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Precipitation Intensity: Duration Based Threshold Analysis for Initiation of Landslides in Upper Alaknanda Valley

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Abstract**—**The entire Himalayan range is globally renowned for rainfall-induced landslides. The prime focus of the study is to determine rainfall based threshold for initiation of landslides that can be used as an important component of an early warning system for alerting stake holders. This research deals with temporal dimension of slope failures due to extreme rainfall events along the National Highway-58 from Karanprayag to Badrinath in the Garhwal Himalaya, India. Post processed 3-hourly rainfall intensity data and its corresponding duration from daily rainfall data available from Tropical Rainfall Measuring Mission (TRMM) were used as the prime source of rainfall data. Landslide event records from Border Road Organization (BRO) and some ancillary landslide inventory data for 2013 and 2014 have been used to determine Intensity Duration (ID) based rainfall threshold. The derived governing threshold equation, $I= 4.738D^{-0.025}$, has been considered for prediction of landslides of the study region. This equation was validated with an accuracy of 70% landslides during August and September 2014. The derived equation was considered for further prediction of landslides of the study region. From the obtained results and validation, it can be inferred that this equation can be used for initiation of landslides in the study area to work as a part of an early warning system. Results can significantly improve with ground based rainfall estimates and better database on landslide records. Thus, the study has demonstrated a very low cost method to get first-hand information on possibility of impending landslide in any region, thereby providing alert and better preparedness for landslide disaster mitigation.

Keywords**—**Landslide, intensity-duration, rainfall threshold, Tropical Rainfall Measuring Mission, slope, inventory, early warning system.

I. Introduction

LANDSLIDES are defined as the movement of rock mass, debris or earth material down a slope under the force of gravity [1]. Rainfall has been the reason for many hazards and events which make an adverse effect on daily human life, landslides are one of them. Rainfall or any type of precipitation plays an important role in initiation of landslides, as any type of precipitation adds up moisture to the local rock, soil which increases pore water pressure, facilitates weathering and swelling of clay minerals and in simpler term it loosens up slope forming materials. So, if there is sufficient slope, landslides can be triggered. Other important factors include geology and geomorphology which also controls slope instability. Increase in urbanization and expansion of roads also increase the pressure on the landscape, and it leads to higher degrees of vulnerability. Deforestation activities and change in land use/land cover (LULC) also loosen up the top soil increasing landslide susceptibility of the terrain [2].

The concept of rainfall thresholds as presented by Caine [3] built upon earlier recognition by Campbell [4] of the relationship of high intensity rainfall in the triggering of shallow landslides and by Starkel [5] who theorized a critical rainfall which was a combination of rainfall intensity and duration. Rainfall thresholds which have been considered as a triggering factor for shallow landslides are also used for landslide warning system and indication purpose [6]. Not surprisingly, the thresholds are distinctly different due to the data sources and varying geologic settings. Real-time rainfall data can be integrated with rainfall thresholds in a landslide warning system, as demonstrated in Hong Kong [7], [8]. Intense rainfall is considered as a triggering factor for shallow landslides which is widely observed around the globe is a complex and widely discussed topic [9]. Rainfall infiltration under unsaturated conditions may reduce soil moisture suction; however, this process is not generally viewed as capable of triggering debris flows. As a known fact, many results show that debris flow occurs due to positive pore water pressure that in subsequently affects material permeability [10].

Remote sensing techniques have been widely used in landslide research where spectral and spatial information content of imagery has been utilized [11].

Various researchers [12] advocate DEM models for evaluating slope stability to identify shallow landslides during the time of expected daily rainfall, evident for spatial refinement to the application of rainfall thresholds. The reason is that the radar based rainfall data which are optically refined to 1-km pixel spacing suggest that the possibility of landslide warnings can be utilized as near real time rainfall estimates in combination with topographic and other spatial datasets. Our research includes image-interpretation and inventory of large landslides wherein the spatial extent, textural and spectral information were considered for landslide detection and discrimination between unstable and stable zones, i.e. detection of vulnerable zones. Overall, the present study aims to understand precipitation as a triggering mechanism and to

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establish ID based precipitation thresholds for landslide initiation.

II. Study Area and Geological Setting

The Alaknanda river basin in Uttarakhand is characterized by deep gorges, rugged mountains, and highly undulating terrain, which has a high frequency of landslides encountered majorly during the monsoon season. The part of the National Highway 58 taken up for the study runs for 126 km, running alongside the river Alaknanda from Karanpryag to Badrinath. The highway has been made by excavations involving variety of materials including terrace deposits, fluvio-glacial materials, massive and fractured/jointed rock mass and talus deposits on the valley slopes. The small towns and human settlements are generally established and developed along the road within the valley slope areas. The expansion of this road together with rapid urbanization has rendered these unstable hill slopes, apparently more susceptible to slope failures.

The Alaknanda river basin extending from 29° 58' 11.315''N to 31° 6'21.183'' N and 78° 32 31.406''E to 80° 17' 26.161'' E. was studied. It encompasses important places and river basins like Chamoli, Mandakini, Badrinath, Pindar, Dhauliganga, Devprayag, and Birehiganga. Impact analysis was carried out for the entire Alaknanda valley. The intensity-duration (ID) threshold analysis was carried out for eight major sections along NH-58 highway between Karanprayag to Badrinath [13]. The study area is characterized by deep gorges and rugged mountains, with a maximum elevation of 7811 m and minimum elevation of 445 m with respect to the mean sea level (CartoDem). Frequent slope failures are observed during monsoon majorly along NH-58 highway. Landslides here are the outcome of intense rainfall, complex tectonic setting with unique geomorphology of steep slopes and dissected hills.

Geologically, the Alaknanda valley consists of three major lithostartigraphic units known as the Dhudhatoli Group, the Garhwal Group, and the Central Crystalline Group. The zone around Devprayag consists metamorphosed rocks particularly phyllites and quartzites forming the Dhudatoli Group which is separated by the North Almora Thrust trending in NW-SE direction. The rocks of the Garhwal Group are exposed upto south of Vishnuprayag/Joshimath and consist of mainly quartzites, shales, slates, shists, and carbonates occasionally intruded by meta-volcanic. The Garhwal Group is separated from Central/Higher Crystalline Group by Main Central Thrust (MCT) trending in NW-SE direction which, and consists of several shear and fracture zones. The Northern zone extending from south of Vishnuprayag to village Mana along the river Alaknanda and Dhualiganga consists of shists, gneiss, and granite of Central Crystalline Group, which rest over the Garhwal Group. It is observed that the thrust zones have a general trend of NW-SE parallel to the Himalayan range and perpendicular to river Alaknanda which flows in NE-SW direction [14].

III. Dataset and Methodology

The datasets used are shown in Table I.

TABLE I
Datasets Used for the Study

Rainfall Intensity Data	TRMM (3 Hourly Data), Resolution (0.25 by 0.25 degree)
	TRMM (Daily Data), Resolution (0.25 by 0.25 degree)
Optical Data	Resourcesat 2 LISS-IV, Resolution (5.8 m) (2014)
	Landsat 8 OLI, Resolution (30 m) (2013 and 2015)
Software's used	Arc GIS 10.3
	Quantum GIS
	Erdas Imagine 2014
	R Software
Ancillary Data used	BRO and ancillary landslide inventory data (2013 -2014)

The methodology applied for the calculation of ID based threshold for the study area is shown in Fig. 1.

IV. Processing

A. For I-D Thresholding

In the present study, TRMM 3B42 V.7 data have been used. The rainfall intensity data at three-hour interval and daily interval from 1st June 2013 to 1st October 2014 have been downloaded for the purpose of I-D thresholding. The TRMM 3B42 data have been downloaded in NETCDF format and then converted to TIFF for further processing. The maximum intensity values are derived from the 3-hourly files. For each day, eight 3-hourly files were stacked to generate a daily file, and from this stacked daily file, the maximum intensity corresponding to the particular hour was picked. The duration is calculated from the daily files which are stacked to generate a monthly file and from the monthly stack the duration is calculated as per the number of days of continuous rainfall till the event date. The landslide records pertaining to 2013 and 2014 have been gathered from BRO.

For the generation of the I-D equation, a database of maximum intensity on the day of event and the total duration of rainfall till the event day for the 60 unique landslide events was prepared. A graph of maximum intensity to total duration on a log-log plot was prepared to devise the I-D equation for landslide initiation. The validation of the equation was carried out using a record of maximum intensity to total duration for the entire stretch of monsoon, i.e. from June to September for both the years 2013 and 2014. The records were analyzed for seven major sections along the NH-58 highway namely Karanprayag, Nandprayag, Chamoli, Pipalkoti, Tangini, Joshimath, and Lambagarh.

B. For Landslide Inventory

For the preparation of landslide inventory map, the main focus is on high resolution optical imagery for identification and mapping of landslides. This mapping is done by using Landsat 8 OLI (30 m) multispectral image for post disaster event dated (20.11.2015) and same for pre-disaster event dated (22.05.2013) for identification of landslides. The resulted work is further validated through Google Earth temporal images. Since the study area is not so large, the visual interpretation method was applied to get quick results.

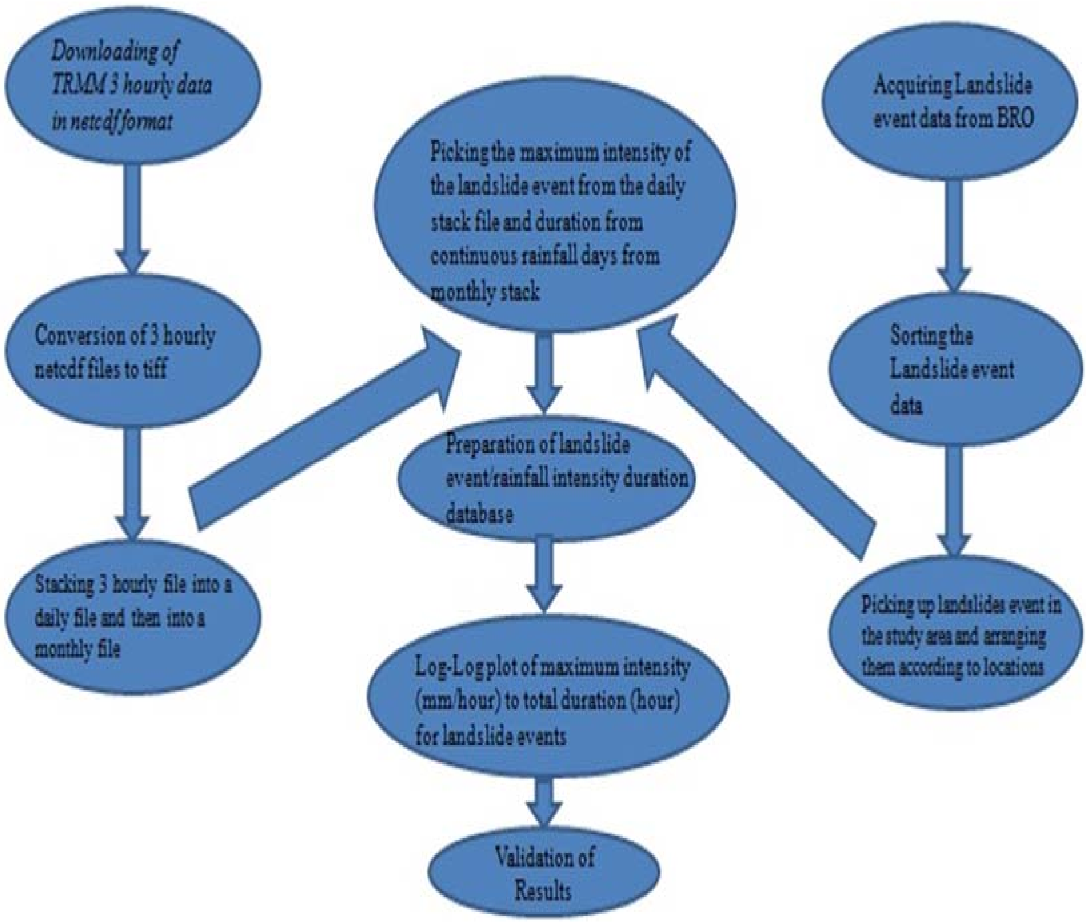

Fig. 1 Flow chart of methodology for I-D thresholding

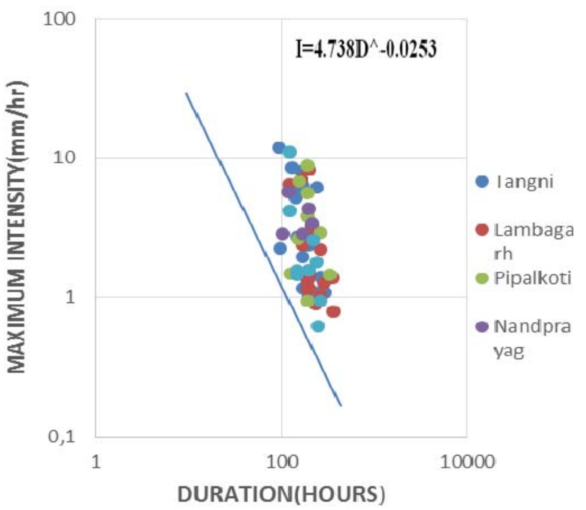

Fig. 2 Log-log plot of maximum intensity to duration

V. Results and Discussions

The log-log plot of maximum intensity (I in mm/hours) to total duration (D in hours) of rainfall events (Fig. 2) which resulted in landslides have been used to derive the I-D equation by drawing a lower bound line to the graph, and the equation is expressed as:

$$I = 4.738D^{-0.0253}$$

The equation can be used to determine the probable duration of events which can initiate slope failures. 61 landslide events from the year 2013 to July 2014 are used for calculation of the intensity-duration equation; events triggering landslide pertaining to the equation have wide dispersion in terms of duration and maximum intensity.

The highest intensity value observed was 12.84 mm/hour, and the lowest one was 0.62 mm/hour. The highest duration was recorded for the intensity value of 0.79 mm/hour for 360 hours and the lowest duration of 72 hours for intensity of 11.96 mm/hours, suggesting that a high intensity value results in slope failure with a short duration of rainfall, whereas for low intensities, rainfall for a long duration of rainfall is required to initiate slope failure. Apart from above mentioned equation, a log-log plot for I-D thresholding for every station under the study area was also plotted.

The I-D threshold equation $I=4.738D^{-0.0253}$ has been validated considering landslide events of the monsoon period from 1st August to 1st October for the year 2014 for stations Nandprayag, Chamoli, Pipalkoti, Tangini, Joshimath, and Lambagarh and accuracy of 70% was observed.

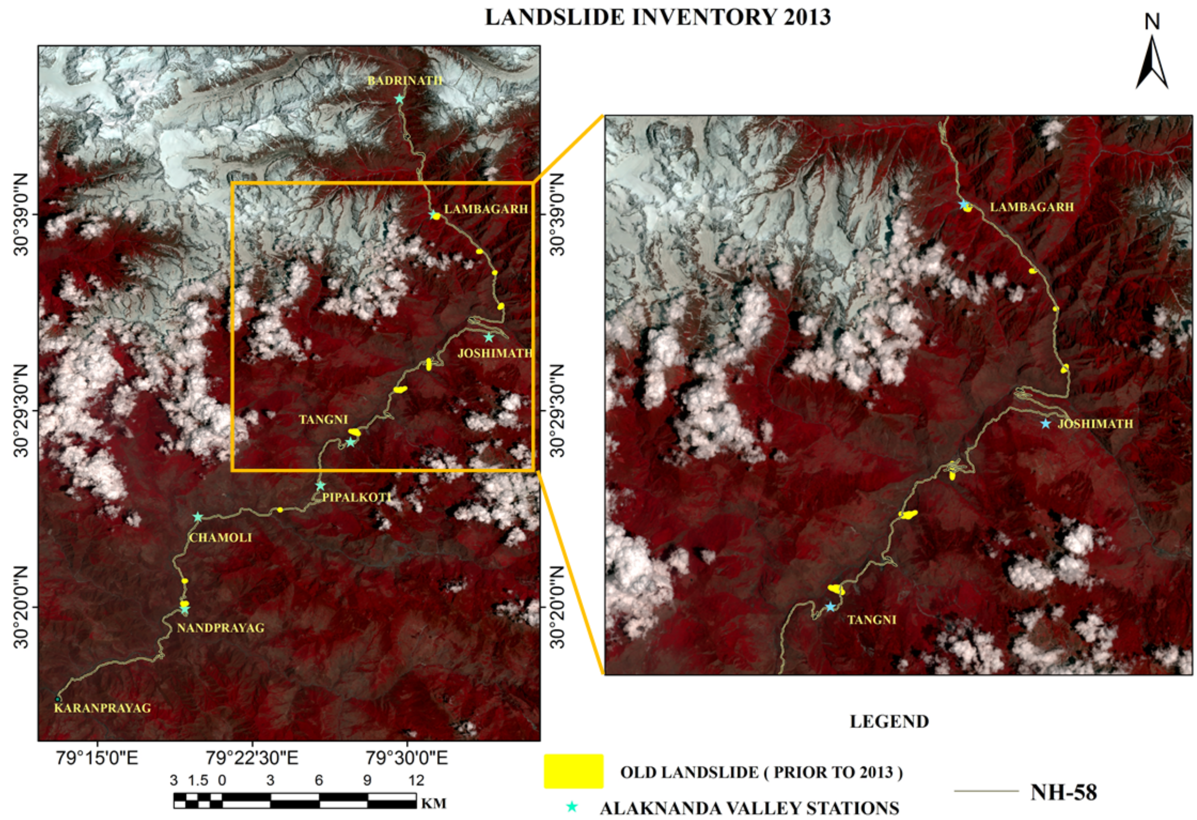

Fig. 3 Landslide inventory map showing landslides occurred prior to 2013 (After author using Landsat 8, Google earth and BRO Landslide data)

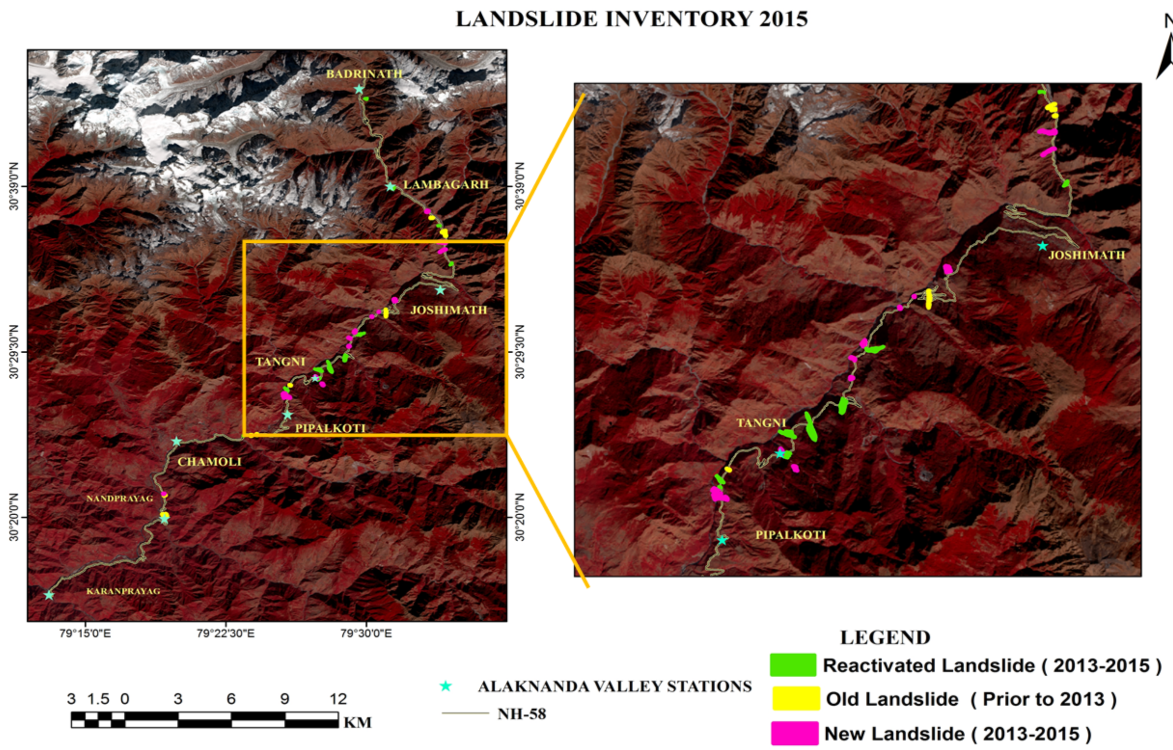

Fig. 4 Landslide Inventory Map 2015 showing Landslides between 2013-2015 under the captions Reactivated, Old, and New (After author using Landsat 8, Google earth and BRO Landslide data)

The present study also gives us a correlation between the maximum intensity of rainfall with the amount of average slope for the stations chosen within the study area; namely, Nandprayag, Chamoli, Pipalkoti, Joshimath, and Lambagarh. A general trend line of this correlation graph is

$$y = -1.237x + 42.10$$

where R^2 is 0.59. This equation shows a negative inversely proportional relation between maximum intensity of rainfall in the study area with respect to the average slope where duration of rainfall is constant. In the equation, y denotes average slope, while x denotes maximum intensity. It depicts that, for a constant duration, the amount of rainfall required for initiation of landslides increases with decrease in slope.

Landslide inventory was also being prepared to monitor the occurrences of landslides over a period of time in the study area (Figs. 3 and 4). Year 2013 is chosen as the reference year to depict the change in the occurrences of landslide events. The common type of landslides are debris flows, rock slides, earth slides, and very few are found to be rotational slides. Most of the landslides are found to be situated near the steep slope. From the inventory map, it is evident that most of the landslides are located on eastern side of the river coinciding the road and villages locations, thus causing damage in the study area.

VI. Conclusions

The present study has established intensity-duration based precipitation threshold for Alaknanda valley which is $I=4.738D^{-0.0253}$. On validation of the equation, it was observed that the accuracy of the I-D equation for the prediction of landslide events was observed to be 70%. Also, it is noted that landslides are triggered when an intensity value of 3.7 is exceeded for a constant duration. The intensity-duration based empirical threshold described is the fundamental element of the real-time warning system. The study essentially focused on establishing a threshold for landslides based on the intensity and duration of the corresponding rainfall events. The TRMM 3B42 V.7 has been used as the source of rainfall intensity, and peak intensity on the day of event was considered. The present study was undertaken because rainfall is the major triggering factor of landslides in Alaknanda valley as it leads to an increase in pore water pressure and a decrease of cohesion which are the main factors of slope failure, along with percolation of water into weak zones. Slope has a very large effect on the mode of landslide initiation. In the study area, the average slope is related to the maximum intensity of rainfall for duration of 80 hours through equation

$$y = -1.237x + 42.10$$

with an R^2 value of 0.59. This equation clearly shows the negative relation between maximum intensity of rainfall and slope of the area. The utility of I-D based rainfall threshold is that any instant using the prevailing rainfall intensity value the likely duration in which threshold will be exceeded can be determined. Thus, it can be used to issue early warning to areas which are susceptible to slope failures. Also, the present study shows that an early warning system is needed in the study area as well as continuous monitoring of rainfall events as the study area comes under high pilgrim tourism area of India.

VII. Suggestions

For further studies of I-D thresholding, it is suggested to use the latest GPM dataset for the monitoring of rainfall events, and also, an attempt should be made to find the correlation between the slope and rainfall duration by making intensity constant. In this way, much better information can be provided to develop an early warning system for the triggering of landslide events.

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