A NUMERICAL STUDY ON RAINFALL-INDUCED LANDSLIDES AND DEBRIS FLOW HAZARDS IN NKHULAMBE CATCHMENT AREA

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ABSTRACT

The increased frequency of extreme rainfall events from tropical cyclones has caused flood disasters with landslides and debris flows in Malawi. This study analyzed the landslides and debris flow hazards in Nkhulambe area caused by Tropical Cyclone Freddy in March 2023. A slope stability analysis was conducted to predict landslide occurrences using the Rainfall and Sediment Runoff Model. Furthermore, a 2-D debris flow model was employed to simulate the detailed runout processes, utilizing the predicted landslide areas as the initial condition. Similarly, analyses were conducted using the predicted post-disaster landform to investigate the area's future landslides and debris flow responsiveness to different rainfall conditions. Based on the inferred local soil conditions in this study area, the threshold of accumulative rainfall depth for the landslide outbreaks was estimated to be 105 mm. The future analyses suggested that even small-scale landslides could potentially trigger larger-scale debris flow hazards due to such soil conditions. Moreover, the high-risk debris flow area was identified under different rainfall conditions, revealing the necessity of considering this in future land use planning.

Keywords: landslides, debris flow, rainfall sediment runoff (RSR), two-dimensional debris flow simulation.

INTRODUCTION

Sediment-related disasters, such as landslides and debris flows, threaten Malawi's natural environments and human society owing to socio-economic and climate change factors that have led to an increase in the occurrence of disasters. Factors such as high rates of deforestation, land degradation, and watershed mismanagement which have worsened in recent years further increase the risk of floods and landslides in Malawi (Government of Malawi 2023) and could increase the number of people affected every year. The Tropical Cyclone Freddy (TCF)-induced rainfall that caused sediment and flood disasters in March 2023, identified knowledge and capacity gaps in understanding and preparing for large flood disaster events associated with landslides and debris flows (Government of Malawi, TCF Report 2023). The lack of a comprehensive understanding of sediment dynamics in the face of extreme weather events poses a great threat to communities settled in low-lying areas. As such, understanding sediment-related disaster phenomena through a comprehensive study and initiative-taking proactive measures can significantly reduce the risk to communities.

Therefore, this study aims to propose a method to predict the occurrence of rainfall-induced landslide and the detailed debris flow runout process, and to apply this method to the landslide and debris flow disaster caused by Tropical Cyclone Freddy in March 2023 in Nkhulambe catchment area. Furthermore,

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the same analyses will be conducted using predicted post-disaster landforms to estimate the future landslide and debris flow hazard responsiveness under different rainfall conditions in this area.

METHODOLOGY

1. The outline of rainfall-induced landslides and debris flows prediction

The proposed method for predicting rainfall-induced landslides and debris flows is illustrated in **Figure 1**, which shows the basin-scale Rainfall and Sediment Runoff (RSR) model developed by Harada and Egashira (2023) and Qin *et al.* (2023). The model was used to predict the occurrence of landslides during the rainfall-runoff process by applying slope stability analysis and then providing the predicted landslide areas as an initial condition for the 2-D debris flow simulation using a depth-integrated 2-D debris flow model (Morpho2DH Model, Takebayashi 2014).

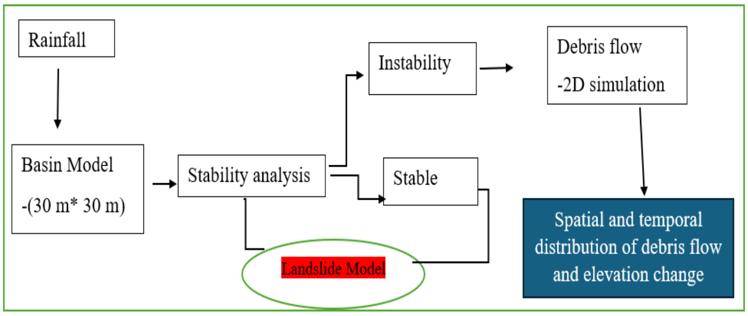

Figure 1. *Methodology for landslides and debris flow prediction*

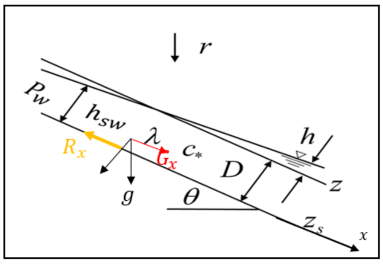

Figure 2. *Schematic structure of a mountain slope*

2. Governing Equations

2.1 Slope stability analysis

A slope stability analysis was applied to predict landslide occurrence on mountain slopes. **Figure 2** shows the schematic structure of a mountain slope in RSR Model, where the model calculates the seepage and surface flow conditions in each grid cell based on the rainfall-runoff process. At each time step, by comparing the difference between the gravity component G_x (see equation (1)) and the resistance force R_x (see equation (2)) due to Coulomb friction and cohesion of the surface soil mixture of water and sediment parallel to the steepest slope direction of the grid cell, if G_x exceeds R_x in any grid cell, that surface soil block is immediately released from its position and identified as a landslide area.

$$G_x = \rho_w g D \sin\theta \cdot \left\{\frac{\sigma}{\rho_w} c_* + \left(1 - \frac{h_s}{D}\right) p_w + \frac{h_s}{D}(1 - c_*) + \frac{h}{D}\right\} \qquad (1)$$

$$R_x = \rho_w g D \cos\theta \cdot \left\{\frac{\sigma}{\rho_w} c_* + \left(1 - \frac{h_s}{D}\right) p_w - \frac{h_s}{D} c_*\right\} \tan\phi_s + c \qquad (2)$$

where ρ_w is the mass density of water, θ is the steepest slope of the grid cell, σ is the mass density of the sediment particle, c_* is the sediment concentration of surface soil in volume, g is the gravitational acceleration, D is the depth of the surface soil, p_w is the water content of surface soil in volume, the maximum value of p_w during the wetting process before the seepage flow forms is given as 0.1, h_s and h are the depth of seepage flow and surface flow, respectively, ϕ_s is the internal friction angle of the surface soil, c is the cohesion of the surface soil.

2.2 Two-dimensional debris flow simulation

2.2.1 Mass conservation equation of debris flow

$$\frac{\partial h}{\partial t} + \frac{\partial uh}{\partial x} + \frac{\partial vh}{\partial y} = \frac{E}{c_*} \qquad (3)$$

$$\frac{\partial \bar{c}h}{\partial t} + \frac{\partial \gamma\bar{c}uh}{\partial x} + \frac{\partial \gamma\bar{c}vh}{\partial y} = E \qquad (4)$$

where h is the depth of the debris flow, u and v are the x and y components of flow depth-averaged flow velocity $\overline{c}$ is the sediment concentration of the debris flow, c_* is the sediment concentration in the stationary layer, γ is the correction factor for sediment transportation, E is the erosion and deposition velocity, which is determined by, where a positive value indicates erosion and negative values indicate deposition, θ_e is the equilibrium bed slope corresponding to the sediment concentration of the debris flow body obtained by Eq. (5).

$$\tan\theta_e = \frac{(\sigma/\rho - 1)c_c}{(\sigma/\rho - 1)c_c + 1}\tan\phi_s \qquad (5)$$

$$\rho = (\sigma - \rho_w)c_f + \rho_w \qquad (6)$$

where ρ is the mass density of the pore fluid containing the very fine sediment, c_c is the volume concentration of the coarse sediment in debris flows, $c_c = p_c c_*$, c_f is the volume concentration of very fine sediment in the pore fluid, $c_f = p_f c_*/(1 - c_c)$, p_c, p_f are the coarse sediment and very fine sediment content in the debris flow, respectively.

2.2.2 Mass conservation equation of bed sediment

$$\frac{\partial z_b}{\partial t} = -\frac{E}{c_* \cos\theta} \qquad (7)$$

where z_b is the bed elevation.

2.2.3 Momentum conservation equation for debris flow

$$\frac{\partial uh}{\partial t} + \frac{\partial \beta uuh}{\partial x} + \frac{\partial \beta vuh}{\partial y} = -gh\frac{\partial H}{\partial x} - \frac{\tau_{bx}}{\rho_m} \qquad (8)$$

$$\frac{\partial uh}{\partial t} + \frac{\partial \beta uvh}{\partial x} + \frac{\partial \beta vvh}{\partial y} = -gh\frac{\partial H}{\partial y} - \frac{\tau_{by}}{\rho_m} \qquad (9)$$

where g is the acceleration due to gravity, H is the water surface elevation,τ_{bx} and τ_{by} are the x and y components of bed shear stress.

2.2.4 Bed shear stress

$$\tau_{bx} = \{\tau_y + \rho f_b(u^2 + v^2)\}\frac{u}{\sqrt{u^2 + v^2}} \qquad (10)$$

$$\tau_{by} = \{\tau_y + \rho f_b(u^2 + v^2)\}\frac{v}{\sqrt{u^2 + v^2}} \qquad (11)$$

$$\tau_y = \frac{\bar{c}^{1/5}}{c_*}(\sigma - \rho)\bar{c}\cos\phi_s\tan\phi_s \qquad (12)$$

$$f_b = \frac{25}{4}(f_d + f_f)\left(\frac{h}{d_{mean}}\right)^{-2} \qquad (13)$$

$$f_d = k_d(\sigma/\rho)(1 + e^2)\bar{c}^{1/3}$$

$$f_f = k_f(1 - \bar{c})^{5/3}/\bar{c}^{2/3}$$

where,τ_y is the yield shear stress, f_b is the resistance coefficient of the flow, d_{mean} is the mean diameter of the debris flow sediment, e is the restitution of the sediment particles, $k_d = 0.0828$, $k_f = 0.16$.

STUDY AREA AND COMPUTATION CONDITIONS

This study has focused on the Nkhulambe catchment area in the Phalombe District, Malawi. The area is located in the Mulanje Mountain basement and has riverine ecosystems that flow from the catchment to the Lake Chilwa Basin. The area registered the highest record-breaking rainfall amount from 11th to 14th March 2023 due to the influence of Tropical Cyclone Freddy. Consequently, the region was subjected to a significant and extensive landslide and debris flow disaster.

This study utilized the digital elevation model (DEM) from ASTGTM with a 30m resolution used for both the RSR model and Morph2D model, and the domain areas and parameter settings for the two models are shown in **Figure 3** and **Table 1**, respectively. The hourly rainfall data from the Gwirima station between March 12th and 14th, 2023 were input into the RSR model for a total of 73 hours (shown in **Figure 5**).

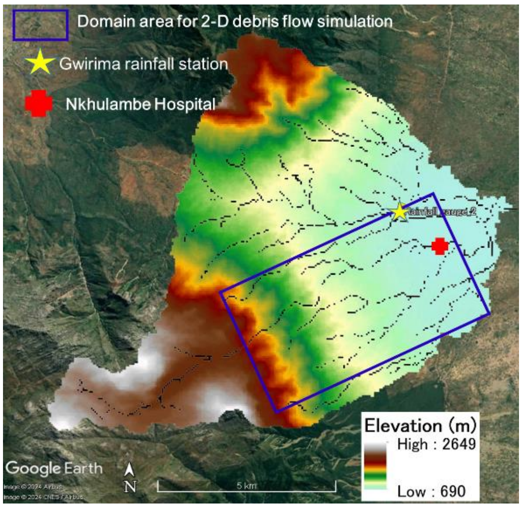

Figure 3. *Study area and computation domains*

Table 1. *Parameter setting for models*

Slope stability analysis (RSR model)			2-D debris flow simulation (Morpho2DH model)	
Equivalent roughness	0.5		Mean diameter of debris flow sediment (cm)	20
Surface soil depth (m)	1.0		Surface soil depth (m)	2
Fine sediment content in surface soil	0.3		Fine sediment content in surface soil	0.3
Porosities of surface soil	0.4		Porosity of surface soil	0.4
Cohesion of surface soil (kN/m^2)	5.0		-	-
Lateral saturated hydraulic conductivity (m/s)	0.001		-	-

To estimate the future responsiveness of landslides and debris flows under different rainfall conditions, three cases were employed (see **Figure 7**). Case 1 has similar rainfall to the TCF event, Case 2 has 20% greater rainfall intensity, and Case 3 has 50% less rainfall intensity. The topographic data was used in the post-disaster landform predicted by the RSR model, with the remaining parameter settings identical to those outlined in **Table 1**.

RESULTS AND DISCUSSION

1. The evaluation of the debris flow runout process during Tropical Cyclone Freddy (TCF)

1.1 Prediction of the spatial distributions of landslide area due to TCF

As illustrated in **Figure 4**, a comparison was conducted between the predicted landslide areas distributed in the upstream area of the domain for the 2D debris flow simulation and the identified landslide areas from the satellite image. The predicted landslide area in the downstream area was found to be lower than the identified data, which is thought to be mainly due to the inability of the low spatial resolution of the DEM to capture steep slopes that appear in relatively small areas. However, the extent and pattern of the spatial distribution were well simulated.

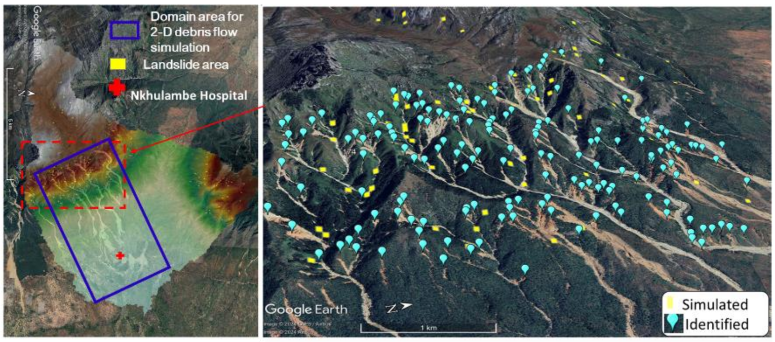

Figure 4. *Predicted spatial distribution of landslide areas*

As shown in **Figure 5**, the accumulated unstable meshes representing the number of landslides in the study area increased during the period of intense rainfall. The maximum number of unstable meshes reached 232 at approximately 16:00 on 13 March 2023, which was 59 hours after the computation started. Based on the assumptions regarding the soil condition presented in **Table 1**, the threshold of accumulative rainfall depth for the landslide outbreaks was estimated to be 105mm (starting from a dry soil condition), which was reached at 40 hours after the computation started.

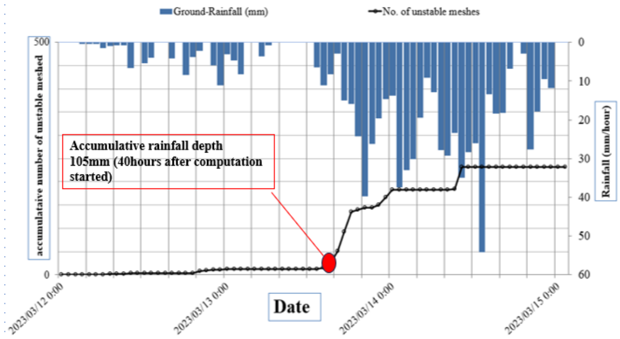

Figure 5. *Temporal changes in rainfall intensity and the accumulative unstable mesh number*

1.2 The simulated debris flow runout process

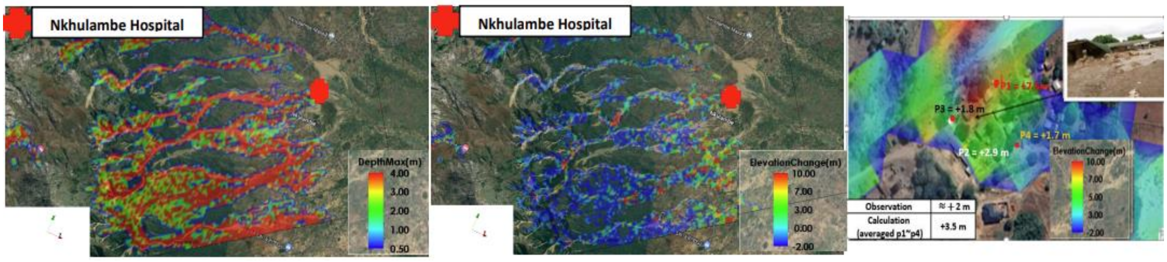

Figure 6. *Simulated debris flow runout process during TCF (**Left**: simulated the maximum debris flow depth in domain area. **Middle**: simulated elevation changes in the end. **Right:** simulated elevation changes around Nkhulambe hospital.*

Figure 6 shows the results of the 2-D debris flow simulation during TCF. The results were validated by comparing the sediment deposition depth around the Nkhulambe Hospital estimated by the photo taken after the debris flow disaster (**see Figure 6**, right). The simulation results indicated that the upstream areas experienced significant erosion, with the elevation decreasing by up to 2 m. As the slope decreased in the downstream area, much of the debris flow was deposited in the plain area that was used for settlement and farming. This resulted in an increase in the maximum depth of debris flow of 3 to 4 m and the maximum elevation aggradation ranging from 7 to 10 m in this area.

2. Estimation of future landslide and debris-flow responsiveness to the different conditions of rainfall

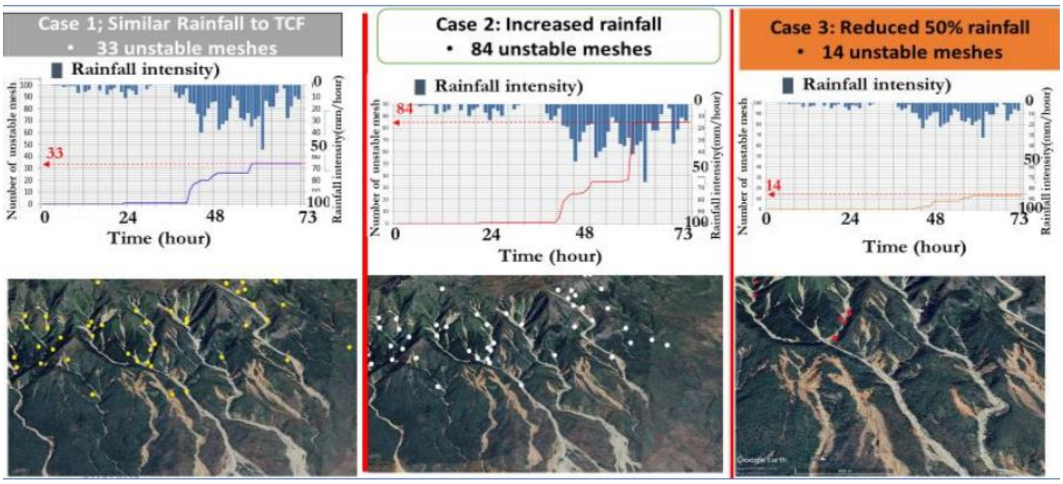

Figure 7. *Predicted future spatial distributions and temporal accumulative meshes of landslide under different rainfall conditions (left: case1, same with TCF; middle: case2, 120% of TCF; right: case3, -50% of TCF.)*

As shown in **Figure 7**, the landslide occurrence was predicted in all cases, and the total number of unstable meshes is much less than the predicted result in the simulation for the TCF disaster. This illustrates that the simulation results were generated reasonably, with consideration given to the reduction in the potential landslide area resulting from the pre-disaster effect. However, in Cases 1 and 2, the landslide areas were distributed over a wide area, with the extent of these areas not significantly different from the extent predicted for the TCF disaster.

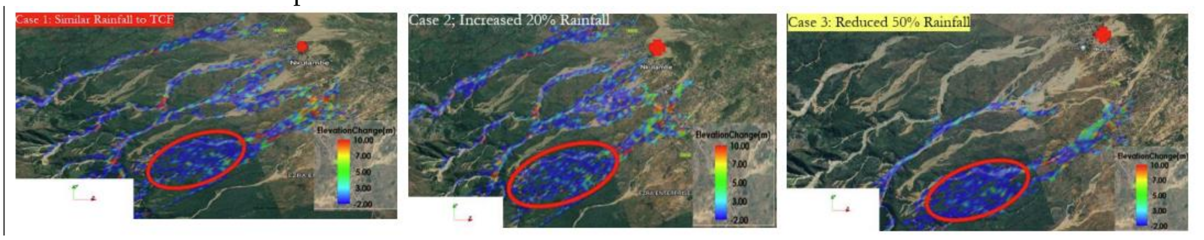

Figure 8. *Elevation changes for the three cases*

Moreover, as illustrated in **Figure. 8**, the areas of elevation change induced by the debris flow in all cases are relatively concentrated along the river channels and extend further upstream than in the simulation for TCF disaster. However, as shown in **Figure 8**, a common wide erosion area was predicted in all cases (encircled in red), indicating a high-risk debris flow area in the future.

CONCLUSIONS

Based on the inferred local soil conditions in this study, the threshold of accumulative rainfall depth for the landslide outbreaks was estimated to be 105mm, and the simulated results demonstrated that, during the TCF, high erosion was mainly concentrated in mountainous regions, while deposition was concentrated in low-lying plain areas where settlements were located. The depth of deposition depth widely distributed from 3 m to 4 m, with some areas reaching a maximum depth of 7 m to 10 m. In addition, the maximum debris flow depth tended to be generated along river channels from upstream to downstream, with a maximum depth ranging from 3 m to 4 m. The future analyses suggested that even small-scale landslides in the study area could potentially trigger larger-scale debris flow hazards due to the inferred soil conditions. Furthermore, a high-risk debris flow area was identified, exhibiting a comparable pattern of widespread erosion under different rainfall conditions, revealing the necessity of considering this in future land use planning.

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