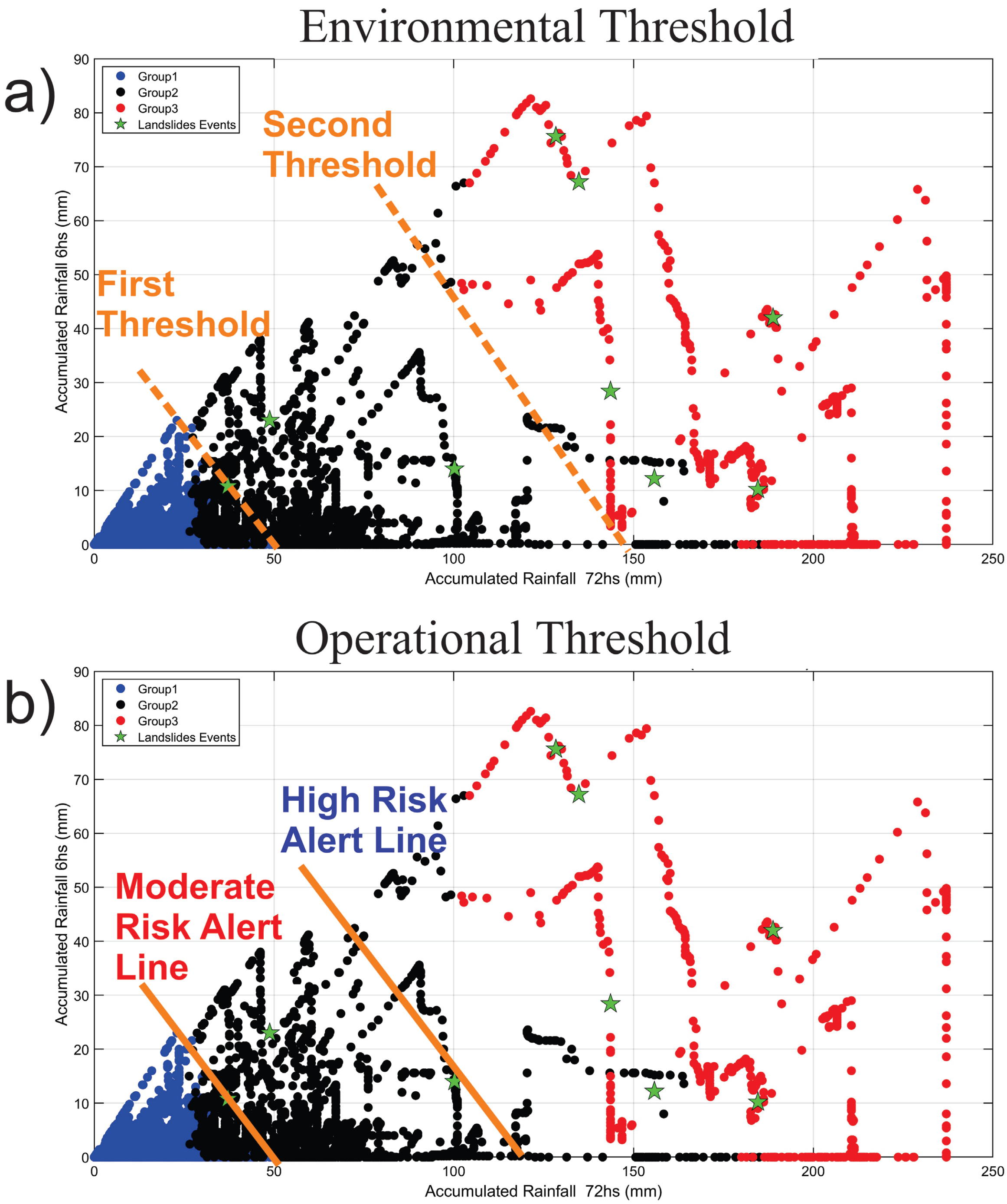

Figure 7. Thresholds obtained through the cluster analysis method. In (a), the environmental thresholds, and in (b), the operational thresholds (Moderate Risk Alert and High-Risk Alert).

correspond to Moderate and High conditions. A notable advantage of this Cluster Analysis methodology is its ability to establish thresholds without requiring prior landslide event data, although including such data can enhance confidence and precision in threshold delineation.

For the first threshold (Moderate Alert Line), we retained the same level as the environmental threshold, as this was highly effective in capturing lower-intensity rainfall events. The derived values closely align with existing literature and encompass all recorded events. Additionally, landslides occurring under rainfall accumulations lower than this threshold are challenging to forecast and usually have minimal impact. These events predominantly occur in locations with significant anthropogenic alterations. As for the High-Risk Threshold (High-Risk Alert Line), we set a value 20% lower than the environmental threshold. This 20% gap aligns with the standard protocol within the Cemaden Situation Room. A substantial majority of events fall within this category, indicating that in a real-world scenario, civil defense would likely have received alerts for both moderate and high risks, thereby allowing time for appropriate response actions.

6. Case Study Application—May 2022

Utilizing the thresholds obtained from the analysis illustrated in Figure 7(b), we were able to establish thresholds for the Metropolitan Region of Recife. To validate these thresholds in a real-world context, we used events from 2022 for verification. Notably, during the events that occurred in May 2022, the cumulative rainfall in Jaboatão dos Guararapes exceeded the monthly average precipitation for May, which climatologically stands at 310 mm. Tragically, these events led to the loss of over 130 lives within the Metropolitan Region of Recife and displaced approximately 6000 individuals. Figure 8 displays a graph of 72-hour antecedent

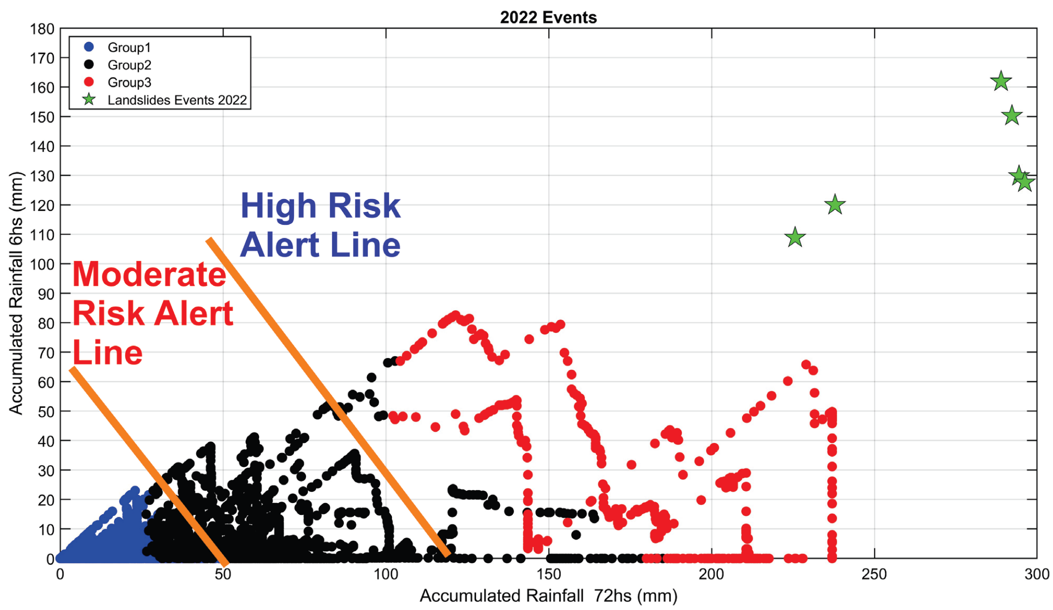

Figure 8. Events that took place in 2022 in Jaboatão dos Guararapes (green stars) on the graph featuring the Moderate and High-risk thresholds.

versus 6-hour triggering rainfall, featuring the Moderate Risk Alert and High-Risk Alert thresholds superimposed on the rainfall clusters from the Socorro station for the 2021 period previously discussed. Importantly, in **Figure 8**, the green stars represent some of the significant events that took place in 2022. It should be noted that in this case, the rainfall accumulations were obtained from a rain gauge near the Socorro station (Cavaleiro Station), as the Socorro station was non-operational at the time. As observed, the rainfall accumulations during these event hours consistently fell within the High-Risk category. The intensity of the 2022 rainfall events is also evident, as these events recorded substantial amounts of both antecedent and triggering rainfall.

7. Conclusion

The findings from this study show significant promise as a foundation for further research focused on establishing critical rainfall thresholds for alert issuance. A major advantage of this methodology is its ability to function without the absolute need for landslide event data—although having such data is advisable. This is particularly useful given that precise event timing is often either scarce or entirely absent. As a result, this methodology could offer more accurate thresholds for regions with limited or no available historical data on landslide occurrences, improving upon current methods that frequently rely on approximate regional values. Following the validation of our results, we have developed a software application called DeLAC [39] to facilitate Cluster Analysis on any dataset sourced from Cemaden rain gauges. This software serves as a valuable tool for future studies aimed at developing operational thresholds within the Operational Room.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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