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Mechanisms of initiation, runout, and rainfall thresholds of extreme-precipitation-induced debris flows

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Abstract

The frequency of unprecedented extreme precipitation events is increasing, and consequently, catastrophic debris flows occur in regions worldwide. Rapid velocity and long-runout distances of debris flow induce massive loss of life and damage to infrastructure. Despite extensive research, understanding the initiation mechanisms and defining early warning thresholds for extreme-precipitation-induced debris flows remain a challenge. Due to the nonavailability of extreme events in the past, statistical models cannot determine thresholds from historical datasets. Here, we develop a numerical model to analyze the initiation and runout of extreme-precipitation-induced runoff-generated debris flows and derive the Intensity-Duration (ID) rainfall threshold. We choose the catastrophic debris flow on 6 August 2020 in Pettimudi, Kerala,

India, for our analysis. Our model satisfactorily predicts the accumulation thickness (7 m to 8 m) and occurrence time of debris flow compared to the benchmark. Results reveal that the debris flow was rapid, traveling with a maximum velocity of 9 m/s for more than 9 minutes. The ID rainfall threshold defined for the event suggests earlier thresholds are not valid for debris flow triggered by extreme precipitation. The methodology we develop in this study is helpful to derive ID rainfall thresholds for debris flows without historical data.

Keywords: Debris flows, initiation, runout, numerical modeling, ID thresholds

1 Introduction

The frequency of extreme weather events under climate change is increasing (Field et al. 2012, Dash & Maity 2021). Consequently, unprecedented extreme precipitation triggers hydrological hazards, i.e., debris flows across the globe (Cannon & DeGraff 2009, Stoffel et al. 2014, Turkington et al. 2016). Mountainous regions in Japan, China, and India have witnessed series of debris flows in the last decade (Furuichi et al. 2018, Fan et al. 2019, Yunus et al. 2021). Examples are the decade-long occurrence of debris flows post the Great Wenchuan earthquake in China (2008-2020); the 2016 typhoon Lionrock triggered debris flows in Hokkaido, Japan; and the 2018 extreme-precipitation-induced debris flows in Kerala, India (Zhu et al. 2020, Hao et al. 2020, Dai et al. 2021). Extreme precipitation during 2018, 2019, and 2020 monsoons induced series of catastrophes, i.e., flash floods, landslides, and debris flows in the Western Ghats, India, resulting in more than 500 casualties and affected over 5.4 million people in 1200 towns (Mishra & Shah 2018, Ramasamy et al. 2019, Sankar 2018, Ramasamy et al. 2019, Vishnu et al. 2019, Yunus et al. 2021). Historically, landslides occurred extensively in many districts in the Western Ghats, both in Karnataka and Kerala. 13 out of the 14 districts in Kerala alone are landslide prone (Kuriakose, Sankar & Muraleedharan 2009). Between 1969 – 2009, 63 fatal landslides causing 257 casualties occurred in Kerala (Kuriakose et al. 2010). Whereas in 2018 alone, landslides caused more than 433 casualties (Abraham et al. 2019). Though landslides were common in the past, their numbers increased significantly during 2018, 2019, and 2020 (Abraham et al. 2019, Achu et al. 2020, Sajinkumar et al. 2014, Sajinkumar & Anbazhagan 2015). For example, in the Idukki district, 64 major landslides occurred until 2010, whose total count rose to 2223 in 2018 (Hao et al. 2020, Kuriakose et al. 2010, Kuriakose, Sankar & Muraleedharan 2009). In addition to the threat to life, debris flows disrupt livelihood and socio-economic activities in mountainous regions, leading to mass population displacements (Jakob et al. 2005, Dowling & Santi 2014, Ding et al. 2016). Hence for mitigation, there is a need to study the initiation mechanisms to define rainfall thresholds of extreme-precipitation-induced debris flows.

State of the art studies in the past decades gives an understanding of initiation mechanisms of debris flows. Iverson (1997) gave insights on the physics of debris flow initiation and runout on a catchment scale and emphasized three processes: (a) widespread coulomb failure, (b) partial or complete liquefaction, and (c) conversion of landslide translational energy to internal vibrational energy (Iverson et al. 1997). Meanwhile, Reid et al. (1997) performed debris-flow initiation experiments using diverse hydrologic triggers and provided exceptionally complete data on conditions preceding and accompanying slope failure and debris-flow mobilization. Later, Imaizumi et al. (2006), through performing in-situ observations of numerous debris flows in a steep channel (>20 deg) in the Ohya landslide area, central Japan, explored the role of partial saturation of sediments. Their work proposed the critical conditions for the movement of unsaturated materials by equating shear stress with solid friction of the channel bed and assessed the mechanism of hydrogeomorphic processes in the debris flow initiation zones. Recently, (Van Asch et al. 2014) proposed an integrated model that defines critical rainfall thresholds for runout distances of debris flows based on the experimentally derived equation of erosion from Takahashi et al. (1992). Many studies focusing on hazard and risk assessment of shallow landslides in the Indian sub-continent are available (Gupta & Virdi 2000, Gupta & Ahmed 2007, Kumar & Bhagavanulu 2008, Kumar et al. 2018, Martha et al. 2013, 2019, Mathew et al. 2014, Solanki et al. 2019, Vijith et al. 2014). However, very few studies are available for debris flows (Kuriakose, Luna, Portugues & Van Westen 2009, Jaiswal et al. 2011, Sujatha & Sridhar 2017, Singh et al. 2018, Chatteraj et al. 2018, Abraham et al. 2021, Dash et al. 2021). Earlier, Kuriakose, Luna, Portugues & Van Westen (2009) performed runout modeling of the 2001 debris-flow event in the Kottayam district of Kerala, India, using the DAN3D program (Hungr 1995, Hungr & McDougall 2009). Abraham et al. (2021), using the RAMMS program (Christen et al. 2010), performed runout modeling of the 2018 Kurichermala debris flows in the Wayanad district of Kerala, India. Dash et al. (2021) studied the runout dynamics of the 2013 Tangni debris flow that occurred in Garhwal Himalayas, India.

Most of the studies for debris flows in India, as mentioned above, analyzed the runout of debris flows with seldom importance given to the initiation and triggering conditions. Both the DAN3D and RAMMS programs require the user to define an initial volume of failure mass assuming that the failure has already occurred and then simulate only the runout of the debris over a terrain (Van Asch et al. 2010). Runout modeling is helpful in benchmark/calibrate models for quick hazard/risk assessments of large landslides (Scaringi et al. 2018, Fan et al. 2020). However, they are not beneficial to study governing mechanisms of initiation and failure time of debris flows (Van Asch et al. 2014, 2018). Previous modeling efforts, i.e., Kuriakose, Luna, Portugues & Van Westen (2009), Abraham et al. (2021), Dash et al. (2021), do not relate the rainfall with debris flow triggering and are not helpful to predict the ID thresholds. To address these research gaps, we modify the modeling framework

proposed in Van Asch et al. (2014) to simulate the initiation and runoff of extreme-precipitation-induced debris flow in this study.

Using the numerical model developed in this study (Van Asch et al. 2014, Domènech et al. 2019), we analyze the 06 August 2020 debris flow to understand the triggering conditions. Through parametric numerical simulations, we derive the triggering intensity-duration (ID) thresholds under various rainfall intensities. In addition, the ID thresholds reported in previous studies for this region for the period between 2010-2018 do not distinguish the landslide type, i.e., shallow landslides and debris flows (Abraham et al. 2019, 2020, Sajinkumar et al. 2020). Further, previous studies defined ID thresholds using statistical approaches and historical data. Inaccuracies are inevitable in such methods since thresholds are from statistical correlations of past events. Historical data may not contain extreme rainfall events, and corresponding debris flow occurrences (Guzzetti et al. 2008). More extreme rainfall than 2018, 2019, and 2020 events occurred in 1924 and 1961, but no record of debris flow occurrences was available (Yunus et al. 2021). It is not prudent to use previously established thresholds to predict the Pettimudi event as earlier studies did not consider debris flows triggered by heavy rainfall (Abraham et al. 2019). To address the challenge mentioned above, we attempt numerical modeling to derive ID thresholds for the Pettimudi debris.

We organize the rest of the manuscript as follows. Section 2 introduces the characteristics of the disastrous debris flow event that occurred in Pettimudi, Kerala, India. Section 3 first details the data and methods we adopt in this study, including the rainfall data and other site-specific information. Then, the numerical model explanation is presented, focusing on the improvements made in this study compared to the original model by Van Asch et al. (2014). After this, we detail the ID threshold method we adopt in this study. Section 4 comprises the results of the numerical modeling and ID threshold analysis. We discuss the recent increasing occurrences of debris flow events in the Western Ghats of Kerala, India, and highlight the improvements needed in ID threshold analysis in Section 5. We explicitly mention the limitations of the study. Finally, in Section 6, we conclude the main findings of this study and imply the necessity of future works.

2 Characteristics of the 6 August 2020 debris flow

Around 22:45 (IST) on 6 August 2020, a catastrophic debris flow struck in the Pettimudi village, Idukki district, Kerala, India ($10^{\circ}10'18.04''$ N and $77^{\circ}0'40.42''$ E), 10 km away from the tourist town of Munnar, causing more than 60 casualties (Achu et al. 2021). Pettimudi village is located deep within the "Shola forests" and covers many tea estates surrounding the area (Fig. 1a). The site is within the west draining slopes of the Rajamalai range. Settlements mostly of laborers of the tea estate were present very near to the confluence of the second-order stream with the main flowing Anaimudi river channel. A

network of one-line (single lane) estate roads connects these settlements with the uphill tea plantations. We delineate the extent of the debris flows from the February 2021 (post-event) Google earth imagery. Superimposing the debris flow boundary over the February 2020 (pre-event) boundary reveals the debris flow intersects multiple times (Fig. 1a) with the one-line estate roads. A first- and the second-order stream is also visible from the pre-event imagery, which follows the same path as the debris flow (Fig. 1a). Preliminary investigations suggested that the debris flow traveled through the first-order and second-order drainages of the catchment transporting a large amount of eroded and entrained materials. Across the first-and second-order drainage, tea plantations and cut slopes were present (Achu et al. 2021). This study uses remote sensing products, numerical analysis, and interpretations to understand the mechanism of initiation and runout of the debris flow. We find that the debris flows traveled through tea plantation areas, across many single-lane roads on the hillslopes, collapsing embankments, and taking the materials through drainage that connects the main river (see Fig. 1b).

The initiation of debris flows took place within the steep Shola forests. Above the initiation zone, a hollow region with barren soil and rock might supply an enormous amount of runoff water through the first-order stream. The debris flow fan that spread over the river is more than 120 m in length. The total travel distance of the debris flow is 1250 m. After crossing several embankments of the estate road, the debris flow traveled downward (Fig. 2a), damaging the nearby settlements (Fig. 1b). Besides, most of the settlements (more than four rows of continuous housing blocks) were located just before the stream's confluence with the Anaimudi river. These settlements are destroyed and washed out thoroughly (Fig. 2), resulting in more than 60 casualties. The geology in this area is predominant of Precambrian crystallines of Southern Granulite Terrain (SGT). The principal rock types are granite and migmatitic gneiss (Achu et al. 2021). Within the initiation zone, unconsolidated overburden (2 – 5 m thick), mostly of soil and slope debris, was present above the moderately weathered granitic gneiss (GSI, 2020). Water absorption of weathered granitic soil could be a causal factor of such kind of heavy rainfall-induced debris flows (Furuichi et al. 2018, Zhu et al. 2020). The initiation zone of the debris flow is around 2100 m a.s.l. (above sea level) while the deposition zone is approximately 1595 m a.s.l. (Fig. 2c). The debris flow volume is estimated to be around 280500 m³, and the total area of the event was about 70125 m² (Achu et al. 2021).

3 Data and methods

3.1 Rainfall and other site-specific data/information

Achu et al. (2021) report the rainfall data available nearest to the disaster site from Nyamakad estate station (Fig. 3a), located 8 km away from Pettimudi. The rainfall record at Nyamakad estate station exhibits an enormous down-pour (600 mm/day) on the day of the disaster, 6 August 2020. In addition to

Fig. 1: Pre- and post-event satellite images of the 6 August 2020 debris flow in Pettimudi, Kerala India (source: Google Earth). (a) Pre-event imagery dated February 2020 (the traveling path of the debris flow is marked in white), (b) Post-event google earth imagery dated February 2021: sediments are marked in white color, (c) Debris flow extent superimposed over a digital elevation model, and (d) location of the disaster site in Pettimudi, Idukki district, Kerala, India.

Fig. 2: Photographs taken during the field investigations. (a) Trailing path of the debris flow viewed from the bottom of the slope along the second order stream, (b) Location where the debris flow fan was spread near the Anaimudi river, (c) Buildings damaged by the sudden impact of the high-velocity debris flow.

this site-specific data, we collect station-wise rainfall data from India Meteorological Department (IMD). These data are monitored by IMD through stations (see Fig. 3b for locations) at different towns within the Idukki district, viz. Peermade, Thodupuzha, Munnar, Idukki, and Myladumpara (shown in Fig. 4a and b).

Preliminary reports classify this rainfall event as a cloudburst (Achu et al. 2021, Sajinkumar et al. 2020). Other places within the district, i.e., Peermade, Thodupuzha, Munnar, Idukki, and Myladumpara (see Fig. 1b for locations), also record heavy rainfall during the months from June to August 2020. However, none of the station's daily rain exceeds 250 mm/day on 6 August 2020. Besides, the cumulative rainfall from June to August is between 1500 mm and 2500 mm among these four stations, almost 75 % of the total annual rain recorded between 2018 and 2019 (Yunus et al. 2021).

In our analysis, based on the information from site investigations by the Geological Survey of India (GSI) and Achu et al. (2020), we consider the maximum depth to bedrock (soil depth) as 5 m. Besides, Weidner et al. (2018) and Kuriakose, Luna, Portugues & Van Westen (2009) suggest empirical equations to estimate the distributed soil depth for landslide case studies in Western Ghats, Kerala. Those equations also derive a maximum of 5 m soil depth. GSI report identifies the event initiated as a planar failure at the contact between rock and overburden in debris slide and then transformed into a debris flow.

Fig. 3: (a) Hyetograph showing recorded daily rainfall at Nyamakad estate station, data from Achu et al. (2021), blue line shows the cumulative rainfall and (b) Location of rain gauge stations near Pettimudi and other places within Idukki district.

The relatively thin (0.5 m - 5 m deep) materials at the slope comprise soil, debris, and weathered rock that got saturated during continuous rain, causing the build-up of pore water pressure and reduction in shear strength, favoring the initiation of debris flows.

3.2 Numerical modeling and analysis

This study develops a numerical model for debris flow simulation using the fundamentals implemented by Van Asch et al. (2014). The new model is a modified version of Van Asch et al. (2014)'s work and later applied by Domènech et al. (2019) to study the roles of loose co-seismic materials, grain sizes, and vegetation in the post-earthquake settings. We use the PCRaster platform based on a geographical information system (GIS) and model the governing equations using script/python-based command line (Deursen 1995). The model requires a digital elevation model (DEM), and the resolution of DEM is the mesh size. Other spatial derivatives, i.e., slope and local drainage direction, are computed for the hydrological and erosion analyses based on DEM. For our study and research, we use the freely available 12.5 m resolution ALOS-PALSAR DEM. Other spatial inputs such as the total area of the catchment,

Fig. 4: Hyetographs of rainfall for the period 01-06-2020 to 30-08-2020 from rain gauge stations located at Peermade, Thodupuzha, Munnar, Idukki, Myladumpara town in Idukki district, Kerala, India (data from IMD), a) Daily rainfall and b) Cumulative rainfall.

soil depth information, a scalar map with heights of the erodible bed materials, a map showing the location of precipitation, a map to allow flow through the DEM, i.e., Local Drainage Direction (LDD) are given input as ASCII formats through pre-processing by ArcGIS version 10.7.1 (Ormsby et al. 2004) and transferred to the PCRaster program.

The model splits the rainfall data into infiltration and overland flow runoff as follows (Van Asch et al. 2014):

$$R_u = (I - k_s) \quad (1)$$

where R_u is the overland flow runoff (m/s), and I (m/s) is the infiltration.

$$I = ASW + R_{ui}^* \quad (2)$$

where ASW denotes the available surface water (m/s) calculated from the input rainfall, and R_{ui}^* refers to the runoff water (m/s) contributed from upstream pixels. At each timestep, the model calculates unsaturated-saturated seepage inside each pixel based on the estimated infiltration. Based on the hydraulic conductivity of the soil at saturation, the model determines the available surface water that can infiltrate into the soil ground.

$$ASW = (P_r) \times \zeta \text{ and } \zeta = \begin{cases} 0, & P_r > k_s \\ 1, & P_r \leq k_s \end{cases} \quad (3)$$

where P_r is the precipitation (m/s), and k_s (m/s) is the hydraulic conductivity of soil at saturation. Along with the calculation of ASW, the model estimates the surface runoff generated from each pixel and routes towards the neighboring pixels based on the concept of Hortonian overland flow (Horton 1933, Corradini et al. 1994, 1998, De Roo et al. 2000, Van Der Knijff et al. 2010):

$$R_{ui^*} = (R_{uu}) \times \Omega \text{ and } \Omega = \begin{cases} 0, & R_{uu} > k_s \\ 1, & R_{uu} \leq k_s \end{cases} \quad (4)$$

where R_{ui^*} is the upstream contributed water that can infiltrate into the soil (m/s), and R_{uu} is the runoff from upstream contributed runoff water (m/s), which is a sum of all the infiltration excess runoff water from the upstream pixels. The available water for infiltration I (m/s) can infiltrate the soil/bed depending on the hydraulic conductivity and initial moisture content conditions. The model computes the infiltration in the soil based on the percolation theory as follows (Berkowitz & Balberg 1992):

$$P_e = \begin{cases} k_s \times \left[\frac{\theta - \theta_{\text{res}}}{\theta_{\text{sat}} - \theta_{\text{res}}} \right] \times \Delta t, & \theta > \theta_r \\ 0, & \theta < \theta_r \end{cases} \quad (5)$$

where P_e is the percolation in soil layer (mm/day), θ is the volumetric water content of soil (m^3/m^3), θ_{res} is the residual volumetric water content of soil (m^3/m^3), θ_{sat} is the volumetric water content of the soil at saturation (m^3/m^3), and Δt is the incremental time step. The volumetric water content at complete water saturation is equal to the porosity of the soil, and the model considers a fraction of this maximum as the volumetric water content at a residual degree of saturation. All liquid water storage and fluxes are in units of volume of water. At any time during the numerical simulation, the model can convert this value into a relative degree of saturation to make it convenient for calculating the percolation/infiltration within an unsaturated soil. The degree of saturation of soil S_r is defined as: (Lim et al. 1998, Fredlund 2006):

$$S_r = \frac{\theta - \theta_{\text{res}}}{\theta_{\text{sat}} - \theta_{\text{res}}} \quad (6)$$

The value of S_r varies between 0 and 1, respectively, at soil's residual (θ_{res}) and saturated states (θ_{sat}) of volumetric water contents. The model determines the rate of percolation based on the hydraulic conductivity and initial moisture content of the soil layers. The volumetric water content of the soil is given by:

$$\theta = \left[\theta_i + \frac{(ASW - P_e) \times \Delta t}{H} \right] \quad (7)$$

where P_e is the percolation in the soil layer (m/s), θ is the volumetric water content of soil (m^3/m^3) is the initial volumetric water content of soil (m^3/m^3), and H is the soil thickness (m).

In the model debris flow initiation occurs when the bed shear stress (τ, kPa) is larger than the critical erosive shear stress (τ_c, kPa), and the volumetric concentration of solids in the debris flow (C_v) is smaller than an equilibrium value ($C_{V\infty}$). The equilibrium value is also called the transport capacity of the flow. To define the transport capacity based on the stability theory, we use the expression proposed by Takahashi et al. (1992):

$$C_{V\infty} = \frac{\rho_w \tan \theta}{(\rho_s - \rho_w) (\tan \phi_{bed} - \tan \theta)} \quad (8)$$

where ρ_w (kg/m^3) is the density of water usually assumed $1000 kg/m^3$, ρ_s (kg/m^3) is the density of the solids, ϕ_{bed} ($^\circ$) is the angle of internal friction of the bed/slope materials and α ($^\circ$) is the slope angle of the hillslope which is derived from the DEM. The rate of erosion (e_r) is expressed based on Takahashi et al. (1992):

$$e_r = \delta_e \frac{a_c}{d_L} U = \delta_e \frac{C_{V\infty} - C_V}{C_{V*} - C_{V\infty}} \frac{q_t}{d_L} \quad (9)$$

where δ_e is the coefficient of erosion rate which is non-dimensional and back-calculated for any given analysis, a_c (m) is the depth within the sediment layer under the condition $\tau_c = \tau$, d_L is d_{50} mean diameter of the grain, U (m/s) is the velocity of the flow-through vertical section, C_{V*} is the volumetric fraction of solids and q_t (m^2/s) is the routed total discharge of the sum of sediments and water per unit width expressed as (Van Asch et al. 2014):

$$q_t = (H_s + H_w) V = (H_s + R_u T_s) V \quad (10)$$

where H_s (m) is the equivalent height of solids, H_w (m) is the equivalent height of the water, V (m/s) is the flow velocity, and T_s (s) is the time step. The model calculates the H_s (m) using the following equation:

$$H_s = (H_{si} + \delta_e) \times (C_{V\infty} - (1 - C_{V\infty}) S_r) \quad (11)$$

where H_{si} (m) is the equivalent height of solids at the beginning of the simulation, δ_e is coefficient of erosion and S_r is the degree of saturation of bed materials (value range from 0 to 1, see Eq. 6). The solid materials of a debris flow begin to deposit when V is smaller than a critical flow velocity V_e (m/s), and at the same time, C_v is larger than $C_{v\infty}$. For V_e the model uses the equation proposed by Takahashi et al. (1992):

$$V_e = \frac{2}{5d_L} \left(\frac{g \sin \theta_e \rho}{0.02 \rho_s} \right)^{0.5} \lambda^{-1} h^{1.5} \quad (12)$$

where g (m/s^2) is the gravity, h (m) is the flow height, θ_e ($^\circ$) is the flattest slope on which a debris flow that comes down through the change in relief does not stop, and ρ (kg/m^3) is the bulk density of the debris flow. We define θ_e , ρ , and λ^{-1} as:

$$\theta_e = \text{atan} \left(\frac{C_v (\rho_s - \rho_w) \tan \phi_{bed}}{C_v (\rho_s - \rho_w) + \rho_w} \right) \quad (13)$$

$$\rho = C_v (\rho_s - \rho_w) + \rho_w \quad (14)$$

$$\lambda^{-1} = \left(\frac{C_{v*}}{c_v} \right)^{1/3} - 1 \quad (15)$$

277 The model accounts for deposition rate i (m/s) of debris flow following
 278 Takahashi et al. (1992):

$$i = \delta_d \left(1 - \frac{V}{pV_e} \right) \frac{C_{V\infty} - C_V}{C_{V*}} V \quad (16)$$

279 where δ_d is a non-dimensional coefficient of deposition rate obtained
 280 through back-analysis and p (< 1) is a non-dimensional coefficient to describe
 281 the initiation of the depositing process. Takahashi (2007) recommend a value
 282 of 0.67 for the latter. Assuming turbulent flow conditions, which seem likely
 283 in steep and rough channels, the model calculates V using Manning's equation
 284 when C_v is below an arbitrarily chosen limit of 0.4 (Montgomery & Buffington
 285 1997, Van Asch et al. 2014):

$$V = \frac{h^{2/3} \sin \theta^{1/2}}{n} \quad (17)$$

286 where n is the Manning's number equal to 0.04 (Van Asch et al. 2014). For
 287 $C_v > 0.4$ (Van Asch et al. 2014), the model uses a simple equation of motion:

$$\frac{\partial V}{\partial t} = g (\sin \theta \cos \theta - k \tan \theta - S_f) \quad (18)$$

288 where k is the lateral pressure coefficient (considered equal to 1; Van Asch
 289 et al. (2014), Domènech et al. (2019)), and S_f is a resistant factor depending
 290 on the rheology of the flow:

$$S_f = \cos^2 \theta \tan \varphi' + \frac{1}{\rho g h} \left(\frac{3}{2} \tau_c + \frac{3\mu}{h} V \right) \quad (19)$$

291 where φ' ($^\circ$) is the apparent friction angle of the flow for a certain pore
 292 water pressure, and μ (kPa.s) is dynamic viscosity.

293 In addition, for debris flows initiating from areas with vegetation, the model
 294 can consider a difference in the erosion rate e_r by increasing and decreasing
 295 the saturated hydraulic conductivity of the soil (Zhu & Zhang 2016, Domènech
 296 et al. 2019). This particular debris flows in Pettimudi originated from the
 297 steep shola forests, and a constant rate of erosion and saturated hydraulic con-
 298 ductivity is assumed (Kuriakose, Van Beek & Van Westen 2009). For further
 299 details of the governing equations of the source model, readers are referred to
 300 Van Asch et al. (2014) and Van Asch et al. (2018). Part of the infiltration and
 301 seepage schemes are from Siva Subramanian et al. (2020). The percolation-
 302 based infiltration model is available from Siva Subramanian et al. (2020) and
 303 van Beek (2002).

304 We run the numerical model with the input parameters specified in Table
 305 1 along with the rainfall data. The model parameters for the simulations are

from Kuriakose, Van Beek & Van Westen (2009) and Abraham et al. (2021). The initial moisture content is $0.05 \text{ m}^3/\text{m}^3$, considering a dry spell before the rainfall. The total duration of the numerical analysis is set as 12 days, starting from 28-07-2020 to 11-08-2020. The time step is seconds (1036800 seconds = 12 days) for convergence purposes. The model used a Courant–Friedrichs–Lewy (CFL) condition (De Moura & Kubrusly 2013) to check the mass balance and convergence at every timestep. The model tracks the volumetric water content response, erosion, and deposition at different locations within the catchment. We estimate debris-flow volumes at each timestep by tracking the materials transported through the first- and second-order streams at an elevation close to the river. The model also provides velocity (m/s) and thickness of debris flow (m) outputs at each timestep.

Table 1: Parameters used for the numerical analysis. ρ_s , Cv^* , ϕ_b , τ_c , ks, μ , and n are referred from literature. d50, δ_e , and δ_d are calibrated by back analysis.

Parameter	d50 (mm)	ρ_w (kg/m ³)	ρ_s (kg/m ³)	Cv^*	ϕ_b (°)	τ_c	δ_e	δ_d	ks (m/hr.)	μ	n
Value	2.0	1000	2600	0.65	35	1	0.1	0.0001	0.015	1	0.004

d50 = mean grain size; ρ_w = density of water; ρ_s = density of solid particles; Cv^* = volume fraction of solids in the erodible bed; ϕ_b = friction angle of soil; τ_c = yield strength; δ_e = coefficient of erosion rate; δ_d = coefficient of deposition rate; ks = soil infiltration capacity; μ = dynamic viscosity; n = Manning’s number.

3.3 Intensity-Duration (ID) rainfall threshold analysis

Rainfall thresholds for shallow landslides and debris flows are traditionally determined based on the relationship of I (rainfall intensity) and D (rainfall duration) using Eq. 20 proposed by Caine (1980):

$$I = \alpha D^{-\beta} \quad (20)$$

Where α and β are constant fitting parameters, though the relationship is empirical, Berti et al. (2020) provided a physical interpretation of the I-D relationship for runoff-generated debris flows and demonstrated the initiation processes. Recently, Jiang et al. (2021) used the ID thresholds to define inter-event-time (IET) of rainfall data for debris flow early warning through machine learning. Due to the practicality and global usage of this approach, in this study, we use numerical modeling to identify the intensity and duration of the debris flow that occurred on 6 August 2020. Numerical simulations modeling the initiation and runout of debris flows can serve as the best alternative to identify the triggering rainfall thresholds where historical data is unavailable (Van Asch et al. 2014, 2018). Once we calibrate the numerical model using the methods given in the above section, we run ten numerical simulations with constant rainfall magnitudes ranging 10mm/hr., 15 mm/hr., 20 mm/hr., 25 mm/hr., 30 mm/hr., 35 mm/hr., 40 mm/hr., 45 mm/hr., 50 mm/hr., and 90 mm/hr. For each set of numerical simulations, the model observes the arrival time of debris flow at the confluence to estimate the duration.

4 Results

The response of the numerical model under given rainfall boundary conditions is tracked for volumetric water content and degree of saturation (averaged throughout the pixels of the catchment, see Fig. 5). The long duration of heavy rain slowly increases the moisture content of the beds, and the beds are entirely saturated on 6 August 2020, resulting in an enormous amount of runoff which might have subsequently triggered the debris flow. The simulated volume of debris flow is 284500 m³ (shown in Fig. 6), similar to the volume reported by (Achu et al. 2021).

Fig. 5: Results of numerical analysis showing volumetric water content (average moisture content, blue line) and degree of saturation of bed materials (shown in red bars) under given input rainfall conditions. Hyetograph of daily rainfall is shown in blue bars. The beds reach complete saturation on 6 August 2020 coinciding with the maximum rainfall.

The numerical model simulates the arrival of the debris-flow fan at the confluence on 6 August 2020. The volume of debris flow is also close to the measured value. The numerical results suggest, initiation of debris flows started around 22:55, and the peak flow was achieved before 23:15, as shown in (Fig. 6c and d). The model suggests the soil/bed might have reached complete saturation on the day of debris flow (see average moisture content and degree of saturation plots in Fig. 6a and b). The observation from the model is similar to the observation reported by (Achu et al. 2021). The numerical model tracks the velocity of the moving mass during the flow process. Fig. 7 shows

Fig. 6: Initiation and deposition of debris flows plotted from 29-07-2020 to 09-08-2020 (a) against average moisture content, (b) against the average degree of saturation, (c) against average moisture content from 22:00 to 24:00 on 6 August 2020 and (d) against the average degree of saturation from 22:00 to 24:00.

the velocity of the moving debris flows mass at selected time durations after 22:55 on 6 August 2020. The mobilization of the debris flow occurred at 22:55 with an initial velocity of 0 – 7 m/s over the crest part of the slopes (this area is the shola forests), as shown in Fig. 7a. Within 60 seconds, the moving mass of debris flow propagated at an increased velocity ranging from 0 – 9 m/s flowing through the first-order stream (Fig. 7b) towards the lower parts of the slope. Due to entrainment effects, the velocity at lower parts of the slopes might have decreased slightly, but the debris flow mass spread through the first- and second-order stream and further moved downstream (Fig. 7c and d). After around 10 minutes of debris flow initiation, further substantial erosion took place at the crest of the slope with a velocity ranging from 0 – 4 m/s (Fig. 7e). We infer this to be the slope failure induced by excess pore water pressure and runoff. Strictly at 23:08, further eroded materials got deposited downstream (areas with settlements) with a maximum velocity of 9 m/s (Fig. 7f). The deposition continued until 23:10 but with a lower propagating speed (Fig. 7g and h).

Similar to the velocity of propagating debris flows, the model tracks the thickness of debris flow during the numerical simulation. Fig 8 shows the thickness of debris-flow deposits from 22:55 to 23:08 on 6 August 2020. The

Fig. 7: Plots showing estimated velocity of propagating debris flow at selected time duration on 6 August 2020, a) 22:55, b) 22:56, c) 22:58, d) 22:59, e) 23:05, f) 23:08, g) 23:09, and h) 23:10. The maximum velocity of the flow was around 8 m/s.

maximum thickness of the debris flow deposits at 23:08 is 9 m. The reported thickness of the debris flow was between 3 m to 7m. Fig 8 g and h show the continued accumulation of sediments but with a reduced velocity.

Through this, we calibrate the numerical model for this particular debris flow event. To analyze the intensity-duration thresholds of debris flow, we run the numerical model with constant rainfall input conditions ranging from 10mm/hr., 15 mm/hr., 20 mm/hr., 25 mm/hr., 30 mm/hr., 35 mm/hr., 40 mm/hr., 45 mm/hr., 50 mm/hr., and 90 mm/hr. Fig. 9 shows the difference in arrival of debris flow against all the constant rainfall intensities analyzed. As the intensity of rainfall increases, the triggering time of debris flow decreases. Under a given rainfall intensity (I) in mm/hr., the duration of the debris flow arrives at the river is considered D (hours). Thus, we obtain an ID threshold for this particular debris flow event under the same material parameters used in the calibration (see Fig. 10).

Out of the ten numerical simulations we perform for the rainfall threshold analysis, debris flow occurs under nine rainfall intensities except for 10 mm/hr. These intensities and durations are plotted in a two-dimensional plane, as shown in Fig. 10. Threshold, especially high-intense rainstorms, is not available from the literature for this study area (Yunus et al. 2021). Previous studies

Fig. 8: Plots showing estimated thickness of debris flow deposits at selected time intervals on 6 August 2020, a) 22:55, b) 22:56, c) 22:58, d) 22:59, e) 23:05, f) 23:08, g) 23:09, and h) 23:10. The maximum thickness was 9 m.

use thresholds with longer duration and lower intensity corresponding to landslides (Naidu et al. 2018, Abraham et al. 2019). These studies also do not explicitly distinguish the landslides, i.e., shallow landslides and debris flows, while determining the ID thresholds. We use the threshold defined by Abraham et al. (2019) to compare the numerically derived rainfall threshold with existing thresholds. A heavy rainstorm induced the debris flow on 6 August 2020. Abraham et al. (2019) reported ID thresholds primarily for short-intensity long-duration rainfall events, different from the Pettimudi case. We find previously established thresholds in the Idukki district are unsuitable to predict debris flows triggered by high-intensity, short-duration rainfall.

5 Discussion

5.1 An unprecedented increase in debris flows

Landslides have been a concern in the Western Ghats of Kerala for the past two decades (Kuriakose, Sankar & Muraleedharan 2009, Kuriakose, Van Beek & Van Westen 2009, Wadhawan et al. 2020). However, until 2018, shallow landslides and rockfalls were more in number than the debris flows (Abraham et al. 2019, 2020). In contrast to previous years, during 2018, the numbers of debris flow occurrences were almost twice higher than shallow landslides

in all 12 out of 13 landslide-prone districts except Idukki (Hao et al. 2020). Hao et al. (2020) identify a total of 2816 debris flows, 1760 shallow slides, and 152 rockfalls that occurred in 2018. These will cause huge implications in soil productivity as more and more sediments are transported to the river every year and subsequently will affect the ecosystem (Yunus et al. 2021). While the Idukki district was identified historically as landslide-prone, most of these landslides were shallow soil slides that occurred within a depth of 5 m (Sreekumar & Aslam 2010, Abraham et al. 2019). Only since 2018, we witness vast numbers of debris flow occurrences all over Kerala. While heavy rainfall is the prime cause of such increased debris flow activity, other drivers, i.e., the positive openness of the terrain and land-use change from forest to tea-plantations, high stream power index, etc., aid this (Yunus et al. 2021). Yunus et al. (2021) found that the locations within Western Ghats of Kerala, having high positive openness and high stream power index, act as hollows and can collect more amount of rainfall (especially during heavy rain) and aid to the easy transportation of flows from the hillslopes to the river. In addition, their study also identified the conversion of forests to tea-plantations and dense construction of roads without proper planning as prime anthropogenic factors for the cause of debris flows.

Fig. 9: Estimated time of debris flow initiation against different constant rainfall intensities (a) 15 mm/hr., (b) 20 mm/hr., (c) 25 mm/hr., (d) 30 mm/hr., (e) 35 mm/hr., (f) 40 mm/hr., (g) 45 mm/hr., (h) 50 mm/hr., and (i) 90 mm/hr. Debris flow initiation is quicker for higher rainfall intensities.

Fig. 10: Intensity-Duration thresholds derived from (a) numerical modeling in this study, and (b) comparison with previously established thresholds in logarithmic scale. Thresholds estimated for Pettimudi event in this study is higher than earlier reported thresholds.

In the case of 6 August 2020 Pettimudi debris flow, all of the causes, as mentioned above, prevailed and were abetted by the heavy rainfall causing a devastating disaster (Achu et al. 2021). Besides all these, the GSI report suggested that the single-lane roads constructed through the hillslopes did not have culverts to ease the flow. Instead, locals built unplanned non-engineered embankments across the first-order and second-order streams to support the roads. Though we cannot avoid extreme hydro-meteorological events, the Pettimudi event emphasizes that there is a scope of resilience against debris flows if we impose proper planning and consider sustainable mitigation strategies (Yunus et al. 2021).

5.2 Improvements needed in the rainfall threshold analysis

Compared with the analysis of rainfall thresholds for the Idukki district done by Abraham et al. (2019), the threshold identified in this study is higher. While we believe the threshold for 6 August 2020 debris flow is reliable despite the uncertainties arising from the model limitations, the difference is still huge. Abraham et al. (2019) developed a multi-source derived inventory of landslide occurrences across the Idukki district and used it to analyze the debris flow thresholds. Their database also included some debris flow occurrences, and the threshold should apply to debris flow events within Idukki. From these observations, if this multitude increase in threshold prevails, efforts should be made to analyze its causes and implications. The number of debris flows within the Idukki district also increased compared to previous years (Hao et al. 2020).

On the other hand, the rainfall recorded at the Nyamakad estate is significantly higher than other stations such as Peermade, Thodupuzha, Munnar,

Idukki, Myladumpara towns in the Idukki district. There is a misperception of whether such an amount of heavy rain within a day is not possible. However, historically such high intense rainstorms are reported in Kerala during 1924 and 1961 (Yunus et al. 2021). Heavy rainfall of 539 mm/day on 7 August 2018 was also downpoured in Pookot town of Wayanad district. In recent times, the terrain response sensitivity for triggering conditions of debris flows in this region may be shifting from low-intensity long-duration rainfall to high-intensity short-duration rainfall patterns (Yunus et al. 2021). It is essential to perform more hydro-meteorological studies in this aspect. Developing inventories and databases of debris flows is fundamental for further detailed multi-disciplinary studies to explore the dynamic rainfall thresholds exclusively for debris flow events.

5.3 Limitations of the study

Using a DEM, the numerical model we develop can simulate the debris flow dynamics from rain input, overland flow, erosion, and debris flow deposition. The limitations of the study are listed below.

- The model uses a freely available 12.5 m DEM. This study does not account for the effect of DEM resolution on the routing of debris flow and does not use interpolation algorithms for re-sampling (Boreggio et al. 2018).
- Boreggio et al. (2018) found that re-sampling the DEM to a finer resolution using various techniques do not significantly affect the model outcomes.
- The erosion equation used in this study is a simplified representation of various erosion mechanisms that could take place in loose materials deposited in the channels.

It is possible to introduce more physically based erosion modules in channel systems (Egashira et al. 2001, Berti & Simoni 2005, Medina et al. 2008, Quan Luna et al. 2011), through performing fieldwork and using advanced monitoring systems. In future works, we aim to achieve in situ monitoring to understand the dynamics and controlling factors of debris flows in the Western Ghats. This study has explored the first-order controls of the Pettimudi event despite the above limitations.

6 Conclusion

An extreme rainfall-induced debris flow occurred around 22:45 IST on 6 August 2020 in Pettimudi village of Idukki district Kerala, India, resulting in more than 60 fatalities. We perform investigations using remote sensing imageries and find that the flow of the debris route through the first-order and second-order drainage of the catchment transporting a massive amount of eroded and entrained materials. The debris flows traveled through tea plantations, cutting across many roads, and took the sediments through the drainage connecting the main river. Developing a novel numerical model for debris flows, we simulate the Pettimudi event to understand the triggering conditions. Through the

analysis, we find that this event occurred only by the extraordinary amount of rainfall caused by cloudbursts. Other factors, i.e., the positive openness of the terrain, land-use change from forest to tea-plantations, and high stream power index, might have aided. The ID threshold derived from the numerical modeling suggests previously established thresholds do not apply to events like Pettimudi debris flow. Separate thresholds identifying debris flows differentiating from shallow landslides are needed to understand the triggering conditions properly. Future works should focus on examining debris flows exclusively induced by extreme-hydro-meteorological events in Western Ghats, Kerala.

Declarations

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Author contributions

SS idealized the concept in discussions with APY and UB and performed the analysis. APY and FJ performed field work and collected the photographs and rainfall data. MTA and NS analyzed the rainfall thresholds for the Idukki district. TVA and SS developed the numerical model. UB and SS wrote and finalized the manuscript.

Code availability

The codes used in this study are publicly available and can be accessed at our GitHub repository: <https://github.com/srikrishnan-ss/aschpeired.git>.

Conflicts of Interests

The authors declare no conflict of interests.

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