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ARHCS (Automatic Rainfall Half-Life Cluster System): A Landslides Early Warning System (LEWS) Using Cluster Analysis and Automatic Threshold Definition

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Abstract

A significant portion of Landslide Early Warning Systems (LEWS) relies on the definition of operational thresholds and the monitoring of cumulative rainfall for alert issuance. These thresholds can be obtained in various ways, but most often they are based on previous landslide data. This approach introduces several limitations. For instance, there is a requirement for the location to have been previously monitored in some way to have this type of information recorded. Another significant limitation is the need for information regarding the location and timing of incidents. Despite the current ease of obtaining location information (GPS, drone images, etc.), the timing of the event remains challenging to ascertain for a considerable portion of landslide data. Concerning rainfall monitoring, there are multiple ways to consider it, for instance, examining accumulations over various intervals (1 h, 6 h, 24 h, 72 h), as well as in the calculation of effective rainfall, which represents the precipitation that actually infiltrates the soil. However, in the vast majority of cases, both the thresholds and the rain monitoring approach are defined manually and subjectively, relying on the operators' experience. This makes the process labor-intensive and time-consuming, hindering the establishment of a truly standardized and rapidly scalable methodology on a large scale. In this work, we propose a Landslides Early Warning System (LEWS) based on the concept of rainfall half-life and the determination of thresholds using Cluster Analysis and data inversion. The system is designed to be applied in extensive monitoring networks, such as the one utilized by Cemaden, Brazil's National Center for Monitoring and Early Warning of Natural Disasters.

Keywords

Landslides Early Warning System (LEWS), Cluster Analysis, Landslides, Brazil

1. Introduction

Excessive precipitation in Brazil presents notable risks of disasters, primarily in the form of floods and mass movements, such as landslides [1] and [2]. Landslides, notably identified as the most lethal hazard in the country [3], were exemplified by a tragic event in the mountainous region of the state of Rio de Janeiro in 2011. This incident resulted in over 900 fatalities and 300 missing individuals [2]. Subsequent to this calamity, the National Center for Monitoring and Early Warning of Natural Disasters (Cemaden) was established by the Brazilian government in 2011.

Further severe landslide occurrences, such as those on the São Paulo State coast in 2020, led to 45 deaths, with 34 in the city of Guarujá and 8 in Santos city. Recent events in Petrópolis, Rio de Janeiro, in early 2022, resulted in over 240 fatalities [4] and [5]. Additionally, a large-scale disaster affected the Recife Metropolitan Region, the capital of Pernambuco state, in May 2022, causing more than 130 deaths [6].

Given the high fatality rates associated with mass movements, the examination and prediction of landslides have become imperative across diverse scientific domains. Cemaden, in particular, underscores the importance of comprehending and predicting landslides, employing an extensive network of rain gauges and soil moisture sensors [7] and [8]. This involves research focused on understanding and mitigating landslides [9]-[16].

In the context of a Landslides Early Warning System (LEWS), rainfall-induced landslides occur when specific thresholds, defined by factors such as precipitation, soil moisture, or hydrological conditions, are met or exceeded [17]. Empirical thresholds for critical daily or hourly rainfall and preceding precipitation that can trigger landslides are determined by analyzing rainfall events known to have caused landslides [18] [19] [20] [21]. This approach proves especially valuable when precise date, time, and prior precipitation data are accessible [22]. These thresholds are typically established by plotting the lower bounds of precipitation conditions known to have caused landslides, utilizing Cartesian, semi-logarithmic, or logarithmic coordinates [23].

However, as illustrated, these thresholds heavily rely on the analysis of previous landslide events for defining critical rainfall thresholds (statistical models). Some more sophisticated ones also rely on definitions regarding clusters of rain gauges, correlations with geotechnical and/or geomorphic aspects. Yet, this information is considerably scarce, particularly concerning landslides, which not only depends on reports of these events but also information about their location and especially the time of occurrence (the most challenging data to obtain). Consequently, defining thresholds in this manner requires a considerable amount of specialized labor and involves complex data acquisition.

In more advanced systems, antecedent rainfall is also taken into consideration [23]. In these cases, thresholds considering these preparatory conditions acknowledge that preceding rains can impact groundwater levels and soil moisture, serving as precursors to slope failures. This antecedent rainfall data can be pivotal in predicting potential landslide occurrences. However, defining how to calculate this preparatory rainfall proves to be a challenge, especially considering that the impact of antecedent rainfall generally diminishes as time elapses from the primary triggering rainfall event. In this context, [24] introduced a method with a diminishing value to calibrate antecedent rainfall, often referred to as "effective rainfall".

Another way to obtain "effective rainfall" is by employing the concept of rainfall half-life presented by [25], where the decay of accumulated rainfall follows the logic of radioactive decay.

Therefore, in order to develop a system that could assist in issuing landslide alerts, this study aimed to develop a new methodology for a Landslides Early Warning System (LEWS) based on the concept of rainfall half-life and the determination of thresholds using Cluster Analysis [18], considering both triggering and preparatory rains. Designed to be applied in extensive monitoring networks, the methodology for defining system thresholds was developed to automatically establish thresholds for each rain gauge. Integrating both a regional perspective (as it can automatically work with a large number of stations) and a local perspective (as it deals with defining a set of thresholds for each rain gauge), the system's results demonstrate the potential application of the methodology and its ability to identify situations more critical to mass movements.

2. The Half-Life Concept

In this study, we employ the concept of Rainfall Half-Life [26], an idea initially addressed in the Tank Model by [25], a hydrological model developed for flow analysis. In the context of this work, half-life is assumed to represent the Soil Saturation Potential. This concept does not define the actual saturation value but rather the potential saturation of the environment, considering the recorded rainfall and a reduction factor. In a simplified manner, this correction excludes from the cumulative total the rainwater that did not infiltrate (runoff) and the rainwater that is no longer present in the soil (evapotranspiration and infiltration into deeper layers) from the cumulative total. This factor is based on radioactive decay, a concept that delineates the time required for the saturation effect of rainfall to decrease by half.

The advantage of Half-Life (T) lies in its implicit and simplified incorporation of various physical phenomena not considered when using simple accumulations. This facilitates regional adaptation rather than site-specific adjustments. The phenomena implicitly considered in the half-life concept can be assumed to be:

Runoff: In the context of rainfall infiltration into soil, runoff refers to the excess water that cannot be absorbed by the soil and flows over the land surface. When precipitation occurs, some water is absorbed by the soil, contributing to soil moisture or groundwater recharge. However, if rainfall intensity exceeds the soil's infiltration capacity, water runs off, typically following the natural terrain slope, forming streams, rivers, or contributing to surface water bodies.

Evapotranspiration: Evapotranspiration encompasses both evaporation and transpiration, where water is lost from the soil to the atmosphere. Evaporation involves the conversion of water from liquid to vapor at the soil surface, influenced by environmental factors. Simultaneously, transpiration occurs as plants release water vapor through stomata on their leaves, contributing to overall water movement from soil to atmosphere. These processes impact water availability, agricultural practices, and broader ecosystem dynamics, influenced by factors like weather conditions, soil characteristics, vegetation cover, and land use.

Infiltration into deeper soil layers, beyond those prone to mass movements (especially in the case of planar movements and mass flows), causing vertical drainage or even subsurface flow that can occur parallel to the slope, leading to lateral drainage of the soil profile.

The concept of half-life primarily deals with the effective rainfall, considering attenuation due to previously described effects (such as runoff and evapotranspiration) and the impact of rains occurring in earlier periods. Rainfall from days or weeks prior can contribute to the current saturation state of the layers, and the half-life accounts for this effect. However, it assumes that the relevance of rainfall diminishes over time. For instance, in the case of 72 hours, only 1% of the rainfall from 21 days ago is still considered.

The calculation of adjusted effective precipitation, incorporating half-life, can be computed using the following equation [27]:

$$R_w = \sum a_{1i} \times R_{1i} \tag{1}$$

R_w: Effective rainfall (mm).

a_{1i}: Reduction coefficient for i hours before ($a_{1i} = 0.5^{i/T}$).

i: Number of hours of antecedence of the hourly rainfall considered in relation to the current moment (hours).

T: Half-life, both for short-term and long-term rainfall (hours).

R_{ij}: Volume of i-hour rainfall before the current moment (mm).

In this study, we utilized the dataset generated by the Cemaden rain gauges, allowing data acquisition at 10-minute intervals in the output format of the

"Analise_Pluviometros_Cemaden" software [28]. In this manner, we calculated the half-life of rainfall for the 1 h, 3 h, 6 h, 12 h, 24 h, 48 h, and 72 h periods at each data acquisition instance (every 10 minutes). This approach aimed to gather as much information as possible regarding the rainfall patterns at each location and the Soil Saturation Potential, accordingly.

3. Cluster Analysis for Half-Life Calculation

Cluster Analysis is a statistical technique within multivariate analysis employed for classification purposes [18] [29] [30]. Its objective is to create clusters comprising elements that share similarities within each group while remaining distinct from elements in other groups [29]. In this study, we utilized Cluster Analysis to classify groups with half-lives of 1 h, 3 h, 6 h, 12 h, 24 h, 48 h, and 72 h, aiming to characterize Soil Saturation Potential as comprehensively as possible. The algorithm employed is K-means, a non-hierarchical method that operates through iterative steps (as in [18]). It assigns data points to the nearest centroid (representing the cluster center) and subsequently recalculates centroids based on the new clusters. This iterative process continues until convergence, resulting in clusters with minimal within-cluster variance and maximal between-cluster variance [31]. To maintain a consistent number of clusters and with the aim of defining three thresholds (moderate, high, and very high), we used the definition of four clusters as our standard.

In this way, the half-life clusters were calculated using the seven described variables (half-lives of 1 h, 3 h, 6 h, 12 h, 24 h, 48 h, 72 h). **Figures 1-3** depict variable pair representations, assuming that the 1 h, 3 h, and 6 h half-lives are considered related to triggering rains (acting as a trigger for landslides), and the 24 h, 48 h, and 72 h half-lives are related to preparatory rains (gradually increasing soil moisture to the point of making it susceptible to landslides with heavier rain). The objective of this cluster analysis is to ideally obtain a pair of "preparatory rain x triggering rain" that exhibits well-defined and separated clusters, serving as a basis to indicate situations of higher or lower Soil Saturation Potential.

One of the assumptions in the proposed system is that there is a correlation between the combined intensity of the triggering rain and preparatory rain half-lives with the probability of landslide occurrence. For this reason, we defined four clusters, and their colors were based on the alert color pattern used by Cemaden: green, yellow, red and black. The generated groupings reflect meteorological contexts defined by rainfall events or their combinations, clearly defined in observed histories from rain gauges.

The green group (observation period) corresponds to lower-intensity half-lives. This group, representing the majority of situations, corresponds to situations where the probability of landslide occurrences due to rain is negligible or nearly nonexistent (often it is difficult to isolate anthropogenic factors increasing the probability of occurrences).

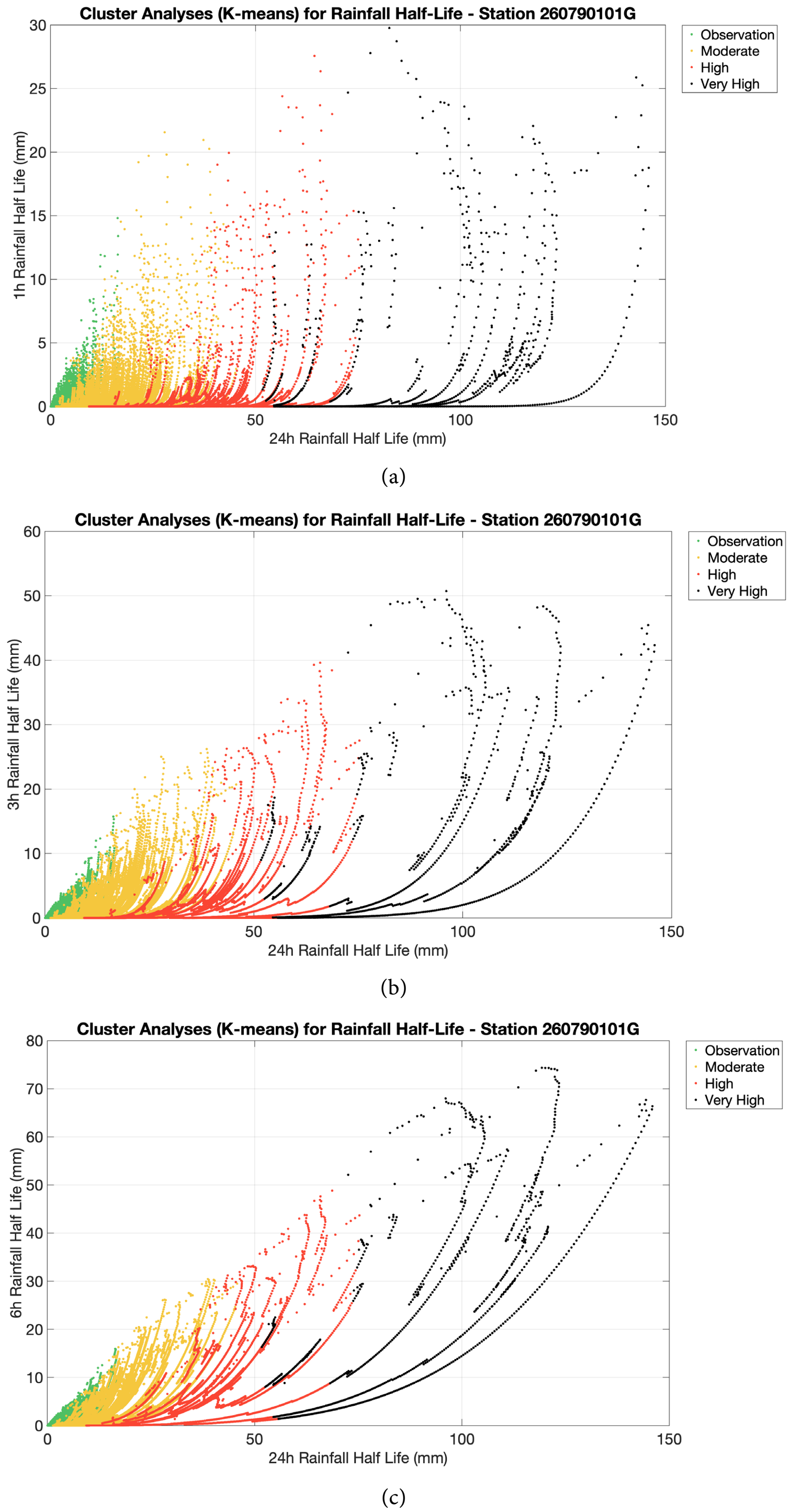
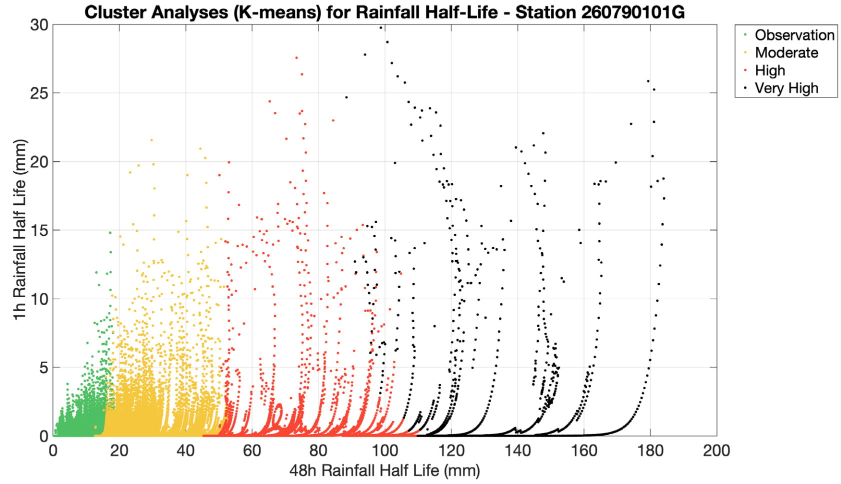
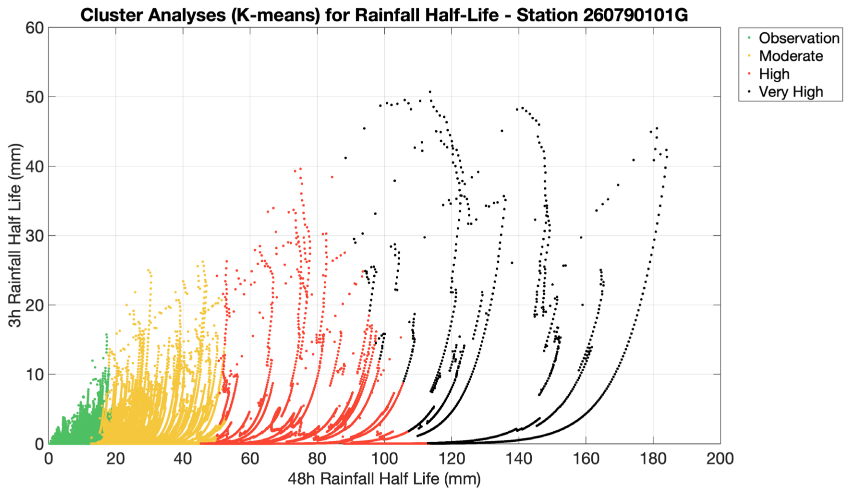


Figure 1. Results for the half-life of the 24-hour preparatory rainfall. In (a), the clusters are separated for the 24 h-to-1 h pair, in (b) for the 24 h-to-3 h pair, and in (c) for the 24 h-to-6 h pair.



(a)



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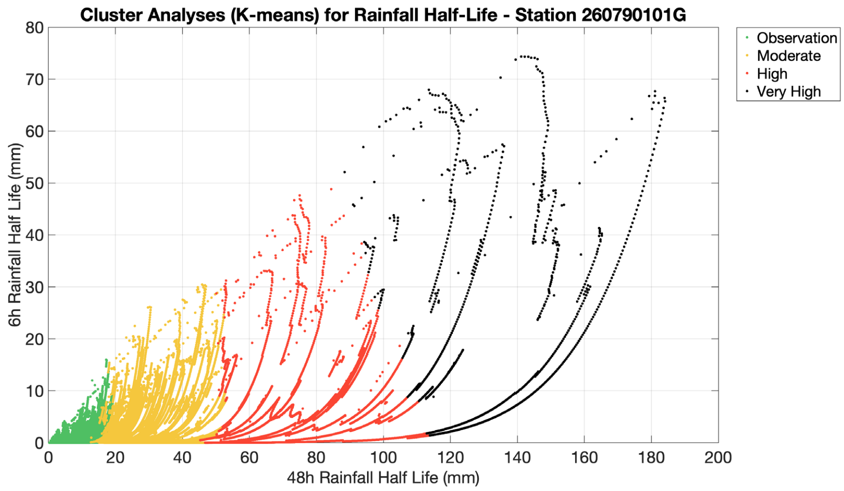
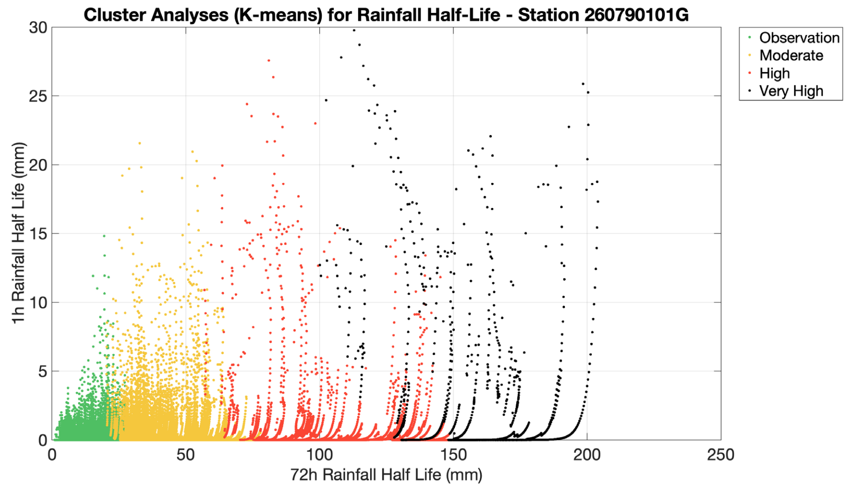
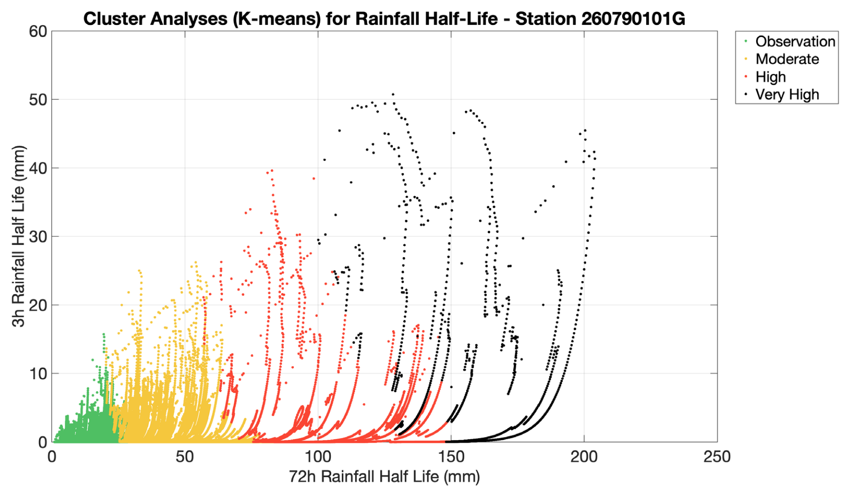


(c)

Figure 2. Results for the 48-hour preparatory rainfall half-life. In (a), there is the separation of clusters for the 48 h to 1 h pair; in (b), for the 48 h to 3 h pair, and in (c), for the 48 h to 6 h pair.



(a)



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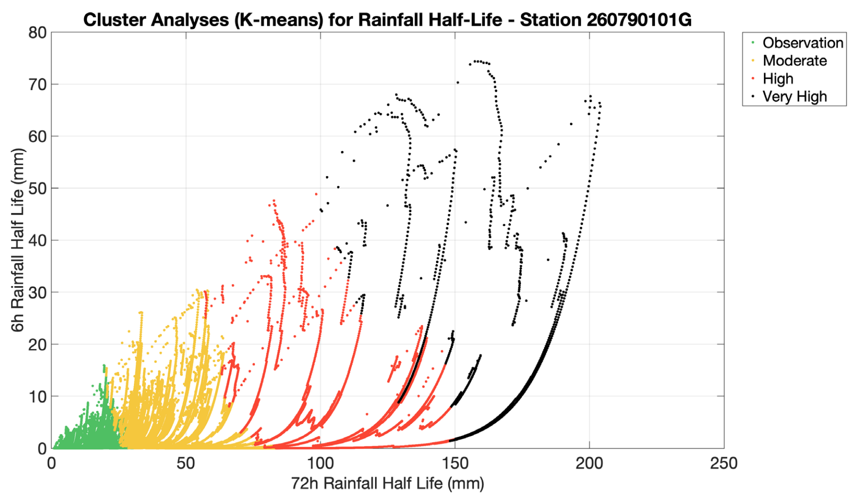

(c)

Figure 3. Results for the 72-hour preparatory rainfall half-life. In (a), there is the separation of clusters for the 72 h to 1 h pair; in (b), for the 72 h to 3 h pair, and in (c), for the 72 h to 6 h pair.

The yellow group (Moderate Alert) corresponds to situations with a moderate risk of landslide occurrence, especially linked to areas with significant anthropogenic activity and severe geotechnical problems related to unorganized occupations (landfills, slope cuts, etc.). The probability is for occasional occurrences of usually small landslides, but it may vary depending on the area's issues. However, attention should be given if there is a forecast of imminent rain.

The red group (High Alert) represents a situation of a high probability of landslide events in highly vulnerable areas due to anthropogenic effects (landfills, slope cuts, etc.) and the potential for mass movements in more susceptible slopes. In this situation, events of greater magnitude are already possible. Issuing risk alerts to the population is advisable, with the alert level potentially considering other factors.

The black group (Very High Alert) corresponds to more extreme situations where landslide occurrences in highly vulnerable areas are almost certain, and the possibility of significant events is very high. Issuing alerts to the population in this situation is mandatory, with the alert level being at least High Risk.

The following results were obtained with data from one of Cemaden's automatic rain gauges installed in the city of Jaboatão dos Guararapes, located in the metropolitan region of Recife (capital of the state of Pernambuco). The rainfall data used corresponds to 13 months, from March 2021 to March 2022. The city of Jaboatão dos Guararapes has a long history of mass movements, with numerous fatalities associated [18], and the year 2021 recorded many incidents. Since a startup period is required for the correct calculation of the half-life (21 days for 72 h), the first 40 days are not considered in the cluster calculation and, consequently, are not presented in the following figures.

In **Figure 1**, the results with a preparatory rain of 24 h are shown. One analysis that can be made is regarding the separation of clusters. In this case, it is observed that the separation of clusters for the pairs 24 h × 1 h, 24 h × 3 h, and 24 h × 6 h does not show a reasonable separation, indicating that for this type of analysis, daily accumulation may not be the most suitable.

In **Figure 2**, the graphs with a preparatory rain of 48 h are presented. In this case, there is a better separation of Soil Saturation Potential clusters. However, it is also observed that the clusters are predominantly separated horizontally, indicating that the parameters are not well coupled, with the 48 h half-life value being much more relevant than the half-lives of triggering rains.

In **Figure 3**, the results obtained with a preparatory rain of 72 h are shown. When compared to the preparatory rain of 24 h, it can be seen that the clusters are much more divided using 72 h. Regarding the coupling between variables, it can be observed that with the 3 h-triggering rain (**Figure 3(b)**), this characteristic is already noticeable. However, it is with the pair "72 h × 6 h" (**Figure 3(c)**), employed in subsequent analyses, that a clear coupling between variables is indeed evident.

In **Figure 4**, the results obtained with the "72 h × 6 h" pair (**Figure 3(c)**) are overlaid with a series of registered occurrences within 3 km of the used rain

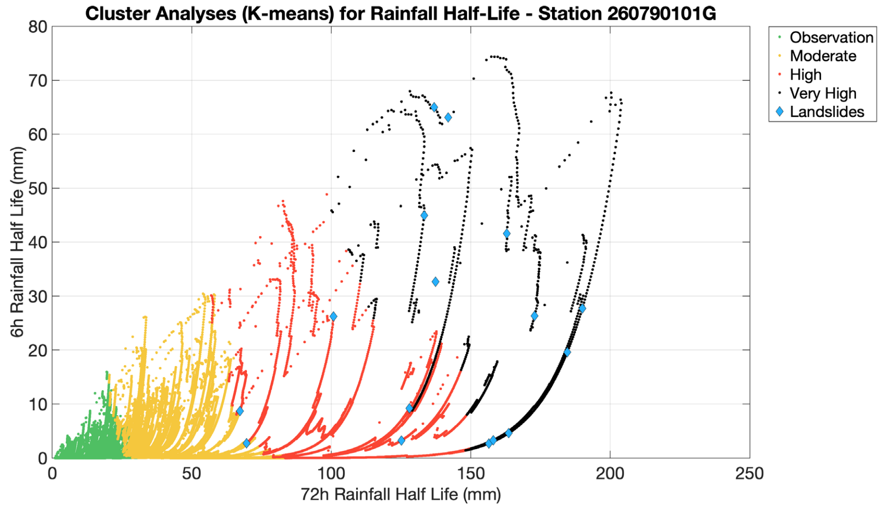

Figure 4. Clusters obtained for the half-life of the 72 h preparatory rain and the 6 h trigger rain, with the overlap of the registered landslide events.

gauge station. As the data indicates, the majority of the recorded landslides, specifically 11 out of the total 16, are located within the region classified as the Very High Alert Group (black points), indicating that this way of classifying high-risk situations correlates with registered landslide data. In the High Alert situation, there are 3 landslides, and in the region between Moderate and High Alert, there are 2 landslides.

Landslide events with little rain are observed in various regions of Brazil, often due to many areas occupied with houses in precarious conditions that increase slope susceptibility to such occurrences. The most observed anthropogenic causes that reduce slope stability are excavations resulting in excessive height and inclination of slopes, landfill on inclined terrain without technological control, pre-saturation of the soil caused by leaks of wastewater, and overload generated by buildings on inclined terrain. These events, closely related to factors other than rain, are difficult to predict. Hence, the need for a Moderate Alert level, which can indicate, to field agents, risks in very critical areas. The graph also highlights the potential for more intense events to generate more widespread events, as there is a concentration of events in the Very High Alert group.

4. Automatic Threshold Definition

The ultimate goal of the proposed system is to attain operational thresholds that can be employed for real-time monitoring in the Cemaden Situation Room, with half-life updates occurring automatically every 10 minutes (the acquisition frequency of Cemaden's rain gauges).

Thus, once the groups were well-defined, the proposal was to automatically establish the thresholds between the groups. This was achieved through an inversion process using the MATLAB nonlinear multivariate optimization algorithm (fminsearch). The developed objective function seeks to define a line that separates the interface between the groups as effectively as possible, with the fewest number of points from the lower alert group above the threshold line and the fewest number of points from the upper alert group below the threshold line that defines the threshold. This means that, for the Moderate Threshold (first threshold line), ideally, there were only green points below the line (observation situation). For the High Threshold, below the line should only contain green points (observation situation) and yellow points (Moderate Group), and above this High Threshold line should only contain red points (High Group) and black points (Very High). Above the last threshold (Very High Threshold), only black points (Very High) should appear.

With these definitions, the obtained results are presented in **Figure 5**. As observed, the automatically defined thresholds well-adjusted to the conditions of the proposed objective function, effectively separating the groups defined by the cluster analysis. The validation of the thresholds in this case is also performed by analyzing the quantity of events in each alert situation. In this case, we also have the majority of events occurring above the Very High Threshold line (11 out of 16 events), 3 events within the High Alert situation, and two events in the Moderate Alert situation. This demonstrates the operability of the thresholds obtained automatically.

One of the objectives of this study is to demonstrate the superiority of utilizing half-life calculations compared to simple rainfall accumulations. In **Figure 6**, the results are presented with cluster analysis and threshold definition using the inversion process carried out with simple cumulative values. Cluster calculations involved accumulations over 1 h, 3 h, 6 h, 12 h, 24 h, 48 h, and 72 h, analogous to the approach employed for half-life calculations. As observed in **Figure 6**, the clusters are not as well-defined as those obtained with half-life calculations, making threshold definition more challenging. However, the point illustrating the superiority of the system using half-life is the distribution of events across alert levels. Using only simple accumulations, out of the 16 registered events,

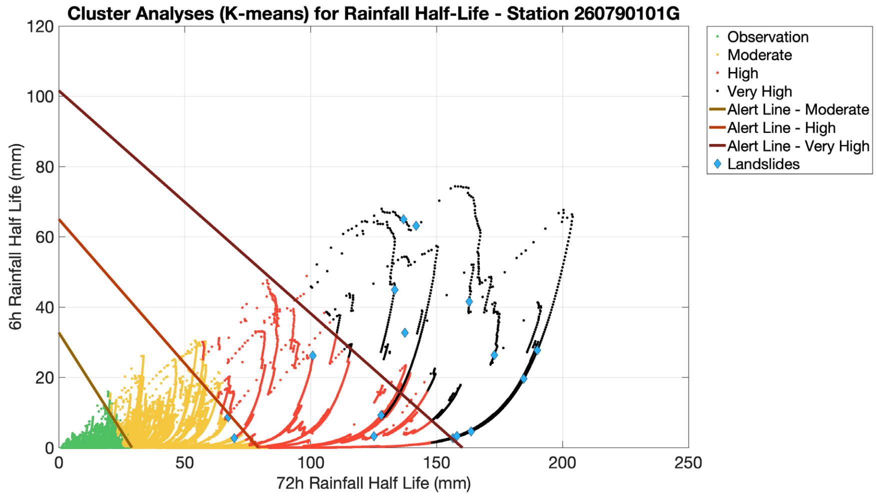

Figure 5. Thresholds obtained automatically using the 72-hour antecedent rainfall half-life and the 6-hour triggering rainfall, with the overlay of registered landslide events.

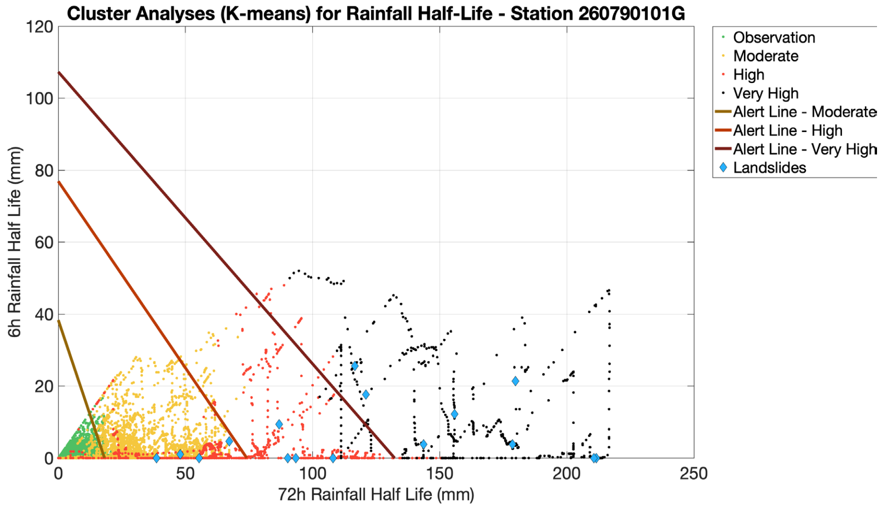

Figure 6. Thresholds obtained automatically using the simple accumulation of 72-hour antecedent rainfall and 6-hour triggering rainfall, with the overlay of registered landslide events.

7 occurred within the Very High Alert (compared to 11 using half-life), 5 occurred in the High Alert (whereas with half-life it was 3), and 4 occurred within the Moderate Alert (compared to 2 using half-life). This indicates that the system utilizing half-life can better define highly critical situations (within a Very High Alert) and critical situations (within a High Alert) than relying solely on simple rainfall accumulations. This underscores the necessity of considering, even in a simplified manner, the physical process of water infiltration into the soil for Landslides Early Warning Systems (LEWS).

5. Proposed Early Warning System

Current alert systems utilized in Brazil and much of the world heavily rely on retroanalysis of past landslide events to establish critical rainfall thresholds (statistical models). In contrast, the proposed LEWS automatically calculates thresholds based on Soil Saturation Potential. It has been designed as a tool for widespread application, such as in the Cemaden rain gauge network. Despite its development for large networks, the system operates at the scale of each individual rain gauge, with a set of thresholds defined for each one. This is accomplished using only the historical rainfall data from the rain gauges. The system also allows for the incorporation of rainfall forecast data, enabling the actual prediction of Soil Saturation Potential.

Regarding the limitations of the proposed system, it's worth noting the calculation of the half-life, which employs a generic equation that does not explicitly consider any physical properties. Additionally, the system lacks integration with other geotechnical, geomorphological, environmental, or social information. Moreover, it relies on a consistent rainfall history. Furthermore, it is necessary to acquire a consistent rainfall history, taking into account a multi-year observational period and the quality of rain gauge records.

6. Conclusions

As presented, a significant advantage of the system lies in its capacity to define thresholds for large observational networks in a standardized manner while operating on the scale of each rain gauge, integrating both local and regional scales.

A comparison of the results obtained with half-life and simple accumulated rainfall revealed the superiority of half-life calculations in defining highly critical (Very High Alert) and critical (High Alert) situations. This is attributed to the effective rainfall calculation (half-life) for calibrating accumulated rainfall, allowing for a closer inference to the expected soil moisture under preparatory conditions, thereby potentially enhancing the accuracy of the alert system.

The results obtained with the proposed Early Warning System demonstrated robustness and the ability to achieve coherent operational thresholds suitable for integration into the decision support system for alert dispatch. Furthermore, the method's simplicity of application and the availability of data from the Cemaden rain gauge network enable immediate implementation in pilot projects for geo-hydro-meteorological disaster alert systems in Brazil.

As for future prospects, additional studies will be conducted to compare the obtained results with landslide thresholds and events. Additionally, a comparative analysis between the proposed systems and those currently in use will be explored.

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Conflicts of Interest

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

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