Catastrophic hydrological event of 18 and 19 September 2010 in Uttarakhand, Indian Central Himalaya – an analysis of rainfall and slope failure

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Heavy rains on 18 and 19 September 2010 in the Ganga watershed associated with a regional monsoon event that occurred between Myanmar and Middle East caused disastrous landslips in Uttarakhand, Indian Central Himalaya and floods in the plains of Punjab, Uttar Pradesh and Delhi. Relation between quantum of rainfall per day and slope failure has been examined in the light of similar studies in other parts of Himalaya. The cloud movement and rainfall pattern during disaster dates have been studied using remote sensing data from *Kalpana-1* weather satellite and weather station data from Uttarakhand. A system for advance warning system is suggested.

Keywords: Advance warning system, cloud movement, Himalaya, landslide, rainfall.

HYDROLOGY of the Indian Himalayan region is complex[1,2]. Three-fourths of the total annual rainfall in the region occur during the short monsoon period, especially during nights[3]. Quantum and intensity of rainfall during the monsoon determines the quantum of surface water discharge as well as infiltration, which have implications for slope processes in the mountains and flooding in the plains downstream[4]. The year 2010 witnessed local to regional-scale catastrophic events associated with monsoon phenomena. These include the 11 August 2010 Leh tragedy resulting from a cloud burst; the 18–19 September catastrophe in Uttarakhand, Indian Central Himalaya and floods in the plains of Punjab, Haryana and Delhi. The present communication analyses the 18 and 19 September 2010 monsoon event and the catastrophe associated with it. Suggestions for preparedness and mitigation of disasters of this kind are also given.

Rapid surveys following the heavy rains on 18 and 19 September 2010 were undertaken to document the damages that occurred in the mountain region of Uttarakhand and in the downstream plains. Detailed coverage of this catastrophic event and extent of damage have been archived by the media[5].

Natural high-resolution *GeoEye* satellite images feature concentrated landslips in the mountain region of Central Himalaya in Uttarakhand (Figures 1 and 2). Triggered by heavy rainfall, water flow in the newly developed and temporary sub-surface channels accelerated the landslips, which caused damages to settlements in the mountains. Landslip in terraced crop fields (Figure 1 *c*) or areas between two successive rural houses on the slopes has caused damage to the lower buildings (Figure 1 *d*). Subsurface water appeared from numerous points in the entire landscape, but more prominently on altered landscape. In most of the villages, ‘Goth’ (ground floor of a rural house used as a cattle shed) was submerged in the water due to discharge of subsurface flow (Figure 1 *e*). Excessive seepage was also responsible for damage to the upper floor of the houses. Flooding downstream, due to heavy discharge from the mountains caused loss of several human lives and cattle, major damages to basic amenities, village pathways and roads (Figure 1 *b*), crop fields, and buildings on the mountain slopes and valleys. It washed away buildings and patches of roads in a 20 km stretch along National Highway 87 that runs through the Kosi river valley in Nainital District. Downstream, in the plains of Punjab, Uttar Pradesh and Delhi, floods affected thousands of people. This included submergence of villages, towns, agricultural lands and blockage of the Delhi–Bareilly–Lucknow National Highway 24 for several days. Here we analyse rainfall data and associated slope processes.

Very high-resolution radiometer visible band satellite imageries from *Kalpana-1* satellite of ISRO archived at India Meteorological Department (IMD; Ministry of Earth Sciences, Government of India)[6] were retrieved for analysis of pattern and movement of clouds. Daily rainfall data were obtained from three weather stations: (1) G.B. Pant Institute of Himalayan Environment and Development (GBPIHED) at Katarmal, Almora District; (2) Aryabhatta Research Institute of Observational Sciences (ARIES), Nainital and (3) Government Inter College, Dwarahat (Figure 3). These include high-resolution rainfall data collected at 30 min intervals from the weather tower located at GBPIHED.

Total rainfall in a month was aggregated at the district level and departure from long-term mean for different districts of Uttarakhand was obtained from the web repository of IMD. Detailed rainfall data at Katarmal station showed that since the beginning of September 2010, except for heavy rain on 4 September, not much rainfall had occurred before 18 September. The 4 September rainfall consisted of a midnight downpour of 19.5 mm and a nine and a half hour spell of 43.2 mm (Figure 4). Comparison of total rainfall during the month of September for the last five years (2006–2010) in different districts of Uttarakhand shows that September 2010 witnessed excessive rainfall, except in Champawat District (Table 1).

Average rainfall (arithmetic average of stations under a district) varies from 382.9 to 799.5 mm, with a very high degree of departure (79–263%) from the long-term mean for the month of September. Hence almost the entire state

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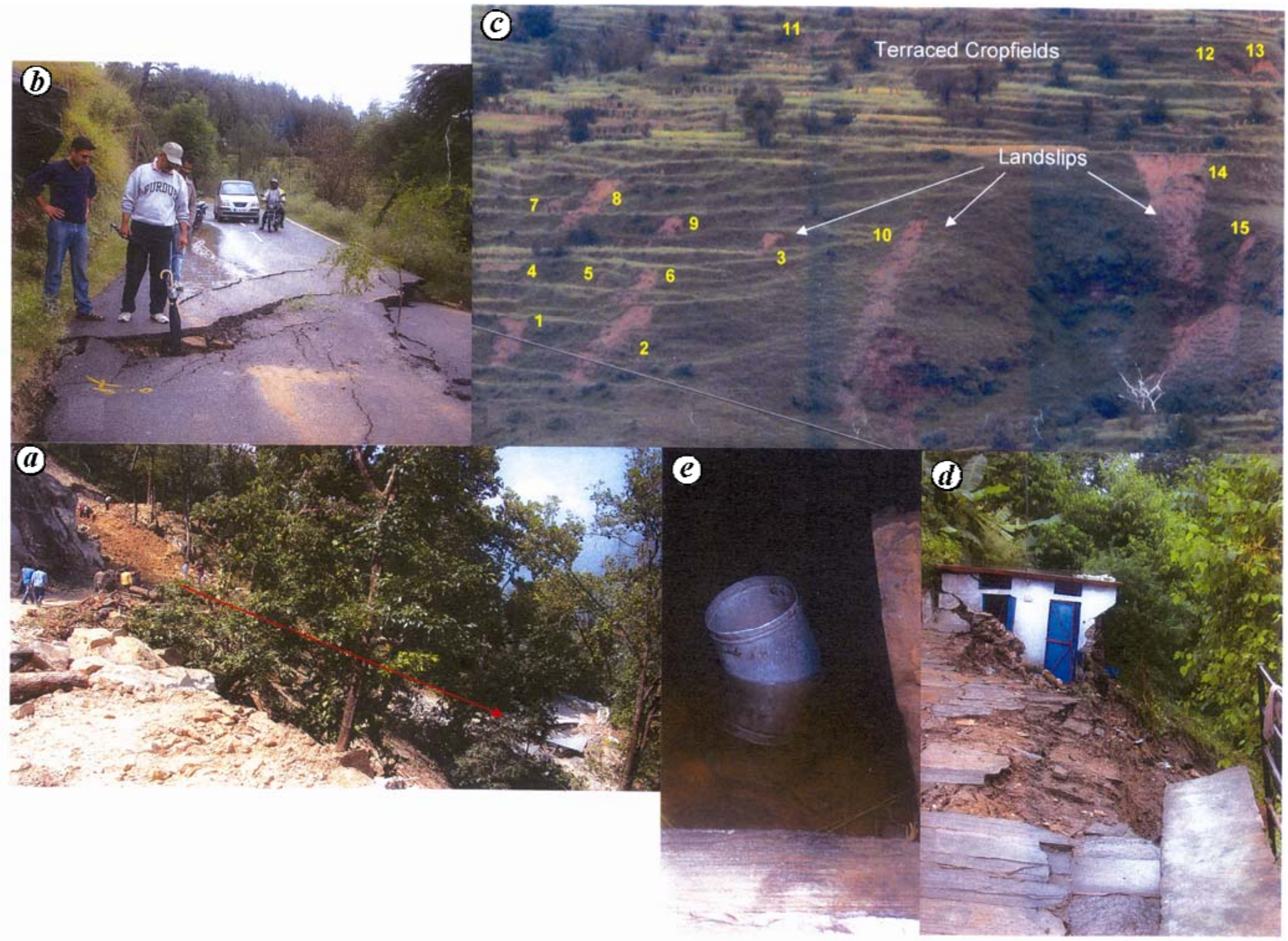

Figure 1. Damages due to catastrophic event. ***a***, Huge mass of landslide which took a piece of the National Highway 87 nearly 30 m downslope in Nainital District. ***b***, Sinking of National Highway 87 in Almora District. ***c***, Numerous newly developed landslips of different sizes. ***d***, Damage to building. ***e***, Water-filled ground floor of a cattle shed in a rural building.

Figure 2. Natural colour high-resolution satellite images from *Geo-Eye* showing numerous landslips in a smaller area of Kosi watershed.

of Uttarakhand received high rainfall in September 2010. To realize the amount of rainfall received during the catastrophic event, data available from three different meteorological stations located in two districts were analysed. These data indicate that about the time of the catastrophic event (15–19 September 2010) considerable rainfall (215.8–711 mm) was received. As much as 64% of this rainfall occurred in one day, i.e. on the 18 September 2010 (Table 2).

Extent of flood-affected areas indicates that this heavy rainfall in Uttarakhand cannot be due local cloud burst at one location, but must be part of a regional phenomenon. Therefore, cloud movement was analysed. Meteorological satellite imageries from *Kalpana-1* show that a jet stream of dense clouds migrated over the Himalayan region from east to west twice between the night of 17 and 19 September (Figure 4). The movement of the clouds was quick between longitudes 100°E (China, Myanmar, Thailand and Indonesia) and 80°E (Uttarakhand in India), covering a distance of about 1950 km in one and half hours, and almost at a similar pace between 80°E and 60°E, reaching Iran. But thick clouds hung over the subcontinent for a prolonged period of nearly 11 h (01.00–12.00 h local time) on 18 September over Himachal Pradesh and Uttarakhand, and parts of West Bengal

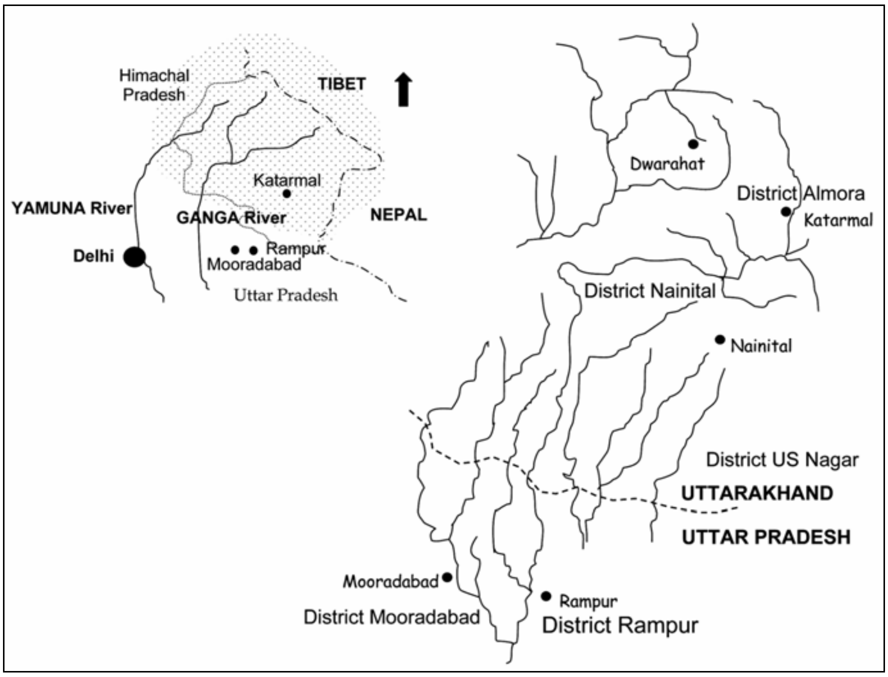

Figure 3. Location of three meteorological stations in different watersheds and downstream affected areas of excessive rainfall.

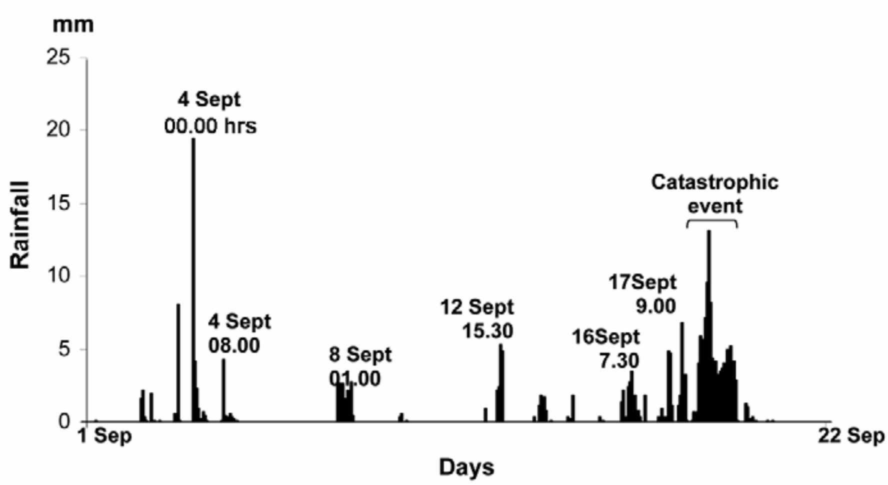

Figure 4. Distribution of rainfall in 2010 at Katarmal (Kosi watershed) in Uttarakhand. Values (mm) are presented as total at 30 min interval (hrs).

and Orissa. Density of cloud cover was highest over Uttarakhand and eastern parts of Himachal Pradesh (catchment of River Yamuna), medium over Jammu and Kashmir, thin over the remaining part of the Himalayan arc and Tibetan Plateau. This pattern recurred on 19 September (01.30–11.0 h), but density of cloud cover was much less. Cloud cover was observed over the plains of Madhya Pradesh, eastern Rajasthan and western Uttar Pradesh, and also over Uttarakhand and Himachal Pradesh of the Himalaya. It extended further to the Trans Himalayan region and Tibetan Plateau.

Further, high-resolution infrared satellite imagery in the Himalaya[7] shows high degrees of cloudiness on the ridges at night (between 20.00 and 07.00 h) peaking between 00.00 and 03.00 h during the monsoon season. Diurnal precipitation characteristics of South Asia obtained from different methods (satellite imagery, rain gauge, and a combination of both) illustrate: (i) afternoon and (before) midnight maximum rainfall[8]; (ii) after midnight peak or nocturnal peak in rainfall[9,10] and (iii) late night–early morning maxima in rainfall[11,12].

The foregoing preliminary analysis of rainfall data and cloud movement, therefore leads to confirmation that the catastrophe occurred due to a regional event (Figure 5) that stayed prolonged over the Ganga watershed in the Indian Central Himalaya.

Table 1. Total rainfall during September for the last five years in different districts of Uttarakhand[15]

	Arithmetic average of rainfall (mm) of Stations under the district					Departures (%) of rainfall from the long period averages for the district				
District ↓ Year →	2006	2007	2008	2009	2010	2006	2007	2008	2009	2010
Almora	55.5	245.4		16	480.8	–64	58		–68	209
Chamoli					437.7					263
Champawat					1.5					–98
Dehradun	195.7	801	159.9	273.2	799.5	–30	186	–43	–3	185
Pauri	121.1	245.6			382.9	–43	15			79
Tehri	19.1	93.5	80.4	133.7	444.6	–87	–36	–45	–8	207
Haridwar				0	456.1				–100	184
Nainital	88.4	11.7	353.1	301	702.5	–68	–84	29	10	158
Pithoragarh				1.7	485.0				–90	94
Rudraprayag					448.8					86
US Nagar	0	16			604.6	–100	–77			188
Uttarkashi					604.2					156

Blank space indicates no data.

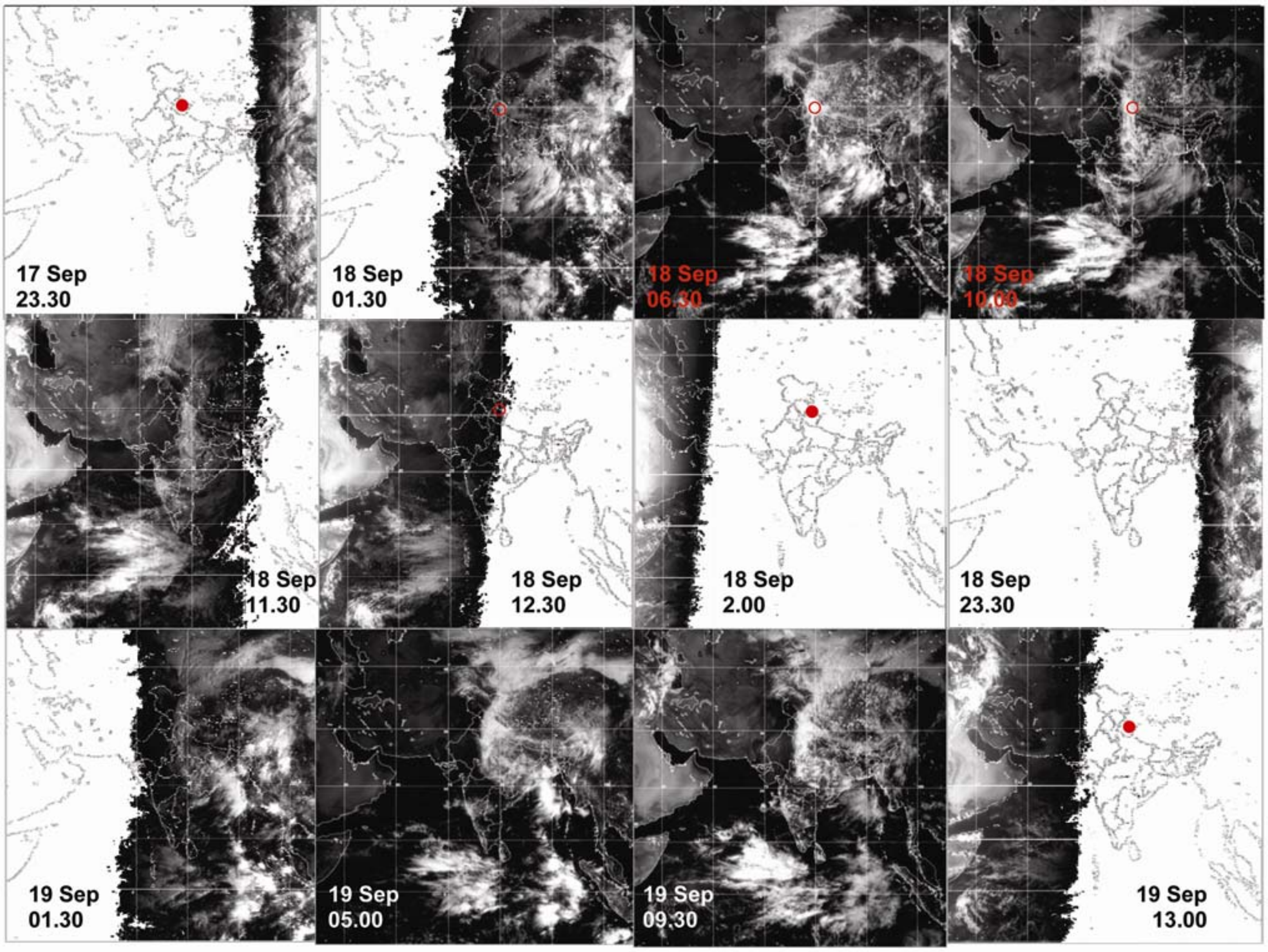

Figure 5. Cloud movement starting in the night of 17 September 2010. Red circle indicates the state of Uttarakhand.

Consequences of excessive rainfall and related water discharge are multifold. Excessive seepage through the uppermost stratum of the soil, results in numerous shallow, underground water channels. Where water through infiltration exceeds the water-holding capacity of the soil, shallow slides on slopes (up to 20 m length) are initiated. Fifteen such slides were observed in a small area of Hawalbagh (Figure 1 *c*). Triggered by subsurface flow,

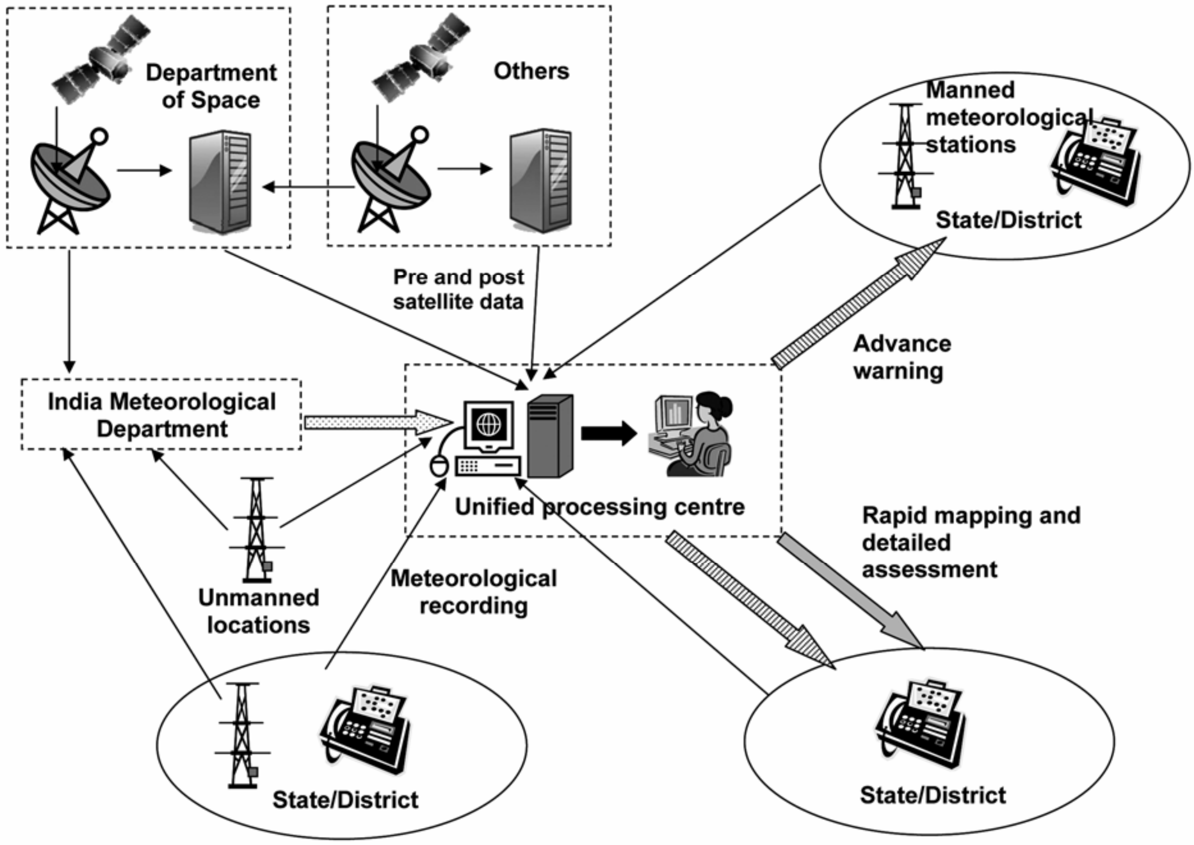

Figure 6. A framework for the Unified Processing Centre for advance warning system and post-disaster assessment.

Table 2. Daily rainfall between 15 and 20 September 2010 at three meterological stations located in the districts of Almora and Nainital

September 2010	Rainfall (mm)		
Day/Stations	Dwarahat	Nainital	Katarmal
15	19.2	6.0	0.7
16	11.2	104.0	32.4
17	46.6	78.0	38.3
18	130.0	458.0	164.2
19	8.8	65.0	36.0

wet and thick soil layers may slide up to 50 m or more. Downward mass movement of mud, stones, rock fall[13], and trees and other vegetation (if any) erodes the slope surface and destroys any man-made structure located in the way of gravitational pull (Figure 1 *d*).

Following the 196.2 mm downpour within 22 h, threshold value for slope stability was surpassed and major devastation in the form of landslips occurred in the upper watershed of River Kosi and floods downstream in Uttarakhand. A 1984–1988 study conducted on slope and channel processes in the Darjeeling Himalaya showed that, shallow slides and slumps on steep slopes occur when rainfall within 24 h reaches 130–150 mm, or when it totals to 180–200 mm within three days[4]. Another study in the Nepal Himalaya[14] showed that slopes became unstable when rainfall was in excess of 144 mm/day. Although threshold values for the slopes can vary from area to area and need to be established separately, slope failures in the Upper Kosi watershed area of the Indian Central Himalaya indicate that threshold values for slope stability here may not be different from what has been recorded in Nepal and Eastern Himalaya.

The catastrophe in Uttarakhand, like elsewhere, underscores the importance of evolving a system that is required to help improve preparedness, minimize the damage and develop efficient mitigation measures for bringing down the losses. A system designated as Unified Processing Centre (UPC) is proposed and illustrated in Figure 6. The system proposed is a sensitive and open one that receives inputs for monitoring from various existing mechanisms such as:

(1) Earth observation satellites that provide comprehensive coverage in real time over large areas.
(2) Unmanned automatic weather stations (of the type installed in the Katarmal campus) at different locations, so that they can transmit data on rainfall, wind velocity, etc. telemetrically through GPRS to a processing centre (e.g. Katarmal campus weather station data are received at C-MMACS, Bangalore).

(3) Information from other organizations by various means, i.e. electronic data, past history, telephonic message, etc.

All the processed information may be used to issue warning in advance to the civil authorities at District/State administration level for effecting preparedness to prevent losses.

Soon after the event, the UPC can also provide vital information, obtained by rapid access, to ground truth data collectors and to emergency authorities/workers who provide services and carry out relief operations under disaster management[5].

Such a system will provide scope for assessment of risk of slope instability in the mountains and with the input from satellite images will be able to sound an alarm regarding flood situation in the plains downstream. Therefore, concerned authorities (State Public Works Department, National Highway Authorities, etc.) would be in a better state of preparedness. Comprehensive and multi-temporal coverage of large areas in real time from satellites can be used for monitoring, assessment and relief management. The system will also be able to guide planning of locations for future projects on hydro-power, irrigation and development of infrastructure (roads, bridges, etc.).

1. Singh, J. S., Pandey, A. N. and Pathak, P. C., A hypothesis to account for the major pathway of soil loss from Himalaya. *Environ. Conser.*, 1983, **10**, 343–345.
2. Pathak, P. C., Pandey, A. N. and Singh, J. S., Overland flow, sediment output and nutrient loss from certain forested sites in the central Himalaya, India. *J. Hydrol.*, 1984, **71**(3–4), 239–251.
3. Bhatt, B. C. and Nakamura, K., Characteristics of monsoon rainfall around the Himalayas revealed by TRMM precipitation radar. *Monthly Weather Rev.*, 2005, **133**, 149–165.
4. Froehlich, W., Gil, E., Kasza, I. and Starkel, L., Thresholds in the transformation of slopes and river channels in the Darjeeling Himalaya, India. *Mt. Res. Dev.*, 1990, **10**(4), 301–312.
5. http://timesofindia.indiatimes.com/topic/heavy-rain-in-uttarakhand; http://articles.timesofindia.indiatimes.com/2010-09-19/india/2826-1879_1_rishikeshgangotri-uttarakhand-rishikesh-badrinath; http://www.ndtv.com/article/india/rain-furyin-uttarakhand-200-villages-washed-away-54110; http://www.ndtv.com/article/india/atleast-40-killed-in-rain-landslides-in-uttarakhand-53121; http://www.thehindu.com/todays-paper/tp-national/tp-newdelhi/article2232084.ece
6. http://202.54.31.45/archive/ASIA-SECTOR/VISIBLE/
7. Barros, A. P., Kim, G., Williams, E. and Nesbitt, S. W., Probing orographic controls in the Himalayas during the monsoon using satellite imagery. *Nat. Hazards Earth Syst. Sci.*, 2004, **4**, 29–51.
8. Nesbitt, S. W. and Zipser, E. J., The diurnal cycle of rainfall and convective intensity according to three years of TRMM measurements. *J. Climate*, 2003, **16**, 1456–1475.
9. Ueno, K. *et al.*, Meteorological observations during 1994–2000 at the Automatic Weather Station (GENAWS) in Khumbu region, Nepal Himalayas. *Bull. Glaciol. Res.*, 2001, **18**, 23–30.
10. Barros, A. P. and Lang, T. J., Monitoring the monsoon in the Himalayas: Observations in central Nepal. *Monthly Weather Rev.*, 2003, **131**, 1408–1427.
11. Ohsawa, T., Ueda, H., Hayashi, T., Watanabe, A. and Matsumoto, J., Diurnal variations of convective activity and rainfall in tropical Asia. *J. Meteorol. Soc. Jpn.*, 2001, **79**, 333–352.
12. Murakami, M., Analysis of the deep convective activity over the western Pacific and Southeast Asia. Part I: Diurnal variation. *J. Meteorol. Soc. Jpn.*, 1983, **61**, 60–77.
13. Paul, S. K., Bartarya, S. K., Rautela, P. and Mahajan, A. K., Catastrophic mass movement of 1998 monsoons at Malpa in Kali Valley, Kumaun Himalaya (India). *Geomorphology*, 2000, **35**(3–4), 169–180.
14. Dahal, R. K. and Hasegawa, S., Representative rainfall thresholds for landslides in the Nepal Himalaya. *Geomorphology*, 2008, **100**, 429–443.
15. http://www.imd.gov.in/section/hydro/distrainfall/webrain/uttarakhand

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Chemico-mineralogical attributes of clays from bole horizons in the Early Cretaceous Sylhet Traps of Meghalaya: palaeoenvironmental inferences

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We report chemico-mineralogical attributes of the clay minerals that occur in the bole horizons associated with the 116 Ma Early Cretaceous Sylhet Traps in Meghalaya. The boles are brick red, greyish-black and yellowish-brown in colour. They have been observed in drill cores between the flows and are exposed in the Mawlong–Tyrna section of the Meghalaya Plateau. Upper sharp contact and lower gradational contact suggest that bole horizons are palaeo-weathering surfaces developed in the time interval between successive eruptive cycles. X-ray diffraction of clay minerals of three bole horizons shows that a lower bole horizon is rich in palygorskite, whereas other two are rich in halloysite and kaolinite. Scanning electron micrographs show that palygorskite forms randomly oriented network of densely packed fibres; kaolinite is characterized by parallel platy texture and halloysite shows matrix-type structure with isometric, spheroidal microaggregates having intragranular porosity. PAAS normalized REE pat-

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