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Numerical Modeling of Debris Flow Originating from Topographic Hollows at Koyalghari and Simaltal Area along Narayangadh-Mugling Highway

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Abstract: Assessment of debris flow runout extent is essential for evaluating landslide hazards and formulating effective land-use plans. This study employed the openly available LISEM (LImburg Soil Erosion Model) to simulate debris flow runout using diverse geospatial and geotechnical input data. By incorporating the spatial distribution of soil geotechnical parameters, the model effectively estimated debris flow runout based on debris height. The research integrates rainfall-induced slope failure and runout dynamics through a physically based modeling approach to predict potential landslide impact zones under extreme rainfall conditions corresponding to 5-, 10-, and 25-year return periods. The study area is the Koyalghari region along the Narayangadh-Mugling Highway in central Nepal. Model validation was conducted in the Simaltal area using the Cohen's Kappa statistic, yielding a value of approximately 0.7, which indicates substantial agreement with observed debris flow patterns. For the analyzed rainfall scenarios, the estimated average debris flow height ranged from 0.92 m to 1.1 m on the highway, highlighting the potential for severe damage to road infrastructure and traffic during extreme events. Overall, the study demonstrates that a physically based model incorporating geotechnical soil parameters can reliably estimate debris flow runout and deposit height, offering valuable insights for hazard assessment, risk mitigation, and land-use planning in landslide-prone regions such as the Narayangadh-Mugling Highway.

Keywords: ***Cohens Kappa, Debris flow, LISEM model, Physical based modelling, Runout distance, Mugling.***

Introduction

The mountainous areas of Nepal are naturally unstable and particularly vulnerable to landslides for several reasons like their rugged topography, which is the result of their narrow north-south distance. Additionally, the presence of soft soil cover, high intensity monsoon rainfall and frequent earthquake amplify the risk (Upreti and Dhital, 1996). Rainfall plays a crucial role in triggering debris flow from topographic hollow, which are natural depressions in the landscape where colluvial material (loose, unconsolidated soil and rock) accumulates over time. In densely populated mountainous areas of Nepal, human life and property remain vulnerable to the wide-spreading effects of rainfall-induced debris flow. This debris flow originating from topographic hollows due to rainfall can travel considerable distances across sloped natural terrain covering a larger area than the topographic hollow. Hazard analysis in these mountainous regions requires an analysis of both the debris flow initiation and runout areas. Despite the risks posed by debris flows, people continue to inhabit the middle mountain and low valleys of Nepal. Understanding the origin of debris flow from topographic hollow is essential for disaster resilience especially in the context of a mountainous country like Nepal.

Debris flow modeling can be carried out by three general approaches: physical modeling, empirical modeling, and dynamic modeling (Chen and Lee, 2000). The distinction between these approaches is that empirical modeling is based on well-documented observations and typically allows for the practical estimation of travel distance without taking debris flow rheology into account, while physical modeling is based on field observation and supported by controlled laboratory experiment (Quan et al., 2014). Furthermore, dynamic modeling is carried out through the application of momentum and energy conservation laws through numerical methods (Hussin, 2011).

The dynamic method is numerically solved using physically based models derived from fluid mechanics. They can offer more precise predictions; however, they require more detailed input data and are computationally intensive than other methods. LISEM (LImberg Soil Erosion Model) developed by Faculty of Geo-Information Science and Earth Observation (ITC) of Twente University is a physically based dynamic model that offers a more comprehensive analysis by considering the physical processes involved in debris flow runout. It uses a physically based approach to model the movement of water and solid material down a slope considering the physical processes involved in debris flow and the interaction with the topography, offering a more realistic representation than simpler models (Bout et al., 2018). LISEM includes mathematical equations related to debris flow. Users can also construct a physically based model through a script that integrates the selected tools and arranges them in the desired order, providing flexibility in the model setup. A more comprehensive scripting environment is offered by the script editor, which uses a modified version of the AngelScript language. The runout was simulated in OpenLISEM using a simple runout modeling or "FlowDebris" function that can simulate two-phase runout flow or flows with different solid contents and flow properties through the integration of solids and water dynamics based on the Two-Phase flow equations proposed by Pudasaini (2012).

Study area

The study area of the research is located at Simaltal and Koyalghari in Ichhakamana Gaupalika, Chitwan district (Figure 1). The area is about 72 km southwest of the capital city, i.e. Kathmandu.

The Koyalghari area lies in the latitude of 27° 48' 45" and longitude of 84° 30' 31'' and Simaltal area lies in the latitude of 27° 49' 11'' and longitude of 84° 28' 39''.

The hollow in Koyalghari area and Simaltal area covers about 2663.25 sq. m. area and 2732.23 sq. m. area respectively. The major highways that connect the study area to most parts of Nepal includes Mahendra Highway, Prithvi Highway and Madan Bhandari Highway. Geologically, the study area lies in the Nourpul Formation of the Lower Nawakot Group of the Nawakot Complex (Stöcklin and Bhattarai, 1977). The formation is part of the Lesser Himalaya Sequence (LHS), which is separated from the Siwalik by the Main Boundary Thrust (MBT) near Jogimara village in Narayangadh-Mugling section. The lithology around the study area comprises grey-green slate, grey phyllite, pink dolomite, grey metasandstone, pink, grey, dirty white quartzite etc. This rock succession was overlain by the silty to clayey colluvial soil of low to high plasticity in the topographic hollow.

The nearest rainfall station from the research area is Devghat station. The rainfall data of Devghat station obtained from Department of Hydrology and Metrology (DHM) shows that the monsoon season (June to September) brings heavy rainfall that accounts for around 80% of the total annual precipitation of the area (Figure 2). These rainfalls are responsible for numbers of shallow landslides along the highway during monsoon.

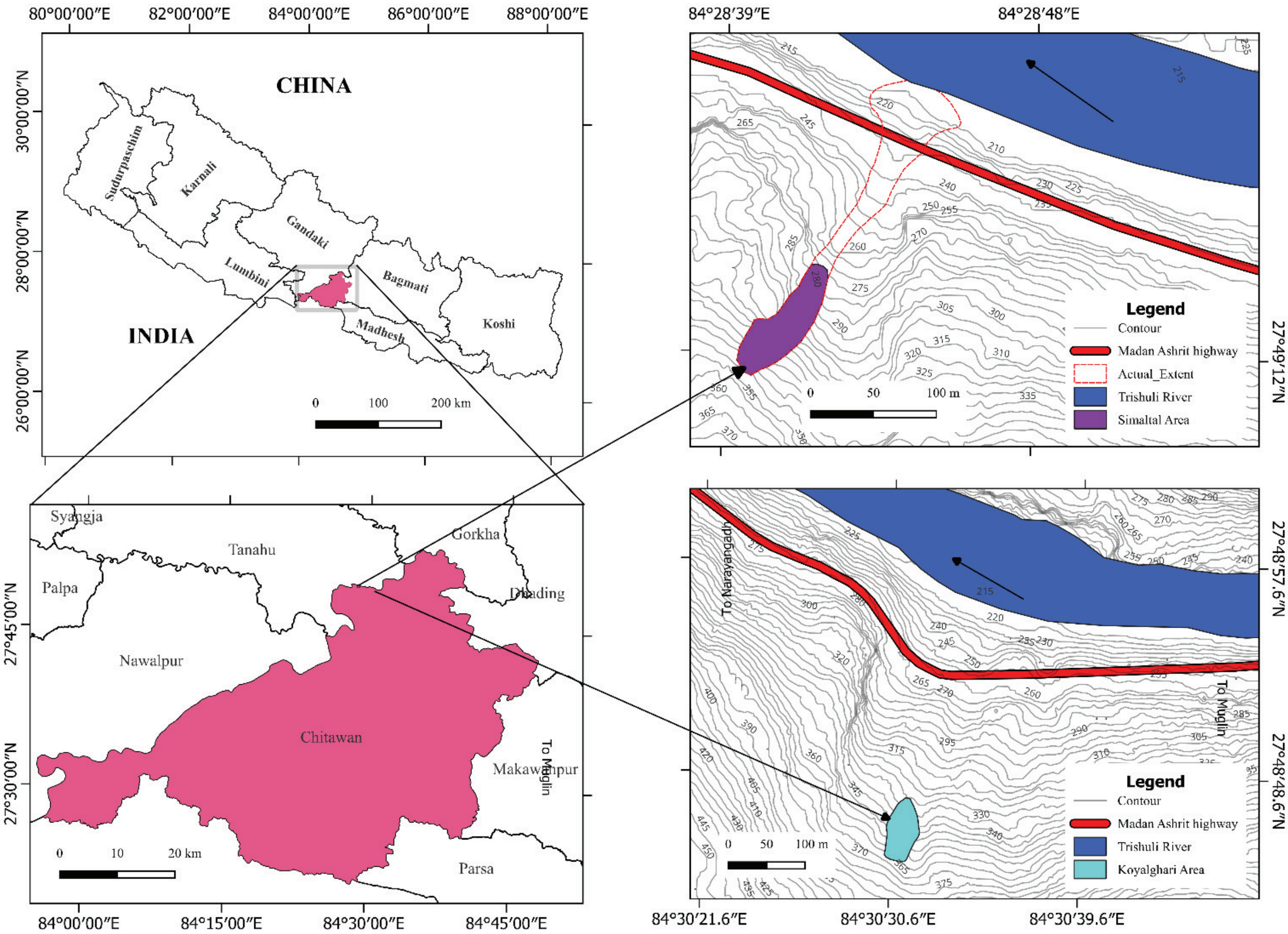

Figure 1, Location map of study area.

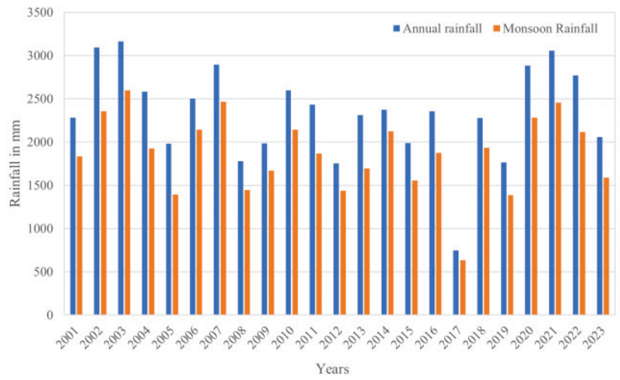

Figure 2, Total monsoon and annual rainfall of each year from 2001 to 2023 in Devghat Station (Source: DHM).

Physical based modelling in LISEM

The objective of the present study was achieved by following methods as presented in the flowchart below (Figure 3).

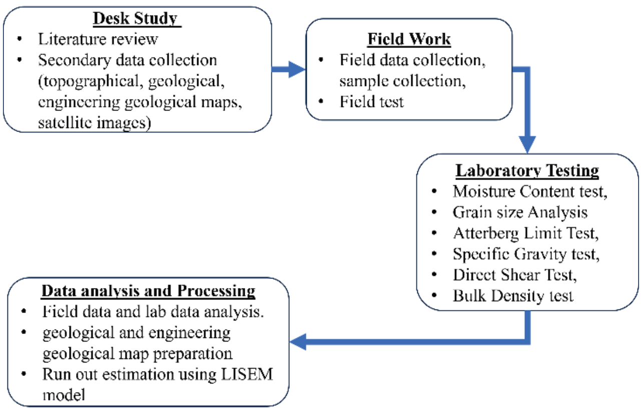

Figure 3, Overview of methods used during study.

For geotechnical investigation, laboratory tests conducted on the collected samples included moisture content, grain size analysis, Atterberg limits, specific gravity, unit weight, porosity and direct shear tests whereas in situ tests conducted includes infiltration test and DCPT. For simulations, geotechnical properties determined from different samples were utilized.

The flow chart of the methods used for modeling debris flow in the LISEM model is shown in Figure 4.

Primary inputs

The primary inputs for the model are grouped into 3 categories: geospatial data, ground truth, and rainfall data. Geospatial data includes Digital Elevation Model, soil depth, and soil hydraulic properties and runout parameters like manning's 'n'. The data related to soil parameters obtained from the average value of the field test and lab test were rasterized to obtain the required input map. The ground truth data is the actual impact area of past debris flow which is used for model validation. It is the observed runout of the debris flow at Simaltal in 2010 obtained from the google earth image.

Two types of rainfall data were used as observed and forecasted. Observed precipitation data for past events was obtained from the DHM to validate the model while forecasted precipitation data was obtained based on extreme rainfall with return periods of 5, 10 and 25 years after processing 23-year daily rainfall data. The various sources of data used in LISEM model are given in Table 1.

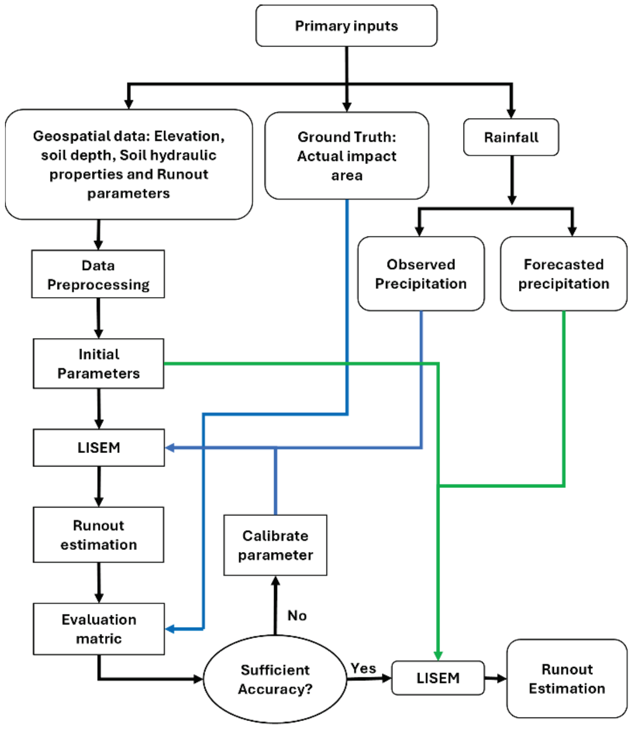

Figure 4, Flowchart of LISEM model employed for debris runout estimation.

Table 1, Data sources required for LISEM model

Data	Input data	Source
Geospatial data	Elevation (5-m DEM resampled into 1 m)	Durham University
	Soil depth	DCPT
	Saturated Hydraulic Conductivity	Infiltration test
	Porosity	Laboratory test
	Particle density	
	Dominant grain size	Sieve Analysis
	Cohesion	Direct Shear test
	Internal Friction Angle (IFA)	
	Manning's n	Manning's n table from Chow, 1959
Ground Truth	Actual debris runout extent	Google Earth pro
Rainfall	Precipitation	23-year rainfall record from DHM

Data preprocessing

This section outlines the data sources and preprocessing methods used to prepare maps for the physically based model. All input data underwent preprocessing steps to ensure compatibility with LISEM. This step includes formatting the data into a specific file, ensuring spatial and temporal consistency between different data layers and filling any data gaps or outliers. The rainfall data were also processed to determine extreme rainfall for 5, 10 and 25 yr return period based on Gumbel method.

Initial parameters

LISEM requires various initial parameters to control the debris flow simulation. These parameters include initial solid internal friction angle, cohesion, rock size, solid density, solid height and water height. The values of these parameters are determined by laboratory test results of the collected sample. The raster map of each initial parameter was prepared using a raster calculator in QGIS. The initial solid internal friction angle, cohesion and solid density was taken from the average of the value obtained from the laboratory test. Similarly, initial rock size was obtained from the average Characteristic Grain Size (D_{10}).

LISEM modelling

The core part of the methods involves running the LISEM model. At first the start time, end time of simulation and time step were selected as per requirement. Then directory of all input maps, rainfall data and output directory were chosen. Similarly, the two options in the SPH model as 'include initial solid' and 'include initial fluid' were selected for simulation. Finally, after running the model the debris flow runout process was simulated considering factors like topography, past rainfall intensity, and debris material properties. In the Simaltal area the past rainfall data was used whereas in the Koyalghari area the extreme rainfall data (forecasted precipitation) was used.

Runout estimation and validation

LISEM generated the debris flow runout zone in the study area in terms of solid height and fluid height. The model was validated in the Simaltal debris flow of 2010. Common metrics for evaluating debris flow models include the root mean squared error (RMSE) and Cohen's kappa. In the present study the accuracy of the model was calculated based on Cohen's kappa (Cohen 1960) by using "MapContinuousCohensKappa" function in a scripting environment of the LISEM model. These metrics enable the comparison of accuracy based on several parameters and are widely used for quantitative evaluations. The Cohen's Kappa matric is preferred over others because it helps to estimate interrater reliability i.e. rater agreement by considering chance agreement. This makes it an effective tool for validating the reliability of models or maps in a variety of fields, including environmental science and risk assessment. The formula to calculate Cohen's kappa (κ) modified from Cohen 1960 for machine learning application based on 2x2 confusion matrix described by Chicco et al. (2021) is given in Equation 1:

$$\kappa = \frac{2*(TP*TN-FP*FN)}{(TP+FP)*(FP+TN)+(TP+FN)*(FN+TN)} \quad (1)$$

For the calculation of Cohen's Kappa, first confusion matrix was constructed as in Table 2. The matrix compares the location of the actual impact area referred to as observed, and the simulated runout area labeled as predicted. In this case, the debris height was chosen to compare the observed and predicted values in the confusion matrix. During accuracy assessment minimum debris flow height should be specified below which the runout is not considered because this small value might not be visible in satellite image of actual runout. Hence, it classifies according to the threshold height and delineate predicted debris height of each pixel into two regions as the runout area and outside (where no runout is expected during the simulation period). Finally, Cohen's Kappa was calculated with the confusion matrix obtained by counting the number of pixels classified as False Positive (FP), False Negative (FN), True Positive (TP) and True Negative (TN). Cohen's kappa value can be classified into various classes based on Table 3.

Table 2, Confusion matrix based simulated debris height (modified from Rossi et al., 2010)

		Predicted	
		Positive	Negative
Observed	Positive	True Positive (TP): Debris height > 0.45 m in 1	True Negative (TN): Debris height < 0.45 m in 2
	Negative	False Positive (FP): Debris height > 0.45 m in 2	False Negative (FN): Debris height < 0.45 m in 1

The number 1 refers to the runout area of 2010 debris flow event, and the number 2 is the outside the area, in which it is assumed that no debris runout occurred.

Table 3, Interpretation Cohen's Kappa value (Landis and Koch, 1977)

Cohen's Kappa Value	Interpretation of Cohen's Kappa Value
< 0.0	Poor agreement
0.0 - 0.20	Slight agreement
0.21 - 0.40	Fair agreement
0.41 - 0.60	Moderate agreement
0.61 - 0.80	Substantial agreement
0.81 – 1.00	Almost perfect agreement

Slope stability and failure volume estimation

To simulate the debris flow in LISEM model from a topographic hollow, a crucial assumption was made regarding the failure mechanism. Instead of employing a separate slope stability model to calculate a Factor of Safety and a specific failed volume, the approach assumes a worst-case, physically possible scenario: that the entire colluvial deposit within the topographic hollow fails and mobilizes simultaneously after extreme rainfall event.

This assumption is based on the known characteristics of debris flows originating from these specific geomorphic features. Topographic hollows are inherently unstable and highly susceptible to complete failure when saturated by intense rainfall. The high permeability and low cohesion of this material, combined with the convergent subsurface flow of water during a storm, lead to a rapid increase in pore water pressure and a sudden loss of shear strength, which can trigger a catastrophic failure of the entire colluvial mass.

By assuming the mobilization of the entire volume of colluvial mass, a conservative, upper-bound estimate of the initial solid and fluid volume was made. This volume directly provides input parameters of "initial solid height" and "initial fluid height" using equation 2 and equation 3 respectively. This method helps in simulating debris flow run out and focus on how the material moves and settles afterward.

Result

Geologically, the study area lies in the Nourpul Formation of the Lesser Himalaya Zone. The slope under study is largely composed of phyllite and quartzite fragments and is characterized by a predominance of colluvial deposits. The area is mostly covered up to 3 m thick colluvial soil, primarily low plasticity silt (ML) and low plasticity clay (CL). The terrain, with slopes facing the Northeast, has gentle angles averaging 30 degrees (Figure 5).

Runout parameter maps

The runout was estimated using opensource software called LISEM which requires various input maps. The input map of the soil parameter was determined from the average value of geotechnical parameter given in Table 4 obtained from field and lab test.

Digital elevation model (DEM)

The DEM of the study area was prepared and it indicates the highest elevation of about 600 m, and the lowest elevation of 210 m is located near the Narayangadh-Mugling Highway in Koyalghari area. Whereas the elevation in the Simaltal area varies from 210 m to 480 m. The landslide scarp of the Simaltal area was at 340 m elevation whereas the deposition was at 215 m elevation on the Trishuli River as shown in Figure 6.

Table 4, Summary of values of various parameters obtained from field and laboratory test for hollow at Simaltal and Koyalghari

Parameters	Values in Simaltal area	Values in Koyalghari area
Cohesion (kN/sq. m.)	13.83	16.51
Internal Friction Angle (radians)	0.46	0.46
Soil density (kg/m^3)	1757.76	1640.12
Porosity	0.323	0.385
Specific gravity	2.58	2.51
Characteristic Grain Size, D_{10} (m)	2.62E-04	1.19E-04
Moisture content (%)	5.04	17.21

Manning's "n"

Manning's 'n' map was prepared from land use map based on Chow (1959). The land use map, as shown in Figure 7, was obtained from ESRI, which was based on Sentinel image. The land use map shows medium to dense brush is dominant in Koyalghari area followed by scatter brush. Similarly, in the Simaltal area, dense brush is dominant. The value of 'n' ranges from 0.04 to 0.1 in the Koyalghari area and the Simaltal area.

Soil depth map

Soil depth map was prepared from point map of soil depth obtained by Dynamic cone penetration test (DCPT) using ordinary kriging interpolation in GIS. The soil depth ranges from 0.6 m to 2.5 m in Koyalghari area whereas it ranges from 2.3 m to 4.5 m in Simaltal area as shown in Figure 8.

Initial solid height

Initial Solid height map was obtained from porosity and soil depth. The highest value of initial solid height is 3.045 m at Simaltal area and lowest value is 1.533 at Koyalghari area (Figure 9). Initial solid height map was prepared in QGIS using Equation 2 modified from Das (2008):

$$Solid\ height = (1 - Porosity) \times Soil\ depth \quad (2)$$

Initial Water Height

Initial water height map was based on water content at maximum saturation and soil depth. The highest value of initial water height is 1.453 m at Simaltal area and lowest value is 0.385 at Koyalghari area (Figure 10). It was prepared in QGIS using Equation 3 modified from Das (2008):

$$Water\ height = Porosity \times Soil\ depth \quad (3)$$

Initial solid cohesion

The initial cohesion map was prepared using direct shear test data obtained from the laboratory. The average value of cohesion in Koyalghari area is 16.51 kPa whereas that of Simaltal area is 13.83 kPa.

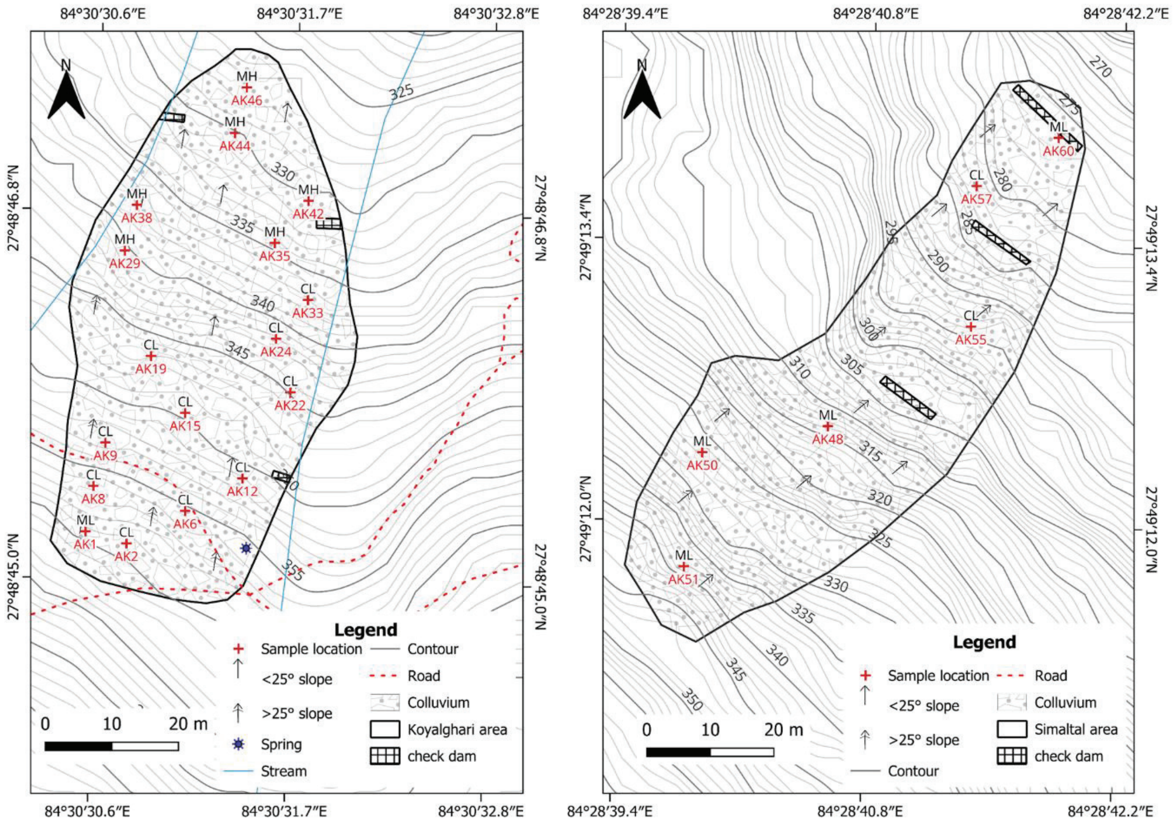

Figure 5, Engineering geological map of Koyalghari area (left) and Simaltal area (right).

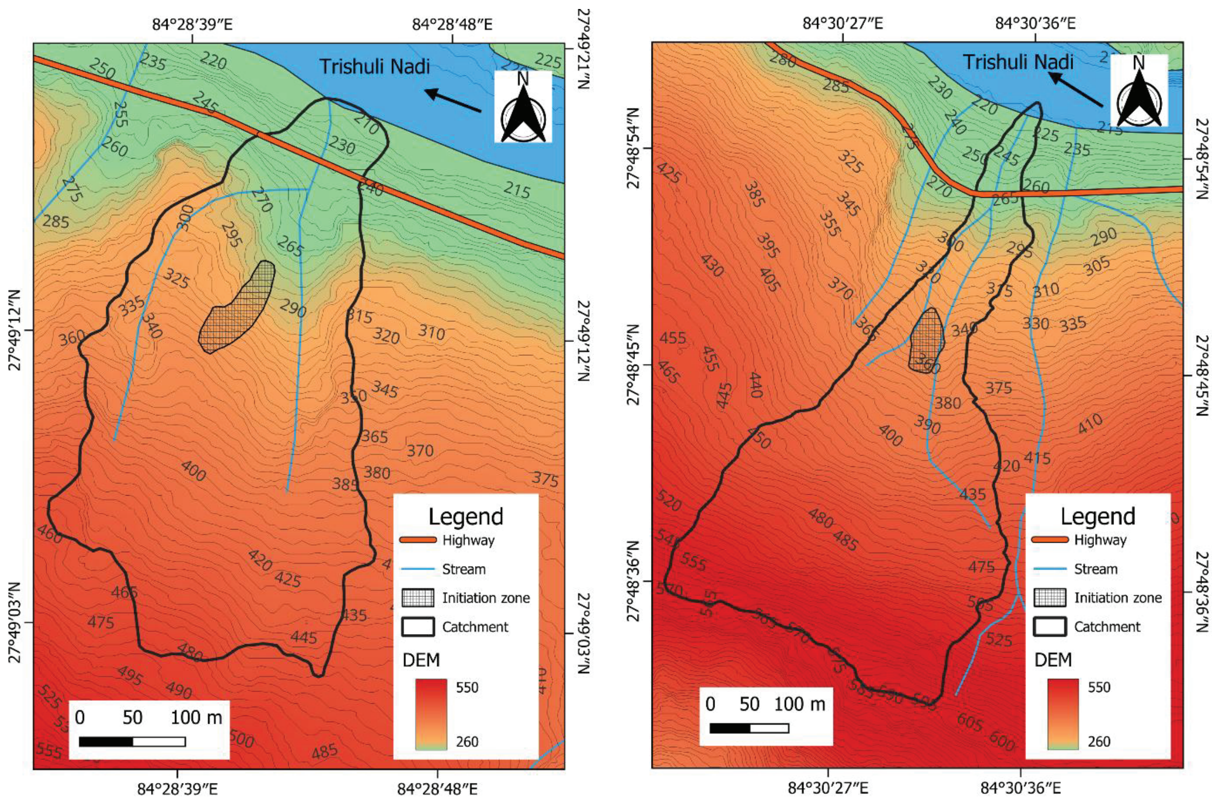

Figure 6, DEM of Simaltal area (left) and Koyalghari area (right).

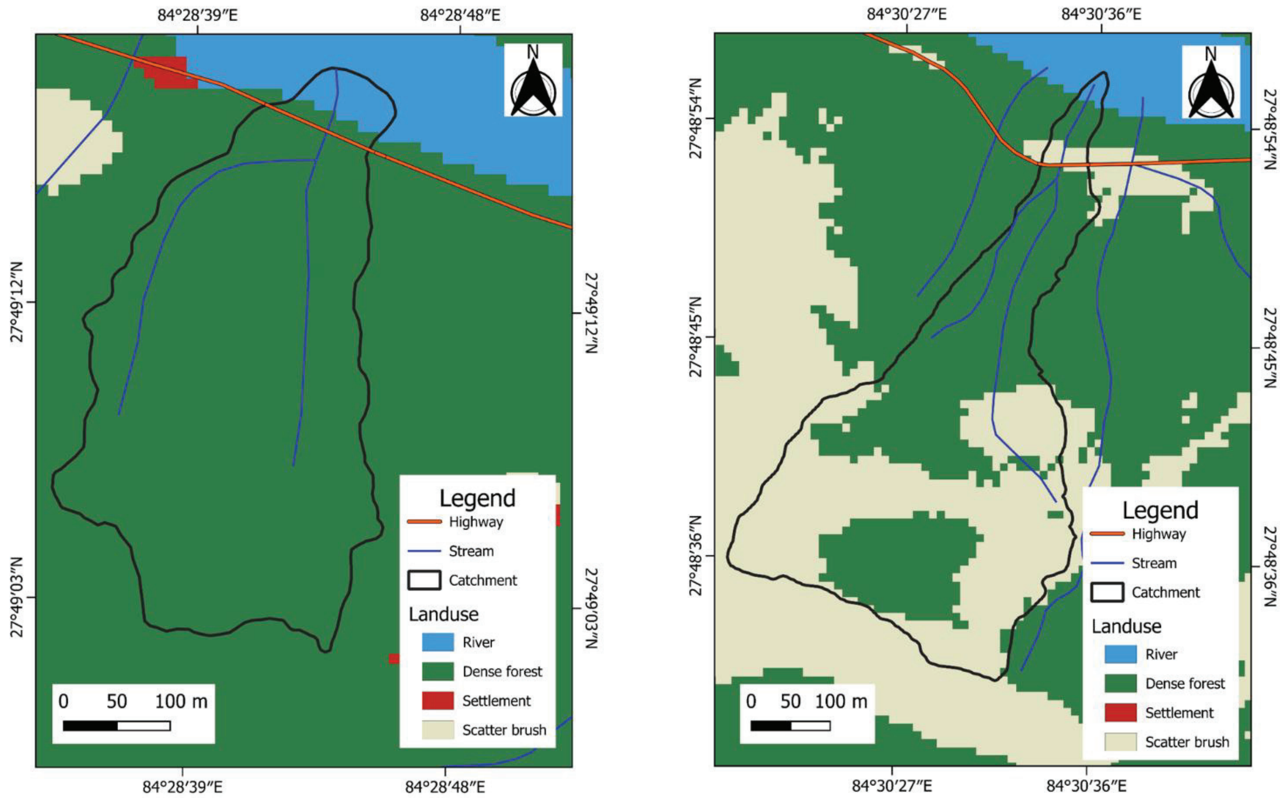

Figure 7, Landuse map of the Simaltal area (left) and Koyalghari area (right).

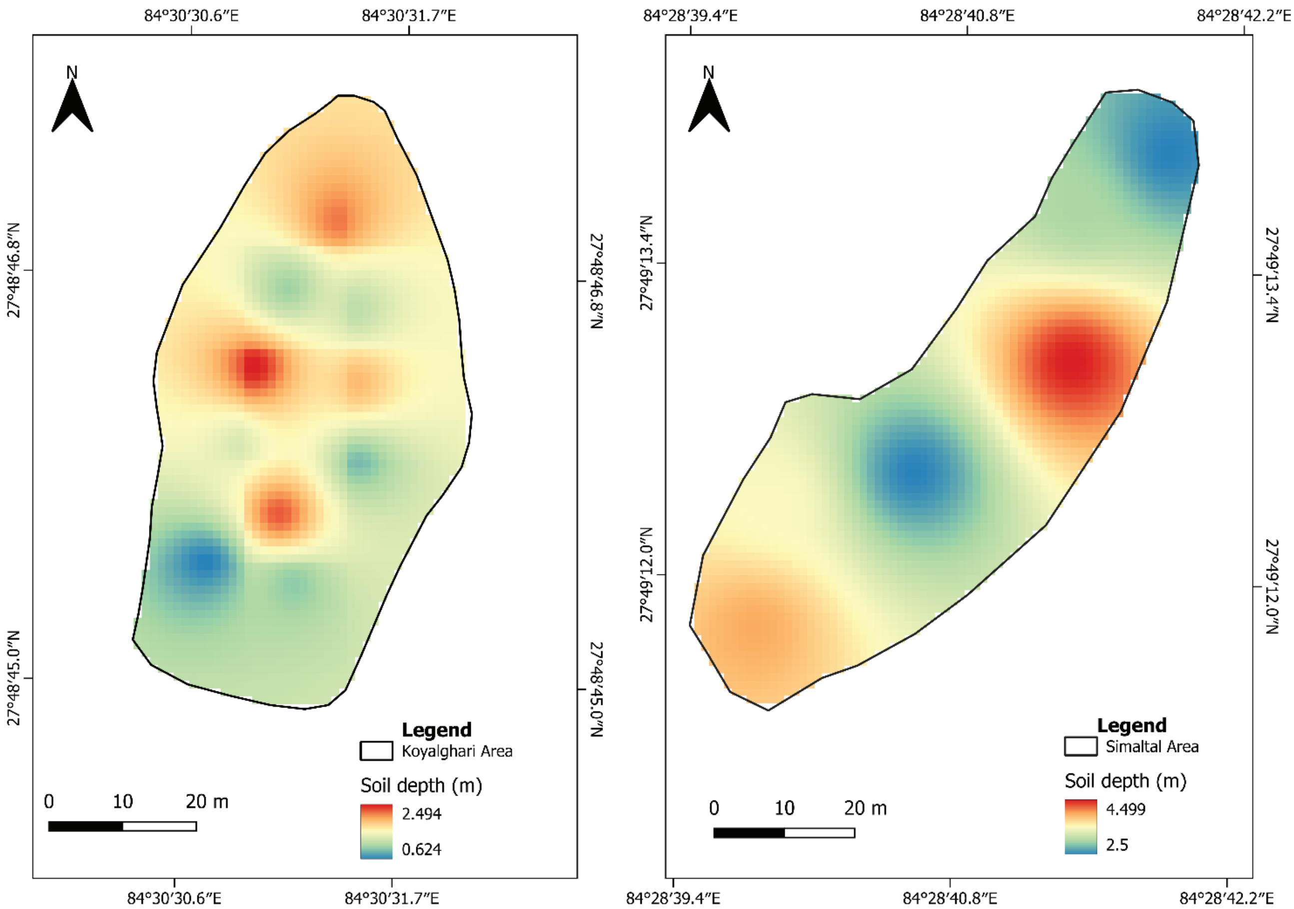

Figure 8, Soil depth map of Simaltal area (right) and Koyalghari area (left).

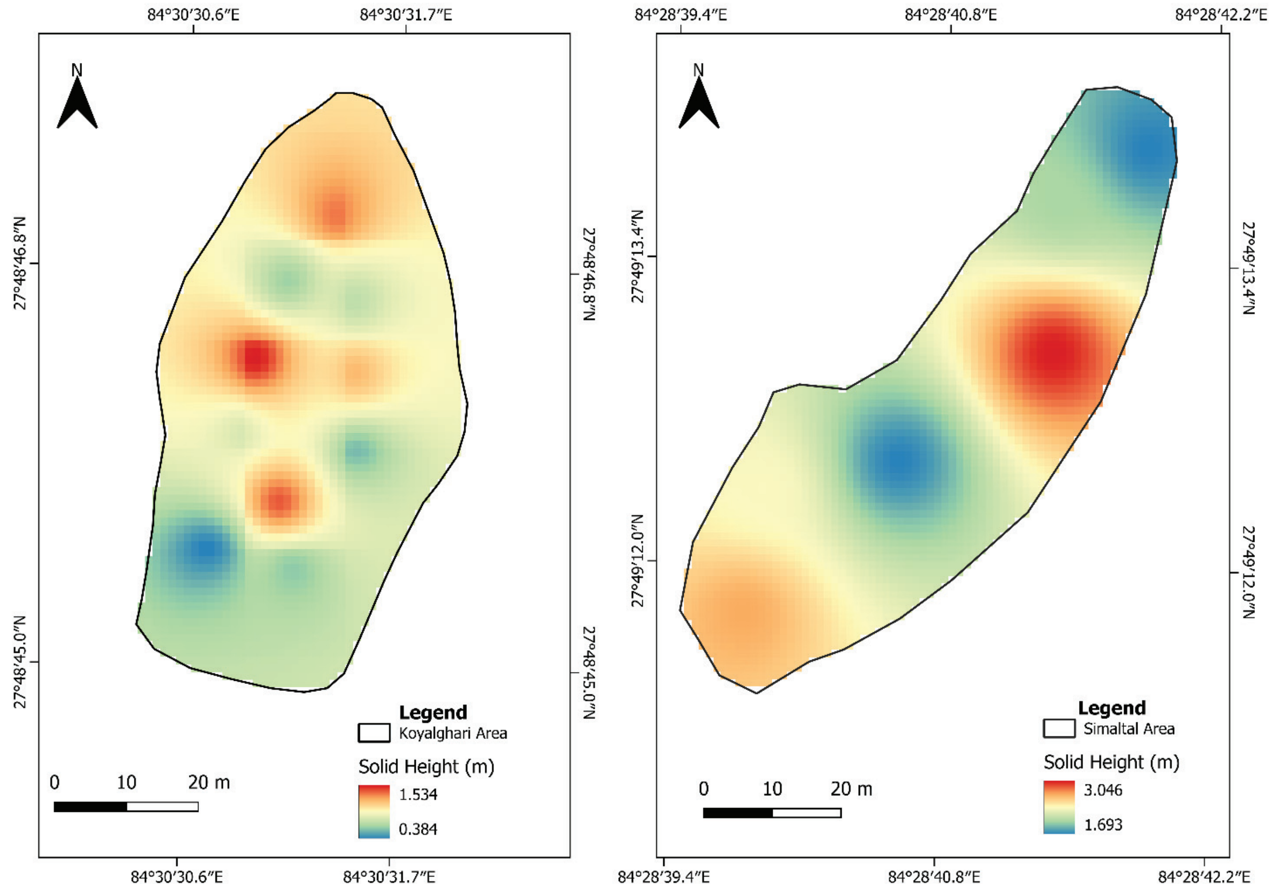

Figure 9, Map of solid height at Simaltal area (right) and Koyalghari area (left).

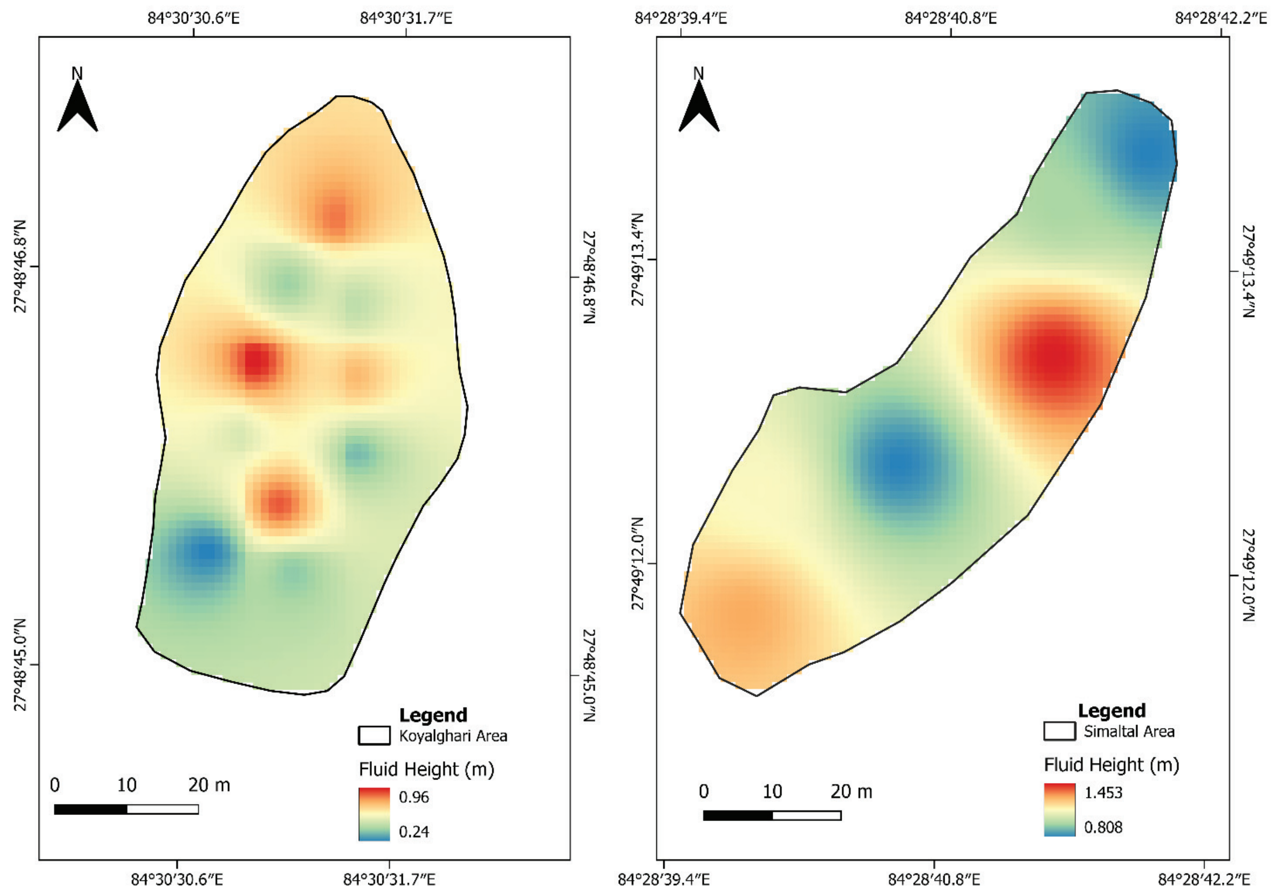

Figure 10, Map of initial fluid height at Simaltal area (right) and Koyalghari area (left).

Initial solid internal friction angle

The Initial Solid Internal Friction Angle map was also prepared using direct shear test data obtained from the laboratory. The average value of internal friction angles in both Koyalghari area and Simaltal area is 0.46 radian.

Initial solid density

The initial solid density map was prepared using soil density data obtained from the laboratory. The average value of solid density in Koyalghari area is 1,640.12 kg/m^3 whereas that of the Simaltal area is 1,757.76 kg/m^3.

Initial solid rock size

The initial Solid Rock size map was prepared from grain size analysis based on D_{10} value. The average value of initial rock size in Koyalghari area is 1.19x10^{-04} m whereas that of Simaltal area is 2.62x10^{-04} m.

Simulation result

Runout modeling was performed in LISEM model for two areas i.e. first in the Simaltal area to represent debris flow occurred in 2010 using actual precipitation that triggered debris flow and then in the study hollow using extreme rainfall intensity. The satellite image of the Simaltal area of 2010 debris flow is shown in Figure 11. This event was triggered by rainfall of 6th September 2010. The simulation result gives a map of maximum and final debris height and maximum and final debris velocity. The maximum debris height of 9.243 m was obtained at central part (Figure 12) of debris runout whereas the maximum velocity of 29.99 m/s was obtained at initiation part (Figure 13). The debris flow runout covers total area of 15,492.24 sq. m.. On the highway the average maximum debris flow height was 1.107 m and ran out to extend beyond the highway depositing debris finally at the bank of the Trishuli River. The debris flow affected about 60 m of highway from chainage 23+630 m to 23+690 m which aligns with satellite image.

The accuracy of the runout modeled in Simaltal area was calculated using Cohen's Kappa. The sensitivity analysis was carried out changing debris flow height during accuracy estimation to understand how different thresholds height impacts the performance of a model. This process helps to identify the optimal threshold value that balances sensitivity (true positive rate) and specificity (true negative rate), ultimately improving the model's accuracy. Map obtained using observed precipitation in the Simaltal area that resulted in maximum Cohen's kappa value is shown in Figure 14. The value of Cohens kappa at various threshold heights is shown in Figure 15. The maximum value of Cohen's Kappa was 0.7453 using the threshold height of 0.45 m. The total runout area obtained using threshold height of 0.45 m is 10,844.91 sq. m.

The actual runout extent was mapped from satellite imagery obtained 3 months after the event. By this time, lower-height debris areas were likely restored by vegetation growth and were therefore not visible in the satellite images, leading to an apparent mismatch if a lower threshold were used. Furthermore, the runout extent above 0.45 m debris height visually matches with the actual debris flow extent of the satellite image. This justifies the selection of threshold height 0.45 m for estimation of Cohens Kappa value.

Figure 11, Satellite image of debris flow at Simaltal triggered by 2010 rainfall from GoogleEarth (2010/11/02).

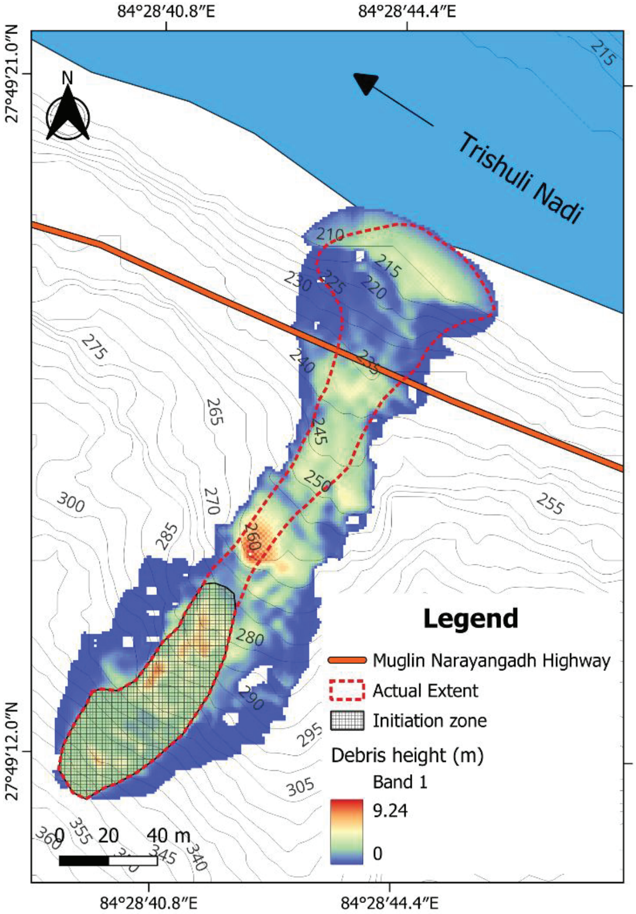

Figure 12, Debris flow runout in Simaltal area obtained from LISEM model considering all range of debris height.

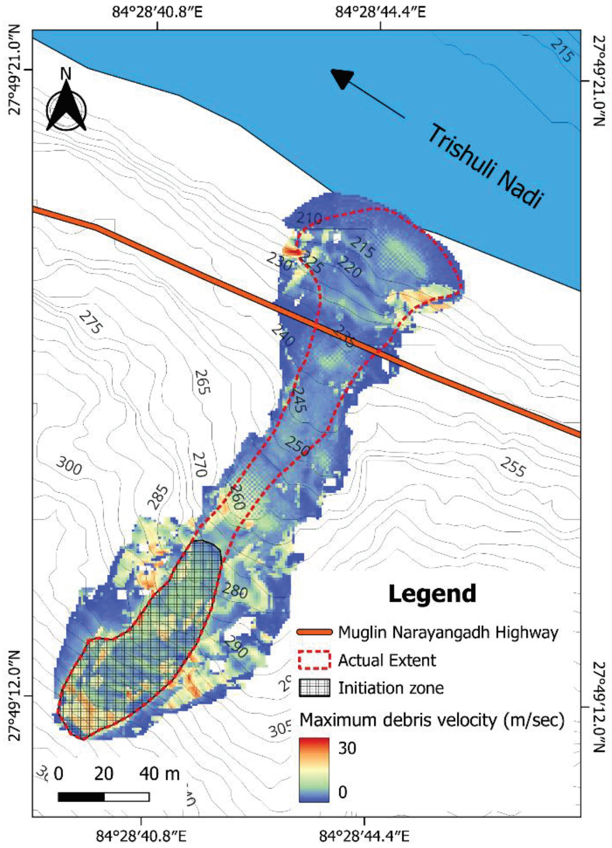

Figure 13, Maximum debris velocity in Simaltal area.

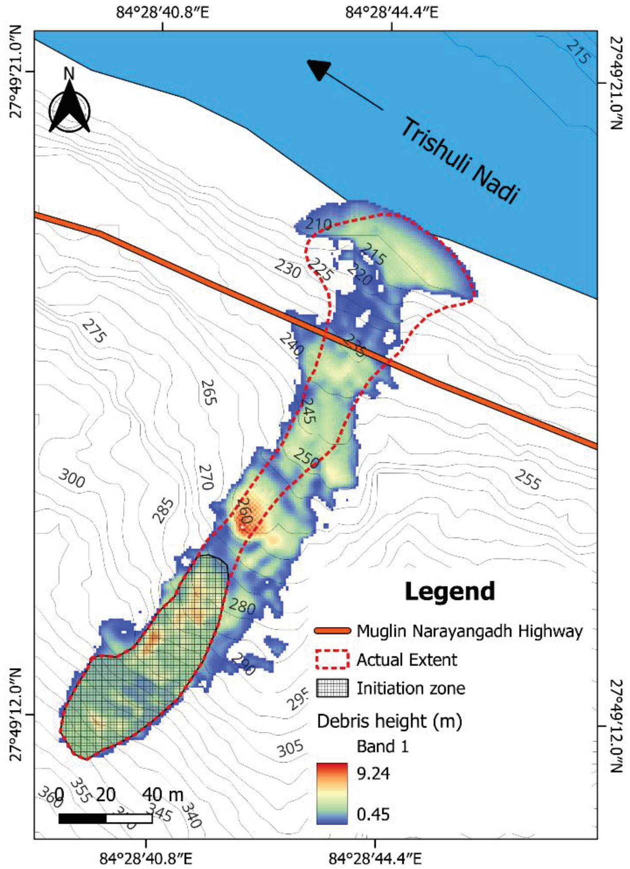

Figure 14, Debris flow runout in Simaltal area for threshold height that results maximum value of Cohens Kappa.

Simulation was also performed in Koyalghari area along Narayangadh-Mugling Highway section. The hollow in the area was modelled for various extreme events based on 23-year rainfall data. The rainfall data of 1-day and 3-day maximum were used to model the runout. Based on the result, the total area of runout for various rainfall events is shown in Table 5. The average debris flow height at the highway due to material from the hollow at various rainfall events are given in Table 6. Among the simulated rainfall, the maximum debris height at highway was 2.3 m for 3-day maximum rainfall of 2006 (Figure 16, Figure 17 and Figure 18).

Table 5, Runout area at highway for various rainfall events

Maximum rainfall	Total runout area (sq. m.) of debris flow for various return period rainfall			
	Actual	5-yrs	10-yrs	25-yrs
1 day	16767.64	16400.77	16419.17	16702.09
3 days	16484.72	15859.10	16081.06	16165.02

Table 6, Average debris height at Highway in Koyalghari area for various rainfall periods

Maximum rainfall	Average debris height (m) at highway for various return period rainfall			
	Actual	5-yrs	10-yrs	25-yrs
1 day	0.9626	0.9266	0.9482	0.9689
3 days	1.1153	0.9563	0.9341	0.9333

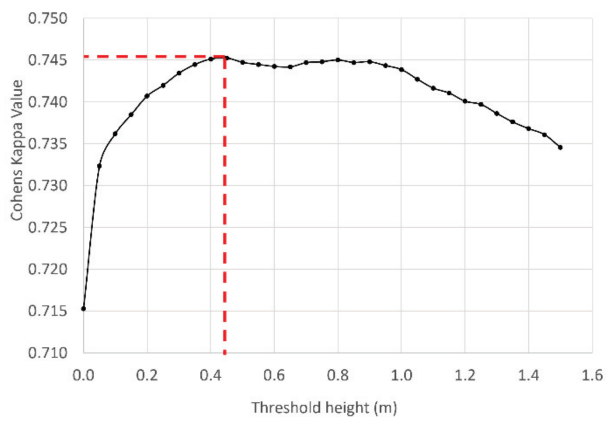

Figure 15, Cohens Kappa value for various threshold heights.

Discussion

Unlike earlier empirical and statistical approaches to debris flow modeling (e.g., Chen and Lee, 2000), which often relied on general observations and simplified assumptions about flow behavior, this study utilized a physically based dynamic model. The integration of geotechnical parameters specific to the local colluvial deposits, such as cohesion, internal friction angle and porosity, allowed for more accurate simulations of debris flow behavior under different rainfall scenarios.

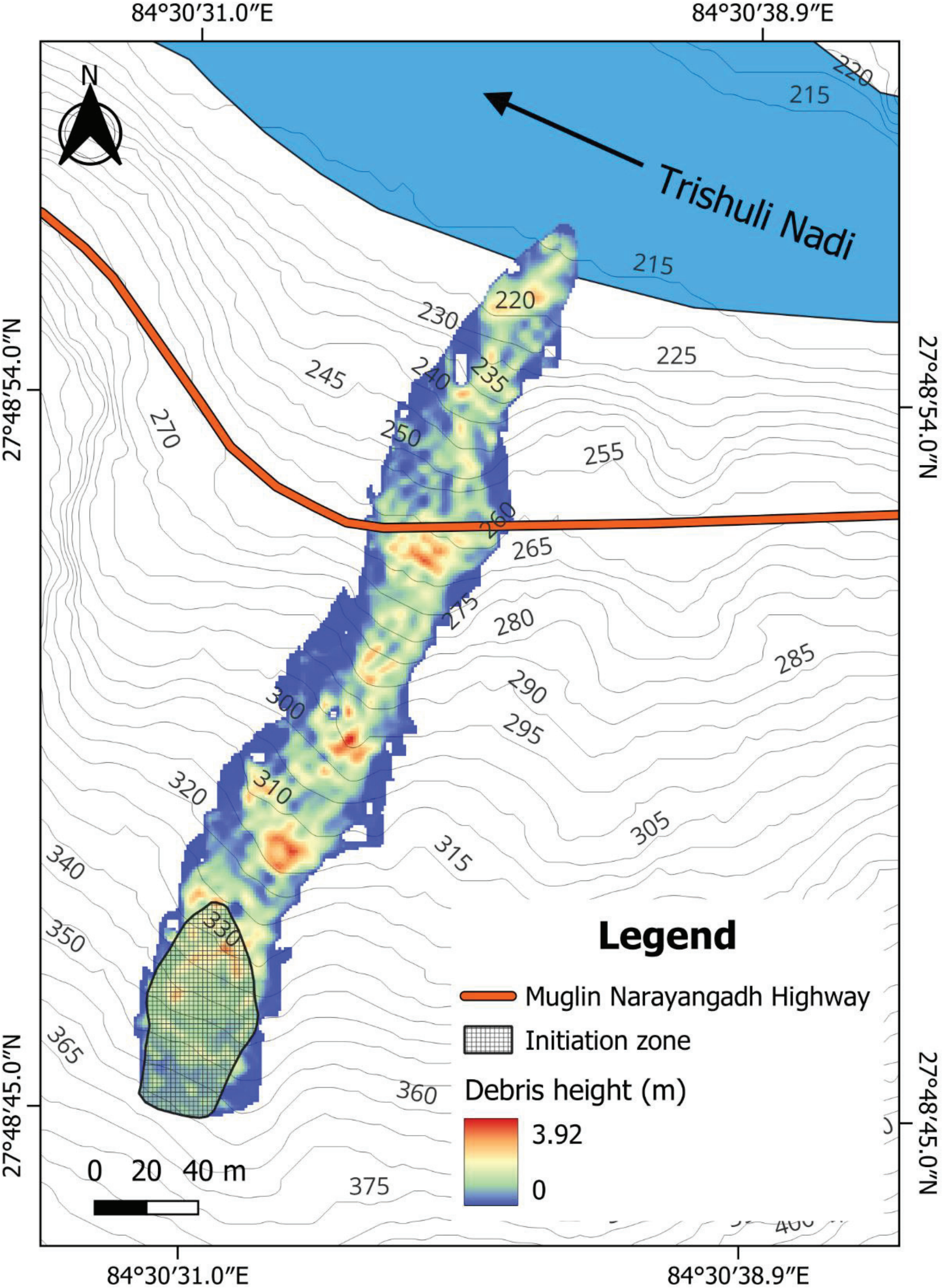

Figure 16, Debris height initiated from Koyalghari area for 3-day maximum rainfall of 2006.

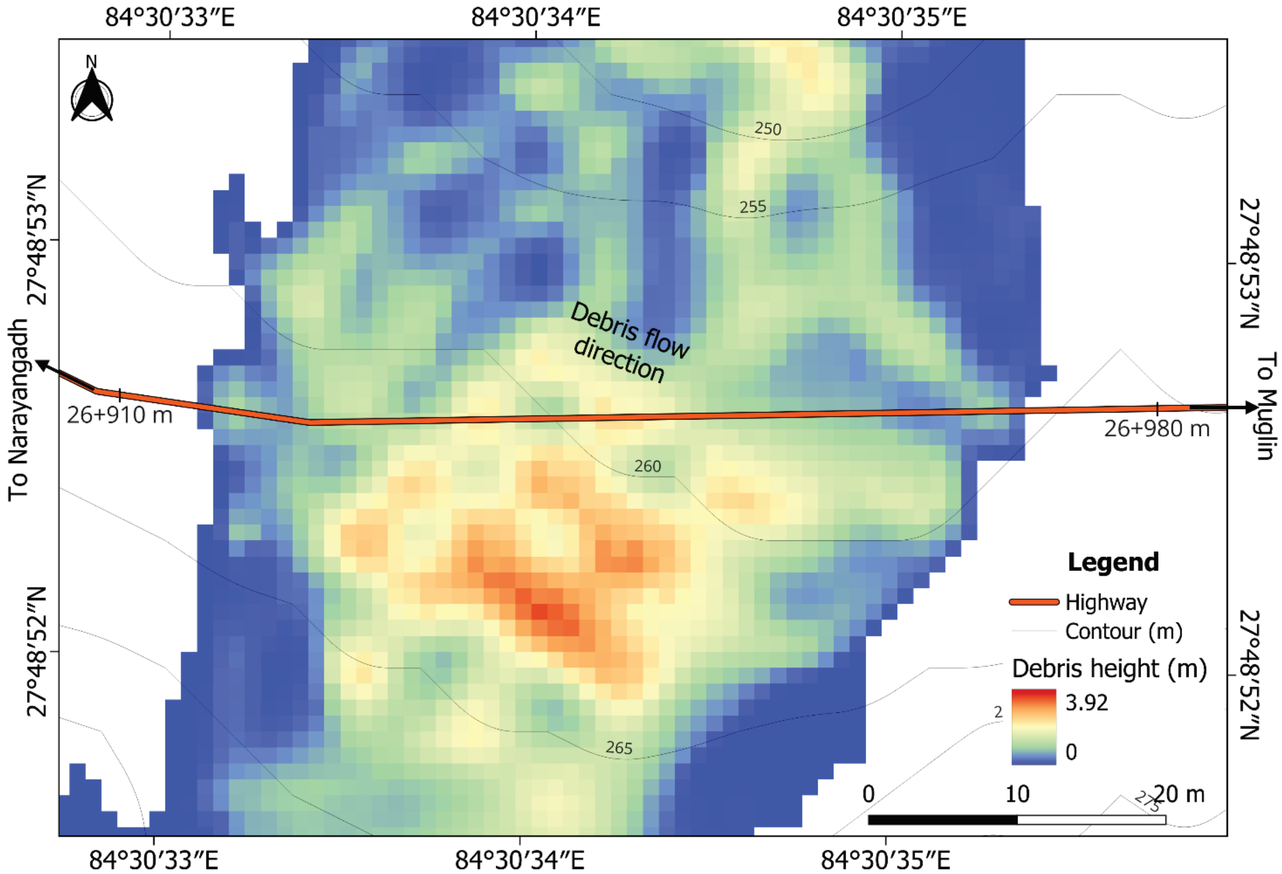

Figure 17, Debris height at Koayalghari area of the Narayangadh-Mugling Highway for 3-day max. rainfall of 2006.

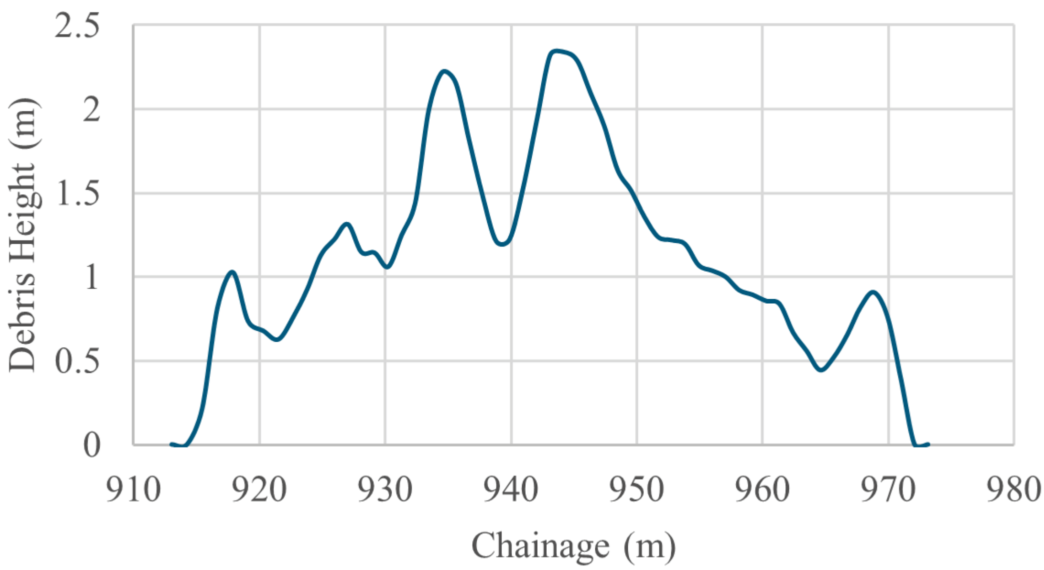

Figure 18, Debris height profile along highway for 3-day max rainfall of 2006 from chainage 26 km+910 m.

This approach is in line with the dynamic modeling method outlined by Pudasaini (2012), but this study takes it further by validating the model with actual historical events in the Simaltal area.

One of the key advancements in this study is the use of Cohen's Kappa for validating model accuracy, which is not commonly applied in debris flow studies. Like the approach used by Rossi et al. (2010) in their assessment of landslide susceptibility models, this validation method demonstrates substantial agreement between simulated and observed runout areas, lending credibility to the model's reliability. Such rigorous validation techniques were not emphasized in earlier debris flow modeling efforts, particularly in the context of the Nepal Himalayas.

While some studies, such as Paudel et al. (2021), have used GIS-based empirical models to assess debris flow runout in Kulekhani watersheds, this research distinguishes itself by using a physically based dynamic model. This approach moves beyond empirical correlations and offers a more robust tool for hazard management in a geologically complex and dynamic environment like the Lesser Himalaya Sequence. By demonstrating a substantial agreement with historical runout patterns using Cohen's kappa, the findings support the application of advanced physically based models for hazard assessment in landslide-prone regions in Nepal. This is a crucial step toward developing more accurate and proactive early warning systems for critical transportation corridors.

The findings of the study are consistent with and build upon previous research on landslide hazards in the Nepal Himalaya. The significance of high-intensity monsoon rainfall in triggering shallow landslides and debris flows, as observed in the study area, has been well-documented by others, such as Dahal and Hasegawa (2008), who established representative rainfall thresholds for landslides in the region. The potential for debris flows originating from topographic hollows to travel considerable distances and affect vital infrastructure, like the Narayangadh-Mugling Highway, is a key concern in Nepal. The potential threat to infrastructure demonstrates the need for early warning systems and robust hazard management strategies.

Additionally, the results align with global observations that debris flows triggered by extreme rainfall can cause extensive damage, as described by Jakob and Hungr (2005) and Hungr et al. (2005) in their comprehensive analysis of debris flow hazards. The prediction of debris flows in study area with heights exceeding 1 m during extreme rainfall events shows similar findings of Berti and Simoni (2007) who have documented comparable debris flow heights and runout distances.

This study enhances understanding of debris flow runout modeling by integrating geotechnical parameters into the LISEM model and validating it with historical data. It provides a significant advancement over empirical and statistical methods, which often rely on simplified assumptions and may lack precision when conditions vary from historical observations. However, the model relies on geotechnical parameters like cohesion and the internal friction angle, which introduces a level of uncertainty. These parameters are derived from samples collected in a limited number of locations and may not fully represent the spatial variability of the soil, which can lead to disagreements in the output of the model. Slight variations in the cohesion, internal friction angle, porosity or soil depth alters the rheology of the mixture and volume of debris which thereby affecting the predicted runout extent and height. Similarly, Pudasaini (2012) two-phase flow equations also make certain assumptions about fluid mechanics and solid-water interactions that may not perfectly capture the complex rheology of real-world debris flows, which often include a mixture of fine sediment, large boulders, and entrained woody debris. Further, the capability of models to simulate entrainment and deposition processes, while an improvement over simpler models is still a simplification of highly dynamic natural phenomena.

Compared to earlier works, which either lacked dynamic modeling approaches or omitted crucial validation steps, this research demonstrates importance of incorporating both rainfall and geotechnical factors for accurate hazard prediction. The predicted average debris flow of 0.92 m to 1.1 m at the highway is substantial enough to not only bury highway and block drainage culverts but also to potentially sweep away passing vehicles. The result of the study clearly demonstrated the capacity of these flows to extend beyond the highway and deposit debris at the bank of the Trishuli River. These findings align with global observations that rainfall-triggered debris flows can cause extensive damage and are comparable to documented events in other mountainous regions, which have recorded similar debris flow heights and runout distances. It supports the applicability of physically based models, such as LISEM, in debris flow-prone regions like Nepal, contributing to debris flow hazard assessment and risk mitigation. The use of this physically based model provides a valuable tool for authorities to develop more robust land-use plans and early warning systems to protect vulnerable infrastructure and human life.

Conclusion

The study successfully applied the LISEM model to simulate and estimate debris flow runout in topographic hollow based on debris height at Koyalghari area. The model validation in the Simaltal area demonstrated substantial accuracy and supported the conclusion that physically based models can reliably predict debris flow runout in similar geotechnical and topographical settings. The findings indicate that the debris flow runout encompasses 13.74% of the catchment area that is triggered by 2010 rainfall. The kappa value for validation area ranges from 0.716 (2 m height) to 0.745 (0.45 m height) which shows substantial agreement (Landis and Koch, 1977) with the actual landslide runout. The average debris flow ranges from 0.92 m to 1.12 m for various extreme rainfall events, which shows the risk to infrastructure along the Narayangadh-Mugling Highway. The accuracy shows that this model can serve as a valuable tool for estimating debris flow risks and providing hazard mitigation strategies in mountainous regions of Nepal.

For future studies more refined input data can be integrated, which includes updated geotechnical parameters and high-resolution topographical maps, which help to improve the precision of the model. Additionally, the incorporation of real-time rainfall monitoring data would enhance the predictive capability of early warning systems to protect human lives and infrastructure. Finally, the application of the LISEM model demonstrates its potential for widespread use in debris flow-prone regions to estimate road section affected by the potential debris flow.

Author contributions

Aakriti and Ranjan wrote the manuscript, prepared figures and tables. Both authors reviewed the article.

Data availability

No datasets were generated or analyzed during the current study.

Declarations

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this article.

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