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Assessment of 2016 Mantam Landslide at Mangan, North Sikkim Himalayas using Geospatial Techniques

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Abstract: **North Sikkim Road Corridor in Sikkim Himalayas is characterized by fine-grained, less permeable earth material and is thus vulnerable to landslides. Mantam is one of the new and active massive rock-cum-debris slides, initiated during the rainy season of 2016.In the Himalayan foot-hills, rainfall precipitation is a major triggering factor for the incidence of landslides. There is no previous study of the rain-induced landslide in the region with geospatial analysis of landslide data and application of rainfall threshold model. In the present study, the causative factors of the Mantam landslide is derived from the analysis of Very High-Resolution satellite images (Cartosat-2B) and High-Resolution LANDSAT 8 (30m) retrieved from National Remote Sensing Center and USGS. This paper presents geological, and geo-hydrological analysis of the Mantam landslide using High-Resolution satellite images and a rainfall threshold is suggested for the prognosticate sliding. This present study suggests a threshold value of ≥284.1 mm of cumulative rainfall over a 10 days period for the Mantam landslide initiation. After examining all the data, it is observed that groundwater seepages from the uncovered joint planes are common across the area. This is indicative of the role of the aquifer induced pore pressure, antecedent rainfall, and escarpment stress condition as probable causative factors of the Mantam landslide occurrence.**

Index Terms: **Cumulative Rainfall, Rainfall Threshold, Sikkim Himalayas, Susceptibility, Vulnerability.**

I. Introduction

Landslide is a major natural hazard severely affecting life and property across the globe. Rainfall is one of the main factors responsible for the landslide initiation, specifically in regions characterized by heavy monsoonal rainfall. Previous researchers have proposed that a strong correlation exits between rainfall precipitation and landslide initiation (Glade et al. 2000, Sengupta et al. 2009).Rainfall triggered landslides mainly occur due to the build-up of pore water pressures in the ground (Sengupta et al. 2009). Slope failures depend on the groundwater condition of the region, which in turn is related to rainfall intensity, soil characteristics, antecedent degree of saturation, and historical records of rainfall events. Due to the lack of availability of reliable data and monitoring plan, the predictions of rainfall induced landslides in different areas have been problematic.

The massive Mantam landslide shown in Fig.1, Fig. 2 (Pre-Event), and in Fig. 3 (Post Event) occurred very close to the village of Mantam opposite to the Passingdang-Mantam Road in North Sikkim at around 13:30 hrs. (IST) on the 13th of August, 2016. The landslide was active up to 17th of August, 2016 (BRO). According to afield survey report, approximately 30 houses were damaged, 11 houses washed out and Upper Dzongu was disconnected from the state capital, Gangtok. The Mantam landslide has a steep surface slope of >35° (Fig. 7). The debris from the landslide had blocked the flow of the Kanaka River/Ringpai Chu which is one of the main tributaries to the Teesta River. This resulted in a 5 to 7 m high flood downstream up to 20 km from the site. Though the middle portion of the slide is barren due to the movements of rock cum debris material, the toe of the slide is sparsely vegetated. The study area receives a very high amount of monsoon precipitation (Table I), and the landslide was activated by accumulated rainfall. It was noticed that in the Mantam sliding there is no direct correlation with the cloud burst event. So, in the present study, a comprehensive examination has been done to find out the cause for the activation and also for monitoring of this landslide. This study

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also incorporates geophysical and geological investigations. Here, an assessment of previous rainfall events has been done to find out the threshold value which triggered the Mantam landslide. Geospatial data was also evaluated to mark the other probable causative factors of the present landslide. This study aims at the development of an early warning system which will help to design a proper disaster mitigation management strategy.

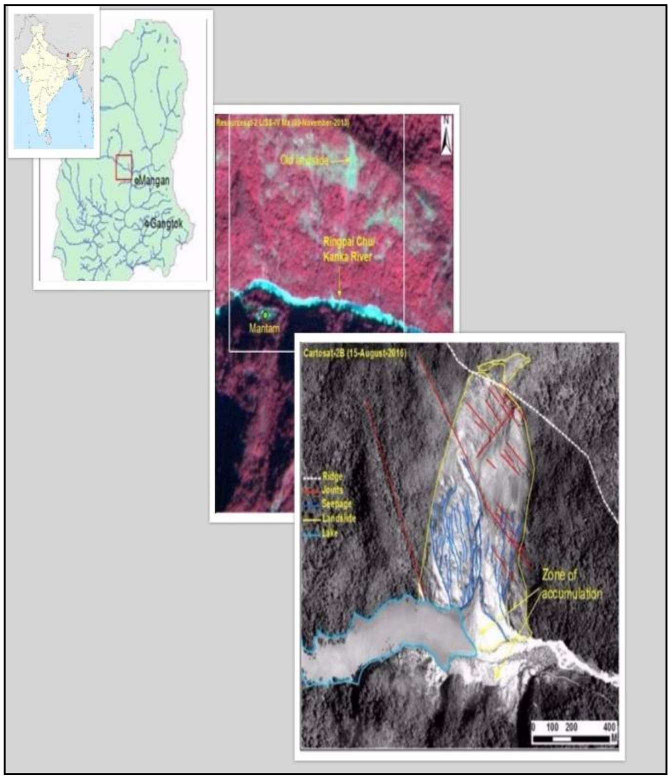

Fig. 1. Location of the study area (Mantam Landslide)

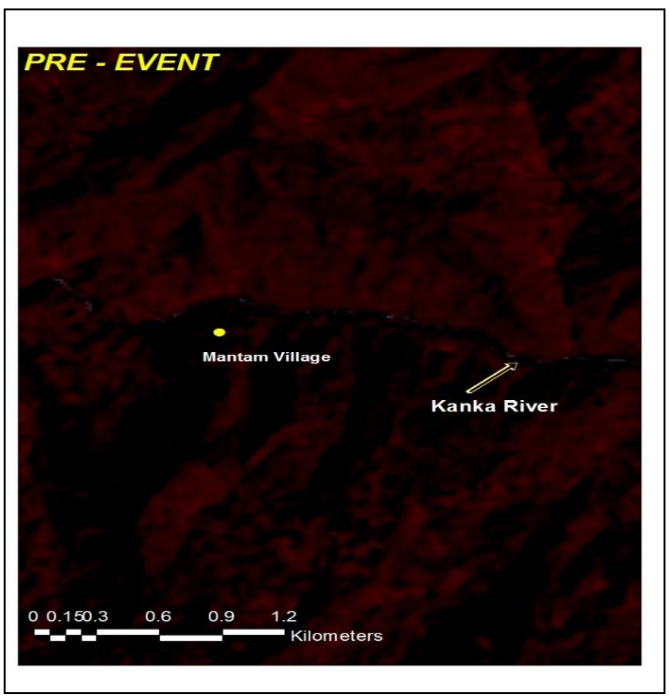

Fig. 2. Pre-event of the Mantam landslide location and shown without landslide (Landsat 8 Image, March 2016)

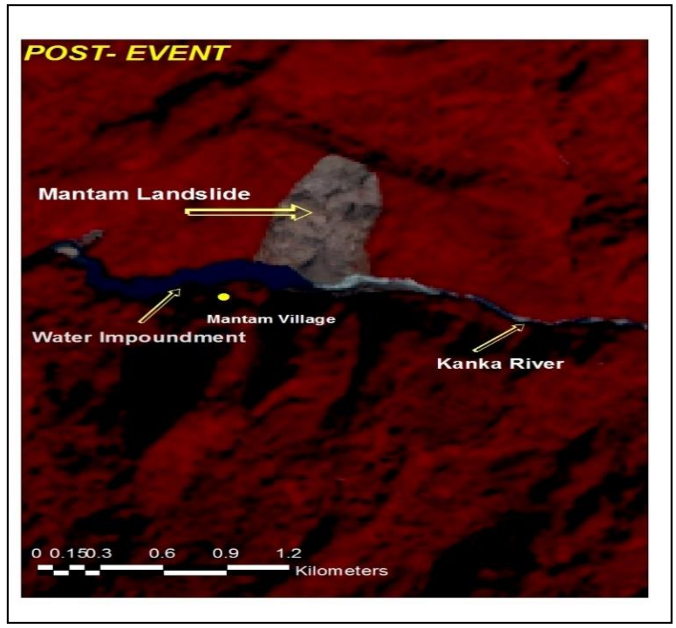

Fig. 3. Post-event of the Mantam landslide and shown the landslide (Landsat 8 image, September 2016)

II. THE MANTAM LANDSLIDE (STUDY AREA)

The Mantam Landslide (Fig.1) is located on longitude 88° 29' 53.11" E and latitude 27° 32' 21.73" N and is 14 km away from Mangan, the district headquarters of North Sikkim, India. Entire Sakkyong in the upstream region of the Kanka River has also witnessed severe landslide occurrences during the Sikkim earthquake on 18th September 2011(Sharma et al. 2012).The collapse area along the Mantam bench has subsequently evolved into one of the largest unstable zones on the Passingdang-Mantam Road in North Sikkim (Sharma et al. 2009). Following the heavy rainfall on 24th July (50.3mm), 29th July (65 mm), 2nd August (97.2 mm), and 10th August (58.2 mm) 2016, diverse, non-cohesive soil and rock/debris started moving downwards along the valley bed. The width and length of the newly active landslide was 530 m and 790 m. The landslide is of a rectangular shape, with an average surface slope (of the debris materials) of around 35°. The landslide generated a huge cloud of dust engulfing the nearby settlements (Fig. 4). From the field photograph, it becomes visible that it is a rock cum debris slide and the dust cloud was formed from the rapid downslope movement of dry rocky mass resulting in the air blast. The debris from the landslide is believed to have blocked the flow of the Kanaka River/Ringpai Chu, resulting in 5 to 7 m high flood in the downstream for up to 20 km. A water impoundment or an artificial lake of 2.2 km length and 209 m width was created north of the Mantam (Fig. 5 and 12). Debris deposits were visible on either side of the ridgeline. All of the joints exposed after the landslide suggested a wedge type failure near the crown of the landslide followed by the translational type of failure in the main body of the landslide.

Fig. 4.The dust cloud from the Mantam landslide

Fig. 5. Artificial lake formation due to the landslide

A. Geological Structure

. The paucity of any bedrock in the region made it difficult to estimate the debris thickness at Mantam and the depth to potential slip surfaces. The slope forming material on either bank of the Kanka River (Ringpai Chu) consists mostly of loose micaceous sandy – silty soil embedded with heterogeneous rock fragments of rock. Spatial analysis of satellite data reveals a highly weathered and intensely fractured slope. A major portion of the rock mass is decomposed into the soil. The formation of the rock structure is of very poor quality and belongs to the fractured and crushed category. This area is very close to a Litho Contact (Inferred) (Fig.6), which takes a convex turn in the landslide area and Kanka River window. Geologically, the area is in proximity to the Main Central Thrust (MCT), which is convex to the north and forms a tectonic window known as the Rang it window (Gosh et al. 2012). Due to the presence of MCT, high-grade rocks of Proterozoic Central Crystalline Gneissic Complex (e.g. quartzites, schists, and granite gneisses) are exposed in this area were subjected to shearing which is evident from the density of joints in the landslide scarp region (Neogi et. al. 1998). The area around Sakkyong in the upstream part of the Kanka River /Ringpai Chu (Past) also witnessed severe landslide occurrences during the Sikkim earthquake on 18th September 2011 (Chakraborty et. al. 2011). A number of seepages have been observed in the slide zone form where small tributaries have been generated that flows over the slide zone. Therefore, the role of groundwater seepage induced pore pressure and escarpment stress conditions can be put forward as probable causative factors for the initiation of the newly activated landslide. Cracks or Joints in the ground have been observed in the slide zone, especially near the crown zone. A sub-vertical slope of the main scarp and sub-horizontal slope of debris material is seen in the accumulation zone.

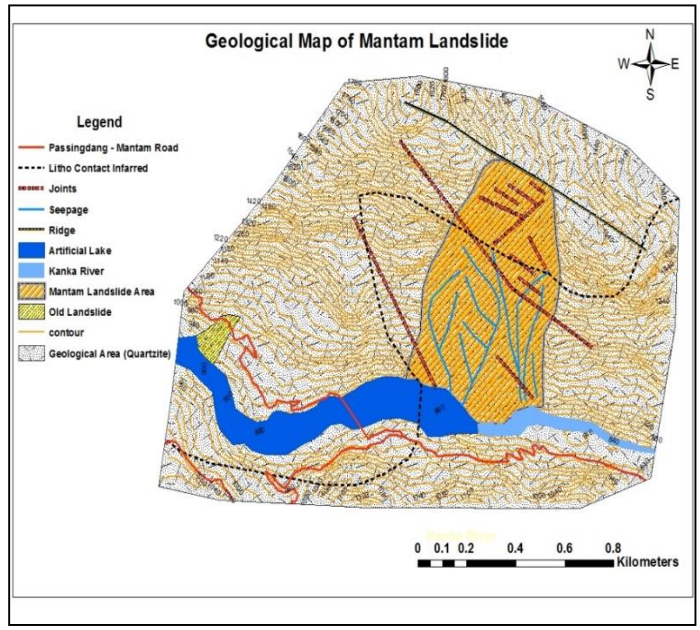

Fig. 6. A Large Scale Geological map showing Geological Condition of the study area.

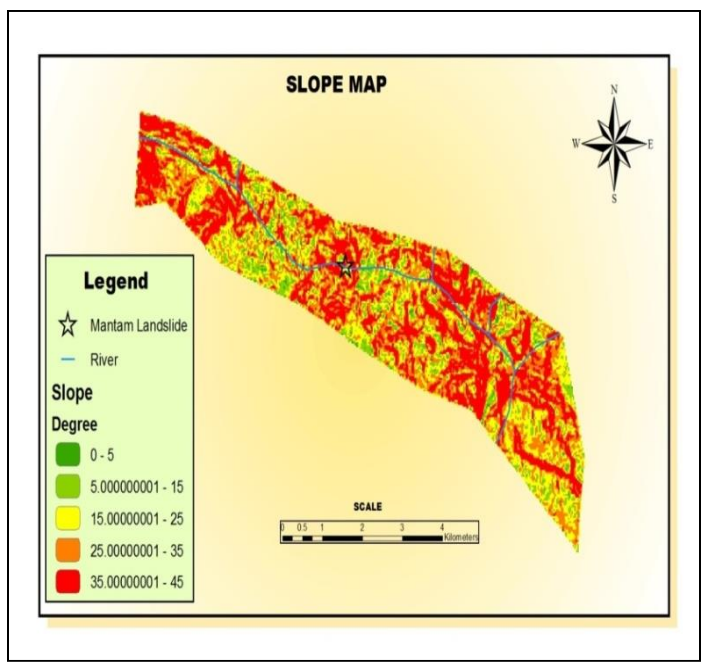

Fig. 7. Map showing Slope analysis of the Study area.

B. Rainfall Distribution

For the study area the local rainfall data was collected from 2010 to 2016 from Mangan rainfall station (IMD, Sikkim). The rainfall data shows that the northern district of Sikkim has received a very high amount of rainfall during the monsoon period. Mangan received a Mean Annual Precipitation (MAP) of 2800 mm (approx.) and during the monsoon season (June and September) the area received approximately 2300 mm of rainfall. Pre-monsoon and post-monsoon season have received about 300 mm, and 200 mm of rainfall respectively. Table I shows the rainfall data during the monsoon season at Mantam between the years 2010 to 2016 (Fig. 9). Interestingly, none of the landslide events corresponds to the periods of peak rainfall. Rather the landslide events occur after a period of continuous precipitation with very heavy rainfall for several days. Observation of the earth materials of the Mantam slide mostly shows siltydebr is with low permeability. For this to happen, a certain amount of rainfall is required to saturate the ground surface material at the slide location. Sengupta et al. (2009) proposed that "the earth material is only saturated after a certain amount of rainfall has occurred, and is therefore influenced more by the total amount of rain that occurs during an event, rather than the intensity of the rain". Maximum water retention by the ground occurs in the shear zone of the slope surface. With the help of this water, debris loses solidarity and starts to move downhill along with the rocks, and thereby trigger a landslide. Hence, a significant correlation can be established between the cumulative rainfall events, duration of rainfall, and the occurrence of the landslide.

Incessant rainfall causes the landslide occurrence by the percolation through the joints and cracks. The earth materials also become saturated and this increases the effective weight of the materials. This results in the decrease of the slope stability and resistance of the parent rocks. Fig. 8 shows the average rainfall data at the Mantam throughout the year (Jan to Dec). Fig. 9represented the rainfall data (TableI) of May to September from the years 2010 to 2016 at Mantam in Mangan station. The distribution of cumulative rainfall of the last week of July (24^{th} to 31^{st}), last 10 days prior to the landslide event ($3^{rd}$to 12^{th}August), and 72 hours before the occurrences of the landslide, were 262.9mm,284.1mm, and 94.2 mm respectively (Fig. 10).

Table. I. shows the rainfall data on the monsoon period from the years 2010 to 2016

Year	MAY	JUNE	JULY	AUG	SEPT
2010	424.9	582.8	531.6	599.1	329.1
2011	190.8	393.8	442.8	397.2	261.5
2012	139.7	599.2	595.9	316.2	785.4
2013	615.5	313.6	530.2	301.8	310.3
2014	417	651.6	605.1	629.8	297.5
2015	498.4	796.4	393.6	664.7	320.2
2016	437	620.9	578.9	368.8	463

Source: Mangan Station, IMD, Sikkim

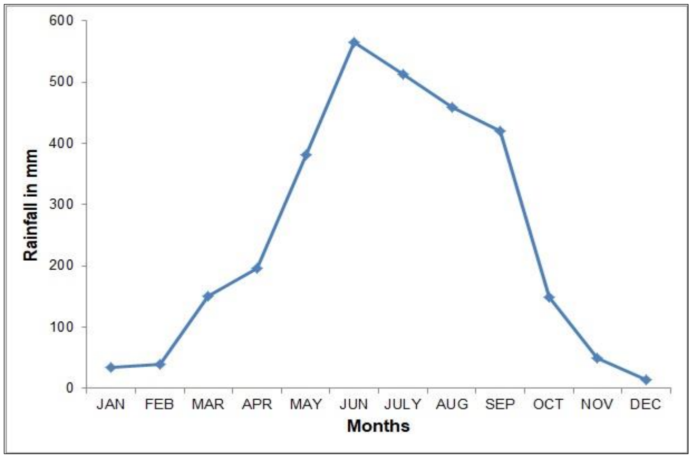

Fig. 8. Average monthly rainfall of the study area

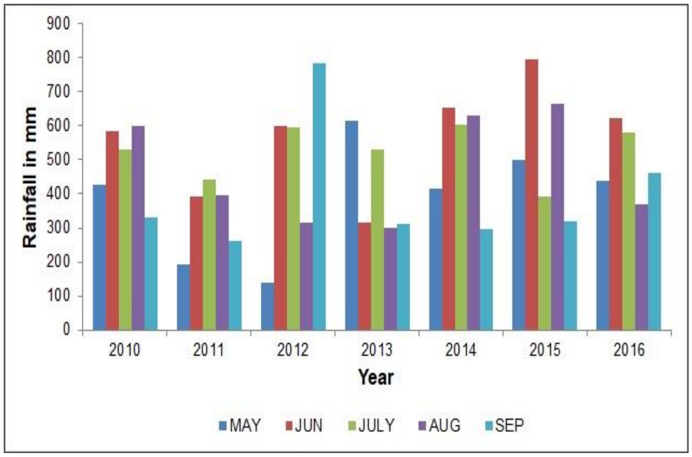

Fig. 9. Rainfall distribution during the monsoon of the study area

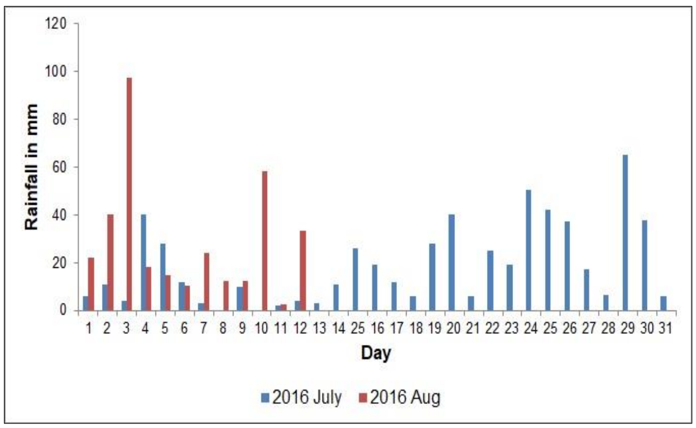

Fig. 10. Rainfall of 1st July to 12 August 2016 of the study area

III. RELATION BETWEEN GEOLOGY AND TRIGGERING FACTORS OF THE STUDY AREA

Landslides are persistent problem in the North Sikkim Himalayas, where losses of life and property due to such hazards are high. In landslide prone areas varied triggering factors lead to the occurrence of the landslides. The occurrence of the landslide in the study area and its adjoining area of Mangan was triggered by either intense rainfall or earthquake with high seismicity (GSI 2016). Complex geological conditions that lead to susceptibility of land sliding by these triggers are identified in this study.

A. Geology vs. Rainfall

Groundwater in any geological structured connects, the joints, factured zone, and weathered zones into various lithological units. Groundwater is available from rainwater and perennial or non-perennial springs in all the geological formations of the region. The movement of groundwater is mainly controlled by geological structures and natural topographical configurations. When the groundwater movement increases due to rainfall then the structurally weak planes- mainly joins, fractures, small scale faults, weathered rocks etc., lose their configurations and move downwards along the slope. The rapid infiltration of rainfall, causing soil saturation and a temporary rise in pore-water pressures, are generally believed to be the mechanism by which shallowest landslides are generated during monsoon. Some seepage (Fig. 14) also occurs, which indicates a slower movement of groundwater through the rock strata covered by a thick mantle of weathered rocks.

B. Geology vs. Earthquake

Sikkim Himalayas also lie within a seismically active Fold-Thrust Belt (FTB) where occurrence of earthquakes of magnitudes 5.0 and above on Richter scale is common. This also acts as another important triggering factor for landslides. These landslide-prone cones also belong to the maximum earthquake-prone areas in India (Zone-IV and V; BIS, 2002), where earthquakes of Modified Mercalli Intensity (MMI) VIII to IX can occur frequently and this makes the region prone to earthquake-induced landslides. Earthquakes also act as an important trigger for the reactivation of landslides in an earlier landslide affected zone. Several landslides were triggered in this region by the Sikkim Earthquake of 2011 (Mw: 6.9) (Ghosh et al., 2012; Martha et al., 2014).

Lithology and geomorphology have also played a significant role in causing landslides. Strong ground-shaking during earthquakes also trigger landslides in different topographic and geologic settings. Rock falls, rock slides, and debris slides from steep slopes, of relatively thin or shallow disaggregated rock or soils structure can also trigger landslides after an earthquake. The debris-laden slope which is made of loose unconsolidated material and the slope covered by thin unconsolidated scree deposits are most prone to failure by earthquakes. Frequency of rock-fall and rockslides are more in areas that are generally vulnerable due to weathered and fractured lithology and unfavourably jointed and kinematically-unstable slopes (Parkash, 2011).

In the case of sedimentary rocks, the boundary between the weathered soil cap and the underlying rock is generally more abrupt and the surface layer readily separates from the rock below. These rocks have much lower cohesive strength than the crystalline and metamorphic rocks and when such rocks form high scarps, portions of the solid rock itself may be thrown off. Thus, besides the energy of earthquake waves, landslide is also controlled by the lithological and structural conditions of the hill slopes of the region. After the earthquake, during the monsoon, the rainwater percolation along the bedding joint/plane) had reduced the shear strength of strata along slope which resulted in rock fall/slide.

C. Other parameters

Preliminary field observations confirmed that the Mantam Landslide was characterized by a very rapid sliding movement along with fall of bedrock material along a steep slope (>35°; Fig. 7), due to the action of gravity and seepage through weak planes (Fig. 14), which resulted in the accumulation of the huge amount of rock debris. These weak planes have provided the conduit to the rainwater creating hydrological pressure, resulting in slope failure. The rocks are highly fractured (Fig. 12 and 13) and a prominent discontinuity surface like joint planes and fracture planes has also been observed (Fig. 12).The surrounding area of the landslide exposes streaky quartzites, Garnate-kyanitesillimanite - schist belonging to Chungthang Formation of CCGC (Central Crystalline Gneissic Complex) along with basic intrusive rock (Fig. 6). The intrusive rock at places shows concordant relationship with the country-rock. The margins between intrusive and country rock are sheared. Geo-morphologically the affected area was moderately dissected with sparse vegetation cover, since landslide is stillactive and intermittent movement of slide material is also observed in the entire zone of accumulation area.

IV. Rainfall Thresholds Analysis

A threshold is the minimum amount of rainfall required for the occurrence of the landslide (White et al. 1996). The intensity of rainfall (I) and rainfall duration (D) determine the thresholds. The amount of precipitation of rainfall over a period of time along a hill slope is called rainfall intensity (I).It is measured in millimeters per hour.

Antecedent rainfall determines the soil moisture and groundwater levels. It is also used to predict landslides initiation (Glade et al. 2000). Sengupta et al. (2009) observed that a common process of using antecedent precipitation measurement as a basis for establishing a threshold has been widely used, Kim et al. (1991), Chleborad (2003), Aleotti (2004), Cardinali et al. (2005), (Sengupta et al. 2009) have correlated antecedent rainfall with landslide initiation.

The rainfall threshold measurement of the Sikkim Himalayan region has been done by several researchers (Bhandari et al. 1991; Gabet et al. 2004; Sengupta et al. 2009). They proposed the following rainfall thresholds relation:

$E_{MAP} < 0.05$ for ‘low probability of landslides’

$0.05 < E_{MAP} < 0.10$ for ‘intermediate probability of landslides’

$0.10 < E_{MAP} < 0.20$ for ‘high probability of landslides’

$E_{MAP} > 0.20$ when ‘landslides will always occur’

Where,

E = Cumulative rainfall event,

MAP represents the Mean Average Precipitation of the study area.

E_{MAP} is the normalized cumulative rainfall event. So, E_{MAP} = Cumulative rainfall (E) divided by MAP (E_{MAP} = E/MAP). Sengupta et al. (2009), studied the Lanta Khola slide area in the North Sikkim Himalayas, and estimated an empirical threshold for landslide initiation based on the antecedent rainfall. They also predicted that the landslides are induce when antecedent rainfall exceeds 250 mm over a 15 days period

Fig. 8 represents the monthly rainfall data at Mantam. Yearly average rainfall has been calculated from historical rainfall records of this rainfall station. The cumulative rainfall (E, in mm) and the duration of rainfall (D, in days) are plotted for all the peak rainfall events (Fig. 11).A cumulative rainfall event and duration (E&D) have been shown in Table II. Figure 11shows the thresholds analysis based on the plots of total cumulative rainfall events (E) against the duration of rainfall (D) for the newly active Mantam Landslide. Table II and Fig. 11 shows that the relation of rainfall events that induced landslide at Mantam requires ≥284.1 mm cumulative rainfalls within a 10 days period. If this threshold value E is normalized, the E_{MAP} value exceeds 0.10 which indicates high probability of landslides. So, the landslide may occur at Mantam, if E_{MAP} is ≥ 0.10 for any rain event of 10 days or more (as shown in Fig. 11). Based on this observation as imple exponential relation, between occurrence of landslide and duration of rainfall was plotted. The events of rainfall not associated with landslide are represented in blue dots. The red dots show events associated with cumulative rainfall (E value of 284.1 mm (or E_{MAP} of 0.10), and D of 10 days,). This threshold value is very similar to one proposed by Sengupta et al. (2009), at Lonta Khola Slide in the Sikkim Himalayas. When the rainfall event has an E value of 455.3for 15 days (E_{MAP} value is 0.16) and 609 mm for 20 days (E_{MAP} value is 0.18) duration they represent a high probability of landslides. Thus it can be said that landslide occurs when E_{MAP} value exceeds 0.10 (10 days). Table II represents the data of events in hours and days with maximum intensity of rainfall during the event. Cumulative rainfall during an event and normalized (E_{MAP}) cumulative rainfall for all the rainfall events are thus examined in this study. Considering all observations and estimations it shows that a total of 284.1 mm of cumulative rainfall over at least 10 days is responsible for the occurrence of Mantam landslide.

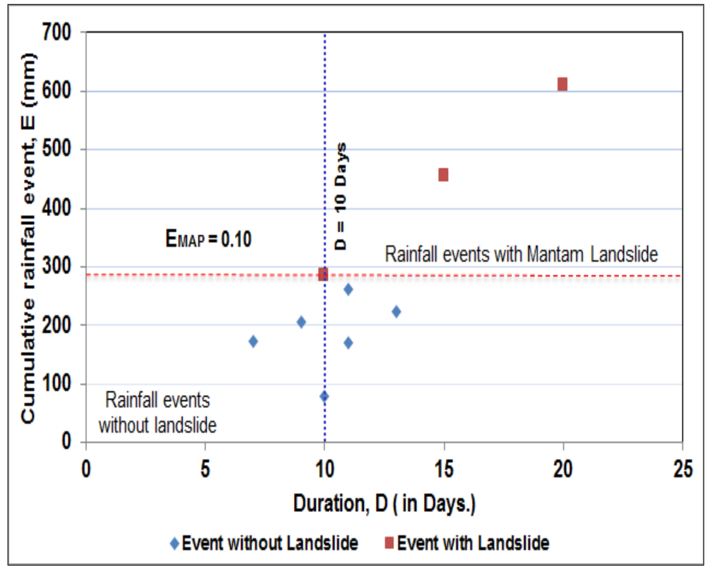

Fig. 11. Rainfall Thresholds based on the plots of total cumulative rainfall (E) against event duration (D) for the newly activated Mantam Landslide. Blue dots area represents not associated with sliding and Red dots predict a high probability of Mantam landslides. The E value of 284.1 mm and D of 10 days, while slide-associated events (in red) occur at higher values.

Table. II. Show the data for each peak rainfall event

Date	**Maximum Intensity of Rainfall, Imax (in mm/h)**	**Duration of event, D**		**Cumulative rainfall event, E (in mm)**	**E_{MAP} (E/MAP)**
		in hours	**in days**		
Rainfall Event with no landslide					
30/7/2013	0.5	240	10	80	0.03
7/7/2014	4.1	210	9	205	0.07
31/8/2014	3.2	168	7	173.2	0.06
14/7/2015	2.1	264	11	262	0.09
18/8/2015	1.3	312	13	223	0.08
1/6/2016	1.6	264	11	170	0.06
Rainfall Event with Mantam Landslide event **(13/08/2016)**13:30 hrs. (IST)					
12/8/2016	2.1	240	10	284.1	0.10
		360	15	455.3	0.16
		480	20	609	0.18

V. Landslide Analysis through Satellite Imagery

The interpretation of the satellite image of the landslide region gives a detail understanding of the ground level scenario. The landslide generated a huge cloud of dust engulfing the nearby settlements (Fig. 4). From the field photographs, it appears that it is a rock and debris slide and the dust cloud was formed due to the rapid downslope movement of dry rocky mass resulting in air-blast. The debris from the landslide blocked the flow of the Kanka River/Ringpai Chu (Past), which is one of the main tributaries to the Teesta River. NRSC monitored the event using very high-resolution Cartosat-2B (80 cm) (Fig. 11) image acquired on August 15, 2016. The water impoundment has resulting in the formation of an artificial lake of 2.2 km length and 209 m width of the lake head, north of the Mantam (Fig. 11 and 12). The height of the natural dam created over this river has been high enough to submerge the 200 ft. high suspension bridge that connects the villages of Tingvong, Sakyong, Pentong, and Lingdem in Upper Dzongu to Mangan. The width of the landslide is 530 m in the middle and length is 790 m. Figs. 12 and 13 show the landslide is of a rectangular shape. The crown of the landslide is on the ridgeline (Fig. 12 and 13). Debris deposits (Fig. 12) are visible on either side of the ridgeline. The joints are exposed after the landslide suggests a wedge type collapse near the ridge of the landslide followed by the translational type of failure in the main body of the landslide. The water impoundment may have presented a serious threat to settlements downstream and to major installations like the Teesta Low Dam Project V of NHPC. Due to the blockage the river water did not drain out creating a possibility of surrounding areas being submerged as the water level rose towards the height of the natural dam. As a preventative measure, the people residing in the low lying areas and downstream of the Teesta River were evacuated and a high alert was issued. According to a survey report, about 30 houses were damaged, 11 houses were collapsed in the in Mantam village in the landslide vicinity. The bridge connecting Mangan to Upper Dzongu was completely submerged, cutting off the road connectivity to the three GPUs of Upper Dzongu. The road formation of about 300 meters on either side of the bridge was also damaged. The electricity supply to Upper Dzongu was cut off due to damages in the landslide area. The landslide was active after 2days of the initiation and continued rocks and debris fall was seen at the site. So, as seen from the LANDSAT 8 image and Cartosat-2B, the river water has overstepped the debris dam and now flowing along its natural course in the form of a turbulent rapid, without any lateral breaching. As a consequence of this, the lake is draining out through the narrow outlet and there is no eminent water level rise. Nevertheless, it is important to monitor the water spread and the volume of the lake over the next few weeks, as a sudden event of high rainfall in the upstream areas, can lead to rapid water level rise and submergence of the habitations beside the lake (Fig.15). The area around Sakkyong in the upstream part of Kanaka River also witnessed severe landslide occurrences during the Sikkim earthquake on 18 September 2011 (Martha et al. 2015, Ghosh et al. 2012).This region is situated on the Main Central Thrust (MCT), a major geological fault where the Indian Plate has been pushed under the Eurasian Plate along the Himalayas. The region has seen hosting several seismic activities (GSI, 2000). At the same time, rainfall plays a significant role and influences slope failure through an increase in the amount of stored water in the rock body which in turn increases fluid pressure with a consequent decrease in effective pressure and shear strength. The analysis of high-resolution satellite imagery and observation of groundwater seepages into the exposed joint planes highlight the role of the aquifer induced pore pressure (due to earlier monsoon rains) and escarpment stress condition and the history of a previous landslide would be probable causative factors for the landslide initiation on August 13, 2016.

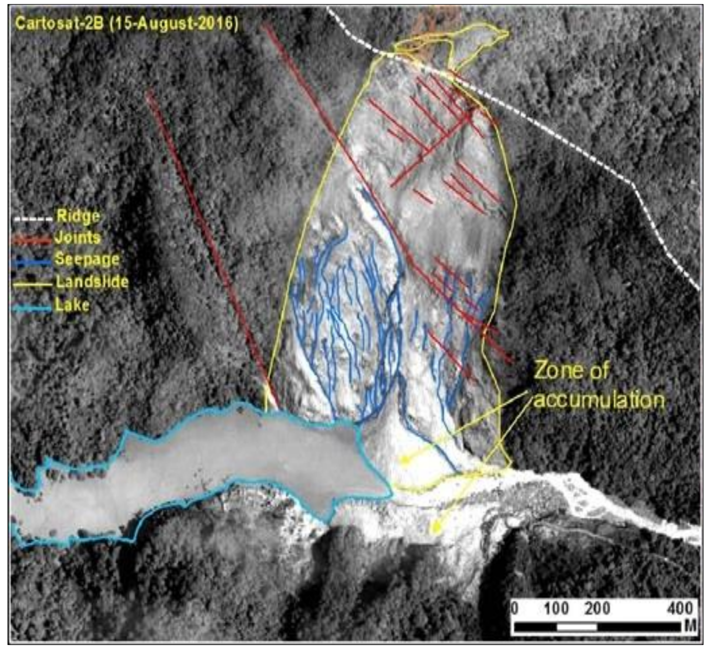

Fig. 12. Analysis of Mantam landslide using Cartosat-2B image (Source: NRSC, 2016)

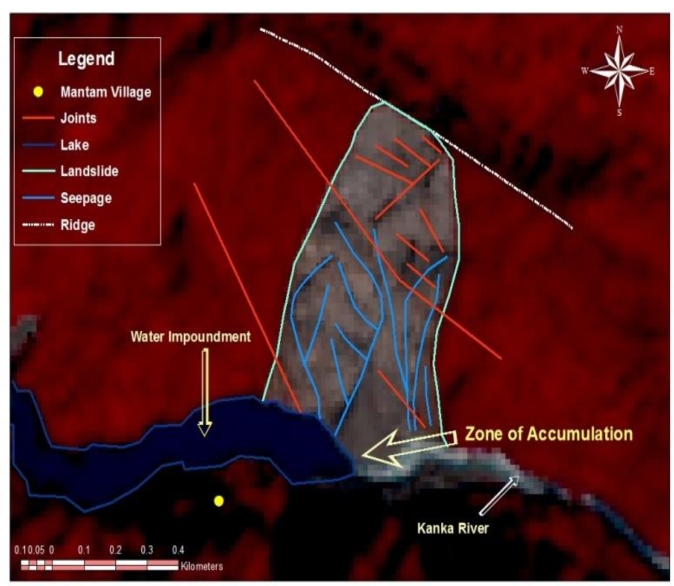

Fig. 13. Analysis of Mantam landslide using False Color Composite images of LANDSAT 8, Sept. 2016

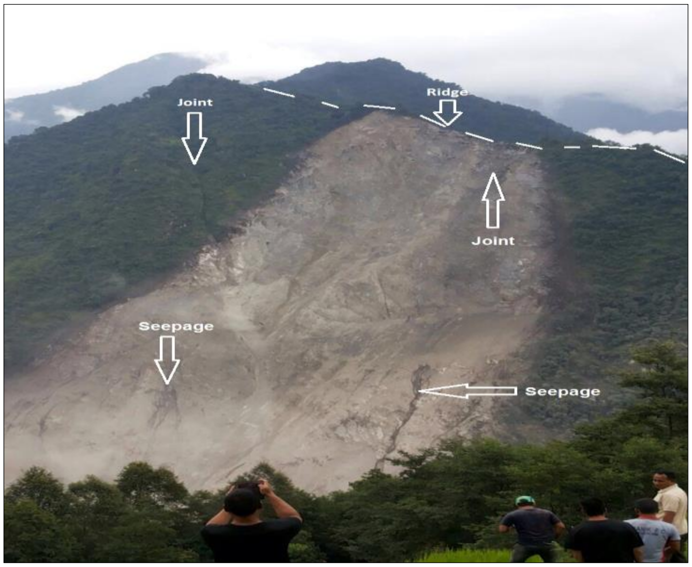

Fig. 14. Analysis of Digital Photograph at Mantam landslide

Fig. 15. Flooding upper catchment due to Landslide at Mantam

VI. RESULT AND DISCUSSION

Analysis of the rainfall and landslide data of the Mantam landslide in North Sikkim Himalayas puts forward a local threshold model estimation based on the E (or E_{MAP}) value. The exponential relation of the model found that the Mantam landslide was induced when E value exceeds 284.1 (E_{MAP} value is ≥ 0.10) over 10 days of cumulative rainfall. The threshold relation also shows that when E_{MAP} value lies between 0.05 and 0.10 over the 10 days period, then there is a moderate probability of landslides and if E_{MAP} value is < 0.05 over the same time period, it is considered as safe. The threshold values have been calculated based on limited available data. Finally, the study suggests that the threshold value is greater than or equal to 284.1 mm of cumulative rainfall over the 10 days period for the Mantam landslide initiation. Thus the threshold displacement for the landslide is E_{MAP} value of ≥ 0.10.

The study also suggests that , multi-resolution satellite imagery can help to assess groundwater seepage, condition of the lithological structure, earth materials of the region, and the nature of landslide for evidence of other causative factors leading to landslide and assist in establishing the threshold. This study aims to aid future researchers in better understanding of the relation between rainfall and landslide and compute similar threshold models at both local and regional levels. This threshold model can also be used to develop an early warning system for landslides which can help in planning protection measures to protect human lives, prevent property losses, and damage to agricultural fields from rain-induced landslides. .

REFERENCES

Aleotti, P. (2004). A warning system for rainfall-induced shallow failures. EngGeol, 73, 247–265.

Anbalagan, R. (1992). Landslide hazard evaluation and zonation mapping in mountainous terrain. EngGeol, 32, 269–277.

Basu, S. R., De, S. K., Bera, B. (2009). Progress of Research in Landslide Studies in India. In: Sharma H. S., Kale V. S. (eds.) Geomorphology in India, Allahabad: PrayagPustakBhawan, India, 171-198.

Bhandari, R. K., Senanayake, K. S., Thayalan, N. (1991). Pitfalls in the prediction on landslide through rainfall data. In: Bell D. H (ed) Landslides, 2nd edn. A.A. Balkema, Rotterdam, 887–890.

BIS (2002). Criteria for earthquake resistant design of structures: General provisions and buildings, Bureau of Indian Standards (BIS) IS 1893:2002 (Part I)

Brand, E.W., Premchitt, J.,Phillipson, H.B. (1984). Relationships between rainfall and landslides in Hong Kong. Proc. 4th, Symposium on Landslides, Toronto, 1, 377-384.

Caine, N. (1980).The rainfall intensity-duration control of shallow landslides and debris flows. Geogr.AnnA 62, 23–27.

Campbell, R. H. (1975). Soil slips, debris flows, and rainstorms in the Santa Monica Mountains and vicinity, southern California. In: US Geological Survey Professional Paper 851. US Government Printing Office, Washington, DC, 51.

Cardinali, M., Galli, M., Guzzetti, F., Ardizzone, F., Reichenbach, P., Bartoccini, P. (2005). Rainfall induced landslides in December 2004 in South-Western Umbria, Central Italy. Nat Hazards Earth SystSci, 6, 237–260.

Chakraborty, I., Ghosh, S., Bhattacharya, D., Bora, A. (2011). Earthquake-induced landslides in the Sikkim-Darjeeling Himalayas- An aftermath of the 18th September 2011 Sikkim earthquake. Kolkata: Geological Survey of India.

Chleborad, A. F. (2003). Preliminary evaluation of a precipitation threshold for anticipating the occurrence of landslides in the Seattle, Washington, Area. US Geological Survey open-file report 03-463

Gabet, E.J., Burbank, D.W., Putkonen, J.K., Pratt-Sitaula, B.A., Oiha, T. (2004). Rainfall thresholds for landsliding in the Himalayas of Nepal. Geomorphology, 63, 131–143.

Ghosh, S., Chakraborty, I., Bhattacharya, D., Bora, A., Kumar, A. (2012). Generating field-based inventory of earthquake-induced landslides in the Himalaya – an aftermath of the 18 September 2011 Sikkim Earthquakes. Indian Journal of Geosciences, 66 (1), 27 – 38.

Glade, T., Crozier, M.J., Smith, P. (2000). Applying probability determination to refine landslide-triggering rainfall thresholds using an empirical ''Antecedent Daily Rainfall Model''. Pure ApplGeophys, 157(6/8), 1059–1079.

Glossary in Seismology (IMD) - http://www.imd.gov.in/section/seismo/static/Glossary.pdf; browsed on 19/10/2011

GSI (2000) Seismotectonic Atlas of India and Its Environs. Geological Survey of India Publication

GSI (2000). In Sikkim Soils, National Bureau of Soil Survey and Land use planning Map, Nagpur, Sheet no. 4.

GSI (2016). Landslide Compendium on Darjeeling-Sikkim Himalayas by Ghosh, S., Ghoshal, T. B., Mukherjee, J., Bhowmik, S., Special Publication 103.

Gupta R. P.,andJoshi B. C. (1990). Landslide hazard zoning using the GIS approach—a case study from the Ramganga catchments. Himalayan Eng. Geol, 28, 119–131

Gupta, V., Sah, M. P., Virdi, N. S., Bartarya, S. K. (1993). Landslide hazard Zonation in the Upper Satlej Valley, District Kinnaur, Himachal Pradesh. J. Himalayan Geol, 4, 81–93

Kanungo, D. P., Arora, M. K., Sarkar, S., Gupta, R. P. (2006). A comparative study of conventional ANN black box, fuzzy and combined neural and fuzzy weighting procedure for landslide susceptibility zonation in Darjeeling Himalayas. Eng. Geol, 85, 347–366.

Kim, S.K., Hong, W.P., Kim, Y.M. (1991). Prediction of rainfall-triggered landslides in Korea. In: Bell DH (eds) Landslides, 2nd edn. A.A. Balkema, Rotterdam,989–994.

Martha, T.R., Govindharaj, K.B., Kumar, V. (2014). Damage and geological assessment of the 18 September 2011Mw 6.9 earthquake in Sikkim, India using very high-resolution satellite data, Geoscience Frontiers, 6(6), 793 - 805.

Mehrotra, G. S., Sarka,r S., Kanungo, D. P., Mahadevaiah, K. (1996). Terrain analysis and spatial assessment of landslide hazards in parts of Sikkim Himalaya. J. Geol. Soc. India, 47, 491–498.

Nagarajan, R., Mukherjee, A., Roy, A., Khire, M. V. (1998). Temporal remote sensing data and GIS application in landslide hazard Zonation of part of Western Ghat, India. International Journal Remote Sensing, 19, 573–585.

Neogi, S., Dasgupta, S., Fukuoka, M. (1998) High P-T Polymetamorphism, dehydration melting, and generation of migmatites and granites in the Higher Himalayan Crystalline Complex, Sikkim, India. J Petrol, 39(1), 61–99.

NRSC (2016). Brief Report on "So Bhir" Landslide on 13/08/2016 near the Mantam village, North Sikkim – Analysis using Cartosat – 2B image.

Parkash S. (2011). Earthquake Related Landslides in the Indian Himalaya: Experiences from the past and Implications for the future. Proceedings of the Second World Landslide Forum – 3-7 October 2011, Rome.

Sarkar, S., Kanungo, D. P., Mehrotra, G. S. (1995). Landslide hazard Zonation: a case study in Garhwal Himalaya, India. Mountain Research and Development. 301–309

Sengupta, A., Gupta, S., Anbarasu, K. (2009). Rainfall thresholds for the initiation of the landslide at LantaKhola in north Sikkim, India. Nat Hazards, 52, 31–42.

Sengupta, A., Gupta, S., Anbarasu, K. (2011). Rainfall thresholds for the initiation of landslide at LantaKhola in north Sikkim, India, Nat Hazards, 52, 31–42

Sharma, M.L., Maheshwari, B.K., Singh, Y.,Sinvhal, A. (2012). Damage Pattern during Sikkim, India Earthquake of September 18, 2011.

USGS report on Sikkim Earthquake of 18th September 2011 http://earthquake.usgs.gov/earthquakes/recenteqsww/Quakes/usc0005wg6.php, browsed on 8/10/2011.

Wieczorek, G. F. (1996). Landslide triggering mechanisms. In: Turner A. K.and Schuster R. L. (eds.) Landslides: investigation and mitigation. Transportation Research Board, National Research Council, Washington, DC, Special Report, 76–90

Wilson R. C. (1989). Rainstorms pore pressures and debris flows: a theoretical framework. In: Morton D. M.and Sadler P. M. (eds.) Landslides in a semi-arid environment, 2nd edition. Publications of the Inland Geological Society, California, 101–117.

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