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Natural Hazards and Earth System Sciences
Discussions

Numerical model derived intensity-duration thresholds for early warning of rainfall-induced debris flows in the Himalayas

Srikrishnan Siva Subramanian[1], Piyush Srivastava[1], Ali. P. Yunus[2], Tapas Ranjan Martha[3], and Sumit Sen[1]

[1]Centre of Excellence in Disaster Mitigation and Management, Indian Institute of Technology Roorkee, Roorkee, Uttarakhand-247667, India
[2]Department of Earth and Environmental Sciences, Indian Institute of Science Education and Research Mohali, Punjab-140306, India
[3]National Remote Sensing Centre (NRSC), Indian Space Research Organisation (ISRO),Dept. of Space, Govt. Of India, Balanagar, Hyderabad - 500037, India

Correspondence: Srikrishnan Siva Subramanian (srikrishnan@dm.iitr.ac.in)

Abstract. Debris flows triggered by rainfall are catastrophic geohazards that occur compound during extreme events. Early warning systems for shallow landslides and debris flows at the territorial-scale use thresholds of rainfall Intensity-Duration (ID). ID thresholds are defined using hourly rainfall. Due to instrumental and operational challenges, current early warning systems have difficulty forecasting sub-daily time series of weather for landslides in the Himalayas. Here, we present a framework that employs a spatio-temporal numerical model preceded by the weather research and forecast (WRF) model for analysing debris flows induced by extreme rainfall. The WRF model runs at 1.8 km * 1.8 km resolution to produce hourly rainfall. The hourly rainfall is then used as an input boundary condition in the spatio-temporal numerical model for debris flows. The models are first calibrated using the debris flows in the Kedarnath catchment that occurred during the 2013 North India Floods. Various precipitation intensities based on the glossary of the India Meteorological Department (IMD) are set and parametric numerical simulations are run identifying ID thresholds of debris flows. Our findings suggest that the WRF model combined with the debris flow numerical model shall be used to establish ID thresholds in territorial landslide early warning systems (Te-LEWS).

1 Introduction

Rainfall-induced debris flow disasters are catastrophic and affect people's livelihood in mountainous regions (Cannon and DeGraff, 2009; Stoffel et al., 2014; Turkington et al., 2016). The increasing frequency and number of extreme-rainfall events driven by climate change aggravates the occurrence of disastrous debris flows in several regions around the world (Field et al., 2012; Dash and Maity, 2021; Westra et al., 2014; Bharti et al., 2016). These make debris flow disaster mitigation an urgent need (Suzuki et al., 2020). Structural and non-structural mitigation measures are practised to mitigate debris flows (Fan et al., 2019; Huebl and Fiebiger, 2005). However, non-structural mitigation measures, i.e., early warning systems, are helpful to adapt on larger scales which is essentially required during extreme events (Piciullo et al., 2018; Guzzetti et al., 2020). Nations, i.e., the United States of America, Japan, Italy, and China, have developed debris flow early warning systems which work at the territorial scale (Baum and Godt, 2010; Osanai et al., 2010; Ju et al., 2020; Alfieri et al., 2012). These systems use radar-based

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rainfall forecasts and intensity-duration (ID) of rainfall to set the triggering thresholds of landslides for early warning. With the help of historical records of debris flows and their corresponding triggering rainfall intensity and duration, the determination of thresholds is usually considered in these early warning systems.

In India, the National Remote Sensing Centre (NRSC), Indian Space Research Organisation (ISRO), developed an "Experimental Landslide Early Warning System for Rainfall Triggered Landslides" along selected road corridors in Uttarakhand, India (Jayaraman, 2013; Khatri et al.; Bharwad, 2019). In the system, historical landslide data and rainfall records are sourced respectively from Border Roads Organization (BRO), and the India Meteorological Department (IMD). Experimentally forecasted rainfall data from Space Applications Centre (SAC) and landslide hazard zonation maps from NRSC are used. Combinations of 24-Hourly rainfall and various antecedent durations based thresholds are statistically combined to estimate the probability of landslide occurrences (Mathew et al., 2014). However, the 24-hourly/daily rainfall threshold may perform well for predicting shallow landslides but not debris flows. Runoff generation depends on shorter duration rainfall intensities, and early warning system thresholds of hourly rainfall become fundamental for debris flows.

Many nations use Territorial Landslide Early Warning Systems (Te-LEWS) as a cost-effective non-structural mitigation measure for landslides. However, most Te-LEWSs or models, i.e., ID, antecedent rainfall or Soil Water Index (SWI), have genetic inaccuracies since traditional methods derive thresholds from statistical/data-driven correlations of past events and monitoring data (Lagomarsino et al., 2013). Implementing Te-LEWSs in new geological settings is very challenging, i.e., the Himalayas and the Western Ghats, India, with limited historical events and precipitation records. With a limited amount of recorded historical landslides, it is very difficult to capture the exact value of the threshold. An alternative way/method is required which could simulate the occurrence of landslides under various magnitudes of precipitation and inform us about the landslide triggering conditions. Early warning systems that use ID for debris flows rely on an hourly forecast of rainfall data. In India, however, the current thresholds are based on daily rainfall. The above reasons invite improvements to India's existing Te-LEWS.

In this study, we present a framework for an early warning system comprised of a weather research and forecast (WRF) model (Srivastava et al., 2022) followed by a spatiotemporal numerical model for debris flows (Van Asch et al., 2014; Domènech et al., 2019; Siva Subramanian et al., 2021). Using the framework, we analyze the debris flows in Kedarnath, Uttarakhand, India that occurred during the 2013 North India Floods. The hourly precipitation time series is obtained from the WRF simulations and compared with observations from India Meteorological Department (IMD). Then, the triggering intensity-duration (ID) thresholds are derived through parametric numerical simulations under various rainfall intensities. Section 2 introduces the debris flow event that occurred in Kedarnath, Uttarakhand, India, during the 2013 North India Floods. The data and methods adopted in this study are first detailed in Section 3. Then, the methodology is detailed, starting from the WRF model followed by the numerical model for debris flows (Van Asch et al., 2014). After this, the ID threshold method adopted in this study is presented briefly. The results of the numerical modelling and ID threshold analysis is presented in Section 4. In Section 5, we discuss the importance of hourly rainfall data for the early warning of debris flows in Uttarakhand, India, and highlight the improvements further needed in ID threshold analysis.

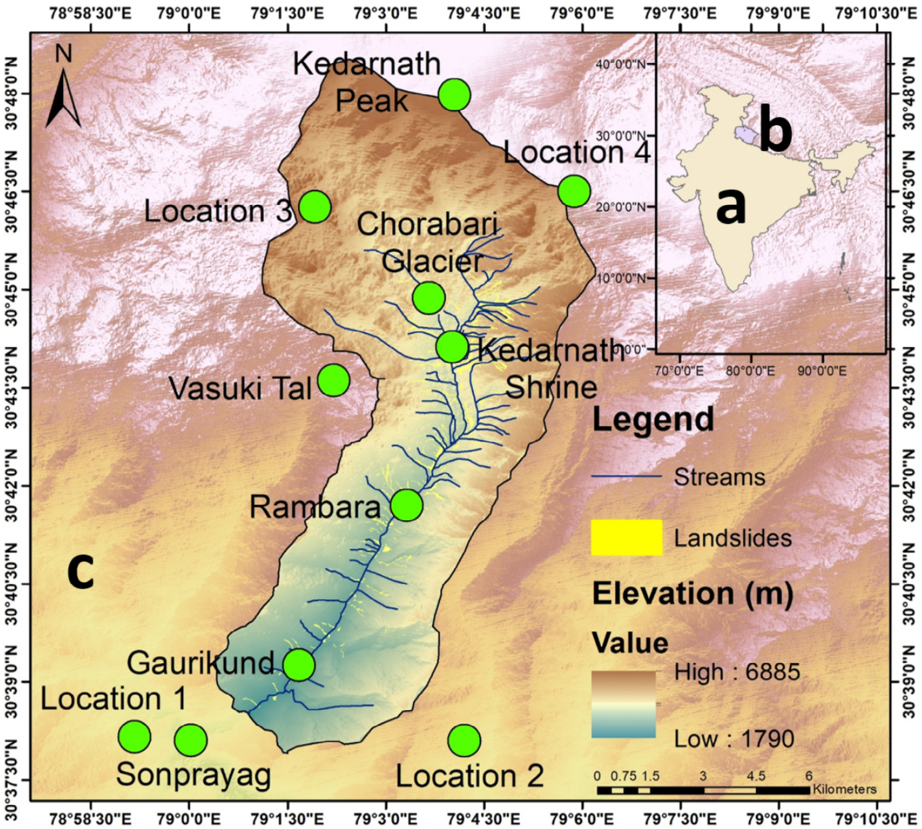

Figure 1. Map showing the extent of the study area within Uttarakhand, India. (a) India administrative boundary highlighting Uttarakhand (Copyright: Geological Survey of India, downloaded from Bhukosh), (b) the Location of Uttarakhand (Copyright: Geological Survey of India, downloaded from Bhukosh), and (c) The extent of debris flows overlaid by a digital elevation model in and around the disaster sites in Kedarnath, Uttarakhand, India.

2 Study area and characteristics of the disaster

In this study, we consider the 2013 extreme rainfall-induced debris flows in Kedarnath as a case example. The study area is located inside the Himalayan tectonic zone, and the landscapes here are very fragile with undulated terrain, narrow valleys, and steep slopes (Fig. 1). The area is situated towards the north portion of the Main Central Thrust (MCT) and Tethyan Detachment Fault bounds the other direction. The rocks are composed of Higher Himalayan Crystallines of metamorphic origin with occasional granitic intrusions. Qaurtzite, Siltstone, Shale, and Schists are major rock types in this area (Fig. 2a). Over this fragile terrain, due to extreme rainfall, over 6000 landslides, mostly of debris flows and slides followed by flash floods, occurred during 15-17 June 2013 (Martha et al., 2013; Champati Ray et al., 2016; Allen et al., 2016). Martha et al. (2013) mapped a total of 6013 landslides and found that 3472 landslides newly occurred over an area of 30.4 km^2. The disaster caused more than 5000 casualties and serious economic impacts. Surrounding the Kedarnath, India Meteorological Department

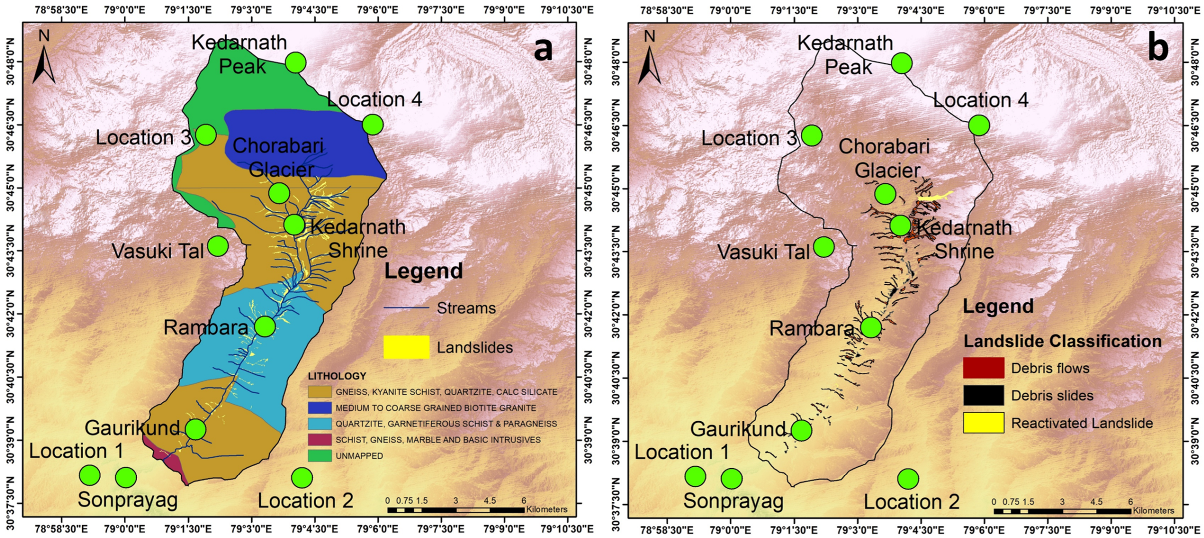

Figure 2. (a) Lithology of the Kedarnath catchment (Copyright: Geological Survey of India, downloaded from Bhukosh Portal, (b) Type of landslides that occurred from 15 to 17 June 2013mapped by Martha et al. (2013)

(IMD) observed unprecedented extreme rainfall amounts of over 350 mm between 14 to 18 June 2013 (Dobhal et al., 2013). Numerical weather prediction model studies have also found the cumulative daily rainfall during 16 and 17 June were close to 200 mm (Shekhar et al., 2015; Kumar et al., 2016; Chevuturi and Dimri, 2016; Dube et al., 2014). Continuous rainfall occurred during 15, 16, and 17 June triggered catastrophic debris flows through runoff-induced erosion of weak sediments overlying the hillslopes (see location of landslides, mostly debris flows/slides in Fig. 1c). Martha et al. (2013) mapped a total of 120 numbers of landslides within the Kedarnath catchment (Fig. 2b). Photographs taken during field work at Kedarnath valley during December 2022 is shown in Fig. 3.

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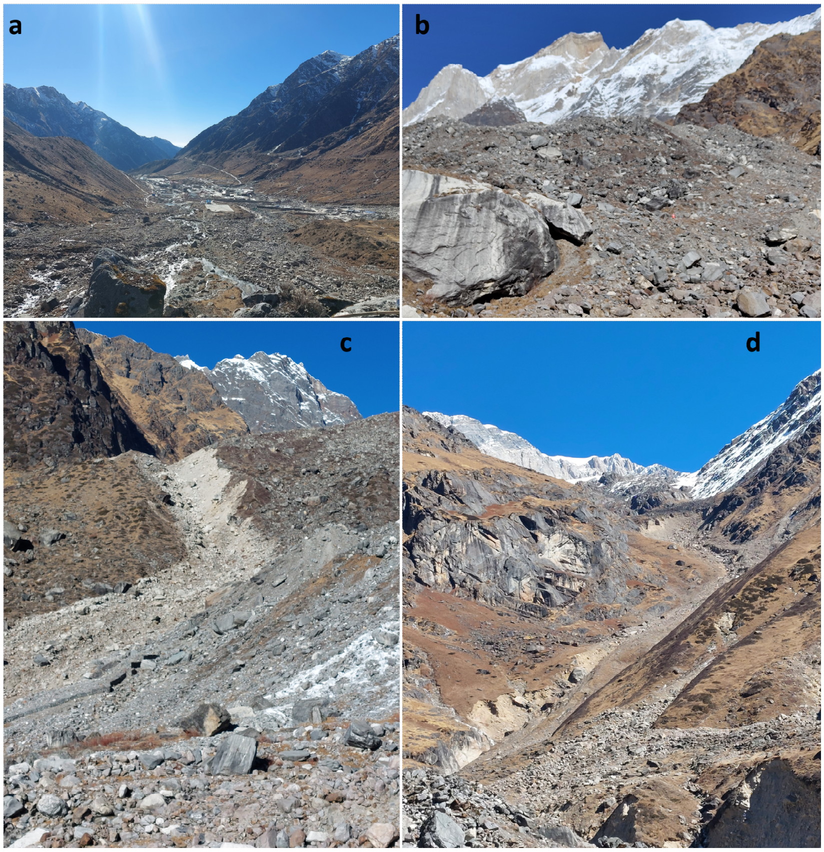

Figure 3. Photographs taken during field work at Kedarnath valley during December 2022. (a) Viewing from North towards downstream side of the Kedarnath valley, (b) Debris flow deposits approximately 1 km behind the Kedarnath Shrine, (c) Runout path of debris flow flood, (d) Major debris flow that hit the Chorabari glacier lake (this photograph was taken climbing above the debris flow deposits shown in Fig. 3(b)

3 Data and Methods

3.1 Meteorological data and WRF simulations

The methodological flowchart used for the modelling is shown in Fig.(4) The WRF numerical model version 4.2.2 is used in this study. The model has a fully compressible setup with a non-hydrostatic dynamical core. For numerical simulations, the model uses terrain-following hydrostatic pressure over the vertical coordinates. Fig.(4) shows the geographical coverage of the WRF model setup. The black rectangular boxes represent two one-way nested domains, domain d01 (9 × 9 km) and domain d02 (1.8 × 1.8 km). The meteorological data, i.e., rainfall obtained at Locations 1, 2, 3, and 4 (see Fig. 2b) from India Meteorological Department for the year 2013 is shown in Fig.6(a). The WRF numerical model-based rainfall during the days 15 June, 16 June and 17 June 2013 are plotted in Fig.4(b). The rainfall at these four locations is averaged and used as an input boundary condition in the debris flow model (Fig. 7).

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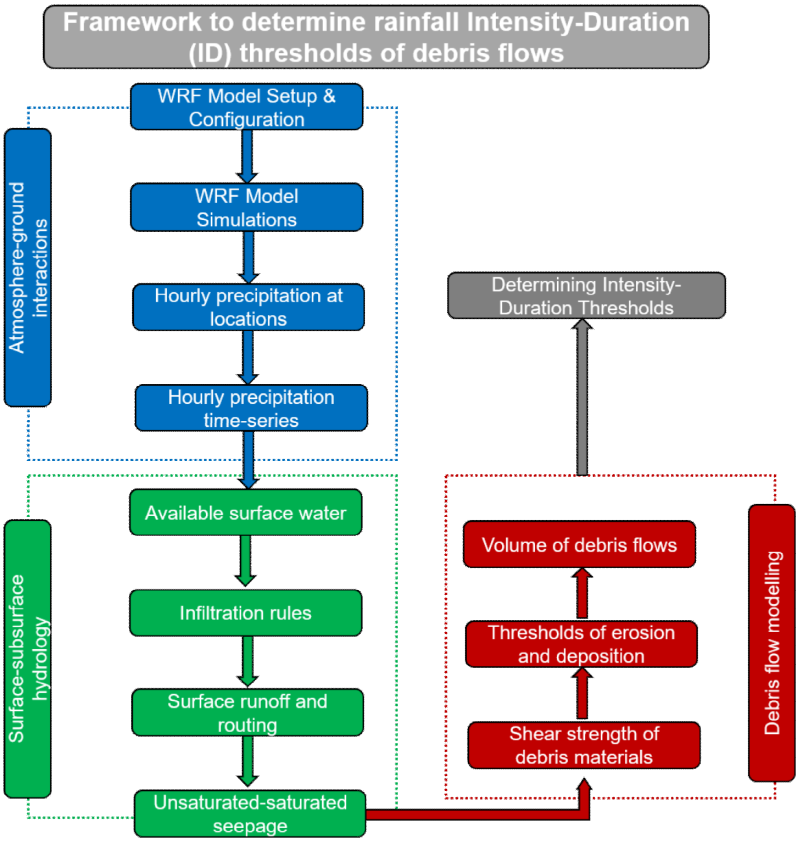
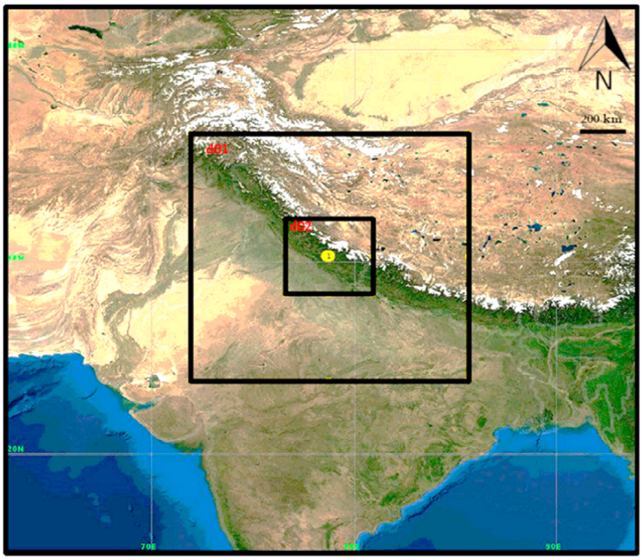


Figure 4. Methodological framework proposed in this study to determine the rainfall ID thresholds of debris flows

3.2 Numerical modelling of debris flows

In this study, we use the numerical model developed by Van Asch et al. (2014) and Siva Subramanian et al. (2021). The model is an updated version Van Asch et al. (2014) in which sensitivity of soil moisture, moisture content dependent hydraulic conductivity and seepage routines are embedded (Siva Subramanian et al., 2021). A python-based script and command line is used to code the model in PcRaster, a dynamic programming tool based on a Geographical Information System (GIS) platform (Deursen, 1995). A digital elevation model (DEM) is required to run the model. The resolution of the DEM sets the mesh size of the model. In addition to the DEM, other DEM derivatives i.e., slope, drainage direction are input as maps having the same resolution. We use the publicly available, 30 m resolution CartoDEM for our study and research. Other spatial inputs, i.e., the area of the catchment, depth of soil or regolith, area of precipitation, and a Local Drainage Direction (LDD) map, are used. Pre-processing of these datasets are done using ArcGIS version 10.8.2 (Ormsby et al., 2004) readers are directed to Van Asch et al. (2014) and Van Asch et al. (2018) for more information on the source model's governing equations. The infiltration and



The two nested domains, namely domain d01 (9 km × 9 km) and domain d02 (1.8 km × 1.8 km) for WRF model simulations are shown with black rectangular boxes

Parameter	Description
Initial and boundary data	ERA5 reanalysis
Temporal interval of boundary data	6 h
Grid size	Domain 1: (146*151) * 50 Domain 2: (226*231) * 50
Horizontal resolution	Domain 1: 9 km Domain 2: 1.8 km
Nesting	One way
Vertical levels	50
Time step	15 s
Land Use and Land Cover	USGS data updates using AWiFS
Topographic data	GMTED2010
Microphysics	Thompson scheme
PBL scheme	YSU scheme
Cumulus parameterization	Kain-Fritsch scheme
Shortwave radiation	Dudhia scheme
Longwave radiation	RRTM scheme
Land surface model	Noah-MP land surface model
Surface-layer	Revised MM5 scheme

Figure 5. The setup and configuration of Weather Research and Forecast (WRF) numerical model to derive hourly rainfall time-series from 15 to 17 June 2013. Modified from Srivastava et al. (2022)

seepage schemes are based in part on the Siva Subramanian et al. (2020) scheme. The governing equations of the model are available from Siva Subramanian et al. (2020) and van Beek (2002).

At first, the input parameters listed in Table 1 and the rainfall data acquired from the WRF model are given to the numerical model. Then, we run the numerical model (see Fig. 6). Considering a dry period prior to the rainfall, the initial moisture content was set to 0.05 m^3/m^3. The numerical analysis will last for a total of three days, from June 15 to June 17, 2013. For the purposes of convergence, the time step is set in seconds (360000 seconds = 3 days). Courant-Friedrichs-Lewy (CFL) condition is used to check the mass balance and convergence at every timestep (De Moura and Kubrusly, 2013). The model monitors changes in erosion and deposition, as well as volumetric water content response, at various catchment areas. The volume of eroded debris is monitored at the confluence of first order and second order streams to the main river.

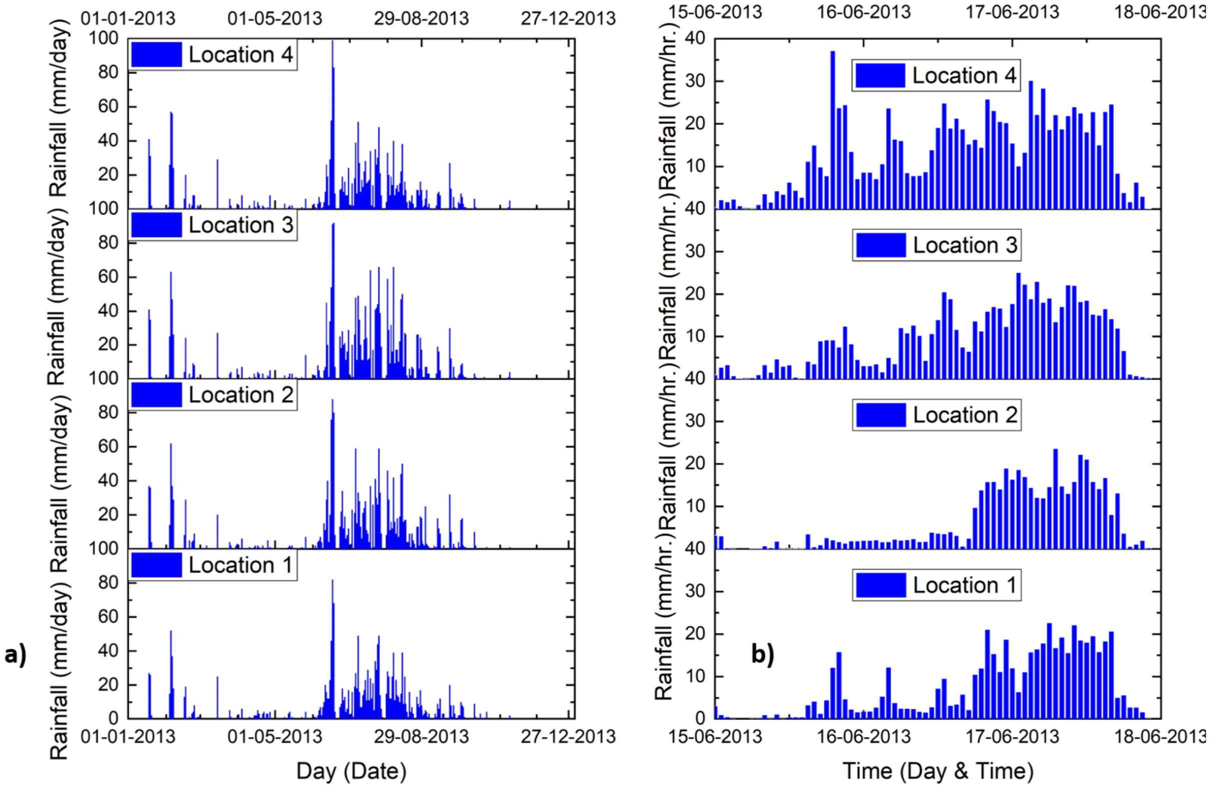


Figure 6. Daily rainfall data at four locations around Kedarnath catchment, and b)Hourly rainfall time-series from 15 to 17 June 2013 derived from WRF numerical model

Table 1. Parameters used for the numerical analysis. ρ_s, $Cv*$, ϕ_b, τ_c, ks, μ, and n are set referring to the literature (Siva Subramanian et al., 2021). d50, δ_e, and δ_d are set by calibration and back analysis.

Parameter	d50 (mm)	$\rho_w(kg/m^3)$	$\rho_s(kg/m^3)$	$Cv*$	$\phi_b(^0)$	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

3.3 Determination of Intensity-Duration (ID) thresholds that trigger debris flows

Caine (1980) propsoed the relationship between I (rainfall intensity) and D (rainfall duration), which is now commonly used to establish rainfall thresholds in territorial landslide early warning systems (Te-LEWS) for shallow landslides and debris flows: Eq.1 :

$$I = \alpha D^{-\beta} \tag{1}$$

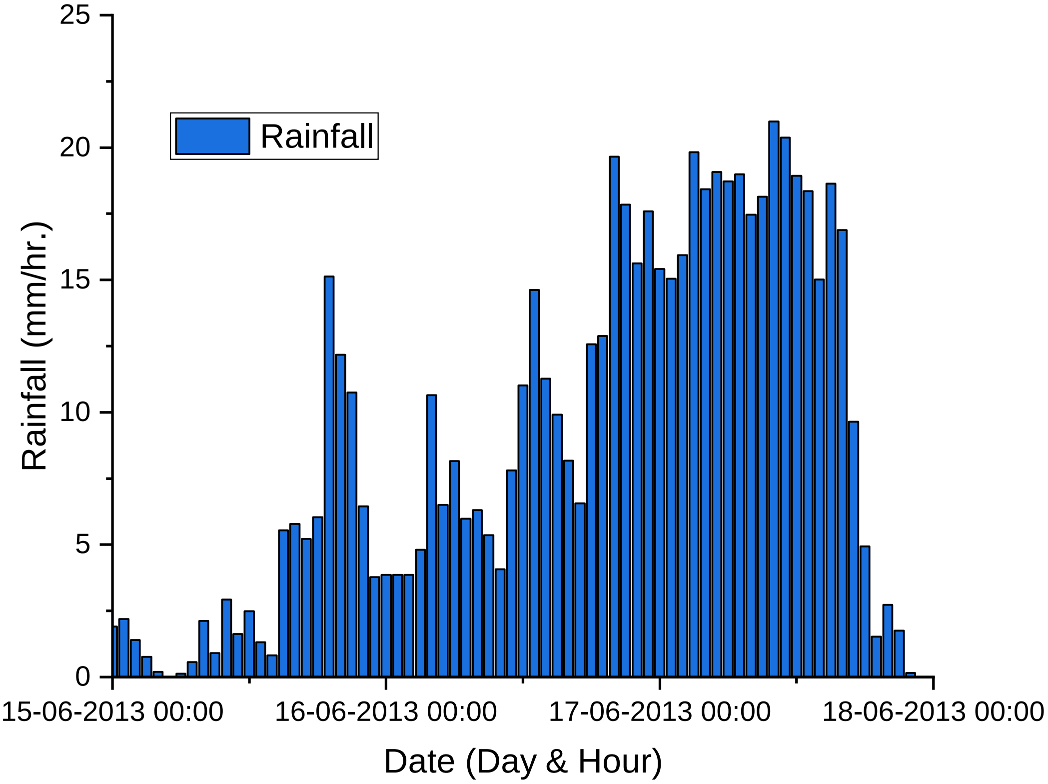


Figure 7. Hourly rainfall time-series from 15 to 17 June 2013 derived from WRF numerical model averaged at the four locations

Here, two constant fitting parameters α and β are used. Berti et al. (2020) clarified the physical significance of these ID thresholds relationship for runoff-induced debris flows.

Very recently, Jiang et al. (2021) defined inter-event-time (IET) of rainfall episodes for debris flow early warning. Because of the global application of this approach, the same method is used in ISRO's experimental landslide early warning system Mathew et al. (2014). Since it is proven that these statistical thresholds hold a physical explanation of the initiation processes of debris flows, a numerical model that simulates debris flow triggering through rainfall and runoff-erosion shall be used to determine the ID thresholds. Where historical data is unavailable, these numerical simulations may be the best alternative to determine the triggering rainfall thresholds (Van Asch et al., 2014, 2018). At first, we calibrate the numerical model using the methods described above and then run ten numerical simulations under rainfall intensities (I) ranging from 10mm/hr. to 15mm/hr., 20mm/hr., 25mm/hr., 30mm/hr., 35mm/hr., 40mm/hr., 45mm/hr., 50mm/hr., and 90mm/hr. The duration (D) for each

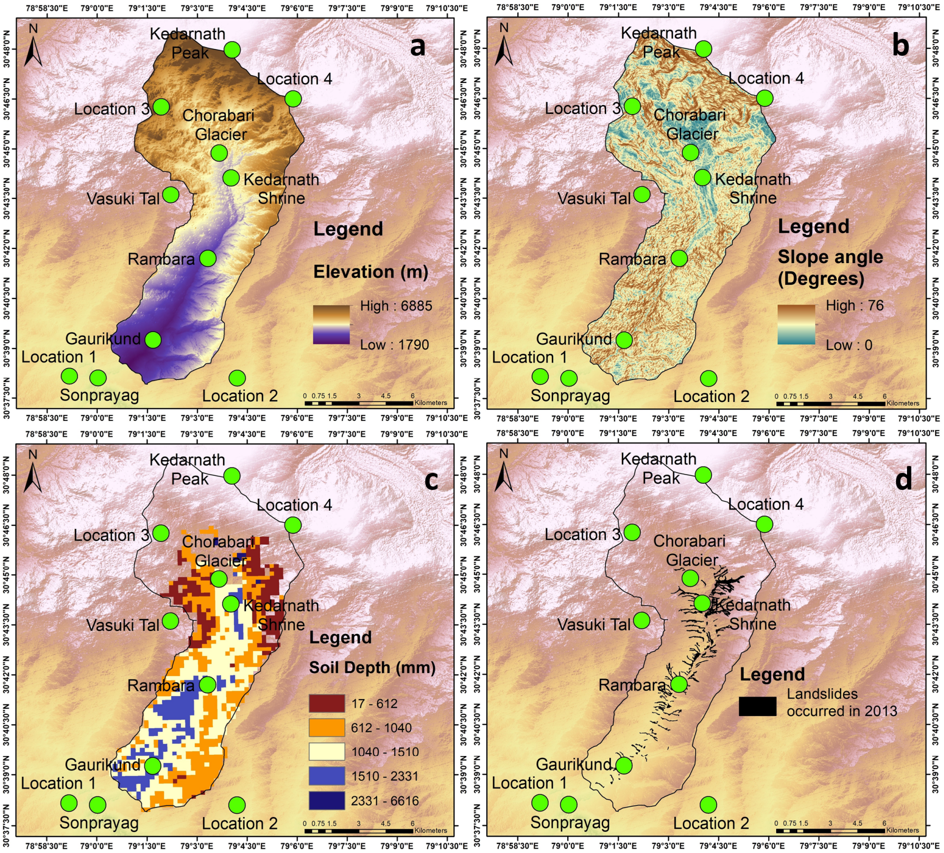


Figure 8. Spatial datasets required for numerical modelling. a) Elevation (m), b) Slope angle (Degrees), Soil Depth (m), and d) Landslide polygons within Kedarnath catchment mapped by Martha et al. (2013)

set of numerical simulations is observed tracking the arrival time of debris flow at the confluence. By correlating the intensity and duration derived from each set of numerical simulations, ID thresholds are established.

3.4 Estimating volume of debris flows

To calibrate the numerical model estimating volume of debris flow is essential. Martha et al. (2013) have mapped the landslide polygons of 2013 Kedarnath debris flows and have estimated the area of landslides. However, no information on the volume of debris flow is available from the literature. In this study, we use an empirical formulation of debris flow volume to estimate the total volume of sediments generated during the 2013 extreme rainfall event in the Kedarnath catchment. For this, the parameters i.e., area of watershed, area of landslides, cumulative rainfall, and duration of rainfall, are considered following the empirical equation by Chang et al. (2011).

$$V = 0.023A_W + 0.064A_L + 13264.6GI - 1399.2D + 38.47C_R \qquad (2)$$

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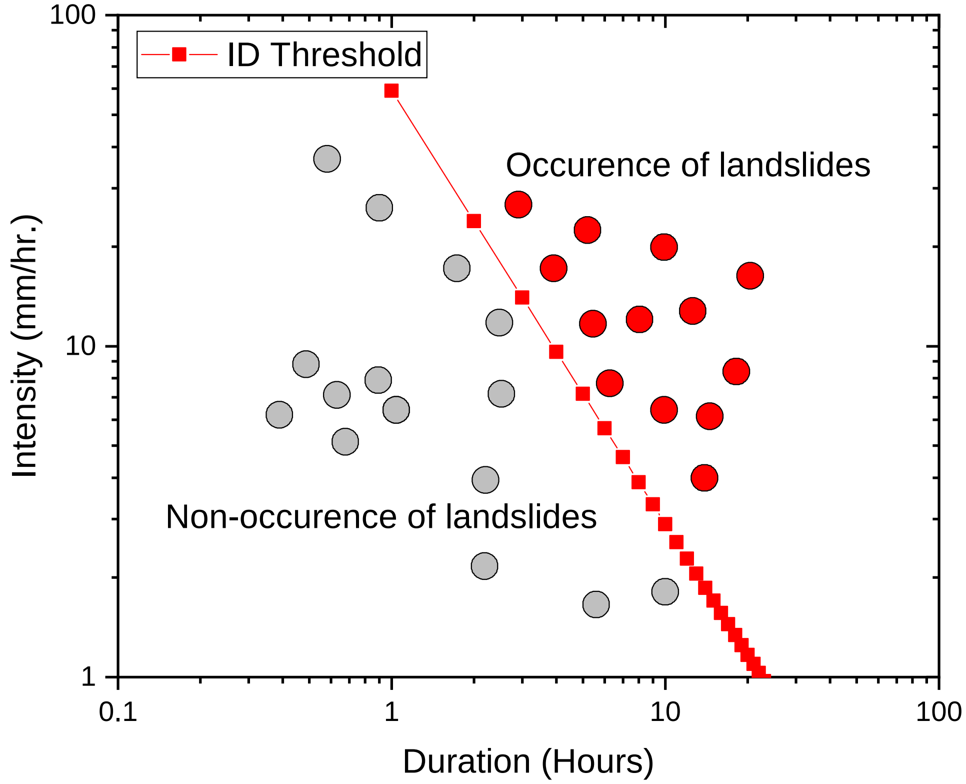

Figure 9. Intensity-duration rainfall thresholds used for classifying occurrences and non-occurrences of landslides

Here, A_W is the area of the catchment (m^2), A_L is the area of the landslides (m^2), GI is the Geological Index based on lithology, D is the duration of rainfall, and C_R is the cumulative rainfall for the debris flow event. The total volume of debris flows generated during the 2013 extreme rainfall within the Kedarnath catchment is estimated as 2290000 m^3.

4 Results

The debris flows extents obtained from the numerical analysis are superimposed over the debris flow polygons mapped by Martha et al. (2013) (see Fig. 10). The estimated volume of debris flows based on the empirical equation by Chang et al. (2011) is 2290000 m^3. The debris flow volume as computed by the numerical simulation is 2560000 m^3 (see Fig. 10). This value is the closest to the empirical estimation achieved by the numerical model after performing rigorous parametric simulations considering a range of values for the parameters d50, δ_e, and δ_d. With this, the model is considered calibrated for the 2013

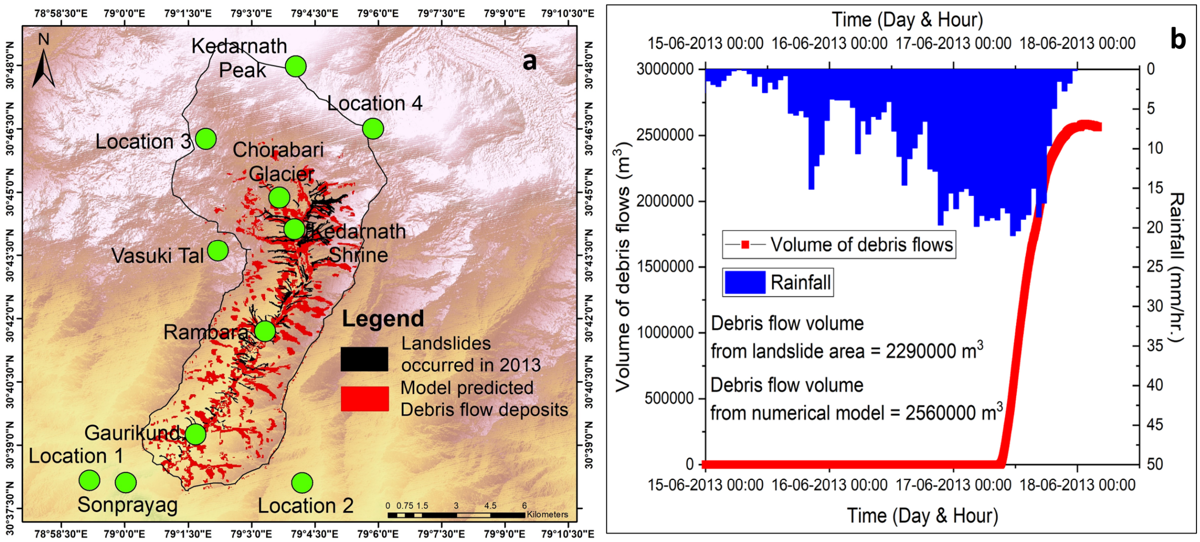

Figure 10. a)Debris flows extents obtained from the numerical analysis are superimposed over the debris flow polygons mapped by Martha et al. (2013) and b) Numerically estimated debris flow volume compared with empirical estimation

rainfall-induced debris flows. It is found that debris flows occur under all nine rainfall intensities except for 10 mm/hr based on the results of numerical simulations. Fig. 12 shows the ID thresholds plotted in a 2D plane from all the nine numerical simulations. The difference in the arrival of debris flows under constant rainfall intensities is shown in Fig. 11. It is observed that the duration of rainfall needed to trigger the debris flow decreases as the intensity of rainfall increases. For a given rainfall intensity (I) in mm/hr., the duration at which the debris flow arrives at the confluence of the river is considered as D (hours). Through this analysis, an ID threshold is obtained for the debris flow event using the material parameters similar to the calibration of the numerical model (see Fig. 12).

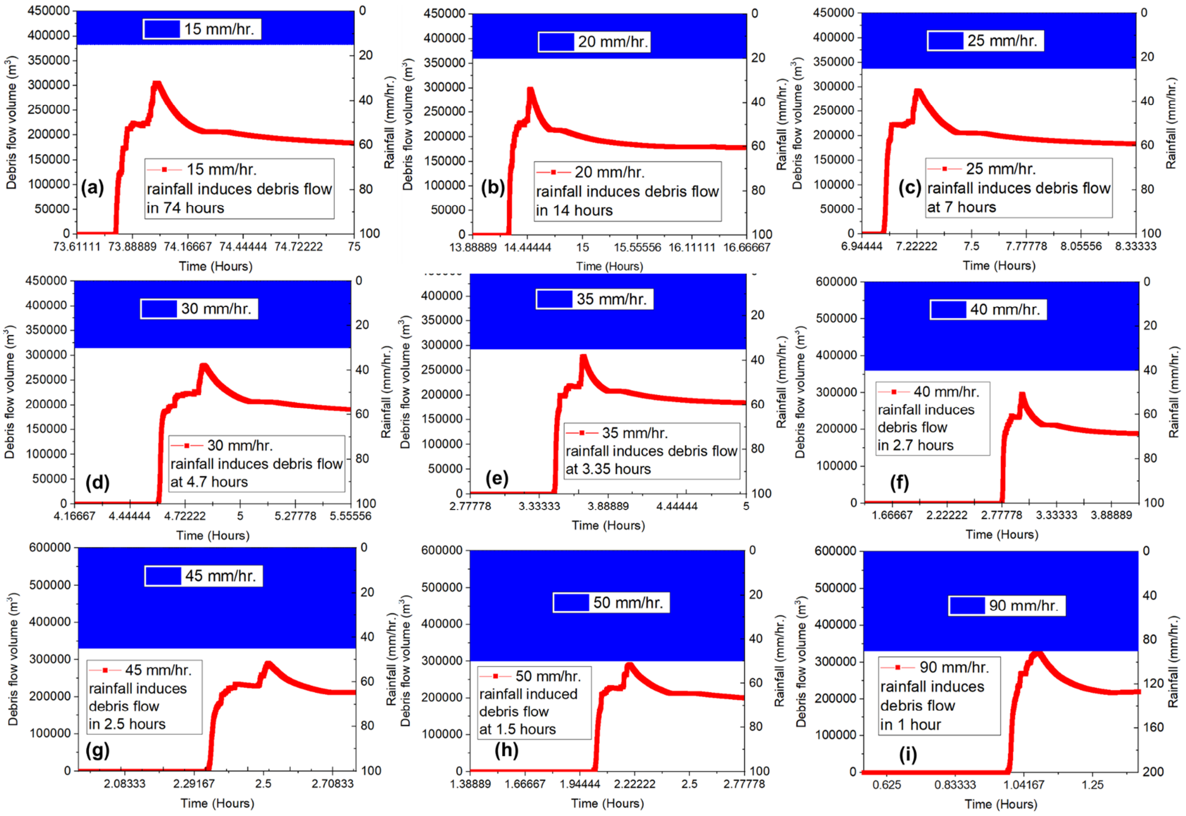

Figure 11. Initiation of debris flows in response to various constant rainfall intensities.(a) Hourly rainfall 15 mm/hr., (b) Hourly rainfall 20 mm/hr., (c) Hourly rainfall 25 mm/hr., (d) Hourly rainfall 30 mm/hr., (e) Hourly rainfall 35 mm/hr., (f) Hourly rainfall 40 mm/hr., (g) Hourly rainfall 45 mm/hr., (h) Hourly rainfall 50 mm/hr., and (i) Hourly rainfall 90 mm/hr.

5 Discussion

5.1 Rainfall Intensity-Duration thresholds for landslides in the Himalayas

Studies that determine the intensity and duration of triggering rainfall for landslides in India, particularly in the Himalayas (Dikshit et al., 2020; Teja et al., 2019; Kundalia et al., 2009; Kanungo and Sharma, 2014) are available. The use of daily, 3-day, and 15-day cumulative rainfall for threshold determination is a major similarity between these studies. The cumulative thresholds could help predict or forecast rainfall-induced shallow landslides. However, for debris flows, the thresholds must be determined using hourly rainfall data. This is due to the fact that runoff-induced erosion occurs during extreme rainfall events that last only a few hours.Te-LEWS for debris flows in the United States, Italy, and Japan also use hourly rainfall data to forecast the ID thresholds of landslides. These countries also use radar-based rainfall forecasts to help predict precipitation magnitudes six hours in advance. However, in India, where such radar-based forecasts are not yet available, the use of WRF

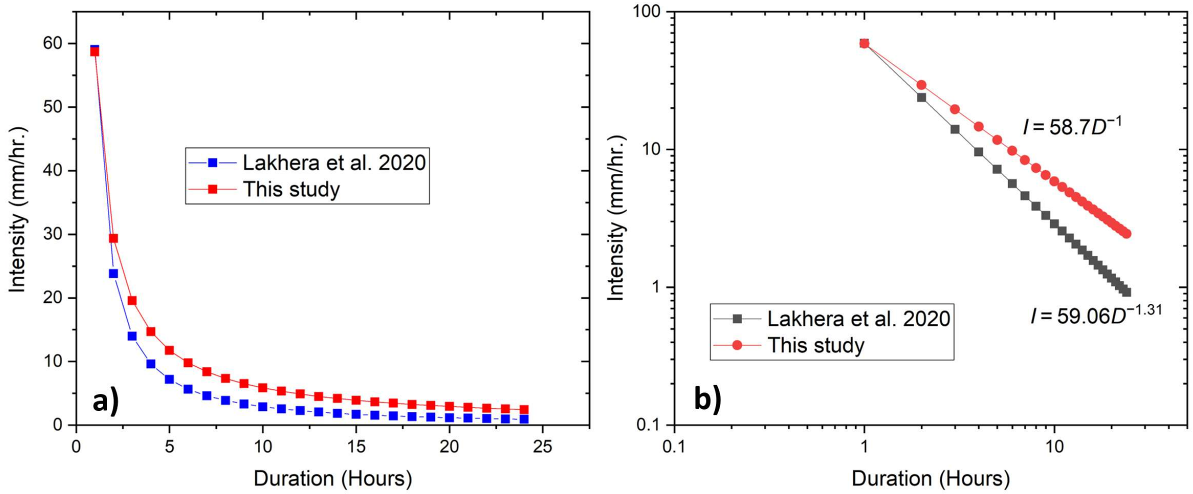

Figure 12. Numerical model derived intensity duration threshold for early warning of debris flows in Kedarnath catchment (a) ID curve compared with Lakhera et al. 2020 (b) ID curves and comparison plotted in log-log plot.

models is unavoidable and prudent. In India the authors could find only one study that consider the sub-daily rainfall as a threshold (Lakhera, 2015; Lakhera et al., 2020). Therefore we limit our analysis to compare the ID thresholds obtained from the numerical model with the results of Lakhera et al. (2020).

5.2 Limitations of the study

This study uses a hydrological model to simulate debris flow dynamics from hourly rainfall. The model considers moisture content-dependent seepage through the unsaturated debris, runoff and overland flow based on Horton's equation, erosion based on critical thresholds, and debris flow deposition based on sediment concentrations. The following are the study's limitations. The model makes use of an open-source DEM with a resolution of 30 m. The effect of DEM resolution on debris flow routing is not considered (Boreggio et al., 2018). However, Boreggio et al. (2018) found that re-sampling the DEM to a finer resolution had no significant effect on the model results. This study's erosion equation is a simplified representation of various erosion mechanisms occurring over loose material deposits in the hillslopes. The numerical model for debris flows that we used and developed in this study is a single-phase flow dynamic model. Through a digital elevation model, it simulates debris flow dynamics from rainfall, runoff, erosion, and deposition of debris flow. An infinite slope model underpins the stability theory. This study's numerical modelling strategy has several limitations due to the simplified numerical approaches and empirical equations. It is possible to introduce more robust erosion modules to simulate the processes in channel systems (Egashira et al., 2001; Berti and Simoni, 2005; Medina et al., 2008; Quan Luna et al., 2011). However, this needs fieldwork and instrumentation of advanced monitoring systems. In future works, we aim to establish an insitu monitoring system in Kedarnath valley to understand the controlling factors and dynamics of debris flows in the Himalayas. This study has explored the use of numerical modelling to derive the ID threshold for debris flow early warning using the 2013 Kedarnath disaster despite the above limitations.

6 Conclusions

Rain-induced debris flows are catastrophic geohazards that multiply in number during intense rainfall events. Rainfall intensity-duration (ID) thresholds are used in early warning systems for shallow landslides and debris flows at the territorial scale. In India, Te-LEWS have trouble predicting and correlating sub-daily time series of weather for landslides in the Himalayas because of instrumental and operational difficulties. Here, we provide a framework for analysing and finding ID thresholds of debris flows caused by rainfall. The framework combines a spatio-temporal numerical model with the weather research and forecast (WRF) model. To generate hourly rainfall, the WRF model operates at a resolution of 1.8 km * 1.8 km. The spatio-temporal numerical model for debris flows is then employed with the hourly rainfall as an input boundary condition. The 2013 high rainfall-induced landslide events in Uttarakhand, India, were used to calibrate the model. The triggering ID thresholds of debris flows are determined against constant rainfall intensities, ranging from 10 mm/hr. to 90 mm/hr. The established thresholds match with the findings available in the literature for Uttarakhand, India. Incorporating the WRF model with territorial early warning of debris flows based on rainfall ID thresholds is promising to Te-LEWS in new geological settings.

Code and data availability. The numerical model developed and used in this study is publicly available together with the datasets for modelling and analysis. It can be accessed from our GitHub repository: https://github.com/srikrishnan-ss/aschpeired.git.

Author contributions. SSS designed the study and performed the debris flow numerical modelling and ID threshold analysis. PS performed the Weather Research and Forecast model analysis. APY performed the debris flow volume calculation and contributed to the design of this study. TRM prepared the landslide inventory. SS provided the required precipitation datasets. All the authors have contributed to the writing of this manuscript.

Competing interests. The authors declare no competing interests

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