Investigating the 7th February, 2021 Landslide Triggered Flash Flood in the Himalayan Region Using Geospatial Techniques

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ABSTRACT

On 7th February 2021 just before noon, news reports came in regarding a flash flood in Rishi Ganga/Dhaul Ganga River in Chamoli district of Uttarakhand state, India. This brief report puts forth the probable causes for this flash flood that has originated in the Nanda Devi Biosphere Reserve using geospatial datasets and techniques. Datasets obtained from MODIS, Sentinel-2B, SRTM, ICESat-2 and ERA5 have been effectively utilized to infer the details about this event. Slow drizzle to severe snowfall has been witnessed during 3rd to 6th February 2021 in various parts of the Himalayan region; even the Rishi Ganga witnessed a heavy snowfall during this time. Data acquired on 10th February shows a scar developed due to a landslide on the shoulder of Ronti Mountain that was situated on the western rim of the Nanda Devi sanctuary. There was a gradual rise in temperature on 7th February 2021 at the surroundings of Ronti Mountain that consequently led to a landslide. The landslide perpetuated a movement under the influence of gravity from ~5900 m to ~3900 m with a mass envelope of ~0.290 km² and a velocity of 198 m/s that may have taken ~20 seconds to hit the Ronti bank. Due to the virtue of heat energy generated during this process resulted in contributing huge moraine filled flood water, that has accelerated towards the downstream of Rishi Ganga River and there after Dhaul Ganga River. Elevation profiles from the ICESat-2 and satellite imageries confirm the pre-existing conditions of landslide that is inclusive of weathering and erosion that led to the unstable condition at transportation back-slope of the Ronti Mountain. The triggering factors that influenced this landslide event and related causes were investigated in this study and reported herewith.

Keywords: Dhaul Ganga, Himalayas, India, Landslide, Nanda Ghunti, Rapid Snowmelt, Rishi Ganga, Ronti Mountain.

Published Online: August 28, 2021

ISSN: 2684-446X

DOI : 10.24018/ejgeo.2021.2.4.170

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I. INTRODUCTION

Himalayas, stands as the highest mountain peak on Earth where snow and icy environmental conditions stands rival to those existing at the Polar Regions that are known as the roof of the world, the third pole and water tower of Asia [1]-[3]. The third pole region influences social and economic development pertaining to the countries that depend on it like India as it plays a pivotal role in ‘water-ice-air-ecosystem-human’ interactions [1]. In recent times it was reported that there has been a significant loss in snow cover change, permafrost degradation, changing stream flows, decreased precipitation, glacier shrinkage, expansion of glacier lakes and increased frequency of extreme climatic events in the Himalayan region; all these consequences were attributed to climate change and anthropogenic activities [4]-[10]. Mal *et al.* [11] and Kumar *et al.* [12] have quantified the amount of recent glacier changes using remote sensing methods.

On 7th February 2021 just before noon, news reports emerged regarding a flash flood in Rishi Ganga/Dhaul Ganga River in Chamoli district of Uttarakhand state, India.

Videos circulated on WhatsApp showing water gushing downstream was reported through the media. There were videos that represented the ground events like a wall of water breaking the bridge and eventually surging into the dams, were widely circulated. Initially, various reasons like glacier break, avalanche and glacial lake outburst floods were suspected to have caused this flash flood. The flash flood has resulted in human loss, sweeping away a 35 MW Hydroelectric project (Run of River type) at the downstream of Ronti Gad (or Raunthi/Rounti Gad), severely damaging an under construction Vishnugad hydropower project of 520 MW in the Tapovan area on Dhaul Ganga River and a large-scale devastation along the downstream of Rishi Ganga/Dhaul Ganga. It was later reported that water levels have significantly reduced in the later part of the day.

This brief report outlines the probable causes for the flash flood that took place on 7th February 2021 in the Rishi Ganga/Dhaul Ganga River streams that had originated in Nanda Devi Biosphere Reserve after investigation had been carried out by using various geospatial data.

II. STUDY AREA

Nanda Devi group of glaciers falls within the upper Rishi Ganga catchment (a tributary of Dhaul Ganga river), Central Himalaya, covering an area of $\sim 690 \text{ km}^2$. Yuji [13] and Jain *et al.* [14] have provided extensive reports pertaining to the geological details of the Nanda Devi region; the area is composed of rocks belonging to the centre crystalline of the Vaikrita Group like garnetiferous mica schist and garnet mica schists which are well exposed along the Rishi Ganga catchment. The catchment is dominated by Higher Himalayan rugged topography with high elevation ridges adjacent to deep glacial valleys. Prominent glaciers in this area are Uttari (North) Nanda Devi, Changbang, Ramni, Bethartoli, Trishul, Dakshni (South) Nanda Devi and Ronti. Glacier systems containing North Nanda Devi, South Nanda Devi, Changabang and Ramani give rise to streams thereby leading to the formation of the Rishi Ganga River. With the Nanda Devi as a peak (7817 m, 7434 m East) in the region, the other peaks like Ronti, Nanda Ghunti and Trisul lies on the western-south rim of the Nanda Devi; from here, the Ronti Gad stream forms a sub catchment of the Rishi Ganga. Rishi Ganga River enters the lower gorge to merge with the Dhaul Ganga near Rini village. Fig. 1 shows the extent of Ronti Gad sub-watershed boundary, Rishi Ganga catchment, relief map of Nanda Devi Biosphere Reserve and the location of dams that were damaged due to the flash floods on 7th February 2021.

Bethartoli, Trishul, Dakshni (South) Nanda Devi and Ronti. Glacier systems containing North Nanda Devi, South Nanda Devi, Changabang and Ramani give rise to streams thereby leading to the formation of the Rishi Ganga River. With the Nanda Devi as a peak (7817 m, 7434 m East) in the region, the other peaks like Ronti, Nanda Ghunti and Trisul lies on the western-south rim of the Nanda Devi; from here, the Ronti Gad stream forms a sub catchment of the Rishi Ganga. Rishi Ganga River enters the lower gorge to merge with the Dhaul Ganga near Rini village. Fig. 1 shows the extent of Ronti Gad sub-watershed boundary, Rishi Ganga catchment, relief map of Nanda Devi Biosphere Reserve and the location of dams that were damaged due to the flash floods on 7th February 2021.

Fig. 1. Location of Ronti watershed, Rishi Ganga catchment and the dams that got damaged due to 7th February 2021 flash floods: (a) Map of India highlighting Uttarakhand state. (b) Uttarakhand state map highlighting the Rishi Ganga catchment. (c) Ronti Gad watershed boundary, Rishi Ganga catchment, dam locations and area where landslide happened shown in a relief map (generated from SRTM) and overlaid with OpenStreetMaps.

Earlier scholars like Aitken [15], Bisht [16] and Kapadia [17] have briefly mentioned the record of historical summiteers to Nanda Devi region and emphasized the difficult topographic conditions in this area in terms of accessibility. Dr. T.G. Longstaff is credited as the first explorer in this region during 1905 and was later followed by the surveyors Tilman and Shipton in 1934 [18]. Shipton [19] has mentioned the experiences of his survey emphasising the interiors of Rishi Ganga catchment. Lamba [20] and Bisht [16] have elaborated the details of flora and fauna of Nanda Devi National Park. Emmons [18], Luvkumar [21] and Lamba [20] during their independent surveys in this region have observed collapsed heaps of rubble and glacial debris at the lower stretches of Ronti glacier giving a hint about the retreating of the glaciers. Lavkumar [21] mentioned the existence of coniferous forests growing in the lower stretches of Ronti valley which is open to moisture-bearing winds from the lower Dhauligorge.

III. DATASETS AND METHOD OF INTERPRETATIONS

Multi-platform and multi-sensor satellite data, open source Digital Elevation Models (DEM), space-borne Laser Altimeter and reanalysed weather data that are disseminated from various web portals have been used in this study for identifying the areas of damage, moraine accumulation and the extent of area where the actual event happened. Table I shows the summary of datasets that were used in this investigation and Fig. 2 represents the method of interpretations.

Fig. 2. Associated datasets and the method of interpretations were done to analyse the disaster event occurred on 7th February 2021 in the region of Nanda Devi glaciers, Chamoli district, Uttarakhand state, India.

TABLE I: DETAILS OF DATASETS USED TO STUDY THE LANDSLIDE EVENT OCCURRED ON 7TH FEBRUARY 2021 IN THE NANDA DEVI BIOSPHERE REGION OF HIMALAYAS.

S. No.	Dataset	Specifications	Remarks
1	Moderate Resolution Imaging Spectroradiometer (MODIS)	MOD09GQ daily data with 250 m spatial resolution which provides surface spectral reflectance corrected for atmospheric conditions in Red and NIR bands	Data pertaining to pre and post events were used to visually interpret and to assess the snow conditions from 2 nd to 8 th February 2021.
2	Sentinel-2B	Visible and NIR bands @ 10 m spatial resolution	Used to assess the areas that got damaged and moraine accumulation due to the landslide event. Data acquired on 1 st January 2021, 16 th January 2021 and 10 th February, 2021 were used in the study.
3	SRTM	30 m Digital Elevation Model	Used to understand the topographic features like elevation, slope and aspect of the study area.
4	NASA's ICESat-2 return photons data	Elevation information from the return photon along-track for every 70 cm.	High precision elevation profiles were generated from ICESat-2 ATL03 product to understand detailed topography of Ronti Mountain.
5	ECMWF Reanalysis Generation (ERA5) data	Regular latitude-longitude grids at 0.25°*0.25° resolution	ERA5 datasets have been used to assess the surface air temperature in the study area. Hourly datasets from 1 st to 8 th February 2021 were used to analyse the surface temperature in the Ronti Mountain and surroundings.
6	News reports and shared videos from WhatsApp app	--	The information from news reports and the shared videos of WhatsApp were used to assess the ground situation.

Daily data from MODIS product namely MOD09GQ with

250 m spatial resolution has provided an opportunity to assess the snow conditions during pre and post disaster of the event. Satellite imagery of 10 m spatial resolution from Copernicus

Sentinel-2 mission dated 1st and 16th January 2021, and 10th February 2021 have enabled to interpret the core of the event. Digital Elevation Models from SRTM and high resolution along-track profiles from ICESat-2 photon data were used to understand the elevation profiles, slope, and aspect of the study area. Surface air temperature from the climatic reanalysis data has helped in assessing the weather settings in the study area and finally the field information/News/WhatsApp videos were used to correlate the reported events in the satellite data.

IV. INITIAL ASSESSMENT OF SNOW CONDITIONS IN THE STUDY AREA

It is understood from various news reports, that heavy to severe snowfall has been witnessed during 3rd to 6th February 2021 in various sections of Himalayan region; Rishi Ganga too received fresh snowfall during this period [22], [23]. Daily data of MOD09GQ with 250 m spatial resolution provides the surface spectral reflectance corrected for atmospheric conditions of Red and NIR bands were used for assessing the snow conditions in the Nanda Devi Biosphere region from 2nd to 8th February 2021. Notarnicola *et al.* [24] has mentioned the advantages of MOD09GQ products of MODIS in assessing the snow covered area due to its spatial resolution and high temporal availability. Fig. 3 shows the satellite data dated 2nd, 6th and 8th February 2021 over Rishi Ganga catchment and its surroundings. Severe snowfall that occurred in the Nanda Devi and surrounding regions is evident from the data acquired on 6th February 2021. Data acquired on 8th February 2021 (one day after the disaster) shows not only the reduction of the snow in the region but also moraine accumulation happened due to the flash flood at Ronti Gad, Rishi Ganga and Dhaul Ganga streams. At the banks of Rishi Ganga (near Rini village), loss of vegetation/or covered with dust has been observed through the data acquired on 8th February 2021.

A. Interpretations and Assessments from the High Resolution Satellite Data: Emphasis to find the Cause of the Event

Fig. 4 (a) and 4 (c) shows the satellite data acquired on two dates, i.e., 16th January and 10th February 2021 pertaining to Ronti bank and Rishi Gad/Rishi Ganga downstream. Fig. 4 (b) and 4 (d) shows the extent of Ronti Mountain where before and after the landslide has happened. Changes in the vegetation cover, moraine accumulation and movement of boulders have acted as keys to interpret the changes in the satellite data belonging to these two dates. Moraine accumulation due to flash flood that occurred on 7th February 2021 along Ronti gad/Rishi Ganga stretch is evident as shown in Fig. 4 (b). The disturbance caused due to the event has actually been observed from the edge of the Ronti bank (evident from Fig. 4 (d)). It is observed that, beyond the toe of Ronti bank and towards Nanda Ghunti bank, there are no significant signs of damage. This clearly shows that actual impact due to the damage has started from the toe of Ronti bank. Thus, emphasis has been given to check for the changes in the Ronti Mountain situated on the left side to the toe of

Ronti bank. Ronti Mountain is situated on the western rim of Nanda Devi Sanctuary with the elevation peak at 6029 m and has a prominence of 435 metres. Ronti lies 2.4 km North of Nanda Ghunti (6272 m) which is its nearest higher neighbour. The other neighbours are Bethartoli (6352 m) that lies 6.6 km towards East-Northeast, which is 8.4 km North-Northwest of Trisul-1 (7120 m). Nanda Ghunti Glacier flowing west to east joins Ronti Glacier that flows from south to north. Both the glaciers drain down through Ronti Gad and join Rishi Ganga after travelling nearly for 5 km. Fig. 5 shows the perspective view of Ronti Mountain and highlights the scar developed due to the landslide event.

Fig. 3. MOD09GQ product of MODIS with spatial resolution of 250 m acquired over Nanda Devi Biosphere Reserve in the Himalayan region. (a) Data dated 2nd February 2021. (b) Data dated 6th February showing accumulation of high to severe snow fall in the Rishi Ganga region. (c) Data dated 8th February 2021 showing moraine accumulation at the mouth of Rishi Ganga.

The dimensions of the scar developed due to the landslide event that are measured from the satellite data are ~570 m (width) and ~1090 m (length) and the total area of the scar retrieved from the satellite data is ~ 0.290 km² (~290333 m²). The shape of the scar is in inverted triangular with irregular sides. The impact area due to the mass fall after the landslide at the toe of Ronti bank is evident in Fig. 4 (d).

Fig. 4. (a) Satellite data dated 16th January 2021 showing vegetation cover along the Ronti Gad stream. (b) Fragile part of the area (indicated with yellow arrow lines) where landslide happened on 7th February 2021 as seen in the satellite data dated 16th January 2021. (c) Satellite data dated 10th February 2021 showing moraine accumulation due to flash floods that occurred on 07th Feb 2021. The disturbance caused due to the event has actually seen from the toe of Ronti bank (earmarked in the image in yellow curved line). (d) Part of the area induced with the landslide on 7th February 2021 (indicated with yellow arrow lines) as seen in satellite data dated 10th February 2021.

Note the impact area (indicated with olive green) at the toe of Ronti bank due the debris flow.

Fig. 5 Perspective view of Ronti Mountain generated using Digital Elevation Model (DEM) from Shuttle Radar Topography Mission (SRTM) overlaid with the satellite data (Sentinel-2B) dated 10th February 2021. Scar developed due to the landslide event on 7th February 2021 is earmarked with red circle. The yellow-dashed arrow lines represent the fall direction of mass due to the landslide that directed towards the toe of Ronti bank.

B. Terrain Characteristics of Ronti Mountain using SRTM DEM

Global DEMs like SRTM height models are an important component pertaining to the knowledge about our spatial environment and its' accuracy is sufficient for several applications in the fields of ecology, volcanology, glaciology, geomorphology and hydrology [25], [26]. In order to perform the landslide susceptibility mapping and to study the parameters related to the landslide conditioning factors, the terrain information from the DEMs, especially elevation, slope, aspect, gradient and curvature are highly useful [27].

In this study, terrain characteristics of Ronti Mountain were deduced using SRTM v.3 DEM with 30 m resolution. The average slope of the Ronti Mountain's shoulder where the scar developed due to the landslide event is approximately

45° (with occasional slope cells containing more than 60°) and majority of the mountain's shoulder is of North-Northeast aspect with elevation starting from ~5800 m and touching the toe of Ronti bank at 3900 m with a down-travel distance of 2.9 km. The main scarp of the landslide area is starting from 5600 m from the crest of Ronti Mountain. From the toe of Ronti bank with an elevation of 3900 m and along the Ronti Gad till Rishi Ganga River, the average slope is 33° and merges with Rishi Ganga at an elevation of 2350 m. Rishi Ganga passes through Rini village and merges with Dhauli Ganga at an elevation of 1950 m; all along with varying sloped conditions. Figure 6 shows the terrain profile of Ronti Mountain drawn along the probable track of mass movement occurred due to 7th February 2021 and also, the profile from the toe of Ronti Mountain bank, along Ronti Gad and Rishi Ganga stream up to the confluence point at Dhauli Ganga.

Fig. 6. Terrain characteristics of Ronti Mountain were generated using SRTM Digital Elevation Model along the probable track of mass movement occurred due to 7th February 2021. (a) Elevation profile of Ronti Mountain starting at 5800 m and reaching the toe of Ronti bank at 3900 m with down travel of 2.9 km. (b) Pencil sketch of Ronti Mountain illustrating snow melt triggered landslide. (c) Elevation profile from the toe of Ronti Mountain bank, along Ronti Gad and Rishi Ganga stream up to the confluence point at Dhauli Ganga.

C. High Resolution Precise Elevation Profiles from ICESat-2 Return Photons over Ronti Mountain

NASA's Ice, Cloud, and Land Elevation Satellite-2 (ICESat-2) is a continuation to the mission targeted for studying the Earth's polar region based on the operational principles of LiDAR technology [28]. Launched in 2018, the applications of ICESat-2 were proposed to extend to other landforms as the data is acquired pertaining to all the surface types like oceans, land, vegetation, and inland water-bodies [29]. The speciality of ICESat-2 is that it hosts a solo sensor

namely Advanced Topographic Laser Altimeter System (ATLAS) instrument with return photon counting technology [30]. The ATLAS instrument transmits a green (532 nm) laser pulses at 10 kHz and the spacecraft velocity from the ICESAT-2 nominal ~500 km yields one transmitted laser pulse for every 70 cm along track. It was reported that accuracy at centimetres level can be achieved using ICESat-2 return photon data by the researchers [31]. Sometimes, based on the surface feature the photons may not reflect back to the sensor; as an example, concave sloped mountain, free face cliffs and crevasses in glaciers [32]-[34].

Fig. 7 shows the elevation profiles that were generated from ICESat-2 data for Ronti Mountain using the beams of three separate ground tracks acquired on different dates falling in the vicinity to the identified scar. These elevation profiles confirm the existence of free face cliff for ~200 m of length from the crest of the mountain. Incidentally the scar observed in the satellite data dated 10th February 2021 was just 200 m below the crest of the Ronti Mountain.

D. Surface Air Temperature before and during the Landslide Event

A climate reanalysis gives a numerical description of the recent climate, assisted by combining models with observations. The latest climate reanalysis products

disseminated by the European Centre for Medium-Range Weather Forecasts (ECMWF) functions as an hourly data on many atmospheric, land-surface and sea-state parameters through the project namely ECMWF Reanalysis 5th Generation (ERA5) [35]. ERA5 data is available on regular latitude-longitude grids at 0.25° * 0.25° resolution, with atmospheric parameters at 37 pressure levels and offers the best agreement and correlation with the real time data [36]. In this investigation, surface air temperature from ERA5 has been retrieved near the vicinity of Ronti Mountain from 1st to 8th February 2021. Table II gives the reading of surface air temperature and Fig. 8 shows the temperature profiles from midnight (0100 hrs.) to afternoon (1300 h).

Fig. 7. High resolution precise elevation profiles from ICESat-2 return photons over Ronti Mountain (a) Satellite data overlaid with the three beams of photon streams from ICESat-2's ATLAS sensor over Ronti Mountain. (b) Elevation profile for the ground track dated 27th March 2019. (c) Elevation profile for the ground track dated 24th December 2019. (d) Elevation profile for the ground track dated 12th Nov 2019. Note the presence of free face cliff of approximately 200 m below the crest of Ronti Mountain.

TABLE II: HOURLY AIR TEMPERATURES RETRIEVED FROM ERA5 FOR RONTI MOUNTAIN AND SURROUNDINGS FROM 1ST TO 8TH FEBRUARY 2021

Date/Time (hrs.)	0100	0200	0300	0400	0500	0600	0700	0800	0900	1000	1100	1200	1300
01-02-2021	-21.8	-21.9	-22.1	-22.2	-22.1	-22.4	-22.1	-19.2	-15.7	-13.5	-12.4	-11.9	-11.6
02-02-2021	-21.1	-21.3	-21.3	-21.4	-21.6	-21.6	-20.9	-20.9	-17.8	-14.7	-12.7	-11.9	-11.5
03-02-2021	-22.2	-22.7	-23.5	-23.9	-24.1	-24.4	-24.2	-21.3	-18.2	-16.6	-15.5	-15.2	-14.9
04-02-2021	-20.7	-21.7	-22.7	-24.4	-23.4	-23.7	-22.8	-20.6	-18.1	-16.6	-15.5	-14.9	-14.6
05-02-2021	-18.5	-18.5	-18.6	-18.6	-19.2	-19.9	-22.4	-21.5	-19.1	-17.9	-17.5	-17.2	-17.1
06-02-2021	-25	-25.3	-25.2	-24.5	-24.7	-24.8	-24.4	-21.5	-18.3	-16.7	-15.9	-15	-14.6
07-02-2021	-20.8	-20.6	-20.6	-20.4	-20	-19.6	-18.9	-16	-12.5	-10.2	-9	-8.4	-7.9
08-02-2021	-16.5	-16.4	-16.3	-16.1	-16.2	-16.4	-15.8	-12.8	-9.3	-7.4	-6.6	-6.3	-6.1

Fig. 8. Profiles of surface air temperatures based on the hourly data retrieved from ERA5 data for Ronti Mountain and surroundings. Note the abnormal temperatures on 7th February 2021 which is almost 5 °C greater than the mean temperature of past 5 days.

The minimum and maximum temperatures recorded from 2nd to 6th February 2021 in the region are highly conducive for snow accumulation; whereas on 7th February 2021 the temperature settings during sunrise happens to be around 5 °C which is more than the previous day's temperature. And by 0900 h., the difference with respect to previous day's temperatures is 6 °C higher.

E. Dynamics of Snow Accumulation and Ablation over Ronti Mountain through Time-series Data

Visual analysis through a time series of Sentinel-2B data has been performed for Ronti Mountain by giving emphasis on glacier retreat process. At high altitudes, glaciers pile up large amounts of snow and ice through the accumulation process during winters. The amount of precipitation leads to snowfall, freezing rain, or wind-drifted snow that accounts for the mass accumulation in the glaciers; similarly in the summer, ablation process makes the glaciers to melt, evaporate, or calving. If the accumulated snow survives for one melt season, it forms a denser, more compressed layer called firn [37], [38]. The snow and firn are further compressed by overlying snowfall, and then the buried layers slowly grow together to form a thickened mass of ice [39], [40]. Fig.9 shows the process of accumulation and ablations in the Ronti Mountain from the years 2017 to 2019. It is observed that the peak of accumulation in Ronti Mountain keeps happening during January and February, and the ablation process is completed towards the end of September. The analysis relating to this time series of this accumulation and ablation process has resulted in concluding that the North-Northeast facing part of the Mountain's shoulder, part of free face cliff and upper part of transportation back-slope are having perennial snow surfaces. This clearly gives the evidence of yearly accumulation of layers of compressed firns and buried layers of thickened mass of ice. A closer observation of the high resolution data of recent times reveal a gap between the free face cliff and the part where scar has developed due to the landslide at the Ronti Mountain.

V. DISCUSSION

Works done by Lamba [20] and Mal *et al.* [11] mentioned about Ronti basin as a part of their studies in the Himalayan region and reported its participation in the glacier retreat process and also highlighted the presence of lateral moraines at the toe of Ronti bank; the participation of retreat process and the presence of lateral moraines at the toes indicates the overall bedrock erosion and evacuation of rocks/sediments in glaciated basins over several years or decades [41]. A closure looks at the Ronti Mountain, in a perspective view composed with the recent high resolution satellite data and DEM shows steep walls with eroded and a disintegrated vertical rock face that gives the evidence of resultant situation of past glacier and erosion activities due to mechanical weathering (like freeze-thaw). Over a period of time, hallows due to the disintegration of rocks associated with earlier mass movement are filled with the snow and thereby initiates a nivation phenomenon [42]. The shoulder of Ronti Mountain exhibits similar frost conditions in line with its nearest mountain neighbour Nanda Ghunti (western Trisul Massif) and thus, has a similar snow line with that area where scar resulted due to the landslide on 7th February 2021. Also, the North-northeast aspect of the Ronti Mountain has made a provision of perpetual snow line; however, the lower part of Ronti Mountain is observed to have undergone rigorous adjustments due to seasonal snow cover.

Studies from the high resolution elevation profiles generated from ICESat-2 photons in this investigation confirm that the part of area where landslide happened is overhanging on a steep slope as there is a detachment from the free face that is aligned to the Crestline of Ronti Mountain; thus the part of area which has induced the landslide has to rely on the support of slope strength of the mountain. Heavy to severe snowfall which happened from the 3rd to 6th February 2021 has resulted in accumulating snowpack in the study area. Analysis done on the hourly temperature profiles in the study area confirms a rapid increase of temperature in the early noon of 7th February 2021 which in turn is the reason for the rapid snowmelt; the case is

similar to the one mentioned by Pack [43] related to the triggering of landslides in the State of Utah. Rapid snowmelt runoff is extremely unlikely except in environmentally homogeneous watersheds or during unusual weather sequences in which sensible heat and condensation heat energy are added rapidly and uniformly to the entire

watershed snow cover [44]. Studies done by Cardinali *et al.* [45] concluded that continuous snowfall regime followed by a rapid increase in temperature can trigger landslides where fragile zones exist. Similar settings might have triggered Ronti mountain landslide on 7th February 2021.

Fig. 9. Process of accumulation (during January-February) and ablations (towards end of September) in Ronti Mountain for the years 2017 to 2019. The time series analysis of this accumulation and ablation process has resulted in concluding that the North-Northeast facing parts of the shoulder, parts of full-face cliff and upper part of transportation back-slope are having perennial snow surfaces.

Ritchie [46] has recognised certain conditions of potential landslides where the frozen ground subjected to local thawing effect by running water. Water from the rapid thawing effect and consequent snowmelt may have induced erosion on slope support at the shoulder of the Ronti Mountain; thus, the area may have lost the support from the slope that is needed for the mass attachment at mountain-flank beneath the area where landslide took place.

A landslide can result due to geological, morphological, physical, and human processes; without actually being triggering factors, pre-existing conditions that set the stage for triggering of landslides are extremely important [47]. In the case of Ronti Mountain's landslide, the pre-existing conditions include weathering and erosion that made the transport slope completely unstable.

Usually, the triggering mechanisms refer to the external stimulus caused by varied reasons and one such reason is rapid snowmelt. These external stimuli cause an immediate or near-immediate response in the form of landslide activity by rapidly increasing shear stress or pore pressure that furthermore increases the ground acceleration by removing lateral support, reducing the strength of slope materials, and initiating the debris-flow activity. However, the short time frame of cause and effect is the critical element in defining a

landslide trigger [48]. Melting of a winter snowpack by sudden warming spells leads to increased infiltration of water into hillside slopes, thus triggering the landslide activity [47]. Similar pre-existing conditions and triggering mechanism might have caused the Ronti Mountain's landslide.

It is evident from the elevation profiles that triggering factors are functional in initiating the landslide with a mass movement influenced by gravity from ~5900 m to ~3900 m with a mass envelope of ~ 0.290 km² (equivalent to ~55 football fields). With a velocity of 198 m/s (on application of free falling object equation) it takes roughly 20 seconds to hit the toe of Ronti bank, where heat energy generated due to the fall might have generated huge moraine filled water (snow and ice melted) leading to a flash flood. The speed of flood water can accelerate and steer its direction based on the available slope downstream. Thus, the content of flood material in the form of moraine and water had gushed towards Rishi Ganga and finally towards Dhauli Ganga River. Figure 10 shows the satellite data dated 16th January 2021 and 10th February 2021 at the extent of a bridge at Rini Village situated at the downstream of Rishi Ganga which got washed away due to the flash flood that took place on 7th February 2021.

Fig. 10. (a) Satellite data dated 16th January 2021 showing the bridge at Rini Village situated at downstream of Rishi Ganga. (b) A screenshot frame from WhatsApp video showing the flash flood breaking the bridge at Rini village on 07th February 2021. (c) Satellite data date 10th February 2021 showing completely collapsed bridge at Rini village due to flash flood occurred on 7th February 2021.

VI. CONCLUSIONS

This report sheds light on the possible causes of the flash flood that happened on 7th February 2021 originating in Nanda Devi region containing a group of glaciers. In order to instil this, various geospatial data and techniques have been utilised to study the environmental settings, triggering factors, identification of landslide site and to understand the post disaster sequence. The following key findings were

drawn from this investigation.

- Part of the shoulder belonging to Ronti Mountain situated on the western side to the toe of Ronti Bank was the core area of the incident
- There is a presence of a 200 m free face cliff from the crest of Ronti Mountain; part of the landslide occurred on 7th February 2021 that is just below this free face cliff; concluding that the part is not having any support from the crest

- Traces of past glacier and erosion activities with mass movements were inferred at Ronti Mountain through high resolution satellite data
- Accumulation of heavy snow for four days before the event and increase of temperature on 7th February 2021 at the surroundings of Ronti Mountain led to the rapid snowmelt and acted as trigger to the landslide.
- The transportation back-slope which was covered with fresh snow accumulation from the previous four days snowfall and the colluvial foot-slope which is approximately at a distance of 2.8 km from the starting of the landslide scar clearly shows the effect of destructive impact at the toe of Ronti bank due to the large mass movement
- Heat energy generated due to this landslide has further generated huge moraine filled flood water that has accelerated downstream towards the mouth of Rishi Ganga and later towards Dhauli Ganga River
- The slope conditions at Rishi Ganga have attributed to the acceleration of this flash flood downstream towards Dhauli Ganga River especially at Topovan

The study has harnessed the potential of remote sensing and geospatial techniques which has allowed investigation of the spatially explicit components of landscape level disaster. Integration of optical remote sensing and DEM, have acted as key tools that allowed undertaking this study in Himalayan rugged topography.

ACKNOWLEDGEMENTS

The authors are grateful to Director, National Remote Sensing Centre, Hyderabad for providing necessary facilities and encouragement to carry out this work. The authors would also like to express their sincere gratitude to Dr. John Mathew, ISRO Hq., Bengaluru for his valuable insights provided for this work. Authors are indebted to Dr. A.K. Bera, Dr. B.K. Bhadra, Suparn Pathak, Dr. Rakesh Paliwal, Sushil Rehpade and Manish Verma of Regional Remote Sensing Centre – West, Jodhpur for critical and helpful comments with respect to this study.

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