Proceedings of 15th IOE Graduate Conference
Peer Reviewed
Year: 2024 Month: May Volume: 15
ISSN: 2350-8914 (Online), 2350-8906 (Print)

Modeling Transient Rainfall Effects on Landslide Occurrence and Debris Flow: Insights from Chandragiri

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Abstract

In the Chandragiri region of Nepal, frequent and intense monsoonal rains pose a substantial threat of landslides and subsequent debris flows. This study utilizes the Transient Rainfall Infiltration and Grid-Based Regional Slope-Stability Analysis (TRIGRS) model in conjunction with the Flow-R model to predict and analyze these hazards. The TRIGRS model was employed to simulate rainfall infiltration and assess slope stability under various rainfall conditions, establishing initial landslide susceptibility. Subsequently, the Flow-R model was used to delineate potential debris flow paths and extents originating from these landslides.Model yielded a predictive accuracy reflected by an Area Under the Curve (AUC) of 0.71 in the Receiver Operating Characteristic (ROC) analysis. Sensitivity analysis revealed that cohesion and the angle of friction are the most influential parameters affecting slope stability, with significant changes in the unstable area observed when these parameters were varied. This integrated modeling approach enhances the predictability and understanding of landslide and debris flow hazards in mountainous regions, providing vital insights for regional disaster preparedness and land-use planning aimed at mitigating the impacts of these geohazards.

Keywords

TRIGRS, Flow-R, Shallow Landslide, Rainfall induced landslide, Sensitivity Analysis, Transient rainfall

1. Introduction

A landslide is a slope failure causing the movement of soil, rock, and other materials due to natural causes such as rain, earthquakes, and volcanic activity [27]. The increasing frequency and severity of landslides worldwide is a cause for concern as they can lead to severe consequences such as loss of lives, injuries, and significant physical, environmental, and economic damages [5]. Rain-triggered landslides are a significant hazard around the globe, particularly in mountainous areas like Nepal, as a major hazard in high mountainous areas which accounts for 83% of the total land topography of Nepal[16]. The country sees a high number of landslides annually, many of which are caused by heavy monsoonal rains that fall between June and September[6]. These rains account for the majority of the yearly precipitation, with more than 90% of deadly landslides in Nepal happening during this period [8]. In the last ten years, landslides have resulted in 1,261 deaths and have caused economic losses of about 2 Arab NPR in Nepal. Incidents amounting to 2512 and 3646 infrastructures were destroyed [15].

Landslide susceptibility is the likelihood or potential of landslides occurring in a specific area. It is a quantitative or qualitative assessment of the classification, volume (or area), and spatial distribution of landslides that currently exist or have the potential to occur [2]. By incorporating landslide hazards in land-use and emergency response planning, the impact of landslides on communities and infrastructure can be minimized and sustainable development can be supported [5]. This study will employ TRIGRS (Transient Rainfall Infiltration and Grid-Based Regional Slope-Stability Analysis) and Flow-R to analyze the site and provide a detailed analysis of the potential landslide hazards.

There has been much research done on the study of landslides, most of which follows a statistical approach like for landslide study [16]. Most of the approaches used in these studies don't include real-time rainfall. Few research considers real-time rainfall [26]. Instead, most of the research is based on the statistical analysis of past landslide events, where TRIGRS considers the natural conditions and tries to create a numerical model of it. Various Studies have been done using the TRIGRS model. It was used in addition to MPI (message passing interface) for the analysis of landslides by Alvioli et.al. [1]. It was also used to develop a stability model for rainfall-induced hazards using TRIGRS along with SHALSTAB [3]. It was also used to find factors of safety variation [14]. In India, landslide assessment was done using TRIGRS [23]. TRIGRS with Scoop3D was used to predict Landslides. This was considering the 3D nature of the landslide site [9]. This Study tries to apply this model in the context of Nepal where data is not readily available, and assess the feasibility of the model. Along with the study of the possibility of the occurrence of landslides, the study of an area of influence of landslides is also important. For that purpose, we have a simple model Flow-R that computes possible areas where landslide may affect. Flow-R was used along with TRIGRS [18].

2. Literature Review

The analysis of the total 469 papers published between 2005 and 2016 on landslide susceptibility reveals that a significant number of these articles were focused on the subject of landslide susceptibility assessment. Most articles published in

2013 were related to this topic (frequency = 72). Between 2013 and 2016, there was an average of 62 articles per year focused on this subject [20]. This data suggests that there has been a significant interest in the field of landslide susceptibility assessment among researchers and practitioners, with a growing number of studies dedicated to understanding the factors that contribute to landslide susceptibility and developing methods for identifying areas at risk of landslides. Nepal contributed to about 3.2% of these research articles [20]. Even though the exact classification is subjective, there are mainly three types of research done in Landslide susceptibility assessment. Heuristic, statistical, and deterministic. Heuristic models are a type of modeling approach that relies on experience and knowledge to solve problems, rather than mathematical or statistical methods [20][25]. Statistical Methods use data from past landslides as a reference and compute landslide susceptibility. Whereas, the deterministic method uses parameters like soil properties(Hydraulic conductivity, Water content, Diffusivity, Cohesion, Angle of friction), rainfall, and elevation data to compute landslide susceptibility.

2.1 Strength Parameters

Cohesion and angle of friction are two important parameters that describe the shear strength characteristics of soils. Cohesion (c) refers to the internal molecular attraction between soil particles, which enables them to resist shear forces. It represents the binding force between particles and is typically observed in cohesive soils such as clay. The angle of friction (ϕ) represents the resistance to sliding or shearing between soil particles. It is related to the interlocking and frictional resistance between particles and is commonly observed in granular soils such as sand and gravel. The angle of friction is typically expressed in degrees.

2.1.1 Direct Shear Test

The direct shear test is a laboratory method used to determine the shear strength of soil and other materials. It involves placing a soil sample between two halves of a shear box apparatus. Shear stress is applied by moving the top half of the box relative to the bottom half. Measurements are taken to determine shear stress and strain. The test helps determine the maximum shear strength of the soil, cohesion (c), and internal friction angle (ϕ). The Normal and Shear stress is calculated and plotted where the slope gives the angle of friction and the y-intercept gives cohesion. The corrected area formula is shown in equation-1[4]:

$$\text{Corrected Area} = A_0 * (1 + \frac{\delta}{3}) \tag{1}$$

Where,

A_0 = initial area of the specimen in cm^2

δ = displacement in cm

2.2 TRIGRS model

TRIGRS (Transient Rainfall Infiltration and Grid-Based Regional Slope-Stability Analysis) is a computer program that models rainfall infiltration and slope stability. It was developed by Baum et al. in 2008, and it is designed to analyze the effects of rainfall on slope stability over large areas. The program uses analytical solutions of partial differential equations to represent one-dimensional, vertical flow in isotropic, homogeneous materials for both saturated and unsaturated soil conditions [2]. TRIGRS uses a combination of models for infiltration and subsurface flow of stormwater, routing of runoff, and slope stability, to calculate the effects of rainfall on the stability of slopes. The program can simulate storms with durations ranging from hours to a few days. TRIGRS uses the theoretical bases of these models to calculate the infiltration, runoff, and stability of slopes, and it presents the results in a grid format [2].

2.2.1 Infiltration Model

The infiltration models in TRIGRS for initial wet conditions are based on Iverson's linearized solution of Richards's equation, and extensions by Baum et al. (2002, 2008) to that solution. The Richards equation is a non-linear partial differential equation that describes the unsaturated flow of water in porous media. The Iverson's linearized solution is an analytical solution of the Richards equation that assumes a linear relationship between the water content and the matric potential. TRIGRS uses a series of Heaviside step functions to implement Iverson's suggested summation of his original solution for rainfall of constant intensity. The Heaviside step functions are used to represent a general time-varying sequence of surface fluxes of variable intensities and durations. The step functions are used to model the infiltration process by assuming that the infiltration rate is constant during each time step and that the infiltration rate changes abruptly at the end of each time step. As an alternative to the solution with an infinitely deep basal boundary, Baum et al. (2002, 2008) added to TRIGRS a solution for pore pressure in the case of an impermeable basal boundary at a finite depth dLZ This solution is used to model the infiltration process when the water table is at a finite depth below the surface. The pore pressure for an impermeable basal boundary at a finite depth is given by the equation-2:

$$\begin{aligned}\psi(Z,t) =&(Z-d)\beta \\ &+2\sum_{n=1}^{N}\frac{I_{nZ}}{K_S}H(t-t_n)[D_1(t-t_n)]^{\frac{1}{2}} \\ &\times \text{iefrc}\left[\frac{Z}{2[D_1(t-t_n)]^{\frac{1}{2}}}\right] \\ &-2\sum_{n=1}^{N}\frac{I_{nZ}}{K_S}H(t-t_{n+1})[D_1(t-t_{n+1})]^{\frac{1}{2}} \\ &\times \text{iefrc}\left[\frac{Z}{2[D_1(t-t_{n+1})]^{\frac{1}{2}}}\right]\end{aligned} \tag{2}$$

In equation 2, ψ is the groundwater pressure head, t is time, t_n is the time of the n^{th} interval, Z is the vertical coordinate, $H(t-t_n)$ is the Heaviside step function, N is the number of intervals, K_s is the saturated hydraulic conductivity in the Z direction, I_{nZ} is the surface flux of a given intensity for the n^{th} interval, D_1 is given by:

$$D_1 = \frac{D_0}{\cos^2(\delta)}, \tag{3}$$

where D_0 is the saturated hydraulic diffusivity, δ is slope angle

$$D_0 = \frac{K_S}{S_S}, \tag{4}$$

where K_S is the saturated hydraulic conductivity and S_S is the specific storage. The function $ierfc$ is given by equation 5:

$$iefrc(\eta) = \frac{1}{\sqrt{\pi}} e^{-\eta^2} - \eta eftc(\eta) \tag{5}$$

where $efrc(\eta)$ is the complementary error function, 1^{st} term in the equation is steady.

2.2.2 Runoff Model

Using Infiltration, I, the Sum of precipitation, P, and runoff from adjacent cells, R_u, and infiltration cannot exceed K_s we find runoff models 6.

$$I = \begin{cases} P + R_u, & \text{if } P + R_u \le K_s \\ K_s, & \text{if } P + R_u > K_s \end{cases} \tag{6}$$

The runoff, R_d, is calculated by the following equation-7:

$$R_d = \begin{cases} P + R_u - K_s, & \text{if } P + R_u - K_s \ge 0 \\ 0, & \text{if } P + R_u - K_s < 0 \end{cases} \tag{7}$$

The D8 method was used as the Flow Routing Method, also known as the Rho 8 method, and is a widely used method for estimating flow directions in hydrological models. It was first suggested by O'Callaghan and Mark in 1984, and it is based on the idea of distributing flow from each cell to one of its eight neighbors along the steepest downslope path. The D-8 method also allows for the calculation of contributing area, which is the total area draining to a particular point, such as a stream or a channel. The contributing area is useful for the calculation of other hydrological parameters such as rainfall-runoff and evapotranspiration [28]. The D8 method is a simple and fast method for estimating flow directions, but it has some limitations.

One of the main limitations of the D8 method is that it assumes that flow can only occur in the steepest direction, either adjacent or diagonally, of eight possible directions. This results in an irregular and unrealistic flow distribution, as the flow cannot be distributed to cells that are not on the steepest downslope path. This can lead to errors in the estimates of flow accumulation and the calculation of other hydrological parameters [18].

2.2.3 Slope Stability

The factor of safety represents the ratio of the available stability to the required stability. In slope stability analysis, the factor of safety is used to determine the stability of a slope against failure. A factor of safety of 1 means that the slope is at its minimum stability and any additional load or reduction in strength could lead to failure. A factor of safety greater than 1 indicates that the slope is stable, while a factor of safety less than 1 indicates that the slope is unstable and susceptible to failure [27]. The model of slope stability in TRIGRS uses an infinite-slope stability analysis, which is based on the ratio of the resisting friction to the gravitationally induced downslope driving stress. The infinite-slope stability analysis is a method that considers the slope as an infinite slope and calculates the Factor of Safety (FoS) by comparing the available shear strength of soil to the shear stress acting on the slope. The FoS is calculated using the following equation-8

$$F_s(z,t) = 1 + \frac{\tan(\Phi')}{\tan(\delta)} + \frac{c' - (z,t)\gamma_W \tan(\Phi')}{\gamma_s Z \sin(\delta)\cos(\delta)} \tag{8}$$

c' is the effective cohesion, which is the soil cohesion for effective stress. It represents the ability of the soil to resist sliding along planes of weakness; Φ' is the effective internal friction angle, which is the soil friction angle for effective stress. It represents the resistance of the soil to shear deformation; γ_s is the unit weight of soil, which is the weight of soil per unit volume. It represents the weight of the soil and it is used to calculate the shear stress acting on the slope; γ_W is the unit weight of groundwater, which is the weight of water per unit volume. It represents the weight of water in the soil and it is used to calculate the pore water pressure acting on the slope.

2.3 Flow-R Model

Flow-R is the spatially distributed model. It is an empirical model developed with the help of Matlab. Its application requires two data sets DEM and Source area. Here debris flow is measured using friction laws. The volume and mass of the flow of debris are not calculated because accurate computation is difficult over large regions. It has a graphical user interface and requires sources to be provided in it. It is the tool for debris flow assessment in landslides [21, 22]. However, it may not give accurate results in modeling a single landslide event because it takes into account a large no of possible events. It is advised to compare the single landslide with the result shown from Flow-R to find the accuracy of results [10] and also use the results for calibrating input parameters [13]. It has also been used to analyze potential social and economic damages[19]. The source area delineation uses an index-based approach, where input datasets represent different types of spatial information and are handled with user-defined parameters. The software allows the user to import source areas that have been generated by another GIS-based approach and assigns a susceptibility value of 1 to the source cells by default, but the user can also assign a spatial grid of susceptibility or frequency values.

3. Study Area

The study area of research is located in the western hills of Kathmandu Valley, Lesser Himalaya, Nepal. We are taking the study area as the landslide-prone zone of Chandragiri. The elevation of our study area ranges from 974m to 2416m above sea level. Its longitude ranges between 85° 10' 20" and 85° 12' 30" longitude between 27° 40' 30" and 27° 43' 30" as shown in Figure 1. Our study area lies in two districts, Kathmandu and Dhading. Our study lies in the Chandragiri and Dhunibsi region. A continuous alluvial fan is found in this region[24].

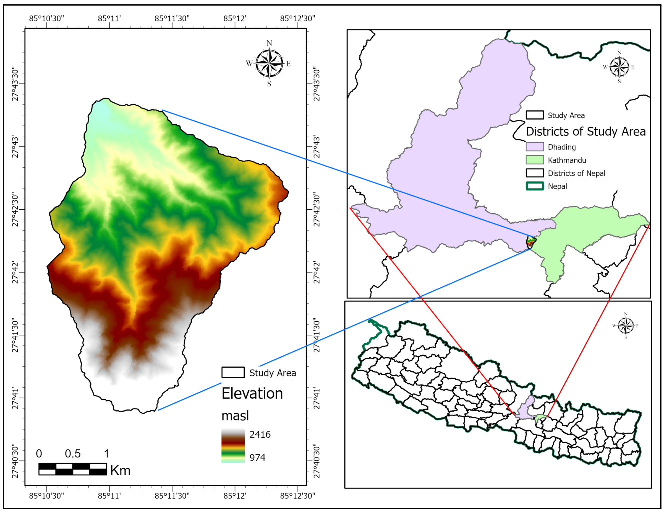

Figure 1: Study Area

4. Landslide Event

This study mainly focuses on the landslide that occurred on the 6/7th of October 2022 in Chandragiri Municipality [17]. In the Chandragiri and Dhunibesi area, about 10 landslides occurred due to the rainfall in October 2022. Among them, one major landslide occurred in the study area around 3:00 am on the morning of the 7th of October. Three people, all members of the same family, died following a landslide at Deurali of Chandragiri Municipality on Thursday night.

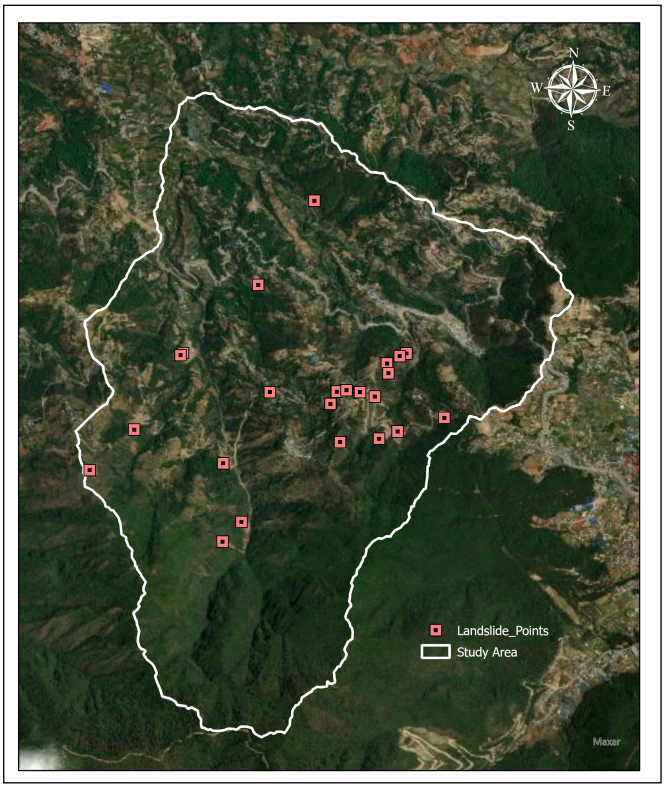

Figure 2: Landslide events in Study Area

5. Methodology

This study accesses the Factor of Safety (FoS) and area of influence of a landslide site through an integrated approach combining location data, including Digital Elevation Models (DEMs) and soil characteristics, with simulation using TRIGRS and Flow-R models. Employing a descriptive study design, we collect and analyze location data alongside conducting simulations. A thorough literature review precedes data collection to identify existing models, methods, and knowledge gaps. Data collection entails gathering secondary data for DEMs and soil characteristics, complemented by primary data collection for the landslide site study. Subsequently, utilizing ArcGIS, we manipulate and analyze the collected data to prepare it for TRIGRS and Flow-R simulations. The TRIGRS model is then utilized to determine the FoS and depth of least stability, which are compared with site conditions, while the Flow-R model identifies debris flow paths and areas of influence, validated against site conditions. Attention is given to acknowledging and addressing potential limitations and challenges inherent in the simulation process.

5.1 Rainfall Characterstics

There is only one rainfall station Dhunibesi rainfall station near the landslide according to the Thiessen polygon drawn. The average rainfall of the station is 1588mm it is highest during monsoon and low during winter in Nepal. During the landslide event, the study site received a large amount of rainfall for a long period as in figure-3 The rainfall data from the graph shows distinctive pattern characterized by an initially dry period followed by a gradual onset of rain that increases in intensity over several days. The peak rainfall occurs early on October 6th, where the highest intensity is recorded between 4:00 am and 5:00 am. After this peak, the rainfall intensity remains relatively high before it begins to taper off, though it still remains at levels that could sustain soil saturation and increased landslide risk. This pattern highlights critical periods of heightened susceptibility to landslides due to soil saturation from sustained heavy rainfall

5.2 Input Parameters

Various parameters including hydraulic factors, topographic factors, soil thickness as well as strength parameters for soil. DEM of resolution 5m was used to create topographic parameters including slope, flow direction, flow accumulation, and TopoIndex outcomes. Soil depth is approximated using a Z-profile. Here, the maximum and minimum thickness are assumed from various literature for soil depths in Nepal[7]. Hydraulic parameters of the soil are taken from the available literature, due to the unavailability of reliable data. Saturated unit weight is taken as 1660Kg/m3 and Hydraulic conductivity is taken as 0.00002m/s [11]. Also, Soil Moisture content for saturated and residual conditions are taken as 0.5 and 0.18 [18]. Also, Diffusivity and Initial infiltration is assumed from recent papers. For the study of debris flow, limiting velocity and Holmgren parameters are taken from literature[10]. We have selected the 112 hrs hourly rainfall data as the input data, and also one outcome is generated at the end of each hour. The initial condition of the site area is considered tension-saturated and wet initial conditions are assumed for the study. Strength Parameters of the soil include cohesion and angle of friction. The soil in the study area was found to be composed of sand and clay with some stone pieces mixed in between them. Direct Shear Test was done with the soil sample from four locations. This was used to Calculate the Cohesion and angle of friction. The result found cohesion to be 7577.07N/m2 and the angle of friction to be 38.67°. High angle of friction and low cohesion may be the result of sandy particles in the sample.

Table 1: Parameters and Values

Parameter	Value	Unit
Friction angle	38.67	°
Cohesion	7577.07	N/m^2
Saturated Unit Weight of Soil	1660	Kg/m^3
Saturated Hydraulic Conductivity, K	0.00002	m/s
Hydraulic Diffusivity	200K	m^2/s
Steady Infiltration Rate	0.01K	m/s
Saturated Volumetric Water Content	0.5	-
Residual Volumetric Water Content	0.18	-
Travel Angle	13	degrees
Limiting Velocity	10	m/s
Holmgren Modified Parameters		
dh	1	–
x	14	–

6. Result

6.1 Prediction of Landslide

The model was run for the duration and after the infiltration started. The main objective of this research is to evaluate the spatial and temporal predictability of the landslide event in Chandragiri Landslide event. The graph shows that the failure is 13 hours past the peak instability condition. It may be due to delayed infiltration than we predicted by the model.

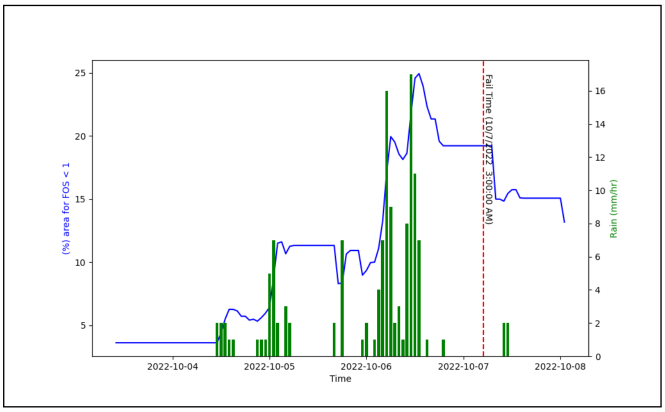

Figure 3: Percentage Area of Failure and Rainfall event at various times

Initially, zero rainfall leads to a stable FoS, indicating no immediate risk. However, as rainfall begins and intensifies, the FoS starts to decrease, particularly during the peak rainfall period on October 6th the highest rainfall coincides with a significantly lowered FoS. This suggests an increased likelihood of landslides due to reduced soil strength and increased pore water pressure, making the slopes more susceptible to failure. After the peak, although rainfall decreases, the FoS remains low for a time, indicating ongoing vulnerability of the slopes to landslide, even with reduced rainfall.

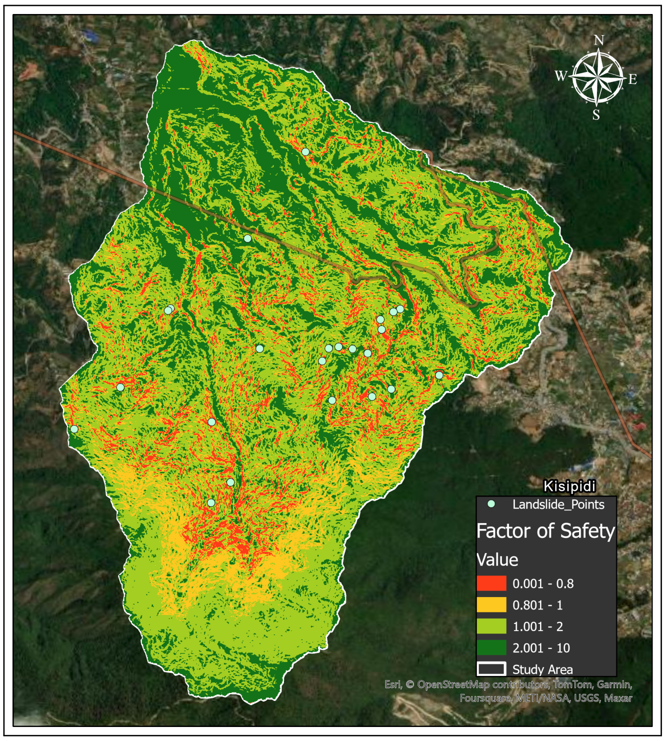

Figure 4: FoS at failure point

For the model to be better suited, the outcomes of the model should represent the actual conditions of the site. The accuracy of the model doesn't represent an efficient model as the model that gives a higher value is almost always more accurate. For that, the ROC method is preferred [12]. ROC (Receiver Operating Characteristic) is a graphical representation used to evaluate the performance of a binary classification model. It shows the trade-off between the true positive rate (sensitivity) and the false positive rate. The curve is created by varying the classification threshold and plotting the corresponding TPR and FPR. The area under the ROC curve (AUC-ROC) is a commonly used metric to assess the model's overall performance, with a higher value indicating

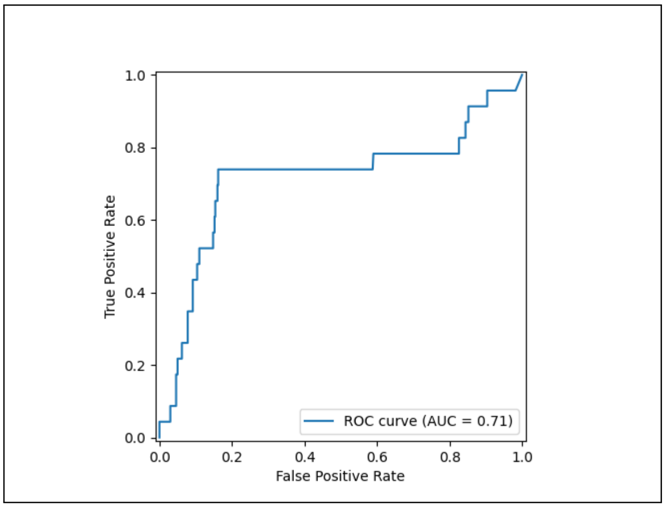

Figure 5: ROC curve

better classification accuracy. The ROC curve helps in determining the optimal threshold and understanding the model's efficiency.

6.2 Sensitivity Analysis

Sensitivity analysis is conducted to understand how variations in key soil parameters affect the area where the factor of safety (FOS) is less than 1, indicating potential instability. The parameters varied were cohesion , angle of friction , unit weight , saturated hydraulic conductivity , soil depth, and diffusivity. Each parameter was altered by -20%, -15%, -10%, -5%, 0%, 5%, 10%, 15%, and 20%, and the corresponding percentage change in the area with FOS < 1 were recorded.

Our findings indicate that cohesion and the angle of friction are the most influential parameters. A 20% decrease in cohesion results in a 12.97% increase in the unstable area, while a 20% increase reduces it by 12.44%. Similarly, a 20% decrease in the angle of friction leads to a 107.97% increase in the unstable area, while a 20% increase reduces it by 58.83%.

Changes in unit weight have a lesser effect. A 20% decrease in unit weight results in a 9.25% reduction in the unstable area, and a 20% increase leads to a 5.97% increase. Variations in Ksat show a moderate impact, with a 20% decrease in Ksat increasing the unstable area by 6.48% and a 20% increase reducing it by 4.73%. Soil depth has minimal influence on the unstable area, with changes ranging from -0.3% to 0.1% for variations of -20% to 20%. Changes in diffusivity have a noticeable effect, where a 20% increase leads to a 4.09% increase in the unstable area, and a 20% decrease results in a 3.23% reduction.

So, cohesion and the angle of friction are critical parameters affecting terrain stability, as changes significantly impact the area with FOS < 1. In contrast, unit weight, hydraulic conductivity, soil depth, and diffusivity have moderate to minor effects.

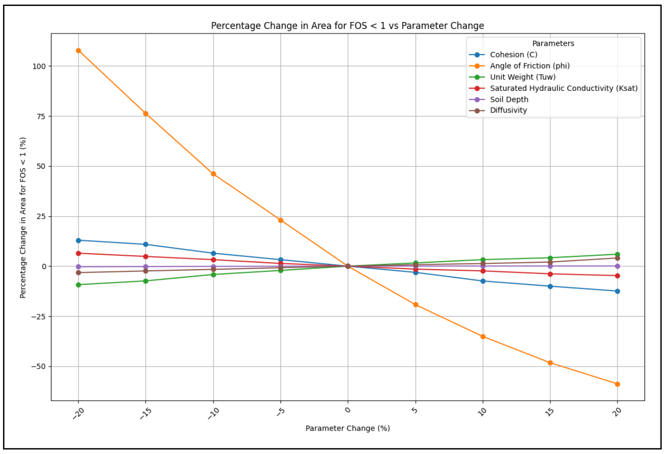

Figure 6: Sensitivity Analysis

6.3 Prediction of Debris flow route

For the prediction of the Debris flow route, Flow-R is used. Flow-R is a distributed, semi-empirical model developed at the University of Lausanne for assessing the susceptibility of debris flow propagations. It incorporates sediment availability, water input, and gradient as critical factors and utilizes calibrated parameters to estimate flow paths and potential areas prone to debris flow events [18] Flow-R shows good agreement with observed debris flow inventories, indicating its effectiveness in identifying susceptible areas. Its ability to estimate flow width and generate spatial distributions of susceptibility enhances hazard assessment and mitigation strategies. Flow-R provides valuable insights for understanding debris flow dynamics and making informed decisions to minimize associated risks. In this study, we take the Source area for landslides generated by TRIGRS and run the model for the flow of it. Holmgren modified is a directional algorithm used in Flow-R for assessing natural hazards. It improves the accuracy of flow direction calculations in complex terrain by considering local topography, slope characteristics, and elevation differences between neighboring cells. This modification enhances the precision of hazard assessments and simulations in the Flow-R modeling tool. For Debris flow, dh is taken as 1 and x=4, for this study, the velocity limit is taken as 10m/s. Travel angle is the most important parameter that needs to be calibrated. The landslide event on the site used for the calculation of travel angle using flow length and elevation difference showed it to be 13 degrees. It is further validated on the single landslide site using the confusion matrix. With an accuracy of 85% and an f-score of 0.52, the model gives a fairly good result, thus Flow-R is used to calculate the Debris flow path.

Table 2: Confusion Matrix

Condition	Model Failure	Model Safe
Actual Fail	TP 8%	FN 3%
Actual Safe	FP 12%	TN 77%

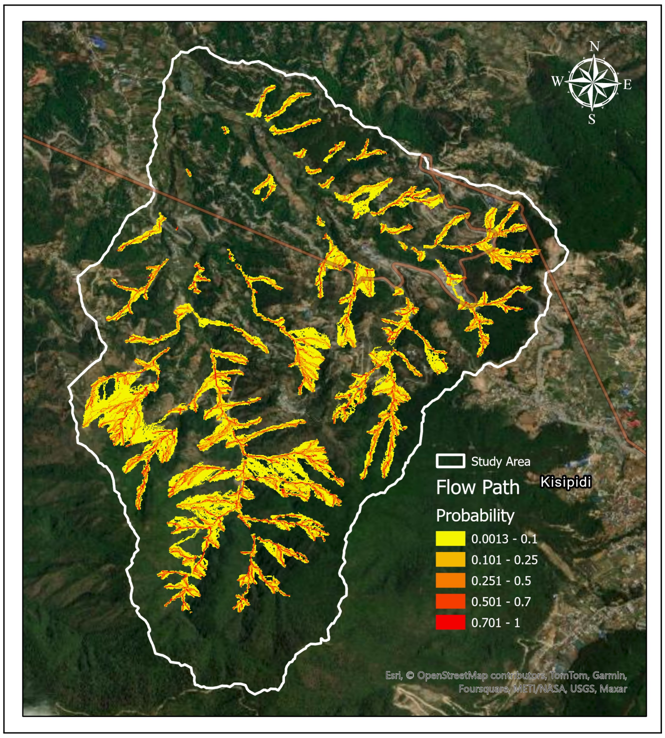

Figure 7: Probable Flow Path

7. Conclusion

This study focused on analyzing the effects of transient rainfall on landslide occurrence and debris flow in the Chandragiri area using the TRIGRS and Flow-R models. TRIGRS was employed to simulate rainfall infiltration and assess slope stability under varying conditions, while Flow-R was used to predict the debris flow paths originating from the landslides.

The TRIGRS model successfully predicted the landslide event approximately 13 hours after the peak rainfall, highlighting the potential delay in slope failure due to delayed infiltration. The model demonstrated a reasonable level of accuracy, with an AUC value of 0.71, indicating a 71% chance of correctly classifying landslide events.

Sensitivity analysis revealed that cohesion and the angle of friction are the most influential parameters affecting slope stability. A 20% decrease in cohesion resulted in a 12.97% increase in the unstable area, whereas a 20% increase reduced it by 12.44%. Similarly, a 20% decrease in the angle of friction led to a 107.97% increase in the unstable area, while a 20% increase reduced it by 58.83%. Other parameters such as unit weight, hydraulic conductivity, soil depth, and diffusivity showed moderate to minor effects on stability.

The Flow-R model effectively identified and mapped potential debris flow paths, providing valuable insights for understanding debris flow dynamics and enhancing hazard assessment. The integration of TRIGRS and Flow-R models offers a comprehensive approach to predicting landslide occurrences and the subsequent debris flow routes.

Future research should focus on collecting more precise and comprehensive data, including detailed rainfall characteristics, soil properties, and topographic factors, to further improve the accuracy and reliability of these predictive models. This study underscores the importance of integrated modeling approaches in enhancing our understanding and predictability of landslide and debris flow hazards, contributing to better disaster preparedness and land-use planning.

References

[1] Massimiliano Alvioli and Rex L Baum. Parallelization of the trigrs model for rainfall-induced landslides using the message passing interface. *Environmental Modelling & Software*, 81:122–135, 2016.

[2] Rex L Baum, William Z Savage, and Jonathan W Godt. *TRIGRS: a Fortran program for transient rainfall infiltration and grid-based regional slope-stability analysis, version 2.0.* US Geological Survey Reston, VA, USA, 2008.

[3] Valérie Baumann, Costanza Bonadonna, Sabatino Cuomo, Mariagiovanna Moscariello, and Irene Manzella. Slope stability models for rainfall-induced lahars during long-lasting eruptions. *Journal of Volcanology and Geothermal Research*, 359:78–94, 2018.

[4] Bureau of Indian Standards. IS 2720-8 (1983): Methods of test for soils, Part 8: Determination of water content-dry density relation using heavy compaction. Indian Standard, 1983. Accessed on [Insert Date].

[5] Jordi COROMINAS, Eric LEROI, and William Z SAVAGE. Landslide susceptibility, hazard and risk zoning for land use planning. *Engineering geology*, 102(3-4), 2008.

[6] Ranjan Kumar Dahal and Shuichi Hasegawa. Representative rainfall thresholds for landslides in the nepal himalaya. *Geomorphology*, 100(3-4):429–443, 2008.

[7] Sanjaya Devkota, Narendra Man Shakya, Karen Sudmeier, Brian G McAdoo, and Michel Jaboyedoff. Predicting soil depth to bedrock in an anthropogenic landscape: a case study of phewa watershed in panchase region of central-western hills, nepal. *Journal of Nepal Geological Society*, 55(1):173–182, 2018.

[8] Melanie J Froude and David N Petley. Global fatal landslide occurrence from 2004 to 2016. *Natural Hazards and Earth System Sciences*, 18(8):2161–2181, 2018.

[9] Jianyin He, Haijun Qiu, Feihang Qu, Sheng Hu, Dongdong Yang, Yongdong Shen, Yan Zhang, Hesheng Sun, and Mingming Cao. Prediction of spatiotemporal stability and rainfall threshold of shallow landslides using the trigrs and scoops3d models. *Catena*, 197:104999, 2021.

[10] P Horton, M Jaboyedoff, al Rudaz, B et, and Markus Zimmermann. Flow-r, a model for susceptibility mapping of debris flows and other gravitational hazards at a regional scale. *Natural hazards and earth system sciences*, 13(4):869–885, 2013.

[11] J Krahenbuhl and A Wagner. Survey, design, and construction of trail suspension bridges for remote areas, skat. *Swiss Center for Appropriate Technology in St. Gallen, Switzerland*, 1983.

[12] Wojtek J Krzanowski and David J Hand. *ROC curves for continuous data.* Chapman and Hall/CRC, 2009.

[13] JI SUNG LEE, Chang-Ho Song, Ananta Man Singh Pradhan, Yong-Soo Ha, and Yun-Tae Kim. Development of structural type-based physical vulnerability curves to debris flow using numerical analysis and regression model. *Available at SSRN 4593842*.

[14] Fabrizio de Luiz Rosito Listo, Maria Carolina Villaça Gomes, and Fabiana Souza Ferreira. Evaluation of shallow landslide susceptibility and factor of safety variation using the trigrs model, serra do mar mountain range, brazil. *Journal of South American Earth Sciences*, 107:103011, 2021.

[15] NDRRMA. BIPAD Portal. `https://bipadportal.gov.np/damage-and-loss/`, January 2023.

[16] Nirdesh Nepal, Jiangang Chen, Huayong Chen, Til Prasad Pangali Sharma, et al. Assessment of landslide susceptibility along the araniko highway in poiqu/bhote koshi/sun koshi watershed, nepal himalaya. *Progress in Disaster Science*, 3:100037, 2019.

[17] Onlinekhabar. Landslide kills 3 in kathmandu's chandragiri, October 7 2022. Retrieved from Onlinekhabar English.

[18] Do Won Park, NV Nikhil, and SR Lee. Landslide and debris flow susceptibility zonation using trigrs for the 2011 seoul landslide event. *Natural Hazards and Earth System Sciences*, 13(11):2833–2849, 2013.

[19] Yoonkyung Park, Ananta Man Singh Pradhan, Ungtae Kim, Yun-Tae Kim, Sangdan Kim, et al. Development and application of urban landslide vulnerability assessment methodology reflecting social and economic variables. *Advances in Meteorology*, 2016, 2016.

[20] Hamid Reza Pourghasemi, Zeinab Teimoori Yansari, Panos Panagos, and Biswajeet Pradhan. Analysis and

evaluation of landslide susceptibility: a review on articles published during 2005–2016 (periods of 2005–2012 and 2013–2016). *Arabian Journal of Geosciences*, 11:1–12, 2018.

[21] Ananta Man Singh Pradhan, Hyo-Sub Kang, Saro Lee, and Yun-Tae Kim. Spatial model integration for shallow landslide susceptibility and its runout using a gis-based approach in yongin, korea. *Geocarto International*, 32(4):420–441, 2017.

[22] Ananta Man Singh Pradhan, Jung-Min Lee, and Yun-Tae Kim. 5 semi-quantitative method to identify the vulnerable areas 6 in terms of building aggregation for probable landslide runout 7 at the regional scale: a case study from soacha province, colombia.

[23] Chiranjib Prasad Sarma, Arindam Dey, and A Murali Krishna. Influence of digital elevation models on the simulation of rainfall-induced landslides in the hillslopes of guwahati, india. *Engineering Geology*, 268:105523, 2020.

[24] Nepal Geological Society. *Journal of Nepal Geological Society*, volume 32. Nepal Geological Society, 2005.

[25] Thomas Stanley and Dalia B Kirschbaum. A heuristic approach to global landslide susceptibility mapping. *Natural hazards*, 87:145–164, 2017.

[26] Nikhil Nedumpallile Vasu, Seung-Rae Lee, Ananta Man Singh Pradhan, Yun-Tae Kim, Sin-Hang Kang, and Deuk-Hwan Lee. A new approach to temporal modelling for landslide hazard assessment using an extreme rainfall induced-landslide index. *Engineering Geology*, 215:36–49, 2016.

[27] Duncan C Wyllie and Chris Mah. *Rock slope engineering*. CRC Press, 2004.

[28] Tsun-Hua Yang, Yi-Chin Chen, Ya-Chi Chang, Sheng-Chi Yang, and Jui-Yi Ho. Comparison of different grid cell ordering approaches in a simplified inundation model. *Water*, 7(2):438–454, 2015.