Establishing Precipitation Thresholds for Landslide Initiation in the Upper Catchment of Alaknanda River, Uttarakhand, India

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ABSTRACT

Every year during intense rainfall periods, many landslides are reported from different parts of the National highway 58, which is the only motorable route connecting Badrinath, an important Hindu pilgrimage centre with the rest of India. Slope failures cause traffic disruption leaving the pilgrims and inhabitants stranded for hours. Landslides and their secondary hazards such as landslide dams and subsequent flash floods often turn into major disasters. It is therefore, imperative to assess and predict the landslide hazard in these Himalayan terrains. However, the spatio-temporal prediction of rainfall-triggered landslides is complicated by the interactions of the varied causes and triggers. Moreover, the accessibility of the terrain and availability of relevant data is usually problematic. The present study aims to understand precipitation as a triggering mechanism and establish (spatial) precipitation thresholds for landslide initiation.

Statistically, the critical rainfall amounts can be established, when a large data set on rainfall and landslide occurrence is available. Thus, an analytical approach is adopted to establish the relationship between rainfall magnitudes and slope failure initiation. Daily rainfall data was collected from rain gauges in Joshimath, Badrinath (from 1987 to 2006) and Pipalkoti (from 2004 to 06). It was compared with the corresponding historical landslide records, which were collected from the road maintenance department and other sources. A comprehensive landslide database with data since 1987 was organized. The study defines a lower-boundary precipitation threshold, based on 72-hours precipitation and 15 days prior antecedent precipitation, combined with daily rainfall. The evaluation of the thresholds, based on the landslides observed in July and August, shows a high probability of landslide occurrence when the lower boundaries of the threshold are exceeded, under other considerations. The thresholds can be further improved by taking into account the spatial variability of other stability influencing parameters to aid in effective landslide hazard assessment in the Garhwal Himalayas. The prediction rates can be significantly improved with the availability of a well-distributed network of weather stations and better recording of the initiation time of slope failures.

Keywords: precipitation threshold, rainfall triggered landslide

1. INTRODUCTION

Every year during intense rainfall periods, several incidences of landslides and related casualties are reported from different parts of the Rishikesh-Badrinath National highway 58, in the state of Uttarakhand, India. This road is the only motorable route connecting Badrinath, an important Hindu pilgrimage centre and other hill cities to the rest of the nation. Slope failures cause traffic disruption leaving the pilgrims, tourists and inhabitants stranded for hours. Breaching of the highway has deeper implications as many towns, villages and hamlets are often marooned from the rest of the country. The situation worsens for the sufferers with the onset of cold waves, which are usually experienced all through the year in the Himalayas. Landslides and their secondary hazards such as landslide dams and subsequent flash floods often turn into major disasters. In July-August 2004 a heavy downpour in Garhwal Himalaya caused debris slides and debris avalanches where at least 25 people died and 5000 people were stranded for days without food on the Joshimath-Badrinath Road. The worst events happened in the monsoon period of 1998, during which large landslides near Okhimath and Malpa, in the Alaknanda Catchment, killed around 400 people.

Given these disastrous effects, it is therefore imperative to assess and predict the landslide hazard in the Himalayan terrain. Landslide hazard is defined as "the probability for a landslide within a given area and within a given period

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of time” [17]. Thus, ideally the identification of landslide hazard must include a spatial and a temporal component, i.e., the probability for the occurrence of landslides at a certain location in space and its occurrence in time [16]. However, the spatio-temporal prediction of rainfall-triggered landslides is complicated by the interactions of the varied internal causes and triggering factors. Slope instability in Himalayas, is not only controlled by the geology, geomorphology and hydrology but also governed by complex tectonics, geodynamics and meteo-climatic factors. Increased urbanization, accompanied by expansion of roads also creates an increasing pressure on the landscape, and leads to higher degrees of vulnerability, as well as to increased landslide occurrence due to improper road and building construction. The destruction of forests and the vegetative cover that binds the top soil has been going on at an ever-increasing pace and the conversion of forest land into agricultural and horticultural holdings also adds to the increasing landslide susceptibility of the terrain.

The economic constraints of a developing nation owing to the problem of allocation of resources, prevents the authorities to implement the pre-disaster site investigations and mitigative measures and these are generally adopted in the post-disaster phase. Moreover, the accessibility of the terrain, poor distribution of weather stations and lack of high elevation rain gauges impedes the collection of data that can contribute towards understanding the mechanism of slope failure due to rainfall triggering. Furthermore, accurate dates of landslides are seldom available due to sparse population of the region and lack of media and official reporting of such events. Thus, the study aims to understand precipitation as a triggering mechanism and to establish (spatial) precipitation thresholds for landslide initiation in a complex terrain with data constraints for effective landslide hazard management.

2. PRECIPITATION THRESHOLD

A review of available literature emphasizes the role of precipitation as an important control on the initiation of slope failures and provides evidence that shallow translational slides and flows are often triggered by meteo-climatic events that are in excess of some threshold. Precipitation thresholds for initiation of failure in slopes have been assessed in many regions of the world, based on a combination of landslide and rainfall information. While empirical thresholds are defined on the basis of landslide occurrences in relation with rainfall amounts, physical thresholds are based on numerical models that consider the relation between rainfall, pore-pressure and slope stability. Several empirical relationships have been deduced, based on the assumption that there exists a direct relationship between the occurrence of landslides and the quantity of rainfall, in terms of rainfall intensity and duration of rainstorm events, or short-term rainfall e.g. 24-h rainfall, and antecedent rainfall.

Campbell introduced the concept of "pluviometric threshold" in 1975 [3]. However, a significant breakthrough was achieved when Caine, in 1980 collected a global data set of rainfall and landslide occurrences on a variety of natural slopes and empirically derived a lower-bound threshold of rainfall intensities and duration for the initiation of shallow landslides and flows [2]. Thresholds based on the intensity-duration method outlined by Caine, have been estimated by different authors, such as Aleotti [1], Corominas and Moya [6], Crosta [7], Crosta and Frattini [8]. The significance of antecedent rainfall in landslide initiation is also recognised [10]. Statistically, the critical rainfall amounts have also been established, when elaborate information on rainfall and landslide occurrence is available [4, 13, 15]. The “intensity-duration” approach can be further refined, by normalizing the intensity value by the Mean annual precipitation (MAP). To obtain a possible correlation between rainfall parameters and the occurrence of soil slip phenomena and to identify the local rainfall threshold for triggering shallow landslides in terms of mean intensity, duration and mean annual precipitation (MAP) in the south Apuan Alps, Italy, Giannecchini [9]analyzed the pluviometric data between 1975-2002 from a single rain gauge. Chleborad [4, 5] estimated a cumulative rainfall threshold (CT), P_3=3.5–0.67P_{15}, defined by rainfall amounts (in inches) during the last 3 days, P3, and the previous 15 days, P15, for slope failure initiation after analyzing historical precipitation data (1933-1997) associated with 187 wet season landslides.

The presence of spatially well-distributed networks of rain gauges and a well-maintained database on the landslide location and initiation, aids significantly in establishing reliable thresholds, by statistical and deterministic methods. However, in Garhwal Himalayas, the Alaknanda river catchment, which is relatively ungauged, limited studies have been carried out. The spatial variability of geological and anthropogenic factors further complicates the defining of a precise threshold for triggering of landslides. Thus, an analytical approach is adopted for the present study to explore a possible relationship between rainfall magnitudes and slope failure initiation, based on which a minimum threshold has been determined for Garhwal Himalaya.

3. STUDY AREA

The Alaknanda river catchment between Badrinath (30°44’31N and 79°29’39E) and Pipalkoti (30°26’05N and 79°25’41E) is studied to establish the rainfall threshold (see Fig. 1). The catchment is characterized by monsoonal climate with frequent intense rainstorms; amount ranging between up to 200-250 mm per hour [12]. The amount of rainfall varies, depending on the location of the place to the windward or leeward side of the high ridges. A mean annual rainfall of about 1137 mm and a general pattern of monthly rainfall are evident. The catchment receives heavy precipitation between July and September.

The study area is characterized by deep gorges and rugged mountains, which have been formed due to the incision of stream. The maximum elevation observed in the area is 5443m and the minimum elevation is 1077m, with respect to the mean sea level. Geologically, the study area is transected by the granites and gneisses of Central Crystallines [11], Quartzites and phyllites of Saknidhar Formation, and the ferruginous shales, quartzites and phyllites of Garhwal group, which are separated along the Main Central Thrust. The major thrusts and faults trend in east west direction, conforming to the longitudinal extension of Himalayas. The presence of several thrusts and faults passing in the area has rendered the rock mass weak.

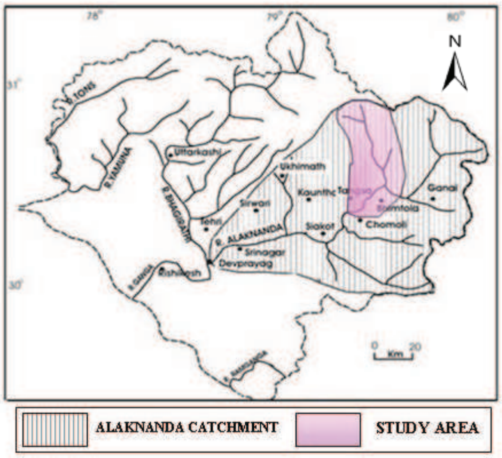

Fig. 1. Alaknanda river catchment and its location in Uttarakhand State

In the study area, National Highway 58 mostly aligned along the river Alaknanda runs for about 78km from Pipalkoti to Badrinath. The important settlements in this area are Joshimath, Hanuman chatti, Lambagarh, Pandukeshwar, GovindGhat, Helang, Pipalkoti and the main centers of pilgrimage are Badrinath and Hemkund Sahib. The towns are generally established along the road. The expansion of this road together with rapid urbanization has rendered these "marginally stable" [14] hill slopes, apparently more susceptible to failures.

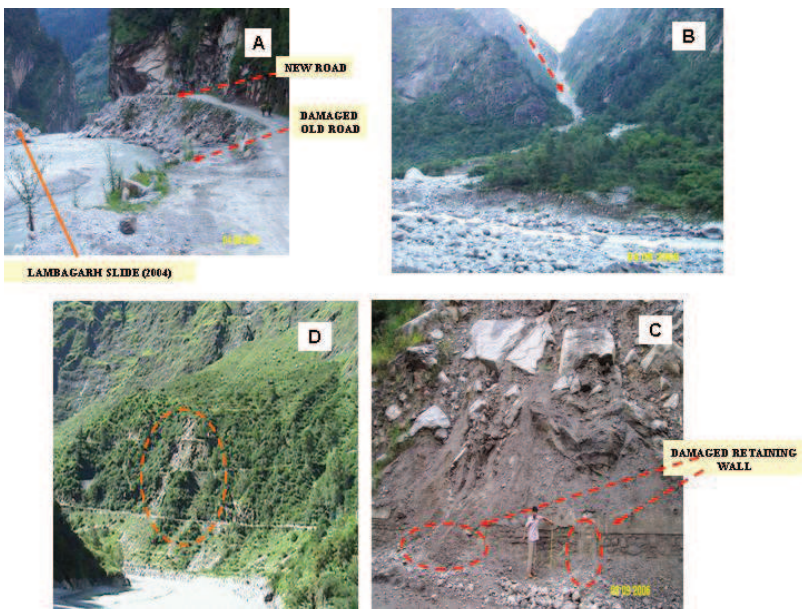

Fig. 2. Landslides in the Study Area *(Note: A,B New Lambagarh landslide(2004) on the left bank of the River Alaknanda; C, Debris slide near Marwari Bridge, Joshimath; D, Debris slides related to road cuttings on NH-58, near Hanuman Chatti).*

The majority of landslides observed were noted to be shallow translational debris slides, some of which subsequently mobilized into debris flow (see Fig. 2). While, most of the landslides originate in steep colluvial slopes, some landslides originate in weathered bedrock along multiple joints (e.g. Patalganga landslide). Many of the landslides represent composite events i.e. more than one landslide has occurred at the surrounding region and some single large events. The area has also witnessed two major earthquakes in 1991 with epicenter in Uttarkashi and in 1999 with epicenter at Chamoli. Thus, landslides here are an outcome of the intrinsic geology, adverse natural topography, i.e., steep slopes in talus accumulation, weathered rocks and soils, and man-made modification of these fragile slopes. These inherently unstable slopes frequently fail during rainstorms, often with catastrophic consequences.

The choice of study area is not based upon easy availability of data; rather it was realized that in spite of the damage caused in the area due to landslides, not much has been investigated in this portion of the catchment owing to complexity of terrain and data constraints.

4. DATA

4.1 Rainfall data

The daily data recorded at the rain gauge in Joshimath, Badrinath was obtained from 1976 to 2005. Similar data was obtained for Pipalkoti between 2004 and 2006 from Border Roads Organization (BRO), Joshimath.

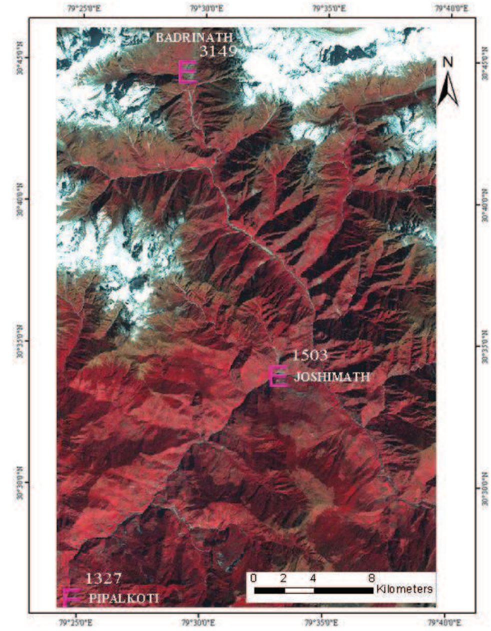

Fig. 3. ETM Image showing the geographic location and elevation of the three rain gauges in the study area.

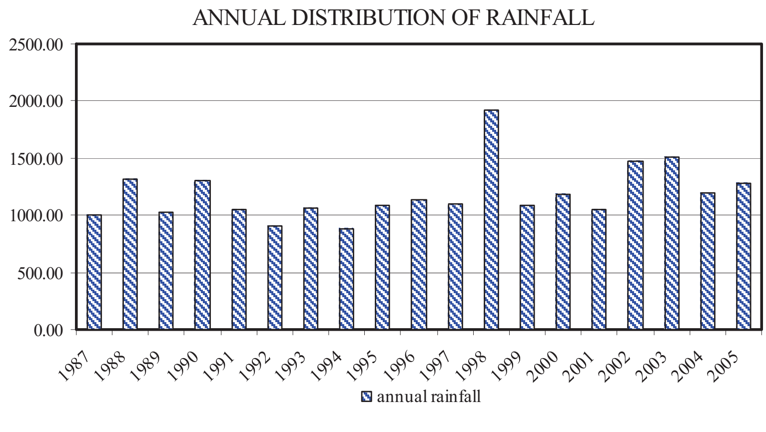

Fig. 4. The distribution of rainfall in Joshimath over the years between 1987 and 2005.

It is suggested that the measurement of rainfall in landslide investigations should be site-specific to each slope failure but this does not exist for the entire study area and the basin is largely ungauged. Thus, the spatial variability of rainfall is disregarded because of data limitations, and the rain gauge at Joshimath, for its location in the centre of the study area and its topographic setting, is believed to be important for the study and representative of the conditions at the site of instability. The daily rainfall data from Pipalkoti was available only from August 1, 2004 onwards. It was taken as reference for the landslides that occurred in 2006. The scatter plot (see Fig. 5) demonstrates the relationship between the rainfalls recorded at Pipalkoti and Joshimath in August 2004 and August 2005.

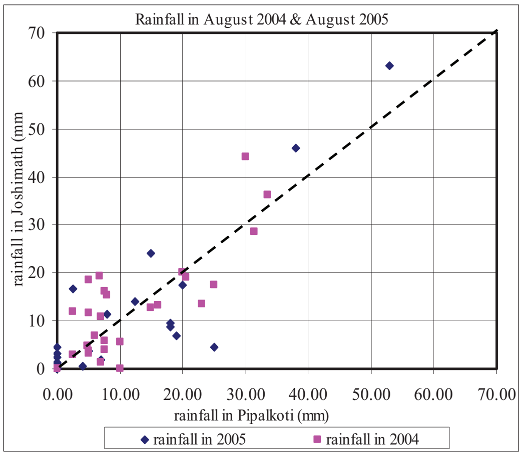

Fig. 5. Scatter plot to show the relationship between the rainfalls recorded at Pipalkoti and Joshimath in August 2004 and August 2005.

The rain gauge data from Badrinath had incomplete entries due to gauge malfunction owing to very low temperatures in the area. Thus, it was found insufficient to estimate the antecedent cumulative rainfall. Moreover, this rain gauge was maintained only between June and November and could not be used for the entire period of study. However, as the monsoon months of July and August are important for landslide instigation, it was decided to scrutinize the daily precipitation records from Badrinath rain gauge as well.

In order to observe the spatial distribution of rainfall in the region, the satellite based daily rainfall estimates (compiled at 6-hour interval, at a spatial resolution of 0.1° x 0.1°) obtained from Climate Prediction Centre (CPC), NOAA, USA, were used. The following graph (see Fig. 6), based on the previous analysis, shows that although some spatial variability does exist, however, rainfall follows the same trend over the entire region.

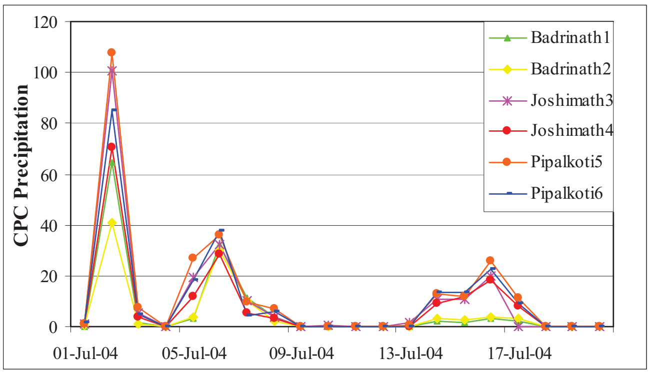

Fig. 6. Graph showing correlation between daily precipitation estimates obtained from CPC, NOAA.

Also, based on the interaction with the local people it was realized that especially during wet seasons there is not much variation in rainfall across the area. However, the pre-monsoon showers often occur as isolated rain events, which may not be distributed evenly over the catchment.

4.2 Landslide data

Historical data on landslide incidences between Pipalkoti and Badrinath was mainly obtained from the daily road damage report maintained by the Border Roads Organization (BRO), supplemented by personal accounts and news paper reports. The report contains information about the road blockage, reason of the blockage, the time when the obstruction is first reported and the time taken to clear the hindrance. The information on the day and location of the landslide as well as information on the extent of damage was easily extracted from the report. The initiation time of slope failure may differ from the time the road damage was first noted as the area is remote and therefore reporting, may not be accurate in case of single isolated events. The field information from various sources were carefully studied to distinguish early morning landslides from those that occurred in the latter half of the day as both will be influenced by different precipitation amounts. However, the information on the time of advent was not available for all landslide incidences and in such cases the study was carried out assuming the landslide event to have occurred on the day it was reported.

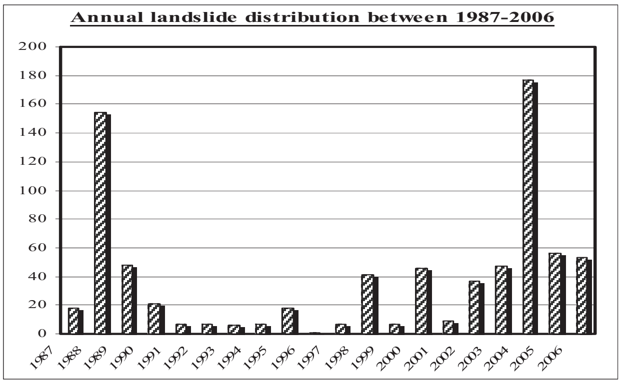

Fig. 7. The annual landslide distribution in the study area between 1987 and 2006.

Published literature and project reports by various agencies such as GSI, CBRI (Roorkee) and WIHG (Dehradun) were also studied to obtain accurate records of landslide occurrences in the study area. Local media reports were also searched thoroughly to look for landslide events. It was observed that only those damaging events had been reported, which caused casualties and/ or property loss including loss of cattle and agricultural land. Moreover, these reports often contained a vague description of the landslide location and usually only the name of the nearby village was mentioned. Although it was difficult to precisely locate the slides based on these reports but often the date stated in them was used to verify the landslide data extracted from the road damage report. These reports also proved useful to cross-examine if some slides had not been reported in the BRO records.

Apart from this field investigation was carried out in two stages: a reconnaissance survey followed by a detailed site study. A Differential GPS (DGPS) survey was carried out to mark the landslide initiation sites. A landslide inventory was maintained to collect information on landslide type, dimension, lithology, slope & aspect, land use, probable causes, and damage.

4.3 Database Organisation

The landslide information was compiled as mentioned above so as to get accurate distribution of slope failures in time and space. A landslide database since 1987 (see Fig. 7) was organized to include information on the landslide incidences recorded between Pipalkoti and Badrinath. The total number of landslide incidences reported between 1987 and 2006 in BRO documents was 768. Most of these incidences included reactivated old landslides and a few first time events. Now, the landslide events taken up for the study include all slope failures on natural and engineered slopes, but essentially related to rainfall. Thus, landslides that were triggered by the Uttarkashi earthquake of October 1991 and Chamoli Earthquake of March 1999 were excluded from the study. The landslides which were mentioned in the road damage reports as most likely to have been caused by blasting in the adjoining region were again, manually filtered out. As the landslides taken are situated along the highway, their locations were entered as a kilometer-stone reading on the highway. Traverses along the route were done to verify the data and ascertain its geographic location. A GPS survey was also carried out to determine the geographic coordinates of every location. It was found during field visit that the some of the old rock falls and soil slips, which were reported in the official records, could not be precisely located on ground as no associated scar or evident damage to the retaining wall was noted. Only those incidences were considered which local people confirmed. The information on the location, slope, and lithology were also entered using the landslide field proforma. Separately, the daily rainfall data from the three stations was arranged using Microsoft Excel software. The monthly and annual rainfall was calculated. Computations were done to get the 3-days, 15-days and 30-days rainfall values (prior to the day of failure).

Landslide data was then re-arranged for all days having minimum 1 mm of rainfall. It was noted (see Fig. 8) that only 1947 days experienced over 1mm of rainfall including 259 landslide days, out of which 131 days had a single landslide event, while multiple events were reported on the rest of the days.

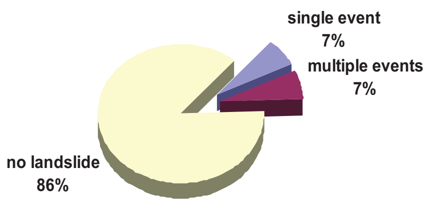

Fig. 8. Graph showing the distribution of single and multiple landslide events and days

Thus, 609 landslide incidences were extracted from the database and were classified into five categories (see Table 1) as per the number of occurrences per day

a) Single event (T_1)
b) Two events (T_2)
c) Three to five events (T_3)
d) Six to nine events (T_6), and
e) More than ten events in a day (T_{10}).

The distinction was made on the basis of slope failures recorded in a day.

Table 1. Statistics showing the classification of landslide events and number of slides in each category.

	Landslide incidences	Landslide days
Single event	131	131
Two events	112	56
Three to five events	183	52
Six to nine events	107	15
More than ten events in a day	76	5

Although, the precise timing of a landslide incidence was not available, the consideration of the cumulative precipitation corresponding to immediate preceding 3 days, including the rainfall on the day of landslide occurrence and 15 days rainfall, prior to the 3 days rainfall reduced the effect of error in assessment [4, 5]. The 3 days cumulative rainfall was considered to assess the immediate rainfall in previous 72 hours and 15 days prior rainfall was considered to assess the influence of antecedent rainfall on initiation of landslides. Thus, a comprehensive landslide database was generated to understand the influence of rainfall on the commencement of failure in a variety of setups in the catchment.

5. ANALYSIS

A threshold, minimum or maximum is defined as the limits within which a process is most likely to occur. The minimum thresholds are generally established for precipitation induced slope failures to delineate the limit below which they are most unlikely to be triggered, whereas, the maximum thresholds are given to identify the limit exceeding which there is a 100% probability of landslide occurrence. The landslide-triggering rainfall thresholds separate events that resulted from those which failed to triggered landslides and can be defined on an empirical or on physical bases. In the present study the precipitation thresholds for landslide initiation are defined based on the relationship between rainfall magnitude reached, over a specified time, at failure and the cumulative antecedent rainfall i.e., the rainfall accumulation over a specified number of days prior to the day on which a slope failed.

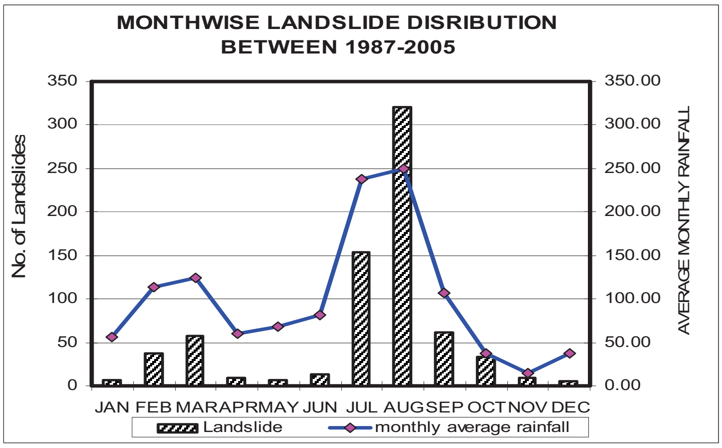

Fig. 9. The landslide distribution coincides with the average monthly rainfall at Joshimath rain gauge observed between 1987 and 2005.

The database was first studied to make certain that the landslide occurrences followed a pattern with the rainfall. The landslide incidences and monthly rainfall were compiled to confirm that maximum landslides occurred during the wet seasons (see Fig. 9).

Based on the statistics for the years between 1987 and 2006, it was observed that in all 511 landslide incidences had occurred only in July and August, which is about 67% of the total landslides reported. A rise in landslide activity was observed in the months of July but major landsliding starts as the monsoon progresses. Maximum landsliding occurs in August, the antecedent rainfall also saturates when the daily precipitation is high and the slope forming materials during July. The situation continues up to mid-September and considerable landslide incidences are reported during this time. Significant landslide activity is also noted in February and March, which can again be correlated with the spring showers and snow melt.

A year-wise comparison was performed between 1987 and 2005 to see the relation of the slope failures with the monthly precipitation shows that maximum landsliding occured in July and August. An exception was noted in the year 1990, when seventeen incidences of landslides were reported in February and March, while only 3 incidences were reported in July and August. A crosscheck with the rainfall data revealed that no major rain event had occurred in the monsoon months of 1990, whereas, significant rainfall events had occurred the same year in February and March. Although, the landslides that occurred in 1990 (see Table 2) are an exception to the general assumption that July and August months are the most crucial for slopes to fail, nevertheless, the role of precipitation is highlighted.

Table. 2. The landslide incidences in 1990 and associated daily rainfall

Landslide day	No. of slides	Daily rainfall (mm)
13-Feb-90	2	35
28-Feb-90	3	34
21-Mar-90	1	25
22-Mar-90	9	97
20-Aug-90	1	26

Also for the year 1996, there was no landslide reported in the monsoon months. The daily rainfall in the aforementioned period exceeded the normal limits on three instances; 28.2 mm on 10th July, 48.6 mm on 13th July and 36.8 mm on 5th August, but no incidence was reported. Even though, the chance that landslides were not reported cannot be totally ruled out, an explanation was offered that on the above dates even with high daily rainfall values the precipitation thresholds (see equations 1- 4) were not exceeded.

The results of comparison between the average monthly rainfall distribution and landslide incidences recorded over the months between 1987 and 2005 (see Fig. 9) substantiate that precipitation is the prime triggering mechanism responsible for the failure of the inherently vulnerable slopes. The high number of landslide events in July and August is also indicative that in Garhwal Himalayas, the monsoon months are most critical for slope failure initiation than the remaining days of the year.

To establish the thresholds for landslide initiation in the study area the database was scrutinized to identify the rainfall magnitudes over different durations to separate combinations of daily and antecedent rainfall that triggered landslides and then establish the probable landslide triggering thresholds. A review of methodologies proposed in the literature shows that the number of antecedent days must be carefully selected [15]. Thus, various antecedent rainfall intervals (3-, 15-, and 30-day prior) were considered to calculate the cumulative antecedent rainfall, which influenced landslide initiation the most. The database was re-arranged to observe the number of landslides occurring in a day along with the daily, 3-day, 15-day, and 30-day rainfall

A comparative analysis was performed to study the relationships between daily and prior 3-day rainfall (Fig. 10), daily and prior 15-day rainfall (Fig. 11), daily and prior 30-day rainfall (Fig. 12), over a period of 20 years. The minimum thresholds for each combination of landslide triggering rainfall cumulative are shown by the green line, which is used to demarcate the lower bound precipitation below which no slope failure initiates. These thresholds are identified visually, on the scatter plots between the daily rainfall and the cumulative antecedent rain.

5.1 Daily / prior 3-day rainfall

The relationship between the landslide occurrences with the daily and the 3 days prior rainfall (see Fig. 10) is defined by the equation

$$^{A}T_1 = R_1 + 1.4696R^3 - 14.645 \quad (1)$$

Where,

R_1 is the daily rainfall measured on the landslide day,

R^3 is the 3 days rainfall prior to the landslide day, and

$^{A}T_1$ is the minimum probable threshold required for a single or more landslide event to occur.

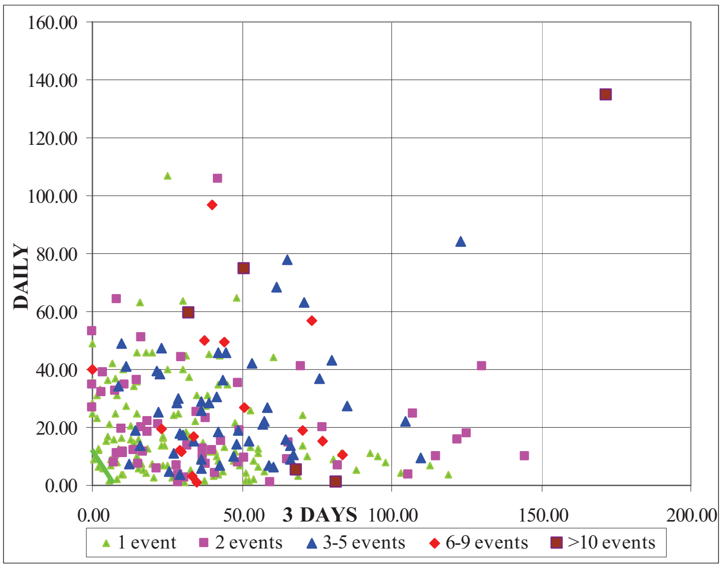

Fig. 10. The scatter plot based on the daily and prior 3-day rainfall on the landslide days.

However, as observed the initiation of landslides is not clearly defined mainly due to lack of antecedent rainfall influence, daily and 3-days rainfall mainly represents the triggering rainfall than the antecedent moisture condition.

5.2 Daily / prior 15-day rainfall

The minimum threshold defined on the basis of the relationship between daily and 15 days prior rainfall total (*see* Fig. 11) is given by the following equation

$$^{B}T_1 = R_1 + 0.548R^{15} - 35.032 \qquad (2)$$

Where,

$\mathbf{R_1}$ is the daily rainfall measured on the landslide day,

$\mathbf{R^{15}}$ is the 15 days rainfall prior to the landslide day, and

$\mathbf{^{B}T_1}$ is the minimum probable threshold required for a single or more landslide event to occur.

The threshold $\mathbf{^{B}T_1}$ implies that the daily rainfall contributes more than the prior 15 days precipitation cumulative in the beginning of the rainy season. At least 50 mm of cumulative rainfall is required with daily rainfall of 25 mm or above to initiate slide, thereafter the antecedent conditions play an important role. Although the lower threshold is well defined for 1-2 events, for higher number of events, the threshold is not well defined; particularly the upper limit for daily rainfall is unreasonably high if storm events corresponding to 10 events or more are considered.

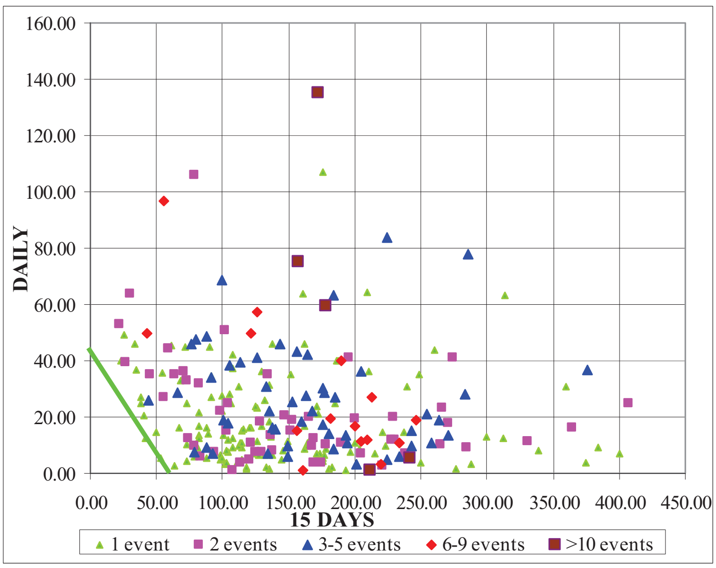

Fig. 11. The scatter plot based on the daily and prior 15-day rainfall on the landslide days.

5.3 Daily / Prior 30-day Rainfall

The minimum threshold defined on the basis of the relationship between daily and 30 days prior rainfall total (*see* Fig. 12) is given by the following equation

$$^{C}T_1 = R_1 + 0.491R^{30} - 51.293 \quad (3)$$

Where,

$\mathbf{R_1}$ is the daily rainfall measured on the landslide day,

$\mathbf{R^{30}}$ is the 15 days rainfall prior to the landslide day, and

$\mathbf{^{C}T_1}$ is the minimum probable threshold required for a single or more landslide event to occur.

The threshold $\mathbf{^{C}T_1}$ implies that the daily rainfall is more significant than the prior 30 days precipitation cumulative in the beginning of the rainy season. At least 60 mm of cumulative rainfall is required with daily rainfall of 25 mm or above to initiate slide, thereafter the antecedent conditions play an important role. Although the lower threshold is well defined for 1-2 events, for higher number of events, the threshold is not well defined.

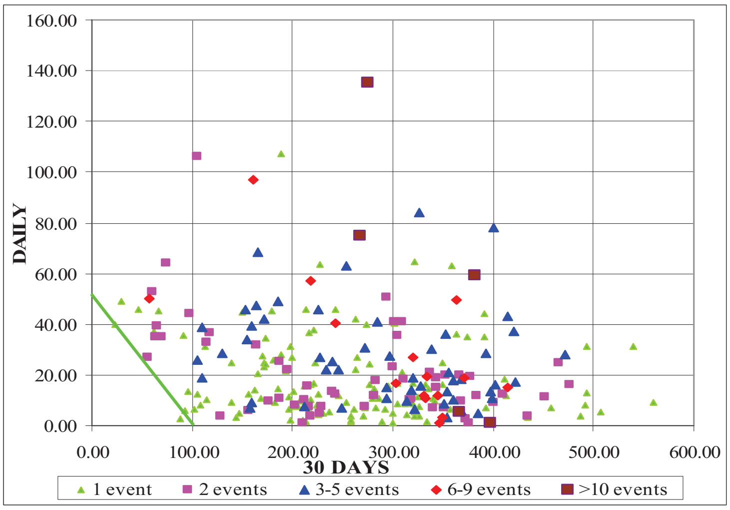

Fig. 12. The scatter plot based on the daily and prior 30-day rainfall on the landslide days.

Based on the above analysis, the influence of 1-3 days rainfall is clearly seen as significant for landsliding in the initial period when antecedent rainfall is around 50-60 mm. It is also observed that most of the slides were not reported on the same day as rainfall but on the following day. For example, on 17th August 1988, 26 landslides were reported, when the same day's gauge records show 1.2 mm of daily rainfall. Investigation of the rainfall data revealed that on the preceding day, 59.3mm of rainfall was recorded and it was responsible for triggering the landslides. The role of antecedent rainfall is somewhat subdued, owing to the fact that the majority of the reported slides is related to road expansion activities (Langsi, Marwari, and Vishnuprayag) and is influenced by the 1-3 days rainfall. Moreover, it is seen that most of the slope failures are observed in the glacio-fluvial colluvium (Lambagarh slide zone) and some in weathered rocks such as slates and phyllites (Patalganga).

5.4 72 Hours / prior 15-day antecedent rainfall

The analysis is carried further with the 3-day rainfall amounts that occurred immediately prior to the landslide events and antecedent 15-day precipitation that occurred prior to the 3-day total. In order to improve the lower threshold for different storm events, a scatter plot (Fig. 13) was included in the analysis to show the relationship between 3-day total (including the daily rainfall) and the prior 15-day rainfall (preceding those 3-days). As explained before, this was done to include rainfall in preceding 72 hours reducing the error due to time of reporting and influence of immediate preceding triggering storm event. It was observed that with a 3-day rainfall cumulative, which includes the previous day's rainfall along with the daily rainfall, the critical conditions prevailing at the time of failure are better defined. The influence of the antecedent rainfall is difficult to quantify as it depends on several factors such as the hydrogeology of the slope forming materials and is subject to a lot of uncertainty. However, the 15 days period seems to be logical to represent the antecedent conditions as for many years it was observed that 50-60 mm rainfall was a prerequisite for landslides to initiate by a single day storm event with 25 mm of rainfall, thereafter the 15 days prior rises to 80-90 mm in the middle of July, when daily rainfall of even 10 mm can cause slides. To avoid ambiguity, the landslide days for which the daily rainfall was less than 1mm were also excluded while constructing the scatter plot between the 3 day cumulative (including daily rainfall) and prior 15 days. The validity of this assumption was verified with the landslide data of 2004, which shows only 4 slides to occur when the daily rainfall was less than 1 mm, which may be attributed to reporting on the following day or variability in rainfall measurement and event location.

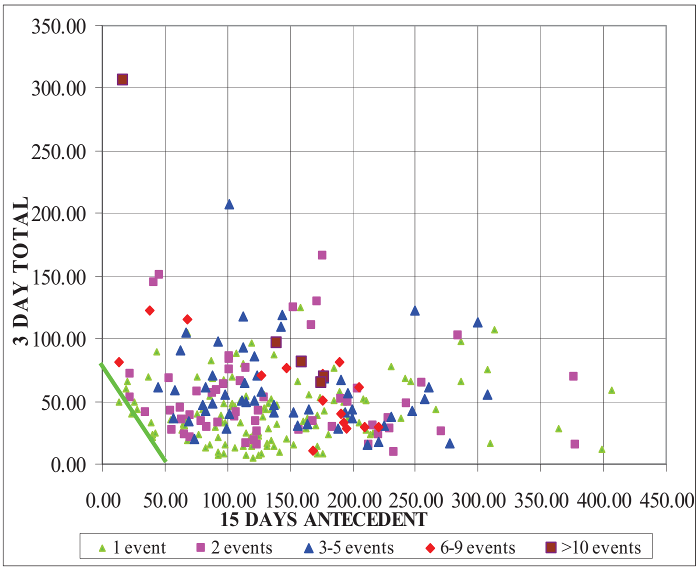

Fig. 13. Scatter plot based on the 3-day total and 15-day prior antecedent rainfall. (Note: The lower bound precipitation threshold represented by the green coloured line was visually identified on the scatter plot and was checked for various storm events starting from 1987 till 2006).

The minimum probable threshold index (see Fig. 13) based on the analysis of the 3 day rainfall total and the prior 15 days accretion associated with the slope failures reported between 1987 and 2006, is defined by the equation given as follows,

$$T_1 = R_3 + 1.5351R_{15} - 82 \quad (4)$$

Where,

R_3 is the 3 day rainfall cumulative including the rainfall on the landslide day,

R_{15} is the 15 days antecedent rainfall prior to the 3 day total, and

T_1 is the minimum probable threshold required for a single or more landslide event to occur.

The approximate lower bounds of landslide-triggering precipitation thresholds for the single and multiple events were again visually identified on the scatter plot and are illustrated in Fig. 14.

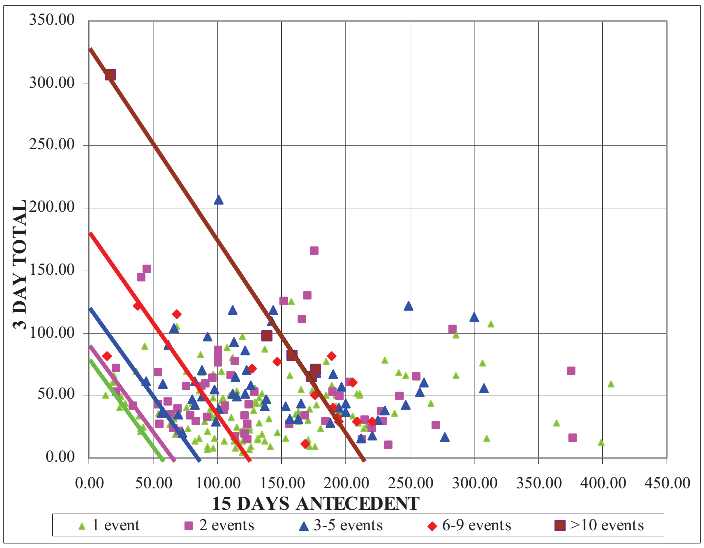

Fig. 14. Scatter plot based on the 3-day total and 15-day prior antecedent rainfall. (Note: The lower bound precipitation thresholds for single and multiple events, shown by separate lines, were visually identified on the scatter plot).

The analysis based on the 3-day and prior 15 days rainfall cumulative resulted in five distinct minimum precipitation thresholds causing single event, two, three to five, six to nine, and more than ten landslide events recorded in a day. However, the threshold for single and 2-events is very close, therefore, clubbed together in the analysis. The minimum probable threshold for the various landslide events are discussed as follows:

Minimum probable threshold, $\mathbf{T_2}$, for two landslide incidences on a day, is defined by the following equation,

$$T_2 = R_3 + 1.5351\ R_{15} - 90 \qquad (5)$$

Minimum probable threshold, $\mathbf{T_3}$, for three to five landslide incidences on a day

$$T3 = R3 + 1.5351\ R15 - 125 \qquad (6)$$

Minimum probable threshold, $\mathbf{T_6}$, for six to nine landslide incidences on a day

$$T6 = R3 + 1.5351\ R15 - 179 \qquad (7)$$

Minimum probable threshold, $\mathbf{T_{10}}$, for more than ten landslides on a day

$$T10 = R3 + 1.5351\ R15 - 328.62 \qquad (8)$$

The precipitation thresholds thus defined, are inferred as an approximate lower-bound threshold above which the particular level of landslide incidences (i.e. 1-2, 3-5, 6-9 and >10 events per day) are more likely to occur on the vulnerable slopes.

However, the threshold for single and 2-events is very close, therefore, clubbed together in the analysis.

5.5 Precipitation threshold for Man- modified slopes

The statistics were also examined to understand the slope failure mechanism in man-modified conditions. A human influence is evident on the instability of the marginally stable slopes. About 48% of the total landslide incidences reported was found directly related to anthropogenic activities such as road expansion and improper drainage. The precipitation threshold required to initiate instability in man-modified slopes were established based on the 3-day and prior 15 days rainfall cumulative. The following figure illustrates the lower limit below which a marginally stable man-modified slope is unlikely to fail.

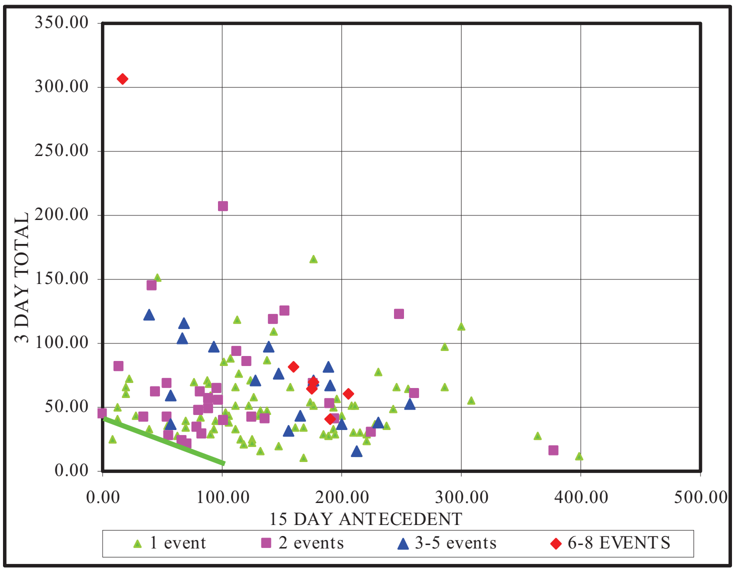

Fig. 15. Minimum probable threshold for man-modified slopes shown by the green line visually identified on the scatter plot

The minimum probable threshold, $\mathbf{T_M}$, required for a single or more landslide event to occur on a man-modified slope is defined by the following equation.

$$T_M = R_3 + 0.2664\ R_{15} - 43.79 \qquad (9)$$

It was observed that the threshold required for failure to advance in the engineered slopes is much below that required to bring down a natural slopes. The study shows that the influence of the antecedent rainfall is not substantial for destabilizing such slopes the rational explanation for this is that the excavation for the hill road in the study area is mostly done in weathered rock masses and colluvium, which are most likely to fail even, once disturbed without significant antecedent rainfall [6].

5.6 Assessment of the threshold during Monsoon

The minimum threshold derived from the 3-day rainfall and prior fifteen days accumulation is used to understand the landslide – rainfall relationship in the Alaknanda catchment. The evaluation of the thresholds is done to verify if they can distinctly separate rainfall events that triggered slope failures from those that did not and also know the probability that a slope fails if the thresholds are exceeded. The assessment of the minimum thresholds is done for the years 2002, 2003, 2004, and 2005 based on the landslides reported in the months of July and August in each year. The July and August months are considered, as the results so far indicate that the monsoons are crucial for landslide activities. Moreover, the uncertainty regarding the spatial variability of the rainfall is more or less insignificant for the monsoon season.

5.6.1. Assessment of the thresholds for July and August, 2004

2004 was an exceptional year with large number of slides reported in the recent past and it shows on 3 occasion, thresholds had exceeded by large values and the extreme event threshold was also exceeded on two occasions. As observed in other cases, the steep rise in threshold values is associated with landslide events.

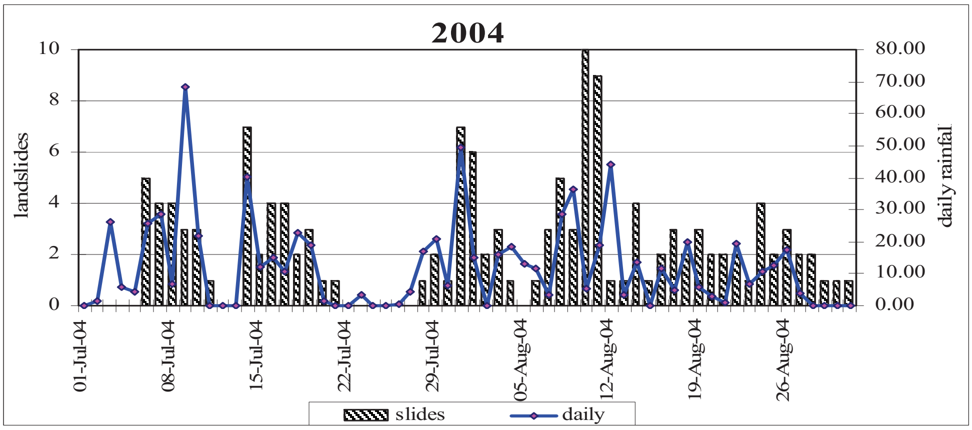

Fig. 16. Daily distribution of landslide incidences and rainfall in July and August 2004.

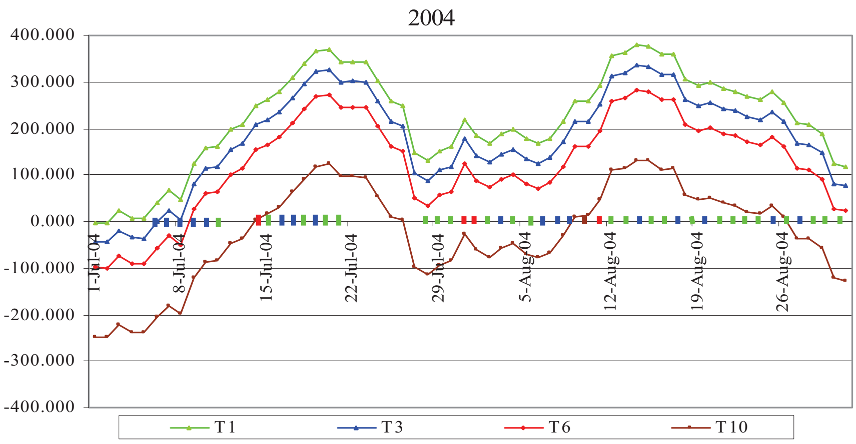

Fig. 17. Graph showing the daily variation in the threshold and landslide events for July and August, 2004. (Note: The thresholds for a single event, 3-5 events, 6-9 events and events>10 in a day are shown by separate lines. Similarly, the landslide events are shown in separate colors, corresponding to a particular landslide event).

As shown earlier, maximum number of slides occurs in July-August, therefore, daily, 3-days and 15 days prior precipitation data of 60 days in 2004 were analyzed (see Fig. 16). It was observed that 87% of days 1-2 landslide events occurred when threshold exceeded for similar events. Now considering the occurrence 1-2 events as marker of initiation of landslides, threshold for 3-5 events, 6-9 events and more than 10 events were analyzed. It was observed that 95% of the days, landslides were reported when T_3 had exceeded. Similarly 96% of days, landslides were reported when T_{10} had exceeded. It was observed (see Fig. 17) that when most extreme event threshold T10 was just positive around 2.5, the T_6 was around 150, T_3 was around 200 and T_1 was around 250, which suggests that T_1=250 represents the major storm event when 10 or more landslides are expected and T1 = 40 shows the initiation of about

87% of slides. Therefore, it can be concluded that the defined threshold is indicative of the triggering conditions leading to landslides in the prevailing geological conditions in the study area.

6. RESULTS AND DISCUSSION

6.1 Rainfall as a prime triggering mechanism

Observation of the landslide distribution over the last twenty years shows that it follows a definite trend with the distribution of rainfall in the Alaknanda catchment, India. The rainfall pattern as studied for the period between 1976 and 2006 indicates that about 50% of the annual rainfall is received in July and August, during monsoon and is accompanied with significant landslide activity. Statistics reveal that about 66% of the slides occur between July and August (see Fig. 9). An observation based on the historical data reveals that maximum landslide activity was reported in the years 1988 and 2004 when the bi-monthly average for July and August was above 50% of the annual total. The significance of antecedent rainfall is also well exhibited by the fact that the slope failures are more frequent in the month of August than July.

6.2 Precipitation thresholds for landslide initiation

An analytical approach is adopted to establish the relationship between rainfall magnitudes and slope failure initiation. Analysis is done based on antecedent rainfall, for different time intervals before the event. Thus, various antecedent rainfall intervals (daily, 3-, 15-, and 30-day prior) were considered along with the 72-hours precipitation and prior 15 days total, to calculate the cumulative antecedent rainfall, which influenced landslide initiation, the most. The minimum probable thresholds (Fig. 10, Fig. 11, Fig. 12, Fig. 13, Fig. 14) for a specified level of landslide activity (i.e. number of slides occurring on a single day) were identified. The assessment of the results is done based on the landslide data of July and August months in the years 2002 to 2005. Analysis of the graphs (see Fig. 16, Fig. 17) suggests that the slope failure of a specified level usually occurs at the instant, when the threshold exceeds the lower bound for the particular level of activity. A success rate of 92% is observed in 2004 based on the 3-day (72-hr) and previous 15 day (before the 72-hr precipitation) when the minimum threshold exceeds and the daily rainfall is over 1mm. These thresholds have been analyzed with respect to initiation of landslides starting from 1988 till 2006 showing validity of this approach. Slopes disturbed by road construction shows lower threshold (Fig. 15) thereby indicating the role of precipitation on initiation of landslides on disturbed slopes.

6.3 Related Issues and future considerations

The presence of well distributed networks of rain gauges and a well-maintained database on the landslide location and initiation is essential to establish reliable thresholds. It is suggested that the rainfall measurements should be made at the site of instability and represent the exact pre-failure conditions of a slope, however, the lack of rain gauges poses a major limitation of the study. The data may be questionable as the measured values at the distant rain gauges may not be an exact representative of the entire area due to differences in slope, aspect and elevation. Moreover, the data from simple rain gauges only gives information on the daily rainfall magnitudes. As a result the role of storm intensity could not be ascertained. The functioning conditions of the rain gauge used are also of concern. Installation of a spatially well-distributed network of rain gauges within the basin is highly recommended. These should be preferably located near the zones of instability. Even at the present rain gauge sites, an hourly monitoring is suggested during July and August, when maximum landslide activity is expected.

The entirety of the landslide data also varies. As the landslide incidence data is mainly extracted from the road damage reports of BRO and other sources, it contains information mainly of those incidences that caused traffic disruption. In most of the cases these are the failures along the road, only rare incidence as that of the Lambagarh slide, which occurred in 2004 on the opposite bank and destroyed the highway, were reported. Also, an uncertainty exists as to the precise time of failure initiation as the time mentioned of a road blockage might vary slightly from that of the slope failure initiation. Thus, a better record of landslide initiation time is needed. Another apprehension is that a considerable number of slides might have gone unnoticed or were not reported due to inaccessibility of the terrain.

The spatial variability of geological and anthropogenic factors further complicates the defining of a precise threshold for triggering of landslides. Thus, the considering precipitation as the only driving mechanism might be an exaggeration. The database shows that considerable numbers of slides are observed in the months of February and March. Although these were very well related to the precipitation distribution, however it is recommended to include the air-temperature index to understand the pre-failure conditions of the slopes. It is during this time, that the snow starts to melt and thus, the inclusion of air-temperature in these studies can give significant results in snow-bound areas.

7. CONCLUSION

The present study identifies precipitation as the main mechanism for slope failure initiation in a part of Garhwal Himalayas and defines a lower-bound precipitation threshold, based on 72-hours precipitation and 15 days prior antecedent precipitation, if the daily rainfall is above a specified limit. The evaluation of the thresholds, based on the landslides observed in July and August, shows a high probability of landslide occurrence when the lower bounds of the threshold are exceeded, under other considerations. The prediction rates can be significantly improved with the availability of a well-distributed network of weather stations and better recording of the initiation time of slope failures. The thresholds can be further improved by taking into account the spatial variability of other stability influencing parameters to aid in effective landslide hazard assessment in the Garhwal Himalayas.

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