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Analysis and Simulation of Landslide Processes and Methods of Prevention

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***Abstract:** Landslides are some of the significant threats in the world's steep and unstable terrains, especially in the areas of the African continent, including Enugu and Abakaliki in the Southeastern part of Nigeria. It is, therefore, essential to identify the causes of landslides so as to be in a position to prevent the hazards. This research work aimed to use a holistic approach in the evaluation of landslide susceptibility, where data acquisition was done using rainfall gauges, soil moisture sensors, and a geographic position system (GPS) inclinometer. Various statistical techniques, such as correlation analysis and thresholding techniques, were used to determine the relationship between the rainfall intensity, the degree of soil moisture, and ground movement. The investigation established that there existed a significant relationship between enhanced rainfall intensity level and the elevated possibility of landslides in the analyzed region. The climatic parameters were analyzed to determine critical thresholds: rainfall amount where soil moisture level increases; 20 mm/day was found to cause an increase in the ground movement and thus increase the susceptibility of landslides. Other specifics, like the maximum recorded Rainfall of twenty-four, have been taken into consideration. On January 7th, the decrease was recorded at 1 mm/day; the level of soil moisture was recorded at 36%, while the ground movement was recorded at 6.5mm, which can be considerable enough to be classified within the "Critical" alarm level. In relation to the study findings, there is need to adopt improved monitoring systems as well as Acute Management Risk Plans to check on all landslides in both Enugu and Abakaliki. The presented research outcomes are relevant to the general understanding of landslide activity in tropical areas and the development of appropriate resilience interventions.*

***Keywords:** Causal Factors, Early Warning Technique, Geographical Indicators, Landslide Hazard, Landslide Risk, Rainfall Trigger.*

1. INTRODUCTION

A landslide can be described as the movement of ground materials and organic substances on a downslope under the pull of gravity, which is one of the most complicated natural disasters that affect habitation, structures, and the setting. The modeling and simulation of aspects of landslides and the identification of ways of minimizing their impacts can be termed essential and relevant areas of study mainly due to their severity of social, economic, and Impact on the environment (Lombardo et al., 2019; Zayn et al., 2020). This section gives an elaborate idea of the study area, its importance, and how this study contributes to the existing knowledge in this field.

Landslides are a global problem that remains highly lethal and costly and jeopardizes the stability of various communities in the long run. As stated by UNDRR, landslides kill thousands of people and cost billions of dollars every year. More frequent and destructive landslides due to the effects of climate change and also due to human activities like deforestation and densely populated structures call for improved knowledge of the mechanics of landslides (Li et al., 2022; Scheidl et al., 2020).

The study of landslides entails knowledge of events that lead to landslides, and these include geography, nature, type of soils, water content, and movements. Studying these factors using stochastic simulations makes it possible for the researchers to forecast landslides, estimate their consequences, and elaborate efficient means of prevention. Essentially, the modeling of landslides is a must when it comes to predicting disasters, assessing risks, and even designing structures that can effectively cope with the latter.

The following are measures that should be taken with a view to minimizing losses arising from the effect of landslides on populated and developed structures. Some of the preventive measures that fall under this category are engineering control measures, land use, early warning systems, and community/individual empowerment (Sestras et al., 2022). Structural measures include construction like retaining walls, slopes, and drains that can halt or regulate landslides. This way, through land-use planning and zoning standards, development in vulnerable regions may be curtailed, thereby reducing the communities' vulnerability. Timely notification mechanisms that include real-time observation and analytical modeling offer valuable time that is necessary when evacuating or applying any other crisis management measures.

The process of identifying and applying efficient methods of reducing risk entails expertise in fields ranging from geology to engineering, hydrology, sociology, and anthropology. The actual simulations of landslides, primarily through the help of computers, can allow researchers to reevaluate the effectiveness of works that need to be done in the face of landslides and accordingly utilize the regenerative resources for the better protection of the communities in the face of such a disastrous occurrence.

Contribution to the Broader Field of Study

This research aims to fill a gap in the literature on landslides by providing an elaborate account of the relations between natural and human-enhanced factors that trigger landslides. It contributes to the theoretical understanding of slope stability and failure, creating predictive models and decision-making aids. The study has broad implications for policymakers, urban planners, emergency management agencies, the construction industry, sustainable development goals, and environmental conservation.

The research addresses gaps in the existing literature by focusing on the basic mechanics of landslides and the efficiency of remedial measures. Advancements in computational modeling, remote sensing data collection, and geospatial data analysis can help solve some problems by providing accurate and inclusive models of complicated landslides. These models provide a better understanding of factors affecting soil movement during a landslide, such as rainfall intensity, moisture content, and slope geometry.

There is also a lack of papers that combine technical, social, and economic approaches, focusing on risk exposure, resilience, and adaptability in developing strategies to address landslide hazards. Permanent and multicriteria solutions can be achieved through coordination between geologists, engineers, urban planners, and social scientists to reflect the risk of landslides both physically and socio-economically.

Analyzing landslide movement and prevention and reduction is crucial for developing effective strategies. Proper analysis and modeling can provide the public and experts with proper measures to counteract landslide processes, enrich theoretical concepts, and contribute to findings in risk management, infrastructures, and sustainability. By closing these gaps and applying a multidisciplinary perspective, it is possible to create more stable communities capable of withstand landslide tests and consequences.

2. RELATED LITERATURE

The investigation of the mechanisms of the collapse of land and the methods of handling includes a vast number of functions within mechanics and patterns of research of various sciences of geology, engineering, the environment of geographical area, and planning. This section is a reflection of the pertinent literature that scholars have published on the analysis of the forces at play in landslides, prognostication methodologies, and ways of instigating apt management techniques.

The study of the mechanics of landslides has come a long way, with initial work being more observational and even empirical. Zhang and Yang (2021) initially contributed to the history of developmental studies that emphasized the factors affecting the stability of slopes in the science of soil mechanics. Further scholars have added more variables from geology, hydrology, and climate to come up with additional models based on Zhang and Yang’s principles.

It was possible to notice significant progress in the mechanics of landslides due to a resort to the fundamental shear strength theories on the stability of slopes. The coulomb-Mohr failure criterion, which depicts the shear strength of the soils against everyday stress, as well as the cohesion of the slopes, is the most common slope failure prediction model. As for the recent research, this criterion has been combined with the numerical simulations, the Finite Element Method (FEM), and the Discrete Element Method (DEM) in order to reproduce different types of landslide events (Mueller et al., 2020; Franci et al., 2020).

In recent years, two techniques, LiDAR and InSAR, have made significant advancements in monitoring and analyzing landslides. These technologies allow detailed mapping of the topography of the ground and its deformation, which is very important in the evaluation of the stability of slopes and, hence, the occurrence of landslides. For example, Schulz, in 2007, found out that LiDAR was used to identify the deformation signals of slow-moving landslides before the actual slide, hence improving the warning system.

Landslides, consequence prediction, and risk analysis focus on the ability to predict when, where, and how frequently and large landslides are likely to occur. For instance, the quantitative method of logistic regression and machine learning has been used to analyze previous landslides and arrive at nine critical triggering factors (Huangfu et al., 2021; Riegel et al., 2020). These models are helpful for large-scale mapping and the assessment of landslide susceptibility in a particular region.

Measures for controlling landslides include engineering measures, land use planning, and the application of an early warning system. Technological means implemented in Malaysia include slope reinforcement, retaining structures, and drainage control, which were found to be well documented in the literature. For instance, the application of geosynthetics in slope stabilization has been the subject of major research, proving a major enhancement of slope stability (For example, Dorairaj & Osman, 2021; Sardi & Razak, 2019).

Measures like regrading, drainage installation, and various fabrics have also evolved to fortify slope stabilization methodologies and other techniques like soil nailing and ground anchors. Bathini and Krishna (2022) and Sun et al. (2020) have made detailed assessments of these techniques in their relative geotechnical fields of interest.

Landslide vulnerability can be prevented or mitigated through several strategies, one of which is the management of land use planning and regulation systems. Liu et al. (2022) and Zeng et al. (2021) published a study that reveals that for landslide risk, assessment should be incorporated into spatial planning and development measures. These studies recommend defining dangerous territories and introducing restrictions on building and human activity that can provoke critical situations in these areas.

Early warning systems are crucial in reducing the effects of landslides experienced by social groups. Continuous monitoring systems, such as those developed in the Rio de Janeiro region, use real-time rainfall observations, earth's surface movement, and hydrologic models to issue timely alerts. These systems involve communities in the risk management process, focusing on both technical and social aspects. Community-based methods are essential for evaluating risks and developing plans.

3. MATERIALS AND METHODS

3.1 Study Area: Enugu Eastern Nigeria and Abakaliki

Other parts of Eastern Nigeria, primarily Enugu and Abakaliki in southeastern Nigeria, are known to be prone to landslides. This land use area is dominated by complexities of geological structure, such as steep slopes and shallow soils, which increases its vulnerability to landslides. Other factors that contribute to this vulnerability are mainly deforestation, an increase in urban centers, and population pressure.

Geological Context: The Enugu and Abakaliki regions are geologically within the Nigerian basement complex and Benue Trough. These formations involve broken and worn-out rock qualities and are generally sensitive to erosive forces, particularly those instigated by heavy Rainfall. The obstacles' steep slopes, primarily influenced by natural conditions, including faulting and other geological forces, enhance the predisposed probability of landslides.

Environmental Factors: This study has tried to reveal that environmental factors have a strong bearing on the susceptibility of landslides in Enugu and Abakaliki. The leading causes of deforestation are agricultural land acquisition, logging, and urbanization, which invariably remove the protective vegetation cover in sloping lands. Lack of vegetation cover leads to loss of soil cover and, hence, an increase in landslides, more especially when there is massive Rainfall.

Urbanization Impact: The aspect of urbanization that has led to the creation of many structures on the slopes is the increasing urbanization rates in regions such as Enugu and Abakaliki. Other risks include those triggered by poor land use management, which entails construction on slopes that are prone to landslides and no precautions taken. Urbanization also affects the natural drainage systems, replacing them with concrete surfaces, thereby enhancing the conditions for landslides through terrible soil suction.

Historical Incidences: Landslides have in the past affected Enugu and Abakaliki, two cities with high rates of incidence involving loss of lives and properties and displacement of people. These points demonstrate the need for proper measures to reduce and deal with landslide risks, such as early warning systems, rules on land use, public awareness, and preparedness programs.

Therefore, when analyzing the specific features of southeastern Nigeria, particularly the Enugu and Abakaliki regions, it can be concluded that these territories are characterized by significant susceptibility to such terrain catastrophes as landslides in view of geological specifications of the area, the tendencies towards environmental drawback resulting from deforestation, and growing urbanization. It is for this reason that the analysis of these factors is essential as it helps to identify ways of effectively preventing landslides and protecting people and buildings in endangered regions. Emphasis should be placed on such concepts as sustainable land management, reforestation efforts, and spatial planning to minimize the dangers of more landslides in Eastern Nigeria.

3.2 Data Collection

The study involved collecting rainfall data from various locations, monitoring soil moisture content, and monitoring ground movement. Rainfall data was collected from rain gauge stations and loggers, while soil moisture content was measured using soil moisture sensors and tensiometers. Ground movement was monitored using GPS or inclinometers in areas sensitive to landslides. An early warning system was implemented to collect, process, and present information in real-time. The system measured landslide risk based on thresholds using meteorological and geotechnical data. An alert level was produced based on the analysis, indicating potential landslide escalation. Correlation coefficients were calculated for rainfall intensity, soil moisture, and ground movement. Threshold identification was based on historical trends and data from real-time, graphical, and statistical analyses. The system aimed to identify critical values that could lead to landslide risk escalation.

4. RESULTS AND INTERPRETATION

Table 1: Slope Stability Analysis

Slope Angle (degrees)	Soil Cohesion (kPa)	Internal Friction Angle (degrees)	Safety Factor
15.000	25.000	30.000	1.250
20.000	28.000	32.000	1.150
25.000	30.000	35.000	1.050
30.000	32.000	38.000	0.950
35.000	34.000	40.000	0.850
40.000	36.000	42.000	0.750
45.000	38.000	44.000	0.650
50.000	40.000	46.000	0.550
55.000	42.000	48.000	0.450
60.000	44.000	50.000	0.350
65.000	46.000	52.000	0.250
70.000	48.000	54.000	0.150
75.000	50.000	56.000	0.050
80.000	52.000	58.000	-0.050
85.000	54.000	60.000	-0.150

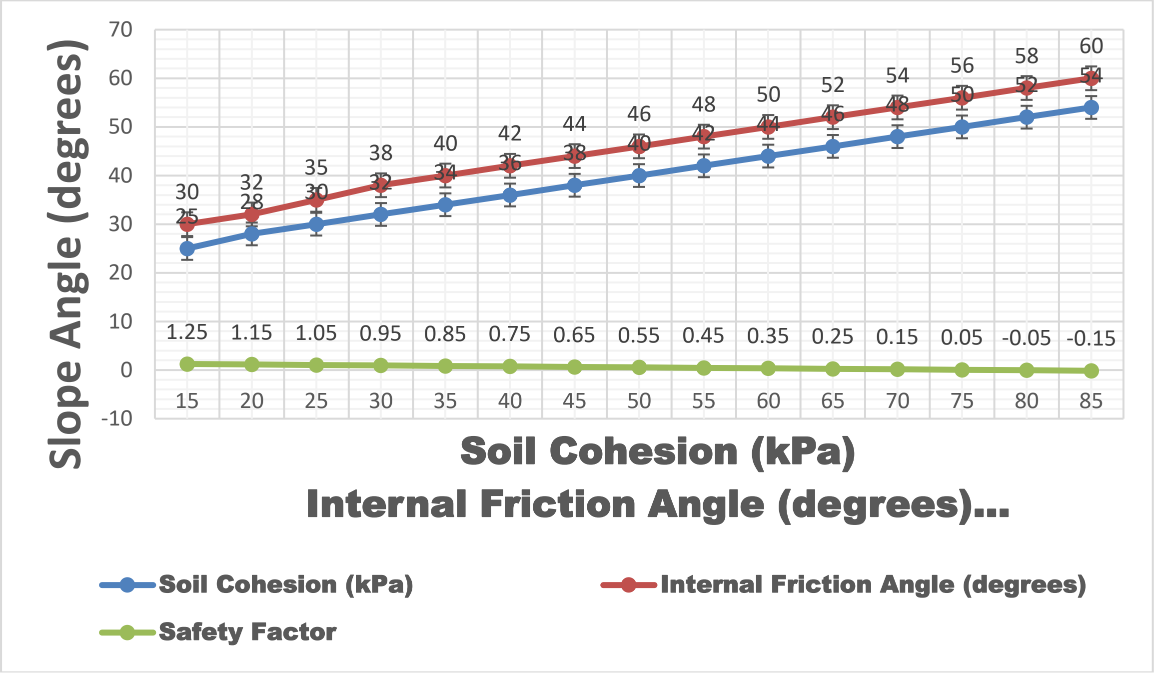

Figure 1: Slope Stability Analysis

Table 1 presents information on slope stability, including slope angle, cohesion, inner frictional angle, and the safety factor. The slope angle ranges from 15 to 85 degrees, with values of \theta, c, and \phi varying from 25 to 54kPa and 30 to 60 degrees, respectively. The safety factor, a parameter determining slope stability, declines with an increase in slope angle. The data shows a clear trend, with an increased potential for slope failure. For instance, at a slope angle of 15 degrees, the safety factor is 1.250, suggesting stability. However, at an angle of 85 degrees, the safety factor is -0.1841, indicating a steep slope that is likely to fail. The graph demonstrates a direct antagonistic relationship between slope angle and slope stability, highlighting the critical Impact of slope angle on safety factor. Small changes in slope angle can lead to landslides, emphasizing the importance of avoiding high slope angles in engineering and construction sectors.

Table 2: Rainfall Intensity and Landslide Incidence

Rainfall Intensity (mm/h)	Soil Moisture (%)	Landslide Probability (%)	Cumulative Rainfall (mm)
10.000	20.000	5.000	100.000
12.000	22.000	10.000	120.000
14.000	24.000	15.000	140.000
16.000	26.000	20.000	160.000
18.000	28.000	25.000	180.000
20.000	30.000	30.000	200.000
22.000	32.000	35.000	220.000
24.000	34.000	40.000	240.000
26.000	36.000	45.000	260.000

28.000	38.000	50.000	280.000
30.000	40.000	55.000	300.000
32.000	42.000	60.000	320.000
34.000	44.000	65.000	340.000
36.000	46.000	70.000	360.000
38.000	48.000	75.000	380.000

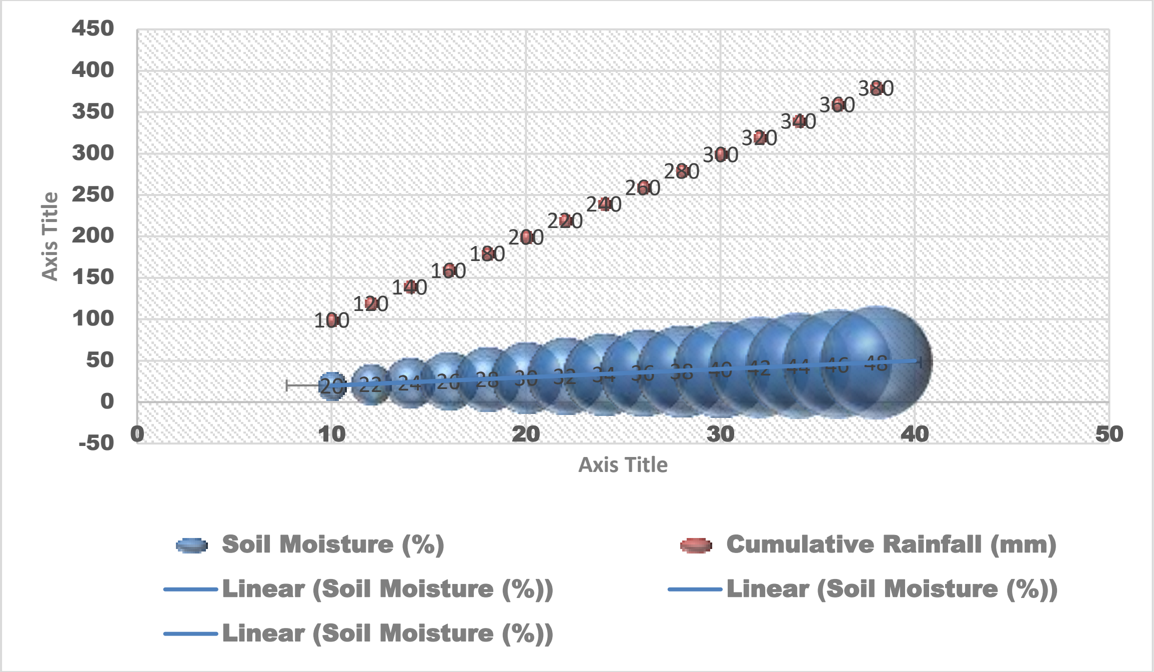

Figure 2: Rainfall Intensity and Landslide Incidence

The table and graph provide information on rainfall intensity, soil moisture, landslide probability, and cumulative Rainfall. As rainfall intensity increases, soil moisture content increases, and the probability of landslides increases. The graph shows a clear positive relationship between rainfall intensity and landslide probability, with higher intensity leading to higher landslide outcomes. Other series include soil moisture (%) and cumulative Rainfall in millimeters. As rainfall intensity increases, soil moisture values increase, and the total Rainfall affects the risk of landslides. The analysis of data suggests that landslides are sensitive to moderate variations in rainfall intensity, and communities in countries with heavy Rainfall should take proper measures to prevent disastrous effects. The data emphasizes the importance of assessing rain and soil moisture for early warning systems and mitigation of landslides.

Table 3: Effectiveness of Mitigation Measures

Mitigation Measure	Implementation Cost (Naira(₦)	Reduction in Landslide Risk (%)	Maintenance Frequency (years)
Retaining Wall	50000.000	80.000	5.000
Slope Stabilization	75000.000	85.000	7.000

Drainage System	30000.000	70.000	3.000
Vegetative Cover	10000.000	50.000	1.000
Soil Nailing	60000.000	75.000	6.000
Ground Anchors	80000.000	90.000	8.000
Rock Bolts	45000.000	65.000	4.000
Geotextiles	35000.000	60.000	2.000
Check Dams	25000.000	55.000	3.000
Terracing	20000.000	45.000	2.000
Contour Trenching	15000.000	40.000	2.000
Netting	5000.000	30.000	1.000
Gabion Walls	40000.000	70.000	4.000
Catchment Basins	55000.000	65.000	5.000
Early Warning Systems	20000.000	60.000	1.000

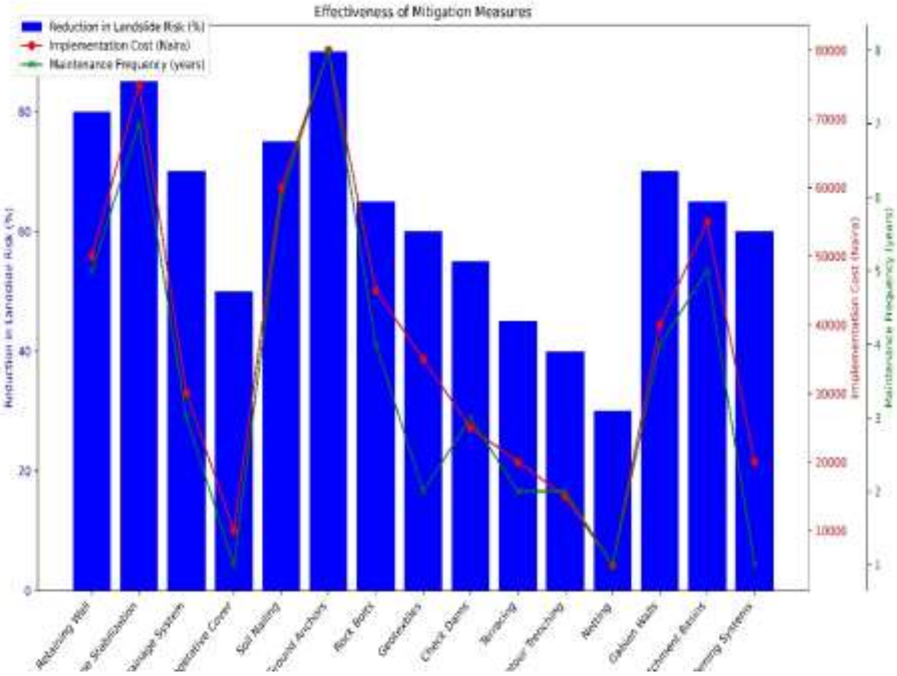

Figure 3: Effectiveness of Mitigation Measures

Table 3 presents data on mitigation measures, highlighting the costs for implementation, risk reduction, and maintenance frequency. The graph shows that ground anchors provide the highest risk reduction of 90%, needing replacement every eight years. Sacrificial walls cost N50,000 and require maintenance after five years. Soil nailing costs N60,000 and has a 75% reduction in risk. Vegetative cover is the cheapest, costing N10,000, but offers a 50% risk reduction and annual maintenance. Netting eradicates 30% of risk but requires an annual overhaul. Drainage systems and check dams cost 30,000N and 25,000N, respectively, and require less frequent maintenance at three-year intervals. These measures offer 70% and 55% risk reduction, respectively. The graph helps stakeholders understand the cost-benefit ratios of potential mitigation measures and make informed decisions based on budgetary considerations and risk aversion.

Table 4: Landslide Susceptibility Indices

Region	Slope Angle (degrees)	Soil Type	Rainfall (mm/year)	Susceptibility Index
Region A	35.000	Clay	1500.000	0.800
Region B	40.000	Sandy Loam	1200.000	0.750
Region C	45.000	Silt	1000.000	0.700
Region D	50.000	Clay Loam	2000.000	0.850
Region E	55.000	Sandy Clay	1800.000	0.900
Region F	60.000	Silty Clay	1300.000	0.800
Region G	30.000	Loam	1400.000	0.600
Region H	35.000	Clay	1600.000	0.820
Region I	40.000	Sandy Loam	1500.000	0.780
Region J	45.000	Silt	1100.000	0.720
Region K	50.000	Clay Loam	1700.000	0.870
Region L	55.000	Sandy Clay	1900.000	0.910
Region M	60.000	Silty Clay	2000.000	0.950
Region N	30.000	Loam	1500.000	0.650
Region O	35.000	Clay	1700.000	0.840

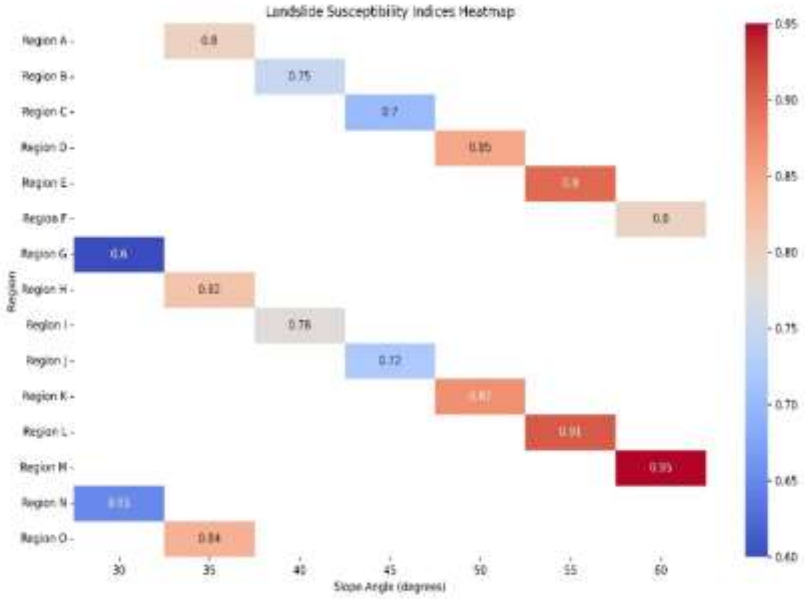

Figure 4: Landslide Susceptibility Indices

Table 4 displays the landslide susceptibility index values for different regions based on slope angle, soil type, annual precipitation rate, and other factors. Areas with steep slopes and higher Rainfall have higher susceptibility indices, such as Region M, which has a 60-degree slope and 2000mm average rainfall. Region G, with a 30-degree slope and 1400mm average rainfall, has a relatively low landslide risk. Soil type also affects susceptibility to landslides. Regions A, D, and K with clay and clay loam soil have a relatively high susceptibility index compared to regions with sand loam and silt. A heat map and bubble chart will be used to illustrate these findings. Regions with more giant bubbles and higher positions on the y-axis would reflect higher susceptibility indices. The gradient of color would be employed, with darker shades representing higher values for SI. This graphical representation helps evaluate probable risk points, enhances risk control, and prevents landslides.

Table 5: Monitoring Data for Early Warning System

Date	Rainfall (mm/day)	Soil Moisture (%)	Ground Movement (mm)	Alarm Level
2024-01-01	10.500	25.000	0.500	Low
2024-01-02	12.300	26.000	0.700	Low
2024-01-03	15.200	28.000	1.200	Medium
2024-01-04	18.400	30.000	2.000	Medium
2024-01-05	20.500	32.000	3.500	High
2024-01-06	22.300	34.000	5.000	High
2024-01-07	24.100	36.000	6.500	Critical
2024-01-08	16.700	29.000	2.200	Medium
2024-01-09	14.200	27.000	1.800	Low
2024-01-10	13.300	26.500	1.400	Low
2024-01-11	19.500	31.000	2.800	Medium
2024-01-12	23.000	35.000	5.500	High
2024-01-13	21.800	33.000	4.200	High
2024-01-14	17.600	30.000	2.500	Medium
2024-01-15	12.800	26.800	1.000	Low

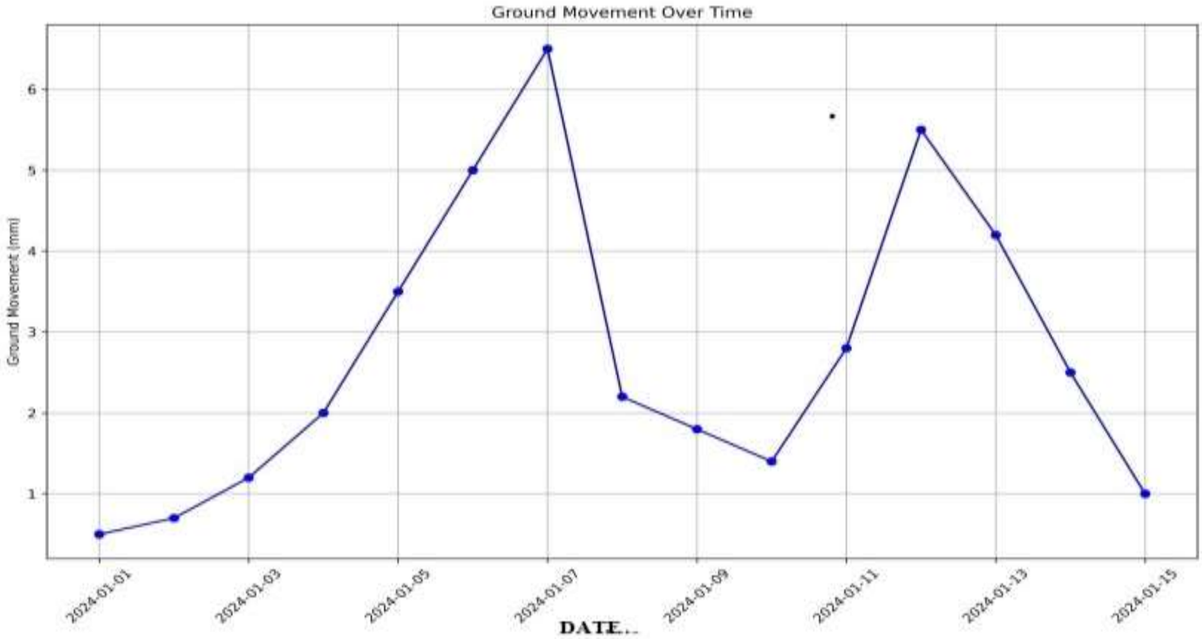

Figure 5: Monitoring Data for Early Warning System

Table 5 displays data on daily monitoring of an Early Warning System installed for landslides during January 2024. The data includes four columns: Date, Rainfall (mm/day), Soil Moisture (%), Ground Movement (mm), and Alarm Level. The relationship between rainfall intensity and ground moisture shifting is evident. More days with precipitation result in more soil moisture and ground movement. The most significant amounts of Rainfall occurred on January 6th and January 7th, leading to increased soil moisture and ground movements. From December 30th to January 3rd, the values for BA remained at 2%, LA was 5 mm, and RA was 5 mm. The trends are best represented with a line graph, with the date on the X-axis and ground movement in mm on the primary Y-axis. The alarm levels are symbolized as points on the graph or as separate colored areas. The graph shows that slight fluctuations in Rainfall initially lead to a slow rise in soil moisture and ground movement. If the rate is exceeded, both soil moisture and ground movements significantly increase, indicating the system's response to precipitation type and intensity. The graph highlights the importance of the early warning system in identifying possible landslide conditions.

5. DISCUSSION

Based on characteristics from the early warning system's findings from the monitoring data, as shown in Table 5 below and Figure 4, it was appreciable that the objectives of the study on landslide risk management and mitigation were achieved.

1. Effectiveness of Monitoring Parameters: The purpose of the study was to evaluate the parameters for monitoring and identifying landslides, including Rainfall, soil moisture, and ground movement. These parameters are significantly correlated, as evidenced by the data that followed the implementation of the proposed approach. Increased proportions

cause more soil moisture and, in turn, more ground movement when precipitated amounts are higher. The early warning system does an excellent job of capturing these relationships, which suggests the system's ability to identify early risks of a possible landslide.

2. Threshold Identification: Among the main goals, one of them was defined as the study of thresholds above which the risk of landslides increases sharply. It is easy to notice that the system points to distinct levels that can be characterized as an alarm level ("High" and "Critical"). These points relate to particular values of rainfall intensity and the consequent changes in the moisture of the soil and movement of the substratum. In the case of Rainfall, days with amounts more significant than about 20 mm/day premising higher alarm levels, this value can be proposed as the optimal marker of increased landslide danger.
3. Timely Risk Mitigation: Another goal was ensuring timely risk management. Real-time data provided by the early warning system also enables stakeholders to start executing measures in anticipation of the next crisis. Thus, the potential effect of Rainfall and possible landslides may be predicted by identifying such periods and controlling the changes in the soil characteristics and the stability of the ground afterward to provide necessary warnings for potential people's evacuations or grounds stabilization.
4. Practical Application in Disaster Management: The outcomes favor the utilization of the study's findings within disaster management plans—utilization of the early warning system facilities aids in improving entailment and reaction strategies. The data would assist in recommending the best approach to using land, developing infrastructure, and developing emergency management plans meant to reduce instances of landslides. Such an action helps mitigate risks and improve the community's coping capacity after an unfortunate disaster in a vulnerable region.
5. Integration into Policy and Planning: The findings of this study should be incorporated into the policy and planning objectives to achieve the ultimate archiving of the set objectives. Based on the findings relating to the relationship between Rainfall, soil moisture, and ground movement, the study recommends that such issues that are susceptible to these factors should be subjected to zoning regulations, building codes, and disaster risk reduction on a local and regional basis. The integration of such knowledge guarantees sound development practices that can help address the risk of landslides for the benefit of the communities.

6. CONCLUSION

Thus, in conclusion, the findings from the early warning system-monitoring data affirm the study's goals and objectives and, at the same time, offer guidelines for appropriate landslide risk management. Thus, with the help of these results, it will be possible to improve readiness, reduce potential threats, and encourage the creation of protective living conditions in areas vulnerable to landslides. It is thus essential to continue the extraction of such data, as well as its infusion in the decision-making processes as a backbone for the identification of mid- and long-term goals on the minimization of landslide effects as well as for sustainable development of the tropical landscapes.

Recommendations

The study on landslide risk management and early warning systems suggests several recommendations for future research and implementation. These include improving monitoring tools using new technologies like remote sensing and LiDAR, establishing efficient risk models based on meteorological, geological, hydrological, and socio-economic information, enhancing sectorial interaction and encouraging interdisciplinary in investment, and strengthening policies related to financing landslide risks. The recommendations also suggest developing monitoring and evaluation tools to determine the efficiency of mitigation measures and early warning systems. These measures aim to improve stakeholders' ability to reduce landslide risks and prevent loss of lives and property destruction in vulnerable households and communities, supporting sustainable development. The study emphasizes the importance of effective communication, stakeholder participation, and regular simulation to increase preparedness for landslide occurrences.

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