**Assessment of landslide hazards induced by extreme rainfall event in Jammu and
Kashmir Himalaya, northwest India**

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Abstract

In the Indian Himalayan region (IHR), landslide-driven hazards have intensified over the past several decades primarily caused by the occurrence of heavy and extreme rainfall. However, little attention has been given to determining the cause of events triggered during pre- and post-Indian Summer Monsoon (ISM) seasons. In the present research, detailed geological, meteorological, and remote sensing investigations have been carried out on an extreme rainfall landslide event that occurred in Sadal village, Udhampur district, Jammu and Kashmir Himalaya, during September 2014. Toward the receding phase of the ISM (i.e., in the month of September 2014), an unusual rainfall event of ~488.2 mm rainfall in 24 h took place in Jammu and Kashmir Himalaya in contrast to the normal rainfall occurrence. Geological investigations suggest that a planar weakness in the affected region is caused by bedding planes that consist of an alternate sequence of hard, compact sandstone and weak claystone. During this extreme rainfall event, the Sadal village was completely buried under the rock slides, as failure occurred along the planar weakness that dips toward the valley slope. Rainfall data analysis from the Tropical Rainfall Measuring Mission (TRMM) for the preceding years homogeneous time series (July-September) indicates that the years 2005, 2009, 2011, 2012, and 2014 (i.e., closely spaced and clustering heavy rainfall events) received heavy rainfalls during the withdrawal of the ISM; whereas the heaviest rainfall was received in the years 2003 and 2013 at the onset of the ISM in the study region. This suggests that no characteristic cyclicity exists for extreme rainfall events. However, we observe that either toward the onset of the ISM or its retreat, the extreme rainfall facilitates landslides, rockfall, and slope failures in northwestern Himalaya. The spatiotemporal distribution of landslides caused by extreme rainfall events suggests its confinement toward the windward side of the Himalayan front.

Keywords: extreme rainfall; landslide hazards; orography; Indian Summer Monsoon

1. Introduction

During the first week of September 2014, the Jammu and Kashmir Himalaya in northwestern India had experienced one of the worst floods because of unprecedented intense rains (Fig. 1). Massive loss of life and property took place owing to extensive flooding in the Jhelum River and subsequent landslides in the region. This catastrophic event occurred as a result of heavy to very heavy rains observed over the Jammu and Kashmir region, India. The India Meteorological Department (IMD) has defined such events with 7-12 cm rainfall within 24 h as heavy rainfall events, while events with rainfall ranging from 13 to 24 cm within 24 h as very heavy rainfall. During the catastrophic rains during 5 and 6 September 2014, a major landslide event that took place at Sadal village in Udhampur district, Jammu and Kashmir, has been identified and chosen for further investigations (Fig. 1B). Sadal village was completely damaged because of a large rockfall-type landslide. About 75 houses, 40 people, and their livestock had been buried below the debris in Sadal village. Such landslide hazards are common and result in the damage to life and loss of millions of dollars of property annually. Landslides triggered by rainfall have been discussed previously by various researchers (Anbalagan, 1996; Takahashi et al., 2001; Dai et al., 2003; Dortch et al., 2008; Tsai and Chen, 2010; Tsai and Wang, 2011; Gupta and Uniyal, 2011; Lepore et al., 2012; Bhan et al., 2015). A few recent examples from the Indian Himalayan region (Rautela and Paul, 2001; Kumar et al., 2003; Mandal and Maiti, 2013; Asthana and Sah, 2007; Sati et al., 2011; Rana et al., 2012; Rautela, 2012; Martha et al., 2015) demonstrate the complex cascading processes that directly threaten the population, including human activities and infrastructure, communication network, and agricultural lands. These landslides and associated mass movements adversely affect the regional socioeconomic setup.

Development and landslide occurrence is a complex physical process. Therefore, understanding the landslide mechanism particularly in the mountainous regions is important for landslide risk management. A large number of studies have been carried out worldwide and also in the Indian Himalayan region, which helped in identifying the causative factors for landslides (Gupta et al., 1999; Arora et al., 2004; Saha et al., 2005; Kanungo et al., 2006; Bathrellos et al., 2009, 2012; Chauhan et al., 2010), by generating landslide hazard susceptibility maps and using physically based models (Alvioli et al., 2014). However, negligible attention has been paid in discussing the evolution of landslides during such a catastrophic rainfall event (Starkel, 1972; Caine and Mool, 1982; Froehlich et al., 1990;

Gabet et al., 2004; Khanal and Watanbe, 2005; Dahal and Hasegawa, 2008; Sengupta et al., 2010).

Landslide hazards evaluation based on rainfall intensity–duration thresholds in any affected area is attained through accurate information on landslide occurrences and associated rainfall conditions (intensity and amount). However, such landslide inventory types are rarely prepared immediately, rather they are assessed years after major landslide events. Initially, Caine, (1980) empirically derived rainfall thresholds and duration for landslide initiation using rainfall data and landslide occurrence data at different time intervals over a variety of natural slopes ($I = 114.82 * D^{-0.39}$). In the Nepal Himalaya, few studies have determined the threshold relationship between landslide and rainfall intensity (Gabet et al., 2004; Dahal and Hasegawa, 2008). Rainfall thresholds have been established worldwide by using intensity and duration of rainfall event relationships (Crosta, 1998; Corominas and Moya, 1999; Crozier, 1999; Aleotti, 2004; Giannecchini, 2006; Ma et al., 2014) along with antecedent rainfall measurements (Glade et al., 2000; Gabet et al., 2004; Guzzetti et al., 2007). Hence, with considering of these limitations, a detailed landslide survey was conducted and the geology and geomorphology of the studied site were assessed. The meteorological conditions of the landslide affected region have also been highlighted. The prime research objective is to understand the causative factors for the development of extreme rainfall related to small scale landslides by integrating various data sets, such as prevailing weather conditions during the events using meteorological data, pre- and post-disaster scenarios using satellite imagery along with topographic maps, and characteristics of the local terrain.

2. Physical characteristics of the study area

2.1. Geology and local terrain characteristics

The study location lies in the inner sub-Himalaya, within the seismic gap between the rupture zones of the 1905 Kangra and 2005 Kashmir earthquakes (Thakur et al., 2010). The Himalayan Frontal Thrust (HFT), trending NW-SE is emergent between the Sutlej and Beas rivers (Fig. 1A). West of the Beas River in the Punjab, and Jammu and Kashmir Himalaya, the HFT trace has shifted to the north; while the contact between the sub-Himalayan front and the alluvial plain is not as sharp, which can be observed in the satellite imageries. In the foothills of the Jammu area, the frontal anticline is mapped as the Surin Mastgarh Anticline

(SMA) by the Oil and Natural Gas Commission (Karunakaran and Rao, 1979; Raiverman et al., 1994). The northern limb of the anticline is cut by the Mandili Kishanpur Thrust (MKT) which represents the eastern continuation of the Reasi Thrust or Medlicott-Wadia Thrust (MWT; Jayangondaperumal and Thakur, 2008; Thakur et al., 2010; Fig. 1A).

Structurally, the affected Sadal village is located on the MWT hanging wall, but on a local scale, in the lower Murree Formation in the vicinity of the ~E-W trending Anji fault mapped by the Oil and Natural Gas Corporation (Fig. 1B; Karunakaran and Rao, 1979). The Murree Formation consists of alternating dark to reddish brown, weak claystone, mudstone, siltstone, purple shales, and strong grey-green sandstones with pseudoconglomerates (Karunakaran and Rao, 1979). The sandstones units are hard, multistoried, cross-bedded, 3-6 m thick, and are interbedded with weak red clay or mudstone. The clay stones are unconsolidated and sometime splintery having a thickness of <1 m. The cover or hillslope materials consist of gravelly silt of colluvial origin, which are underlain by the Murree Formation. The units within the Murree rocks are weak and prone to failure during continuous rainfall of about 72 h (Singh et al., 2010). The Sadal village settlements are situated on the headwall of the large-scale landslides, which creates susceptibility to small-scale slides during the ISM (Fig. 2A) season. The village lies on the upslope spur at a height of ~1900 m amsl, and the lower side is bounded by the Sadal Khad stream at an elevation of ~1600 m amsl (Fig. 2B).

2.2. Climatic conditions

The fundamental climatic pattern of India is governed by summer (July-September) and winter (December-March) monsoons. Jammu and Kashmir cover the north westernmost fringe of India. Physically, the state comprises three distinct regions corresponding to its three divisions; Ladakh, Jammu, and Kashmir. The climatic conditions of Jammu and Kashmir vary greatly owing to its rugged topography and altitude. During summer months the area receives rainfall from monsoon winds; whereas in winter, wind from the Mediterranean causes precipitation in the form of snowfall and rainfall. In July and August, rainfall up to 650 mm occurs monthly at an average, causing frequent landslides during the ISM seasons. Humidity in the monsoon season that stretches over July and August can be as high as 70%, whereas the summer months become uncomfortable with increasing temperature. The seasonal and annual rainfall changes along with rainy days in the Kashmir Valley over the last century have been analyzed in detail by Kumar and Jain (2010).

3. Materials and methods

A detailed mapping was conducted along stream, road, and footpath track in and around the damaged sites. Using Survey of India topographical sheets of 1:50,000 scale, aerial photographs, and satellite imageries, a traverse was taken across N-S sections analyzing the affected sites regional structural framework. Remote sensing data of different time slices enabled us to follow the landslide evolution in the Himalayan range (Gallo and Lave, 2014). The information gathered from repetitive satellite imageries, combining ground observations at high spatial and temporal resolution, helped to identify the landslide zones along with the unstable areas that are prone to such hazards. Landsat-8 images of 30-m spatial resolution for the multispectral bands and 15 m for the panchromatic band have been used for generating primary information in identifying the landslide-affected areas much faster than visual assessment in a repetitive mode. This is because remote sensing data products take advantage of spectral change properties in a near-real timeframe in identifying the landslides. Satellite has a repetitiveness of 16 days and can be freely downloaded from GloVis and/or Earth Explorer. Two imageries have been utilized in the present research, i.e., pre-event image (acquisition date: 18 August 2014) and post-event image (acquisition date: 26 September 2014). Therefore, satellite imagery and field studies along with previously published maps have been used in delineating bedrock orientations on a regional scale.

Slope failure can accurately be predicted, provided a known rainfall intensity threshold is estimated. However, in the Indian Himalayan region (IHR), establishing rainfall intensity thresholds is challenging mainly because of sparse rain gauges, poor Automatic Weather Station (AWS) network, and regional inaccessibility. Considering the above shortcomings, a gridded data set of TRMM 3B42 V7 3-h rainfall product having a resolution of 0.25×0.25 for the past 15 years starting from 2000 to 2014 has been chosen for the present analysis. This analysis has been completed for the ISM months (June-September) during which the region received heavy rainfall. The TRMM v7 is considered as a validated product particularly for the foothills of the Himalayan range (Bharti et al., 2016).

In the present research, satellite-based rainfall data (TRMM 3B42) have been analyzed and validated through rain gauge records at the Katra station monitored by the IMD, located ~18 km away from the damaged site. Detailed meteorological observations and analysis of the present catastrophe over the Jammu and Kashmir region are given by Ray et al. (2015). Hence, rainfall data that supports the present research have also been utilized.

Results have been discussed in terms of the trend and patterns rather than the rainfall amount. The derived TRMM rainfall data reasonably reflects seasonal pattern in rainfall during the selected years for the period of study. Patterns observed in the rainfall occurrences are better reflected than patterns in rainfall amounts observed in the Himalayan ranges.

4. General description of damaged area using optical data

Topographic maps and Landsat ETM/TM were utilized for identifying the landslide boundaries. The pre- and post-landslide stage at Sadal village viewed from Landsat-8 images can be seen in Fig. 3. A band combination of bands 5, 4, and 3 was used for making the False Color Composite (FCC). The post-stage FCC image shows the landslide affected area (white area) marked as a curved line with an arrow showing the direction of movement. The estimated area of the landslide valley is $\sim 0.46 \text{ km}^2$ derived from the image. Similarly, a panchromatic image band-8 of Landsat-8 was also used for comparison. In the FCC image, the cyan areas are related either to barren lands (light white) or water bodies (dark white) revealed by our field observations. In the satellite image, just north of Sadal village, the fault exhibits substantial expression and was previously mapped as the Anji fault by the Oil Natural Gas Corporation (Karunakran and Rao, 1979; Raiverman et al., 1994). The strike of the mapped ground fissure traces is parallel to the Anji fault.

5. Rainfall characteristics during landslide event

In the present research, satellite-derived rainfall estimation has been used to analyze the variability of rainfall events during the monsoon period. The TRMM 3-hourly rainfall data is plotted as a time series and then comparing with the associated rain gauge stations of the IMD (Figs. 4A, 5A). We observed a series of large landslide occurrences during July and August. Therefore, daily rainfall data for the past 15 years, i.e., from 2000 to 2014, is used for identifying the relationship between landslides and rainfall extremes, on a cumulative basis (Figs. 4B, C).

Analysis of the observed rainfall data suggests that the affected region received maximum rainfall of 300-400 mm during July-August 2009-2013 (IMD). However, during the 2014 monsoon season, the damaged area received an abnormal rainfall on 5 September 2014 ($\sim 279.2 \text{ mm}$) and 6 September, 2014 ($\sim 209 \text{ mm}$), compared to the normal rainfall of 0.5 and 4.0 mm, respectively (Fig. 5A). A detailed analysis of this catastrophic events in Jammu

and Kashmir states using rain gauge data recorded by the IMD shows that weekly cumulative rainfall (4 through 10 September 2014) exceeded the average rainfall for the entire monsoon season (i.e., June–September) in 6 districts out of 18 in the states of Jammu and Kashmir (Ray et al., 2015). Using such data sets, we conclude that only one station at Kawa (32°52'14.52" N; 75°8'5.41" E), Udhampur district of Jammu and Kashmir state, recorded the highest rainfall intensity (~490 mm for 4 days), that was very close (~18 km) to the landslide site and orographically situated on the windward side (Ray et al., 2015). From the past 15 years time series of the daily rainfall data, we observed that the years 2005, 2009, 2011, 2012, and 2014 received heavy rainfall during the ISM withdrawal; whilst the years 2003 and 2013 showed the heaviest rainfall occurred at the ISM onset in the region (Fig. 4C). In addition, we have analyzed published records of catastrophic events (Haritashaya et al., 2006; Rana et al., 2012; Dobhal et al., 2013; Kumar et al., 2013; Mandal and Maiti, 2013; Thayyen et al., 2013; Arora et al., 2014; Bharti et al., 2016) during cloudbursts or extreme rainfall events highlighting the frequency type of such regional phenomena (Fig. 5B, Table 2). Our analysis suggests that consecutive (including daily and hourly) high intensity rainfall causes devastating landslides and flash floods in the IHR. Therefore, we conclude that during the monsoon season an abnormal rainfall pattern was observed either toward the beginning or withdrawal of the summer monsoon season resulting in landslides and flash floods.

6. Pre- and post-landslide landscape descriptions

The Sadal landslide extended for ~1.6 km from the ridge top of the main scarp at ~1980 m amsl down to the Sadal stream at an elevation of ~1600 m amsl. A topographic profile constructed (using a Survey of India toposheet) across the damaged site shows a concave upper slope at the top and convex toward downslope (Fig. 2B). From a geomorphological perspective, Sadal village is situated on the spur containing hillslope-forming materials largely composed of purple to bright purple clay admixed with large boulders of Murree sandstone. The cover materials lie above the rocks of the Murree Formation (Fig. 6A). The upper portion of the village is located at ~1980 m amsl and the valley slope is at ~30°-35° toward the SE. Flash flood debris along the Sadal Khad stream caused maximum damage to life and property in the altitudinal zone ranging from ~1600 to 1980 m. From the field evidence and topographic profiles, we observed at the steepest slope section a small, seasonal channel passing through the village (Figs. 2A, B) that is ~2-3 m wide and ~1-1.5 m deep; while after the flash flood incidence and debris flow, an ~5-m- deep

incision, took place. The deep cutting along the channel has generated minor slumps and created vertically displaced cracks of ~50 m length, ~15 to 30 m width, and ~60 to 80 cm depth along with ~10-15 cm in the agricultural field lying close to the channel (Fig. 6B).

The middle portion of the slope is at 45° , having an altitude of ~1800 m amsl. The slide material damaged the hillslopes and created ~10-15 m high and $\sim 60^\circ$ - 65° steep scars at the slide head. This has created a potential site for future slides caused by alteration in the angle of response. The slope's lower reach is at 10° forming a flat surface bordered by the Sadal stream that joins with the Kanji Khad stream. Angular head scars in the rock, huge rock boulders of 9×4 m along the spur, and unsorted slide debris look like glacial till at Sadal village (Fig. 6C). These features suggest that Sadal village is situated on old rockslide materials. The Sadal spur is completely transformed to landslide rock zones in the valley (Fig. 6D). The fractured bedrocks dip 20° - 30° toward SE parallel to the regional trend of spur. A subsidiary landslide at $33^\circ 03' 01.6''$ N and $75^\circ 05' 12.2''$ E location shows an ~5.6-m slip surface with a 9-m- wide zone at a slope of 40° towards the valley (Fig. 7). The slip plane shows an ~WNW strike, with the slip surface towards the SSE. Here, the bedding dips also bear the same direction. Numerous ground fissures along the ridge and in the landslide toe part toward the valley also show an ~WNW strike with land subsidence in the SSE direction.

At the main event site ($33^\circ 02' 45.5''$ N and $75^\circ 04' 53''$ E) near the crown, a large new scarp has developed with two steps and at some places forming three steps. The upper part of the landslide and valley toe form a new pond (water logging), and at the base of the toe numerous ground fissures on the surface were developed (Fig. 6E). The landslide valley contains large rock boulder and with large fragments of house material debris (Fig. 6F). The shattered and fissured bedrocks of the Murrees show uplift of ~2-3 m from the present day Sadal Khad (stream) that borders the toe of the landslide valley. During the investigations, toward the ridge ($33^\circ 02' 52.4''$ N and $75^\circ 05' 04.8''$ E), preexisting fissures and cracks were observed. From observations of Sadal village, subsidence apparently has taken place along the older cracks. The main event location shows dominantly centimeter- to meter- scale ground fissures. We have also mapped and measured structural elements of all the observed ground fissures along the traverses in and around the affected sites using a hand held GPS unit for locations and a Brunton compass for the orientation of structural elements. These fissures are old and very few were developed during the extreme event witnessed by the locals. Another traverse was taken in the unaffected nearby regions (namely Panjar and

Kasuri), confirming the presence of fissures that are preexisting or developed during the main event associated with abnormal rainfall. Detailed characteristics of the ground fissures mapped in and around the affected regions are shown in Table 1.

6.1. Panjar site

The Panjar site is located away from the ridge located at the spur surface (Figs. 8A, B) and is composed of materials forming hillslopes, purple to light purple clay, mud admixed with sandstone boulders, and loose and transported materials that sits above the sandstone intercalated with mudstone of the Lower Murree Formation. The site is a short distance from the Anji fault. At the middle section of the spur, a curved fissure was observed. In places, the slope-forming materials are thick. The rocks are highly fractured and show a dip of $\sim 50^\circ$ toward the NE. The dip direction of the rock follows the regional moderate $\sim 20^\circ$ - 30° spur slope. The ground fissures show an arcuate pattern and dip toward the valley slope (Table 1). A few meters north of the Panjar site, a small gully has been formed because of the deposition of debris that blocked the road. Here, a set of ground cracks have subsided the road locally. The abandoned surface shows disseminated rock boulders, suggesting an old rockfall zone.

6.2. Kasuri site

The Kasuri site lies at the intersection between the Tanhal and Reasi thrusts and the bedrocks (dipping $\sim 20^\circ$ - 25° toward the SE) and belong to the Upper Murree Formation (Figs. 1B, 2A). The investigations carried out at the site show numerous cracks or deep ground fissures on the hillslope of $\sim 30^\circ$ - 45° as well as near the ridge (Figs. 8C, D). All mapped ground fissures show $\sim 220^\circ$ - 240° strike dipping $\sim 20^\circ$ toward the SE. Numerous new fissures and preexisting ground fissures with ~ 2.6 m of subsidence of the land were observed (Figs. 8E, F). Here, the spur and the bedrock dip are in the same direction (Figs. 8G, H). The spur surface shows old subsidence-related scarps ranging from a few centimeters to 1 m. The numerous fissures with associated subsidence are likely caused by (i) bedding plane weakness because of lithological heterogeneity that promotes failure in wet conditions (alternative claystone and sandstone), (ii) heavy precipitation, or (iii) Murree Formation units dipping toward the regional spur with a slope of $\sim 45^\circ$ - 65° . In the present research, no classification of old and new fissures was made. However, as observed in Kasuri village, ground fissures of centimeter to meter scale suggest that the formation of these ground

fissures is associated with rainfall and that these fissures likely form during every summer monsoon season. Also, considering the scope of research we found difficulties in deciphering at what rainfall intensity these ground fissures are formed.

7. Discussion

The combination of earthquakes, weak rock lithologies and structures, and a strong monsoon make each tectonic zone of the Himalaya vulnerable to landslides. The Himalayan region has experienced an increasing number of heavy rainfall events causing flash floods, debris flows, and landslides in the last few decades. In active orogens, an increase in the frequency and intensity of extreme precipitation events causes change in the global climatic pattern (Goswami et al., 2006; Joshi and Rajeevan, 2006; Solomon et al., 2007; Ghosh et al., 2012; Devrani et al., 2015). Recent disasters include cloudbursts and flash floods caused by unusual rainfall patterns that affect loss of life and property not only in the Himalayan region but also in other parts of the Indian landmass (Bohra et al., 2006; Balakrishnan, 2015).

7.1 Relationship between lithology and landslide

During the withdrawal of the ISM in September 2014, an extreme rainfall event associated landslide destroyed Sadal village completely. Geological investigations suggest that the local terrain consists of an alternating sequence of hard, compact sandstone and weak mudstone. The planar weakness in the affected region lies along the bedding plane. Each rock material has its own equilibrium slope angle. Clays generally are unstable at $>10^\circ$ slope (Waltham, 2009). Strong sandstone above weak clay dipping $<45^\circ$ into the valley creates a favorable environment for slope failure during intense rainfall. Creep movement toward downslope has been a continuous process in the hillslopes of the Himalaya. A schematic diagram shows successive stages of landslide development at Sadal village (Fig. 9). The percolation of continuous intense rainfall through the preexisting ground fissures suggests weak claystone removal as seen in the adjoining unaffected regions at Panjar and Kasuri villages. Thus, the bedding plane acts as a planar weakness that dips toward the valley facilitating slope failure. During the progressive surface processes, the associated fissure widening led to the linking of several weak planes into a single planar slip then fell in a single event in the form of landslide as documented in Sadal village (Fig. 9). This continuous process of subsidence and development of ground fissures in the adjoining field areas such as

Panjar and Kasuri villages may produce a major shallow landslide during extreme rainfalls in the near future.

7.2. Relationship between landslides and extreme rainfall events

Table 2 compiles the landslide occurrences caused by extreme rainfall that have been reported so far in the IHR. In general, no systematic pattern can be deciphered from the compilation; however, close examination of the data reveals that the abnormal rainfall pattern is observed either toward the beginning or at the withdrawal of the Indian Summer Monsoon resulting in major landslides and flash floods. In the Midlands and the Fore Himalaya of Nepal, Dahal and Hasegawa (2008) helped to establish the threshold relationship by defining formula for landslide-triggering rainfall events as $I = 73.90 * D^{-0.79}$ (where, I = rainfall intensity in mm h^{-1} and D = duration in hours), which reveals when daily precipitation exceeds 144 mm —the landslide risk on the Himalayan mountain slopes is high. A precise understanding of the climatic conditions associated with landslides in the IHR is lacking because of the small number of observational rain gauge networks that record rainfall amount on an hourly basis, etc. However, we can speculate on the threshold limit of rainfall triggering events based on the compilation plots of rainfall duration observed over the IHR covering from Sikkim in the east to Jammu and Kashmir in the west from the published literature. The continuous observation shows that the rainfall amount varies from 1 to 7 days. In Jammu and Kashmir, maximum ~ 488 mm rainfall occurred in 4 days; while, in the Uttarakhand region, 941 mm rainfall occurred in 6 days. Similarly, in the eastern part of the Sikkim Himalaya a maximum of ~ 500 mm rainfall occurred in 2 days. The mean threshold intensity of rainfall estimated for the NW Himalaya is ~ 290 mm d^{-1} (excluding the Sikkim Himalaya). For the Uttarakhand state the cumulative rainfall at Kapkote and Okhimath is 155 and 212 mm d^{-1} respectively. However, the observed mean intensity of rainfall for a day is little larger, but comparable with the estimated threshold limit of 144 mm d^{-1} in the Nepal Himalaya (Dahal and Hasegawa, 2008). This implies that the threshold limit of rainfall-induced landslides is site specific and that a generalized threshold value cannot be ascribed for forecasting of landslides. Further, in the present study we have not differentiated the rainfall intensity based on the Western Disturbances (WD) and the ISM, but we speculated that the pattern of rainfall intensity varies from west to east along the Himalayan arc, implying that the western states of Himalaya are perhaps largely influenced by WD and by

the ISM. The detailed rain intensity pattern is required to establish the precise limit of rainfall thresholds for landslides.

7.3. Spatiotemporal and orographic distribution of extreme events

In the Himalayan ranges, altitudinal variations in rainfall make rain supply more complex. Studies have been carried out to understand the variability in precipitation with altitude in different mountainous regions of the world (Shrestha et al., 2000; Marquínez et al., 2003; Arora et al., 2006). We observed that, depending upon the mountain relief, a continuous increase in precipitation with altitude may begin to decrease above a particular elevation (Singh et al., 1995; Singh and Kumar, 1997). However, as discussed above, because of lack of observations, no proper precipitation gradient has been established in the IHR, especially in Uttarakhand. Therefore, considering such limitations of various data sets, the present research is only confined to the understanding of its spatiotemporal characteristics using available published records.

Five different longitudinal profiles were constructed across the Himalayan ranges in the NW-SE direction, i.e., AA' in Jammu and Kashmir, BB' and CC' in Himachal Pradesh, and DD' and EE' in Uttarakhand, respectively, using SRTM data. The profiles were selected in such a way that most of the events are crossed by the profile or lie within close proximity. The distributions of the records suggest that the occurrence of extreme rainfall events increases from west to east with a maximum number of events reported in the Uttarakhand region (Fig. 10A). The spatiotemporal distribution of events revealed along different topographic profiles (NW-SE) are mostly confined toward to the windward side of the Himalayan front (Fig. 10B). For example, profile DD' in Uttarakhand, reveals that most of the extreme events occurred on the windward side of the orographic barrier.

8. Conclusions

The present study suggests that numerous ground fissures developed across the spur and regional hillslope that are parallel to planar weakness at Sadal village and its vicinity. Furthermore, snowfall and rainfall in the upcoming winter and monsoon seasons will lead to expansion or widening of ground fissures from water seepage and downward gravitational movement, triggering landslides in the region. The water percolating through these fissures can remove the weathered materials or dilute the claystone intercalated with sandstone

producing either slow slip or creep or sudden rockfall as witnessed recently. Mitigation measures have to be taken immediately. In addition, periodic monitoring of the formation and development of ground fissures should be undertaken to avoid any future possible natural hazard or loss of life and property in the region. Landslides can happen when rainfall amount reaches over a particular threshold of ~155 , 212, or 290 mm making the slopes almost saturated. Landslides induced by extreme rainfall also depend on the initial water content (antecedent), geological local terrain settings and regional factors. This means that sudden landslides are mainly caused by rainfall extremes.

Recently, various prediction models have been successfully used configuring high spatial resolution that simulated the heavy rainfall event in the Uttarakhand region (Kotal et al., 2014; Chaudhuri et al., 2015; Shrestha et al., 2015; Chevuturi and Dimri, 2016; Kumar et al., 2016). Therefore, timely prediction and warning of potentially catastrophic local weather systems over the complex Himalayan terrain are the first and foremost step policy makers can take toward mitigation of landslide risks and minimization of impact.

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1 Table 1
2 Ground fissure characteristics mapped near Sadal, Kasuri, and adjoining site (Panjar
3 villages), Udhampur district, Jammu and Kashmir Himalaya

GPS coordinates with height (m asl)	Location	Nature of terrain in which ground fissures observed	Ground fissure length (m) and type	Ground fissure slip direction (°)	Width (cm)	Depth (m)
<i>In and around Panjar village located ~3 km NNE from main event at Sadal village</i>						
33°03'56.3" N - 75°05'41.8" E (1430 m amsl)	Panjar	Spur slope	1.2, irregular fissures	145	20	-
33°03'57.6" N - 75°05'41.2" E (1438 m amsl)	Panjar	Spur slope	7, fissures	170	30	-
33°03'58" N - 75°05'40.7" E (1450 m amsl)	Panjar	Spur slope	5, step like fissures	140		-
33°03'59.7" N - 75°05'40.5" E (1471 m amsl)	Panjar camp site	Spur slope	0.5, curvilinear	-	8	-
33°04'00" N - 75°05'40.8" E (1471 m amsl)	Panjar near camp site	Spur slope	The arcuate curvature type fissure formed with main rock slide event	200	35	0.73
33°02'22.9"N - 75°06'09.1"E (1453 m amsl)	Road leading to kuargali-sari few m away from the road toward NE	Along the metalled road	0.9 fissure, Moderate size landslide seen	330	15	-
<i>In and around Kasuri village located ~7 km SE from the main event at Sadal village</i>						
33°01'55.5" N - 75°06'48.8" E (1760 m amsl)	Kasuri	Down slope of ridge toward south (i.e. spur)	0.7, irregular hair type ground fissures near the ridge	145	10	-
33°01'54.0" N - 75°06'47.8" E (1764 m amsl)	Kasuri	Down slope of ridge toward south (i.e. spur)	1.5, Ephemeral nala irregular fissures	135	20	-
33°01'54.7" N - 75°06'43.7" E (1770 m amsl)	Kasuri	Down slope of spur	1.2, Fissure follows ephemeral nala	160	55	0.5
33°01'54.5" N - 75°06'42.7" E (1774 m amsl)	Kasuri	Little away from the ridge	0.8, irregular fissures	160	-	-
33°01'56.2" N - 75°06'41.9" E (1784 m amsl)	Kasuri	Close to the ridge	0.5, fissures	200	-	-
33°01'58.3" N - 75°06'41.6" E (1798 m amsl)	Kasuri	Close to the ridge	20, arcuate fissures, opening with compressional mounds	240	20	0.60
33°01'59.6" N - 75°06'41.4" E (1811 m amsl)	Kasuri	Close to the ridge	12, rhomb shape fissures	140	-	0.47
33°02'00.2" N - 75°06'40.6" E (1817 m amsl)	Kasuri	Close to the ridge	29, arcuate fissures	283 240 230 205	30 23 29 11	-

33°02'03.8" N - 75°06'37.8" E (1851 m amsl)	Kasuri	At the top of ridge	0.9, ground fissure with sliding,	110	15	-
33°01'54.7" N - 75°06'33.5" E (1833 m amsl)	Kasuri	At the top of ridge	1.5, ground fissure arcuate	230	40	0.54
33°01'54.1" N - E 75°06'36.3" E (1815 m amsl)	Kasuri	At the top of ridge	0.7, fissure, fissures appears and disappears during raining season as reported by locals	210	38	0.67
33°01'51.0" N - 75°05'47.3" E (1768 m amsl)	Kasuri	Spur slope	1.7 en echelon fissures	220	25	0.48

Ground fissures associated with main event in and around Sadal village

33°02'50.9" N - 75°05'32.1" E (1405 m amsl)	Mongri 4km milestone base of sadal khad	Slope of the mountain	13, en echelon	193	-	0.5
33°02'52.1" N - 75°05'47.3" E	Sadal Village	Spur slope	15, Fissures along with ground slide	180	15	0.8
33°02'53.4" N - 75°05'31.7" E (1430 m amsl)	Foot path goes to Sadal Village	Slope of the mountain	12, Fissures along with ground slide	155	-	-
33°02'53.6" N - 75°05'27.0" E (1449 m amsl)	Sadal Village	Slope of the mountain	20, En echelon fissures	170	20	-
33°02'53.7" N - 75°05'24.9" E (1458 m amsl)	Sadal Village	Slope of the spur	15, step like fissures	165	-	-
33°02'55.7" N - 75°05'24.3" E (1487 m asl)	Sadal Village	Along foot path	5, hair line fissures	125	15	-
33°02'56.4" N - 75°05'18.4" E (1502 m amsl)	Sadal Village	At the intersection of nala	12, curved fissures	110	37	0.5
33°02'58.7" N - 75°05'17.0" E (1544 m amsl)	Sadal Village	Spur slope	10, fissure with steps	150	-	-
33°03'01.5" N - 75°05'13.1" E (1600 m amsl)	Sadal Village	Steep spur slope	Slide	190	19	-
33°03'01.6" N - 75°05'13.2" E (1598 m amsl)	Sadal Village	Spur slope	40, arcuate	120	23	0.56
33°03'01.3" N - 75°05'13.1" E (1593 m amsl)	Sadal Village	Steep spur slope	18, hair line fissures	110	-	-
33°03'00.9" N - 75°05'12.9" E (1589 m amsl)	Sadal Village	Fissure on local slope	1.5, irregular fissure	90-140	40	-
33°03'01.0" N - 75°05'12.9" E (1585 m amsl)	Sadal Village		15, fissures with rhomb shape openings and compressional mounds	175	10-40	-
33°03'00.5" N - 75°05'12.7" E (1581 m amsl)	Sadal Village	-	8, fissures with steps	110	10	-
33°03'00.0" N - 75°05'06.5" E (1994 m amsl)	Sadal Village	Spur slope	Debris flow, irregular fissures developed along nala	-	-	-

33°02'52.4" N - 75°05'04.8" E	Sadal Village	Spur slope	Fissure with ground subsidence	140	-	0.36
33°02'50.0" N - 75°05'02.6" E (1609 m amsl)	Sadal Village	Close to steep spur slope	Arcuate fissures	210	50	0.8
33°02'49.2" N - 75°05'01.9" E (1621 m amsl)	Sadal Village	Steep spur slope	Arcuate fissures	330	40	0.6
33°02'45.5" N - 75°04'53.0" E (1642 m amsl)	Sadal Village	Steep spur slope	Massive slide	300	37	1.5
33°02'46.5" N - 75°05'00.0" E (1624 m amsl)	Sadal Village	Steep spur slope	Debris slide	200		0.82
33°02'45.6" N - 75°05'01.2" E (1613 m amsl)	Sadal Village	Steep spur slope	37, Arcuate	160	28	0.6
33°02'55.5" N - 75°05'18.5" E (1512 m amsl)	Sadal Village	Spur slope	Debris flow with irregular fissures	205	15	-

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Table 2

Recent landslide, cloudburst, and associated flash flood events recorded in the Indian Himalayan region (IHR)

Events	Date	Area	Period
Rainfall-induced landslide ^a	20 July 1970	Belakuchi (Birhi River), Uttarakhand	PM
Rainfall-induced landslide ^a	August 1981	Mandakhal Pauri Garhwal, Uttarakhand	PM
Cloudburst-flash flood ^b	29 September 1988	Soldan Khad, Sutlej Valley, Himachal Pradesh	W
Rainfall-induced landslide ^a	July 1990	Neelkanth, Uttarakhand	PM
Landslide-flash flood ^b	31 July - 2 August 1991	Maling, Spiti Valley, Himachal Pradesh	PM
Cloudburst-landslide ^b	8 July 1993	Nathpa, Sutlej Valley, Himachal Pradesh	PM
Cloudburst-landslide ^b	24 February 1993	Jhakri, Sutlej Valley, Himachal Pradesh	BM
Cloudburst-flash flood ^b	11 August 1997	Chirgaon, Himachal Pradesh	PM
Rainfall-induced landslide ^{c, d}	11-19 August 1998	Malpa and Okhimath Rishikesh-Mana, Uttarakhand	PM
Cloudburst-flash flood ^b	30 July 2000	Sutlej Valley, Himachal Pradesh	PM
Cloudburst-flash flood ^e	5-10 June 2000	Gangotri Glacier, Uttarakhand	BM
Cloudburst-landslide ^f	31 August 2001	Gona Village, Uttarakhand	PM
Cloudburst-landslide ^{g, h}	16 July 2001	Phata Byung, Rudraprayag, Uttarakhand	PM
Cloudburst-landslide ⁱ	10 August 2002	Budha Kedar, Tehri, Uttarakhand	PM
Rainfall-induced landslide ^a	16 July 2003	Shilagarh, Garsa Valley, Kullu, Himachal Pradesh	PM
Cloudburst-flash flood ^j	16 July 2003	Puliya Nal, Kullu, Himachal Pradesh	PM
Rainfall-induced landslide ^k	23 September 2003	Varunavat, Uttarkashi district, Uttarakhand	W
Rainfall-induced landslide ^b	July 2005	Dhanyau village, Rudraprayag, Uttarakhand	PM
Cloudburst-flash flood ^l	June 2005 1 August 2006	Phyang, Igu, and Leh Nalla, Jammu and Kashmir	BM
Rainfall-induced landslide ^a	July 2007	Mandakini basin, Uttarakhand	PM
Rainfall-induced landslide ^f	July 2007 September 2007	Sikkim, Darjeeling	PM W
Cloudburst-landslide ^f	July 12 2007	Devpuri, Chamoli, Uttarakhand	PM
Rainfall-induced landslide ^m	8 August 2009	Kuity Village, Berinag-Munsiyari, Uttarakhand	PM
Cloudburst-landslide ⁿ	4-6 August 2010	Leh, Jammu and Kashmir	PM
Rainfall-induced landslide ^{c, d}	18-21 September 2010	Malpa and Okhimath Rishikesh-Mana highway, Uttarakhand	W
Cloudburst-landslide ⁿ	25 July 2011	Leh, Jammu and Kashmir	PM
Rainfall-induced flash flood ^o	15-25 August 2010 15-25 August 2011	Dokriani Glacier, Uttarakhand	PM
Cloudburst-flash flood ^p	3 August 2012	Asiganga, Uttarakhand	PM
Cloudburst-flash flood ^q	13 September 2012 14 September 2012	Okhimath, Uttarakhand	W
Cloudburst-flash flood ^r	16-17 June 2013	Kedarnath, Uttarakhand	BM
Cloudburst-flash flood ^s	16-17 June 2013	Gangotri Glacier, Uttarakhand	BM

PM=Peak monsoon (July-August), BM=Before monsoon (June), and W=Withdrawal of Indian Summer Monsoon (September).

^a Asthana and Asthana, (2014); Asthana and Sah, (2007); ^b Thakur, (2000); ^c Sati et al., (2006); ^d Sati et al., 2011; Rautela and Paul, 2001; ^e Haritashaya et al., (2006); ^f Naithani et al., 2002; Nathani et al., 2011; Mandal and Maiti, 2013; ^g Chaudhary et al., (2010); ^h Kumar et al., (2003); ⁱ Sah et al., (2003); ^j Mazari and Sah (2004); ^k Gupta and Bist, (2004); ^l Thayyen et al. (2013); ^m Sarkar and Kanungo, (2010); ⁿ Bhan et al., (2015); ^o Kumar et al., (2014); ^p Gupta et al., (2013); ^q Rana et al., 2012, 2013; Islam et al., 2014; ^r Dobhal et al., 2013; Bhambri et al., 2016; ^s Arora et al., 2016.

Figures caption

Fig. 1. Simplified SRTM (Shuttle Radar Topographic Mission) showing seismic gaps in northwestern Himalaya along with active folds and faults. Small box shows location of studied landslide site that lies 39 km NW from Udhampur town. Surin Mastgarh Anticline (SMA), HFT/MFT- Himalayan Frontal Thrust/ Main Frontal Thrust, MCT-Main Central Thrust (A), and (B) geological and structural elements damaged by landslide at Sadal village along with adjoining sites (Karunakaran and Rao, 1979).

Fig. 2. (A) Geomorphic and structural elements of affected site along with location of topographic profile is marked as a thick line with alphabets on either side A-A', and (B) topographic profile showing pre-landslide surface constructed across Sadal village using SOI toposheet, 20-m contour interval, location is shown in Fig 2A.

Fig. 3. Pre-scene (left) and post-scene (right) Landsat 8 satellite image showing landslide at Sadal village.

Fig. 4. (A) Line graph showing 3-hour daily rainfall distribution for different months of Indian Summer Monsoon (ISM) derived from TRMM (Tropical Rain Measuring Mission) (3B42 V7). (B) cumulative distribution of normal rainfall pattern for the years 2000, 2001, 2002, 2004, 2006, 2007, and 2008. (C) Unusual cumulative rainfall pattern (2003, 2005, 2009, 2010, 2011, 2012, 2013, and 2014) during withdrawal of ISM.

Fig. 5. Rain gauge rainfall distribution together with published records of rainfall data for the affected and adjoining sites during the landslide (A) and cumulative distribution of extreme rainfall events that causes catastrophic landslides and flashflood events in the Himalayan region (B). (^aUdhampur, ^bLeh, ^cDodha, ^dKhonmoh-Jammu and Kashmir (J&K); ^eKedarnath, ^fMunsiyari, ^gUttarkashi, ^hKapkote, ⁱAlmora, ^jGangotri, ^kGangotri, ^lDokriani, ^mOkhimath-Uttarakhand (UK); ⁿDarjeeling-Sikkim).

Fig. 6. Field photographs showing Murree Formation (sandstone intercalated with claystone dipping 25° toward SE) at the confluence of the Sadal Khad with the Kanji Khad along road section between Udhampur and Mongri villages (A), ground fissures in the agricultural fields of Sadal village (B), large rock boulder related to paleolandslide across the Sadal stream near

the confluence of Sadal Khad and Kanji Khad (C), pictorial view of rock slide in Sadal village (D), rock debris observed in the Sadal Khad during the torrential rain and pond development (E), and completely damaged houses with wood debris observed in the Sadal village (F).

Fig. 7. (Top) Subsidiary landslide at $33^{\circ}03'01.6''$ N - $75^{\circ}05'12.2''$ E, stereogram showing strike and dip of a slip plane of the shallow landslide (middle), and topographic gradient of land subsidence (bottom).

Fig. 8. Contour map (C.I. 20-m) of Panjar village derived from SOI toposheet (A), (B) topographic profile section (line connecting with alphabets on either end, location shown in 2A), (C) contour map of Kasuri village with its topographic profile showing ground cracks development, (D) location of section shown by line in Fig. 2C, (E) ground cracks with land subsidence towards hill slope at Kasuri village, (F) shallow subsidence towards regional hillslope, (G) Murree rocks dipping toward regional slope, and (H) minor ground fissures developed during torrential rain.

Fig. 9. Schematic model showing different stages of landslide development on the 6 September 2014 event at Sadal village. Note: Planar weakness in the Murree Formation parallels the regional spur slope.

Fig. 10. SRTM showing location of topographic profiles (A-A' to E-E') across the northwestern Himalayan region along with spatial distribution of extreme rainfall associated cloudburst (solid circles), flash flood (solid circles with cross), and landslide (solid triangles) hazards (A), and its topographic profiles (B). Extreme rainfall associated events (red circles) are draped on the profile. Horizontal distance is same for all plots. Thick arrow shows windward side.