Landslide Hazard Map Using the TRIGRS Model Coupled with Probabilistic Distribution: A Case Study in Kvam, Innlandet County, Norway

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ABSTRACT: Mountainous regions with high precipitation levels present a significant landslide risk, posing a threat to local populations. This study assesses landslide hazard in the Kvam region, located in Innlandet County, Norway, using the deterministic Transient Rainfall Infiltration and Grid-Based Regional Slope-Stability Model (TRIGRS) in combination with a probabilistic distribution for the input parameters. The study area covers approximately 32 km² and is characterized by exposed and fractured bedrock in the higher parts, and a thin layer of soil near the valley floor, which favors the occurrence of shallow landslides. The region is primarily composed of four types of material: silt, peat, fluvio-glacial deposits, and bedrock. In June 2011, intense rainfall triggered numerous landslides along the river located in the thalweg, highlighting the area's fragility to this type of instability. The model is based on infinite slope principles to balance the acting forces, incorporating a transient infiltration component that influences effective stress and, consequently, the safety factor over time. TRIGRS-P, a probabilistic variant of the model, allows for variation in input parameters based on a Gaussian distribution. The methodology involves calibrating geotechnical parameters and simulating different rainfall scenarios using TRIGRS-P, with the extreme rainfall event in Kvam in 2011 as a reference. The model performs slope stability analysis and generates landslide hazard map, which are then compared to the landslide inventory map from the same period (Schilirò et al., 2021). The main aspects analyzed include identifying areas most prone to shallow rainfall-induced landslides. Preliminary results indicate that the spatial discretization through zoning has a significant effect on the accuracy of landslide modeling. The use of a 3x3 matrix approach contributed to reducing the number of false positives, enhancing the reliability of the hazard maps. Rather than focusing on the specific advantages of the TRIGRS-P model itself, this study highlights how methodological refinements in input data preparation can improve model performance and support more effective geotechnical risk management.

KEYWORDS: Landslide, TRIGRS, Susceptibility, Probabilistic Analysis

1 INTRODUCTION

The Third United Nations World Conference, held in Sendai, Japan, on March 18, 2015, identified as a lesson learned since the Hyogo Framework that disaster risk prevention requires a broader approach. This approach should consider diverse sectors and risks, being inclusive and accessible for wider applicability. Additionally, it was defined as necessary for public and private sectors, civil society organizations, and academic institutions to collaborate, promoting the reduction of disaster risks (United Nations, 2015).

In this context, the increasing occurrence of rainfall-induced landslides, intensified by climate change scenarios, demands urgent attention, especially in vulnerable regions. In Norway, for example, the first Climate Report to the Norwegian Parliament, Meld. St. 33 (2012–2013), estimates a temperature increase in the country between 2.3°C and 4.6°C by the end of this century, and an average annual precipitation growth of 5% to 30% by 2100, relative to the 1961-1990 period. Average projections indicate an approximate 20% increase in precipitation during autumn, winter, and spring, and 10% in summer. Ten years later, Meld. St. 26 (2022–2023) indicates that 116,000 buildings could be located in risk areas for rainfall events with a 200-year return period by 2090, representing a 60% increase compared to the current number of buildings for the same type of event.

The increase in precipitation is directly related to the higher frequency of landslides, particularly in Norway's mountainous regions. Various types of landslides are triggered by climatic events, with shallow translational landslides being especially common during rainy periods. These events can cause significant fatalities and material damages. To aid in the management and mitigation of these risks, various mathematical modeling tools have been utilized to provide landslide susceptibility maps, facilitating land-use planning. The accuracy of these maps is significantly enhanced when combined with diverse datasets from the same area, thus becoming powerful tools for identifying areas susceptible to landslides and enabling the development of emergency plans for these regions.

Within this framework of increasing vulnerability and the need for effective risk assessment tools, the present study focuses on the evaluation of landslide risk in the Kvam region, located in Innlandet County, Norway. This area, approximately 32 km² in size, presents a complex geology, with exposed and fractured bedrock in the higher elevations, and a thin layer of soil near the valley floor, conditions that favor the occurrence of shallow landslides. The material composition in the region is predominantly silt, peat, fluvio-glacial deposits, and bedrock. The area's susceptibility to this type of instability was dramatically evidenced in June 2011, when intense rainfall triggered numerous landslides along the river located in the thalweg.

To address this issue, this study employs the deterministic Transient Rainfall Infiltration and Grid-Based Regional Slope-Stability Model (TRIGRS), coupled with a probabilistic distribution for the input parameters. The TRIGRS model is based on infinite slope principles to balance the acting forces, incorporating a transient infiltration component that influences effective stress and, consequently, the factor of safety over time. The probabilistic variant of the model, TRIGRS-P, allows for variation in input parameters based on a Gaussian distribution. The methodology involves calibrating geotechnical parameters and simulating different rainfall scenarios using TRIGRS-P, taking the extreme rainfall event in Kvam in 2011 as a reference. The model performs slope stability analysis and generates landslide hazard maps, which are subsequently compared with the landslide inventory map from the same period (Schilirò et al., 2021).

The main objectives of this work include identifying areas most prone to shallow rainfall-induced landslides. Furthermore, this study highlights the importance of methodological refinements in input data preparation, such as spatial discretization through zoning and the application of a 3x3 matrix approach, to improve landslide modeling accuracy, reduce false positives, and ultimately support more effective geotechnical risk management.

2 MATERIALS AND METHODS

2.1 Study Area

The study area is located in Veikledalen, in the upper part of the Gudbrandsdalen valley, Innlandet County, southeastern Norway. The hill slopes of this region are largely characterized by till deposits of variable thickness, whose presence is largely a result of glacial erosive action. These deposits are typically thinner (0.5 m or less) in the upper parts of the slopes, increasing in thickness to several tens of meters in the lower portions (Sletten; Blikra, 2007)

The area is prone to landslide events, as evidenced by the period of June 6–12, 2011, when significant rainfall and high temperatures caused strong snowmelt, triggering several shallow landslides between June 9 and 10 and leading to road closures in Gudbrandsdalen (Schilirò et al., 2021).

2.2 TRIGRS Model

TRIGRS is a Fortran program developed to analyze the timing and distribution of rainfall-induced shallow landslides at a regional scale. For this purpose, it considers several input parameters. The model performs stability analysis over large areas using the infinite slope limit equilibrium concept. Its analytical model, which is one-dimensional and transient flow-based, represents vertical infiltration in homogeneous and isotropic material during a storm, grounded in the linearized solution of the Richards' equation proposed by Iverson (2000).

The model allows for considering the influence of rainfall infiltration over time. Along with a simple scheme for routing runoff between cells, it is possible to calculate pore water pressure for each cell, starting from either saturated or unsaturated initial conditions.

For unsaturated solutions, the model incorporates a simple analytical solution proposed by Srivastava and Yeh (1991) to linearize the Richards' equation. This approach considers four essential hydrodynamic parameters: the saturated (θs) and residual (θr) water content, the saturated hydraulic conductivity (Ks), and a specific parameter related to pore size distribution (α).

Furthermore, the groundwater pressure, when the flow is downward and gravity-driven, can never exceed the value that would be obtained if the water table were at the ground surface itself:

$$\psi(Z,t) \leq Z\beta \tag{1}$$

$$Z = z/cos\delta \tag{2}$$

Where ψ is the groundwater pressure head; t is the time for which we want to calculate ψ; z is the slope-normal coordinate direction; δ is the slope angle and for slope-parallel $\beta = cos^2\delta$.

In practice, when rain infiltrates, a portion is absorbed by the unsaturated soil layer. The remaining water passes through this unsaturated zone and accumulates just above the original water table. In this way, the unsaturated soil acts as a "natural filter" that decreases the intensity, smooths and delays the arrival of surface water at depth (Baum; Godt; Savage, 2010).

To calculate the factor of safety (FS) in unsaturated soils, the model uses the approximation proposed by Vanapalli and Fredlund (2000) for a corrective factor (χ):

$$\chi = \frac{(\theta - \theta r)}{(\theta s - \theta r)} \tag{3}$$

where θ is the soil water content.

This factor, given by equation 3, is then multiplied by the cohesion term in equation (4) to calculate the FS in the case of unsaturated soils. Further details can be found in Baum, Savage, Godt (2008) and Baum, Godt, Savage (2010).

For saturated soils, the factor of safety is given by the ratio of resisting basal Coulomb friction to gravitationally induced downslope basal driving stress (Baum; Godt; Savage, 2010):

$$Fs(Z,t) = \frac{tan\ \phi'}{tan\ \delta} + \frac{c' - \psi(Z,t)\gamma_w tan\ \phi'}{\gamma_s Zsin\delta cos\delta} \tag{4}$$

Where $c'$is soil cohesion for effective stress, ϕ' is the soil friction angle for effective stress, γ_w is the unit weight of groundwater and γ_s is the soil unit weight.

2.3 Methods

In this study, TRIGRS-P, a probabilistic variant of the original model that allows for the variation of input parameters based on a Gaussian distribution, was adopted. The study area was divided into four zones (Figure 1), defined by geological soil type (till, peat, glaciofluvial deposits, and bedrock), as adapted from the Geological Survey of Norway (NGU). For the analysis, a Digital Elevation Model (DEM) of the respective study region, with a 5x5m resolution and dated 2010 (thus, prior to the investigated rainfall event), was utilized. For the calculation of the Factor of Safety (FS), each zone received a set of typical parameters for its soil type, considered as a probability distribution of material properties rather than a constant value, as detailed in Table 1.

For the estimation of the soil thickness in the region, Schilirò et al. (2021) did not use the original model proposed by Saulnier, Beven, and Obled (1997). Instead, they collected and plotted thickness values from field surveys against the tangent of the slope, using a least squares linear fit to derive a specific empirical equation for the study area:

$$y = -2.5692x + 2.607 \tag{5}$$

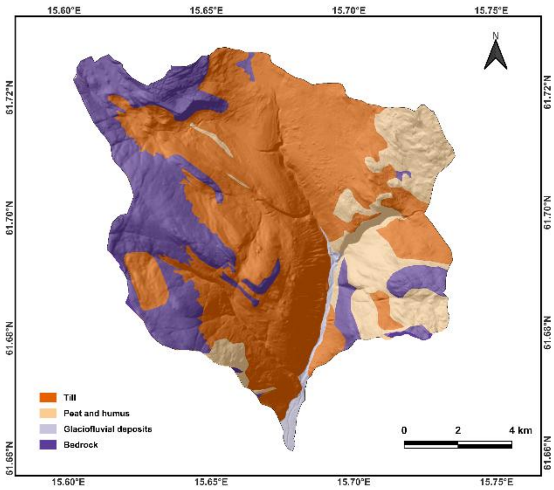

Figure 1. Geological map of the study area divided into four zones (adapted from Abraham et al., 2025).

Table 1. Input parameters for the TRIGRS model (table adapted from Schilirò et al., 2021).

PARAMETER	UNIT	SOURCE*
Zone	-	NGU
Slope (δ)	(º)	5m ×5m DEM
Soil thickness(H)	(m)	Fitting equation (Schilirò et al., 2021)
Friction angle (ϕ')	(º)	(Melchiorre; Frattini, 2012)
Cohesion (c')	(kNm^{-2})	(Melchiorre; Frattini, 2012)
Soil unit weight (γ)	(kNm^{-3})	(Melchiorre; Frattini, 2012)
Hydraulic conductivity (K_s)	(ms^{-1})	(Melchiorre; Frattini, 2012)
Hydraulic diffusivity (D_0)	(m^2s^{-1})	(Melchiorre; Frattini, 2012)
Saturated water content (θs)	-	ROSETTA Lite module (Schaap et al., 2001)
Residual water content (θr)	-	ROSETTA Lite module (Schaap et al., 2001)
Pore-size parameter (α)	(m^{-1})	ROSETTA Lite module (Schaap et al., 2001) and (Ghezzehei; Kneafsey; Su, 2007)
Initial water table depth (d_{wt})	(m)	Norwegian Water Resources and Energy Directorate (Xgeo)
Background rainfall rate (I_{zlt})	(ms^{-1})	Norwegian Water Resources and Energy Directorate (Xgeo)
Rainfall rate (I_z)	(ms^{-1})	Norwegian Meteorological Institute

* The values presented in this table are based on the cited references, but have been calibrated for the specific conditions of the model.

Where x is the tangent of the slope and y is the soil thickness.

The material properties (Table 2) for the TRIGRS model were calibrated by comparing Factor of Safety (FS) values with 2011 landslide source areas from Schilirò et al. (2021) using a confusion matrix. For parameters following a normal distribution, the standard deviation (SD) was heuristically estimated as 10% of the mean, with minimum and maximum limits set at mean ± 2.SD.

For the definition of True Positives (TP), True Negatives (TN), False Positives (FP), and False Negatives (FN), calculations were performed for each model calibration using a 3 × 3 matrix approach. This matrix assumes that if the FS ≤ 1 for a given cell, any of the eight surrounding cells may also fail. This premise significantly reduces FPs when compared to the results reported by Schilirò et al. (2021).

Table 2. Calibrated material properties used in TRIGRS (Abraham, et al, 2025).

Zone	Cohesion (kPa)	Internal friction angle (degrees)	Unit weight (kN/m^3)	Hydraulic diffusivity (m²/s)	Saturated hydraulic conductivity (m/s)	Saturated moisture content	Residual moisture content
	Mean value, normal distribution			Constant value			
Till	4	35	20	4×10^{-3}	1×10^{-5}	0.40	0.08
Peat and humus	20	5	15	4×10^{-7}	2×10^{-6}	0.50	0.15
Glaciofluvial deposits	3	35	20	4×10^{-3}	1×10^{-4}	0.30	0.03
Bedrock	60	40	26	4×10^{-7}	1×10^{-8}	0.05	0.01

3 RESULTS

In landslide studies over large areas, as anticipated, the number of True Negatives (TN), meaning the correct prediction of no landslide occurring, was significantly higher. In such cases, the Matthews Correlation Coefficient (MCC) stands out as a robust metric for binary classification problems, especially with imbalanced classes. The MCC is effective because it considers all four components of the confusion matrix (TP, TN, FP, and FN), offering a comprehensive evaluation that is resistant to distortions caused by class imbalance. In this study, the MCC was 0.33, whereas in Schilirò et al., 2021, it was 0.15.

4 CONCLUSIONS

This study successfully applied the Transient Rainfall Infiltration and Grid-Based Regional Slope-Stability Model (TRIGRS), a deterministic model, with a probabilistic distribution for its input parameters to assess landslide hazard in the Kvam region, Norway. Our methodological refinements in input data preparation, specifically spatial discretization through zoning and the use of a 3 × 3 matrix approach for calibration, led to a significant improvement in model performance.

The results show that these methodological improvements directly enhanced the model's predictive capability, as evidenced by a higher Matthews Correlation Coefficient (MCC) of 0.33, compared to the 0.15 reported in the reference study by Schilirò et al. (2021). While this approach led to an increased number of False Negatives (FNs), the rise in the MCC demonstrates a more reliable correlation between our model's predictions and actual landslide occurrences, thereby improving its utility for risk assessment.

The main contribution of this work is that it proves methodological refinements, even with established models, can significantly improve performance and the reliability of hazard maps. This study highlights the importance of a nuanced approach to data preparation and calibration, providing a more effective tool for geotechnical risk management and supporting land-use planning in landslide-prone areas. Future research could focus on optimizing the parameter calibration process and applying this refined methodology to other regions to further validate its effectiveness.

REFERENCES

Abraham, M. T., Piciullo, L., Liu, Z., Drøsdal, I. N., Robinson, H., Rudjord, Z. C., Blomberg, A. E. A., Maio, E. C., Ribeiro, W. N., & De Mendonça, M. B. (2025). Operational regional scale landslide forecasts: Physics-based and data-driven models. In Z. Liu, J. Dai, & K. Robinson (Eds.), *Proceedings of the 9th International Symposium for Geotechnical Safety and Risk (ISGSR)*. Oslo, Norway: ISGSR.

Baum, R. L., Godt, J. W., & Savage, W. Z. (2010). Estimating the timing and location of shallow rainfall-induced landslides using a model for transient, unsaturated infiltration. *Journal of Geophysical Research*, v. 115, F03013.

Baum, R. L., Savage, W. Z., & Godt, J. W. (2008). *TRIGRS—A Fortran Program for Transient Rainfall Infiltration and Grid-Based Regional Slope-Stability Analysis: Version 2.0*. Reston, VA, USA: U.S. Geological Survey. (Open-File Report 2008-1159), 75 p.

Ghezzehei, T. A., Kneafsey, T. J., & Su, G. W. (2007). Correspondence of the Gardner and van Genuchten-Mualem relative permeability function parameters. *Water Resources Research*, v. 43, W10417.

Iverson, R. M. (2000). Landslide triggering by rain infiltration. *Water Resources Research*, v. 36, p. 1897–1910.

Melchiorre, C., & Frattini, P. (2012). Modelling probability of rainfall-induced shallow landslides in a changing climate, Otta, Central Norway. *Climatic Change*, v. 113, p. 413–436.

Norwegian Ministry Of Climate And Environment. (2023). *Meld. St. 26 (2022–2023) Report to the Storting (white paper): A changing climate – united for a climate-resilient society*. Oslo: Norwegian Ministry of Climate and Environment.

Norwegian Ministry Of Climate And Environment. (2013). *Meld. St. 33 (2012–2013) Report to the Storting (white paper): Climate change adaptation in Norway*. Oslo: Norwegian Ministry of Climate and Environment.

Saulnier, G. M., Beven, K., & Obled, C. (1997). Including spatially variable effective soil depths in TOPMODEL. *Journal of Hydrology*, v. 202, p. 158–172.

Schaap, M.G.; Leij, F.J.; Van Genuchten, M.T. (2001). ROSETTA: A computer program for estimating soil hydraulic parameters with hierarchical pedotransfer functions. *J. Hydrol*., 251, 163–176.

Schilirò, L., Cepeda, J., Devoli, G., & Piciullo, L. (2021). Regional Analyses of Rainfall-Induced Landslide Initiation in Upper Gudbrandsdalen (South-Eastern Norway) Using TRIGRS Model. *Geosciences*, v. 11, n. 35.

Sletten, K., & Blikra, L. H. (2007). Holocene colluvial (debris-flow and water-flow) processes in eastern Norway: stratigraphy, chronology and palaeoenvironmental implications. *Journal of Quaternary Science*, v. 22, p. 619–635.

United Nations. (2015). *Sendai Framework for Disaster Risk Reduction 2015-2030*. Genebra: United Nations Office for Disaster Risk Reduction (UNDRR).

Vanapalli, S. K., & Fredlund, D. G. (2000). Comparison of different procedures to predict unsaturated soil shear strength. In: SHACKELFORD, C. D., HOUSTON, S. L., & CHANG, N. Y. (Eds.). *Advances in Unsaturated Geotechnics*. Reston, VA, USA: Society of Civil Engineers