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Regional Rainfall Thresholds for Predicting Shallow Landslides: A Case Study from Wayanad District, Kerala

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ABSTRACT

Landslides are devastating geological hazards that triggered by various factors, with rainfall being a primary influence most significantly in mountainous regions that causes huge loss of life, property and infrastructure. About 12.6% (0.42 million km^2) of India's land area possesses landslide risk in that 0.09 million km^2 in the Western Ghats. Landslides in the Western Ghats are becoming a significant concern for authorities, particularly in context of the tragedies that occurred during the 2018–2019, 2020 and 2024 monsoon seasons. Wayanad, a district in Kerala, India, has been severely impacted, with landslides posing threat to both lives and property. Since landslides are a persistent problem in the region that can be caused by high intensity, short duration and prolonged rainfalls establishing their relationship are the prima facie. Thus, identifying an optimal rainfall threshold for landslide prediction focusing on rainfall intensity and duration using landslides and observed rainfall data for the period from 1991 to 2019 has been derived. By adopting the CTRL-T tool (a frequentist statistical method) to determine the most effective approach for selecting reference rain gauges and identifying rainfall events associated with landslides, 217 rainfall event condition were established which are likely responsible for triggering landslides in Wayanad. The rainfall thresholds at various non-exceedance probabilities (1%, 5%, 10%, 20% and 50%) using cumulative rainfalls days varying from 1 - 6 days prior to failure were used. The derived equations T50% $E = (207.3\pm17.3)\times D^{(0.62\pm0.03)}$ are integrated in Short Range Forecast (SRF) to develop rainfall induced landslide forecasting system for Wayand.

***Keywords* - Rainfall thresholds; Short range forecast; Wayanad; LEWS; Dry condition.**

INTRODUCTION

Landslides are the most challenging disastrous events in mountainous and hilly regions. Landslides events can occur in various landscapes globally, with rainfall often being the primary triggering factor (1). During the period from 1995 to 2014, India witnessed a significant rise in fatal landslides (2). Understanding the causes, triggers, and prevention strategies for landslides are crucial in mitigating their devastating consequences. In India, Kerala is one of state with the most frequently impacted by landslides during monsoon, fatal landslides are on the rise in the State (3). Further, Wayanad district in Kerala, is the most severely affected, where landslides have caused immense damage to life, properties and infrastructure (4).

Analysed data of landslides and rainfalls shows that the monsoon rainfall has caused all most all the landslide, the shifts in the monsoon patterns in the Western Ghats, with both South-West and North-East monsoons exhibiting increased intensity and erratic behaviour since 2018 to 2024 has aggravated the landslide scenario. Recent years these landslides being triggered by monsoon rainfall shows an upward trend on fatalities every year. These changes were mainly influenced by variations in rainfall intensity, duration, and the shifting timing of monsoons coupled with soil saturation, deforestation, and climate change, have led to a noticeable increase in landslide occurrences. The state of Kerala in India is witnessing unprecedented death and damage since last 3 years due to recurring landslides triggered by heavy rainfall (5,6).

The landslide events occurred in 2018 of Kerala state faced exceptionally heavy rains that triggered widespread landslides, particularly in the Idukki and Wayanad region there is a remarkable rise in the number of debris flows since 2018, due to very high-intensity rainfalls (7,8). One of the most devastating incidents was the Puthumala landslide in 2019, where a massive slide claimed the lives of 69 people in Wayanad. The trend continued in 2020, when intense monsoon rainfall caused devastating landslides in both Kerala and Kodagu (Karnataka), leading to significant loss of life and widespread damage to infrastructure. In 2024, the region again faced tragic debris flow landslide incidence struck the villages of Punjirimattom, Mundakkai, Chooralmala and Meppadi causing extensive destruction resulted in loss of 359 lives (3).

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The growing vulnerability of the region to such catastrophic single events or widespread events by rainfall emphasizes the need for landslide early warning systems (LEWS) to forecast future landslide events. Developing a Landslide Early Warning System (LEWS) for the Wayanad district requires establishing a regional rainfall threshold, based on relationship between rainfalls and landslides. This necessitates a substantial dataset of past landslide events and corresponding rainfall data to ensure the reliability of these thresholds. Several attempts and extensive research on rainfall thresholds for landslide initiation are going on worldwide. The relationships between rainfall intensity, duration and the likelihood of landslide occurrence established by defining empirical rainfall thresholds using landslide events and corresponding rainfall data (9,10,11,12,13).

In the present study cumulative intensity-duration rainfall thresholds for the initiation of shallow landslides for Wayanad district have been develop for implementation on a regional landslide forecast. The threshold is developed using the methodology developed by Melillo et al. (14) which has been effectively implemented in different frameworks and areas (15,16,17,18). The paper outlines the data utilized, analysis process, and challenges faced in calculating thresholds through a statistical method. The empirical thresholds are classified based on rainfall data from specific rainfall event (E), and account for the rainfall characteristics, including intensity (I) and duration (D) that led to the landslides. Optimizing the selection of rainfall parameters (nearest rain gauge) and landslide (with date) effects the development of most reliable rainfall thresholds for landslide prediction. This enhances the accuracy of landslide early warning systems to forecast the occurrence of landslides induced by rainfall in Wayanad District.

STUDY AREA

Wayanad district forms a part of Western Ghats, situated in the northeastern part of Kerala State. It is represented on Survey of India (SOI) toposheets no. 49M/13, 14, and 58A/1, 2, 3, 5, and 6. Wayanad is divided into three administrative blocks: Vythiri, Mananthavady, and Sulthan Bathery shown in Figure 1. Wayanad district shares borders with Karnataka to the north and Tamil Nadu to the south. Geographically, it spans an area of 2,131 sq. km, bound by the coordinates North latitudes 11° 30’ 08” - 11° 58’ 40” and East longitudes 75° 47’ 23” - 76° 26’ 40”. District is characterized by a hill range with elevations ranging from 126 m to 2,220 m above mean sea level, and an easterly flowing drainage system. Major part of the district is drained by the Kabani River and its three primary tributaries, Panamaram, Mananthavady, and Tirunelli. Kalpetta is the district headquarters located around 70 km from the Kozhikode railway station. The study area experiences a tropical monsoonal climate with mean rainfall of 2786 mm, South West Monsoon (SWM) starts from June to September and followed by North East Monsoon (NEM) from October to November. Lakkidi, Vythiri and Meppady areas receive the highest rainfall during NEM. June is the wettest month, with substantial rainfall, followed by heavy rainfall in July, August, and October.

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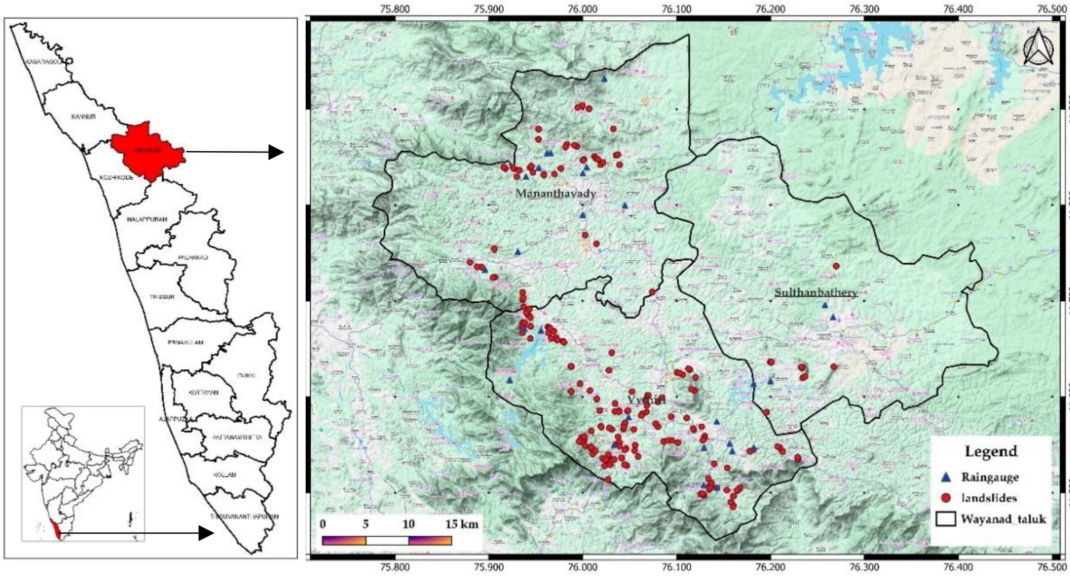

Figure 1. Study area map showing the taluk wise distribution of Landslide and Rain gauge station in Wayanad District.

CATALOGUE OF DATA SET AND SOURCE:

The input data required for developing the rainfall threshold comprises of i) landslide occurrences date Table 3. ii) landslide location Table 3. iii) daily rainfall data Table 1. iv) rain gauges measuring unit Table 2. v) rain gauge location Table 2. Landslide events and rainfall data for the period from 1991 and 2019 are utilized for analysis. However, the datasets are subject to several uncertainties. These include the availability and quality of rainfall measurements, potential gaps in the rainfall data series due to limitations in the data sources, and uncertainties related to the geographical and temporal accuracy of the landslide events. Such data sets are not used in the analysis.

	Rain Gauge			
Date	**Mananthavady**	**Vythiri**	**Ambalavayal**	**Kuppady**
01-01-1986	0	0	0	3
02-01-1986	0	0	0	14
03-01-1986	0	0	0	4
04-01-1986	0	0	0	1
05-01-1986	0	0	0	0
06-01-1986	0	0	0	2

Table 1. Sample daily rainfall data for various rain gauge stations

Rain Gauge	Longitude	Latitude	Measurement Unit (mm)	Source
Mananthavady	76.00	11.8333	mill meter	IMD
Vythiri	76.0333	11.55	mill meter	IMD
Ambalavayal	76.20	11.6167	mill meter	KWRIS
Kuppady	76.2667	11.6833	mill meter	KWRIS

Table 2. Sample rain gauge location, measuring unit and source of data provider

Landslide No	Longitude	Latitude	Slide Type	Date	Source
KRL_0102	76.0215	11.5356	Debris slide	14-06-2018	GSI
KRL_0033	76.16493	11.50273	Debris slide	08-08-2019	GSI
KRL_0127	76.00147	11.55508	Debris slide	08-08-2018	GSI
KRL_0166	76.02647	11.53444	Debris slide	09-08-2018	GSI
KRL_0077	76.13	11.559	Debris slide	06-07-2007	GSI

Table 3. Sample landslide data with location, date and slide type

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LANDSLIDE IN WAYANAD:

Landslide or 'Urul Pottal' is one of the common natural hazards in the Western Ghats of Kerala. The Wayanad experience several types of landslides, of which shallow debris slides, debris flows and cut slope failures are the most common. The geographic coordinates, along with the date and time of each landslide, serve as the primary data for generating the threshold. The first reported landslide in the district was in Chempra in July 1961, while the most recent tragic debris flow incident took place on July 30, 2024. Notable landslide events in chronological order are as follows i) Kappikulam Debris Flow in June 1992 ii) Valanthode in May 2007 iii) Kanthanpara & Nellimala in July 2009, iv) Kurichiar Mala Debris Flow in August 2018 and v) Puthumala Debris Flow in August 2019. The most wide spread event in Wayanad was during the 2019 monsoon which led to the displacement of thousands of people, many of whom were forced to leave their homes and move to temporary relief camps (19). The historical landslide information was gathered from Landslide Inventory of Kerala (20), National Landslide Susceptibility Mapping (NLSM), Post Disaster Landslide Studies (PDLS) of Geological Survey of India (GSI), Global Landslide Catalog (21,22), Stake holders (Public Work Department, National Highway Authority of India, Tea & Coffee Estate), newspapers and direct interactions with the communities during the field validation. A total of 318 landslide incidents were collected for the study out of which 227 landslides have the event dates and useable for analysis.

RAINFALL AND RAIN GAUGE:

Rainfall is the primary triggering factors for landslides in Wayanad. High altitude terrain combined with heavy rains makes it more susceptible to rainfall induced landslides. Rainfall-induced landslides (23,24) are typically more frequent during prolonged and intense rainfall events, particularly when the rainfall exceeds a certain threshold value. This threshold values varies depending on the specific terrain and soil conditions of an area. For effective landslide forecasting and risk management, understanding the association between rainfall and landslide occurrences is vital. Detailed rainfall data, such as rainfall intensity, duration, and distribution, plays a pivotal role in predicting landslides accurately. For this study rainfall data for the period from 1986 to 2022 were collected from various state agencies Kerala State Disaster Management (KSDMA) provided the rainfall data's of Indian Meteorological Division (IMD), Stake holders (Tea & Coffee Estate) collected during the extensive field work. A total of 27 rain gauge stations have been identified, including 4 stations of IMD provided by KSDMA and 23 stations collected by GSI fieldwork. Rainfall data's were collected in various measuring units (Millimeters - mm, Inches – in, Centimeters - cm) in the field were subsequently converted to a common scale of mm for consistent analysis. As data gap on landslide inventory with date was their rainfall data from 1991 to 2019 were used in the analysis. The monthly distribution of effective rainfall and landslide distribution in the Wayanad district for the period from 1991 to 2019 is shown in the box plot Figure 2a & 2b.

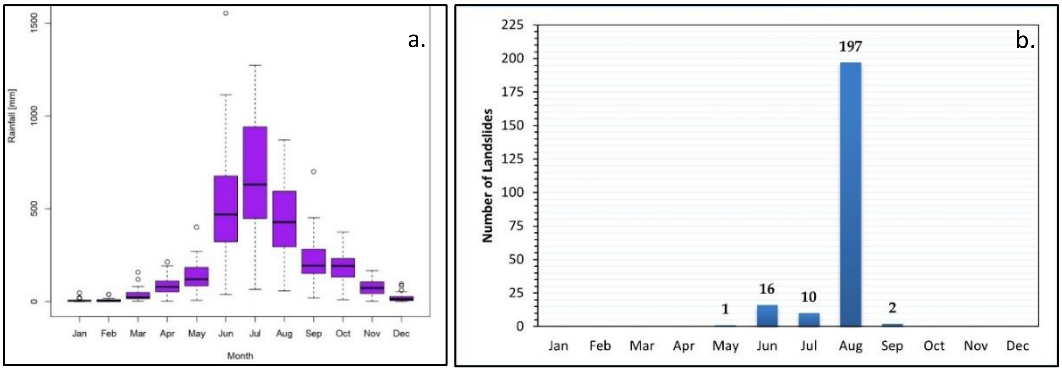

Figure 2a. Annual distribution of monthly rainfall b. monthly distribution of landslides in Wayanad District for the period from 1991 to 2019.

METHODOLOGY:

For defining the rainfall conditions responsible for initiation of landslides in Wayand District the automatic tool CTRL-T (Calculation of Thresholds for Rainfall induced Landslide - Tool) developed by Melillo et al. (14,25,26) were utilized. A total of 227 rainfall events were analysed on frequentist statistical methods to determine rainfall thresholds at various non-exceedance probabilities. The approach defines critical probability levels for the likelihood of landslides based on historical rainfall conditions from 1991 to 2019. The daily observed rainfall, rain gauge station with spatial location, historical landslides incidences with spatial location, date and time is used to (1) reconstruct rainfall events (separation of rainfall days from non-rainy days); (2) automatically identify the

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representative rain gauges with a buffer range of 15kms radius; (3) identify multiple rainfall conditions responsible for the landslide initiation; (4) calculate the probability to each rainfall condition; and (5) calculate probabilistic rainfall thresholds and their associated uncertainties.

The process is divided into three logical phases. First phase (Reconstruction of Rainfall Event) identifying rainfall events from continuous rainfall periods and separating the other events with a criteria having a dry spell of rainfall 24hrs, 48hrs, 72hrs, 96hrs, 120hrs. Second phase (Combining Rainfall Events with Landslide Information) this phase identifies which rainfall events led to landslides and calculates the rainfall duration (D) and accumulated rainfall (E) responsible for triggering the landslides. Rainfall conditions are reconstructed using data from rain gauges within a 15 km radius of the landslide location (closest proximity of rain gauges to each landslide). Considering the uncertainties two criteria are possible may arise i) distance between the rain gauge and the landslide to overcome this weighting function is applied which considers D & E to select the most representative rainfall events and conditions ii) when more than two slides occur under the same rainfall conditions first one is considered in order to prevent duplication that would invalidate the frequentist method adopted to establish the thresholds. Third phase (Calculation of Rainfall Thresholds) in the final phase calculates rainfall thresholds for different non-exceedance probabilities using a frequentist statistical approach (23,27). The thresholds are defined by a power-law relationship between cumulated event rainfall E (in mm) to the rainfall duration D (in days) $E = (\alpha \pm \Delta\alpha) \times D^{(\gamma \pm \Delta\gamma)}$ Where, α is a scaling constant (the intercept), γ is the shape parameter (that defines the slope of the power law curve), and Δα and Δγ represent the uncertainties of α and γ, correspondingly.

A bootstrapping statistical technique (27) was adopted to calculate and limit the uncertainty in Δα and Δγ in the observed data set. For the reconstructed rainfall events following steps are followed i) checking the rainfall event individually ii) significant rainfall condition required for triggering landslide event with inference to the date iii) multiple correlation on landslide date and rainfall amount were checked manually iv) removal of uncertain landslide events. Manual removal of 10no's of landslide with questionable instances were discarded and only 217 landslide events were used for defining the rainfall threshold.

COMPARISON OF LANDSLIDE DISTRIBUTION AND RAINFALL CONDITION

Quantification of the distribution of landslides in the given rainfall condition provide an assessment on the relative number of landslides that can be expected above a threshold based on the past events. To simply the landslide is categorised into three class i) low impact – rainfall condition that triggered between 1-5 landslides (less severe) ii) moderate impact – rainfall condition that triggered between 6-10 landslides (moderate severe) and iii) high impact – rainfall condition that triggered more than 10 landslides (high severe). Assessment the results of landslide severity impact by comparing with the rainfall duration (D) and rainfall intensity (E) distribution shown in Figure 3 as box-and-whisker plots. Landslide associated with the single rainfall condition ranges between 1 to 64 (event occurred on 9th August 2018). Box and whisker plots shows the result increasing in the impact of landslide as the D and E distribution increases.

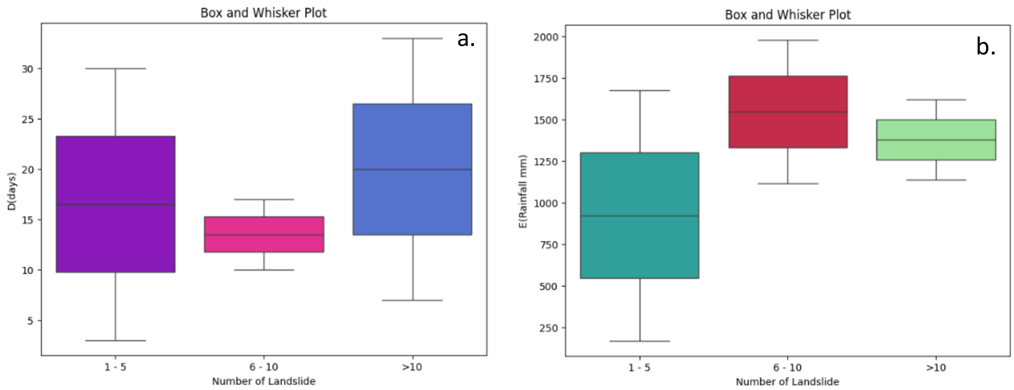

Fig. 3a. Box-and-whisker plots of landslide impact a. 1-5 low impact against b. 6-10 moderate impact and c. >10 high impact for 217 rainfall conditions used to calculate rainfall thresholds with respect to duration in days (D) and cumulated event rainfall in milli meter (E).

RAINFALL EVENTS AND THRESHOLD:

Multiple dry days breaks for assessment for defining the rainfall events is used to check the impact on the threshold. The dry days for defining a no rainfall day has been chosen as i) dry condition (Dc) of 24hrs (Dc-1), 48hrs (Dc-2), 78hrs (Dc-3), 96hrs (Dc-4) and 120hrs (Dc-5) ii) removing the rainfall during less than 4.8mm in 24hrs under the given antecedent condition. A comparative analysis was established using the various Dc for the threshold at different non-exceedance probabilities from T1% to T50% for Dc - 1 to 5 shown in Figure 4a with relative uncertainties in the α parameter shown in Figure 4b and γ parameter. Threshold values show variation in

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Dc-1, Dc-3 however Dc-2, Dc-4 and Dc-5 shows consistency, similarly relative uncertainties in the α parameter for Dc-1 shows on higher range, Dc-3 shows on lower range and consistency seen in Dc-2, Dc-4 and Dc-5 for γ parameter Dc - 1 to 5 ranges between 4.5 to 5.8. Considering the consistency of Dc-2, Dc-4, Dc-5 and relative uncertainty the derived equations of T50% $E = (207.3 \pm 17.7) \times D^{(0.62 \pm 0.03)}$ at Dc-2 is being used as the optimal threshold equation.

The calibrated thresholds for the 217 number of rainfall conditions associated with landslides in the Wayand have a duration ranging between one and forty-one days (24–792 h) and cumulated rainfall varying between 120 and 1978.3 mm (average value = 647.7 mm). Frequentist rainfall thresholds defined is shown in Table 4. lists the parameter values and uncertainties for thresholds at different non-exceedance probability levels. Figure 5b. shows, in a log–log plane, the rainfall conditions responsible for the failures and considering dry condition (Dc) of 48hrs the rainfall thresholds at T50% non-exceedance probability levels. Landslide prediction using daily rainfall thresholds are constructed for a whole day on a daily rainfall durations D basis either it can be of 24hrs (1Day), 48hrs (2day) & 76hrs (3day) and multiple days. These thresholds can only be applicable to landslide prediction on a whole day accumulation excluding the possibility of prediction of rainfall events on intermediate durations. Figure 5a. shows, the uncertainty associated with the thresholds at T50% non-exceedance probability levels under the shaded areas considering Dc at 48hrs. The relative uncertainties in the γ parameter, Δγ/γ, are equal to 4.8% and α parameter, Δα/α are 8.3% these two uncertainties are lower than 10% and considered for reliable threshold as anticipated by (27).

Threshold	Number of rainfall conditions	Threshold equation (rainfall in mm)	Duration range (days)
$T_{1\%}$	217	$E = (85.4 \pm 10.5) \times D^{(0.62 \pm 0.03)}$	1 – 6
$T_{5\%}$	217	$E = (110.7.0 \pm 12.2) \times D^{(0.62 \pm 0.03)}$	1 – 6
$T_{10\%}$	217	$E = (127.1 \pm 13.2) \times D^{(0.62 \pm 0.03)}$	1 – 6
$T_{20\%}$	217	$E = (150.4 \pm 14.5) \times D^{(0.62 \pm 0.03)}$	1 – 6
$T_{50\%}$	217	$E = (207.3 \pm 17.3) \times D^{(0.62 \pm 0.03)}$	1 – 6

Table 4. Threshold Equation (E) at different (T1%, T5%, T10%, T20% and T50%) non-exceedance probabilities for the Duration (D) range (1-6days) of the probable initiation of landslides in Wayand

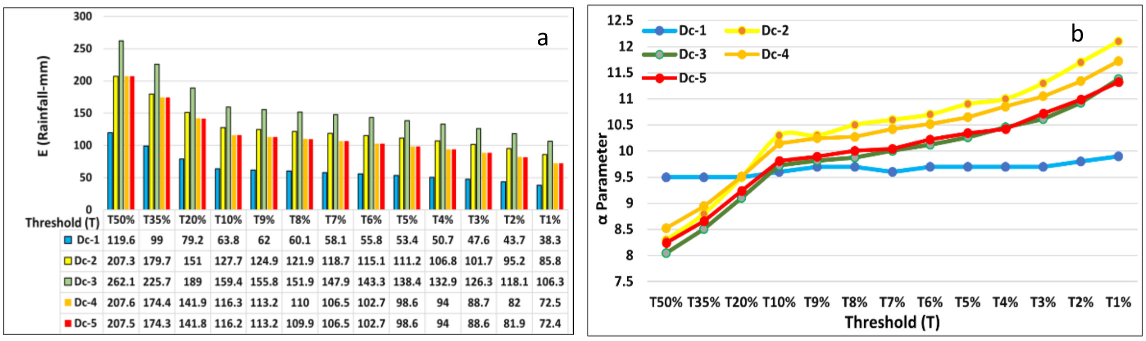

Fig. 4a Threshold at different non-exceedance probabilities from T1% to T50% for Dc - 1 to 5 comparison of rainfall thresholds with respect to duration in days (D) and cumulated event rainfall in mm (E). 4b comparison of relative uncertainties in the α parameter from T1% to T50% for Dc - 1 to 5

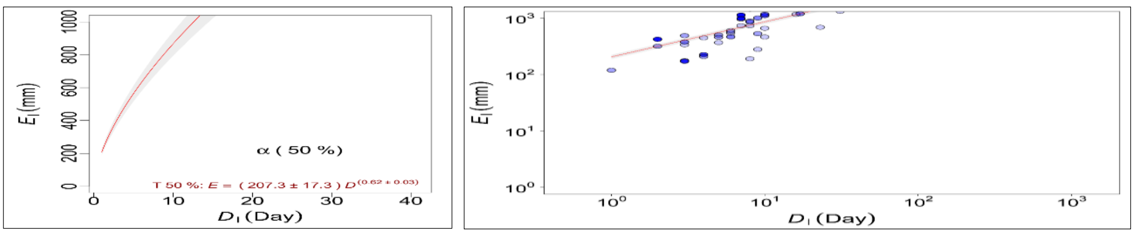

Fig. 5a. Duration vs Intensity plot at 5% non-exceedance probability showing associated uncertainty under the shaded areas that have resulted in landslides in Wayanad. 5b data of DE condition shown in log–log plane considering Dc of 48hrs.

DISCUSSION AND CONCLUSIONS:

In summary efforts are made to establish a reliable rainfall threshold at a regional scale for possible landslide occurrence based on observed rainfall condition for Wayand district in Kerala State. The rainfall thresholds derived from historical rainfall conditions that resulted in landslides will be used as a threshold value in SRF to anticipate rainfall-induced landslides which can effectively contribute to a Landslide Early Warning System Wayand district. Thresholds are defined for Wayand district based on 217 landslide triggering rainfall conditions using the database of daily rainfall data for the period from 1986 to 2019 and 27 rain gauge stations (13 station of Vythiri, 11 station of Mananthavady and 3 station of Sulthan Bathery). From the analysis the rainfall conditions responsible for the catastrophes and the rainfall thresholds at 50% non-exceedance probability is 207.3mm Certain limitation is associated with rainfall thresholds are due to the temporal and spatial distribution of daily rainfall data, moisture content estimation is not used in the analysis. However, the thresholds established for Wayand district have acceptable values of uncertainties and depend primarily on the number and distribution of the (D, E) pairs. Threshold models are essential for effective landslide early warning systems, enabling to use them in the broad framework of regional forecasting ahead of heavy rainfall events. The inclusion of detailed rainfall data, such as rainfall intensity, duration, and distribution, plays a crucial role in predicting landslides accurately. We further expect validation of threshold will be attempted for evaluation and refinement after 2019 data's by assessing the rainfall, landslides, forecasting and operational capabilities. The completeness and paucity of data on landslide dates and evenly distributed rain gauge stations is a prerequisite for improving the thresholds in the region. However, implementing a Regional Landslide Forecasting System (RLFS) in the region with institutional mechanisms for creation of new data can improve the thresholds with respect to variable themes for reducing underdensities in assessment.

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