

Visual Evidence of Constrained Area of a Cloudburst, 12 June 2018, Tirisha Village, Nubra Valley, Ladakh, India

Renoj J. Thayyen^{1*}, Mritunjay Kumar Singh¹ and A.P. Dimri²

¹W.R.S. Division, National Institute of Hydrology, Roorkee, Uttarakhand, India

²School of Environmental Sciences, Jawaharlal Nehru University, New Delhi, India

✉ renojthayyen@gmail.com

Received February 20, 2020; revised and accepted July 5, 2020

Abstract: On 12 June 2018, the Tirisha village in Nubra valley, Ladakh experienced a flash flood from a cloudburst that occurred over the mountain ridge. This event was captured in a Sentinel 2B satellite image at the time of its occurrence. The image also provided unique visual evidence of the constrained area of a cloudburst for the first time. Field survey of impact area at the Tirisha village was carried out on 13 June 2018. It was followed by assessment of the impact at the place of occurrence and further downstream using satellite data taken on, before and subsequent days. Satellite data show small area where cloudburst impact ($< 1\text{ km}^2$) from a cumulonimbus (Cb) cell of $\sim 2.97\text{ km}^2$ of cloud top area. Rest of the flood catchment remained cloud-free during the event and floodwater in the stream is clearly visible in the imagery. The flash flood entered the Tirisha village situated at the Nubra valley foothills, which destroyed a stretch of 100 m road. Previous studies have suggested inherent atmospheric instability over the arid Ladakh region with an extremely high-temperature lapse rate of $>9.8\text{ K/km}$ during 40-70 days during summer months. The extremely constrained nature of this event highlights the challenges involved in monitoring, forecasting and managing such events in the Himalayan region.

Keywords: Cloudburst; Flash flood; Remote sensing; Cold-arid Himalaya; Ladakh.

Introduction

Ladakh region has very low mean annual precipitation of $\sim 115\text{ mm}$. The region is generally perceived to have the least chance of recurring flood disasters from extreme rainfall. Even after the devastating floods associated with August 2010 cloudbursts (Thayyen et al., 2013), the common view of researchers and administrators leaned towards the sporadic nature of such floods in the region. This view implied that no urgency is warranted to formulate and implement necessary adaptive measures for the region. Over the last eight years, the 2010 event emerged as the most studied cloudburst flood event in the Indian Himalaya (Kumar et al., 2012; Rasmussen and Houze, 2012; Hobley et al., 2012; Thayyen et al., 2013; Dimri et al., 2017).

During these studies, frequent occurrence of flash floods around Leh and nearby regions has been highlighted. It established that the recurrence of cloudburst is likely in the cold-arid region. However, these studies were mostly focussed around the main Indus valley around Leh. While traversing across Ladakh, outside the main Indus valley, many more instances of flood occurrences and devastation are reported. Along with cloudbursts, glacial lake outburst floods (GLOFs) and landslide dam outburst flood (LDOF) are also cited as reasons for flash floods in the region during the last decade (Dimri et al., 2016). Most often, flash flood events from remote glaciated mountain ridges in the region are attributed as GLOF. The increasing evidence of cloudbursts have put a question mark on the source of such flash floods in the region. For public and

*Corresponding Author

administrators, the distinguishing characteristics of a flash flood source, either as a cloudburst or as a GLOF, are the presence or absence of rain and thunder in the region. In the absence of any rain in the vicinity, flash floods are invariably attributed to GLOF. The unofficial definition of India Meteorological Department (IMD) also contributed to the idea of large spatial extent of cloudbursts, which says that the cloudbursts occur “*at a rate equal to or greater than 100 mm per hour featuring high-intensity rainfall over a short period*” and “*it is a remarkably localised phenomenon affecting an area not exceeding 20-30 km²*” (Ashrit, 2010). However, Das et al. (2006) suggested that the cloudbursts could have smaller spatial extent and occur at the meso-gamma scale (2-20 km²). Thayyen et al. (2013) suggested that the cloudburst impact zones could be as small as <1.0 km², which pointed out the need to improve the spatial scale of analysis and monitoring to study cloudburst and resultant flood. Proper understanding of flash flood source is very important to formulate appropriate response because the adaptive strategy for cloudburst and GLOF vary significantly. However, monitoring framework of cloudbursts and floods is insufficient in the region. Present study highlights the challenges involved in the cloudburst identification and monitoring. It shows that some cloudburst can be spatially very constrained, occurring in the remote glaciated mountains and making it difficult to distinguish from a GLOF.

Study Area

This paper discusses a very recent cloudburst event and associated flash flood in the Nubra valley of Leh

district, which belongs to the newly formed union territory (UT) of Ladakh. Ladakh is the northernmost Indian state known as the cold desert region. Three major mountains, Zaskar, Ladakh and Karakorum range runs through Ladakh. The present study area is on the Karakorum mountains (Figure 1) and the flood-damaged village of Tirisha is located at 34°44'32.01" N, 77°34'12.5" E, at 3300 m a.s.l. The Tirisha village is located approximately 3 km before Panamik en route to the Siachen glacier. Barren valleys and mountains characterise the whole area of Ladakh with ridges occupied by snow and glaciers.

Methodology

Fieldwork

The event occurred during our field visit to Nubra valley in Ladakh during June 2018 under the National Mission on Himalayan Studies (NMHS) supported by the Ministry of Environment, Forest and Climate Change (MoEF & CC), Govt. of India. On 12 June 2018, a flash flood near Panamik was reported to the BRO office at Hunder, Nubra valley. According to them, the flood struck the foothill village around 11:00 hrs (IST) and a 100 meter stretch of the road to Panamik was washed off. A field survey was carried out to study the affected area (Tirisha village) on the following day (13 June 2018). Information for the same was collected from the local eye-witnesses, BRO workers, local Member of Legislative Assemblies (MLAs) and other officials of district administration visiting the area. The general assessment by the locals, administrators and BRO personnels suggested that the flood could be

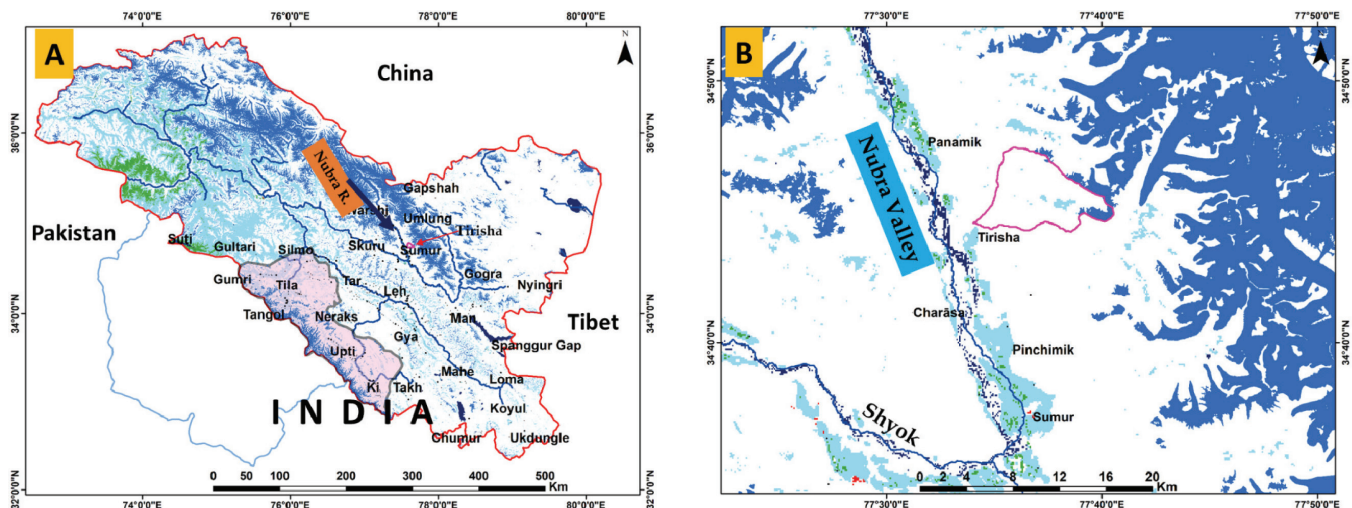


Figure 1: Study area showing (A) Kargil and Leh districts of Union Territory of Ladakh and (B) location of Tirisha village in the Nubra valley.

caused by a GLOF. The main reason for this assessment was the absence of any rain in the surrounding area of Nubra valley on 12 June 2018. Residents working for the BRO were eye-witness to this event who informed us that the water flow in the stream was persistent till around 1500 hrs. The riverbed was almost dry during our visit on the 13th morning.

Satellite Image Processing

Recent studies from the Google earth images showed no glacier lake in the catchment. We confirmed it using the most recent satellite images of Sentinel 2B data, which is found to be of good quality over the region. Both GPM and INSAT-3D images of the day covering the flood period is downloaded and studied. However, no indication of precipitation or dense cloud was visible in these images (Figure 2). Freely available satellite archives (Landsat and Sentinel) have been explored for getting the cloud-free images between 05 June 2018 and 12 July 2018. While Landsat archive does not have any cloud-free good images during the period for study location, Sentinel 2 had cloud-free and partially cloud-

free data sets for pre and post-Cb dates. Moreover, Sentinel 2 had an image of 12 June 2018, captured at the time of occurrence of the cloudburst. Based on the analysis, the study is focussed on the Sentinel 2B data. Sentinel data of the flood event has given three sets of images depicting pre-flood, during the flood and post-flood ground situation. The imageries used in the present study are listed in Table 1. Data of 7, 12, 14 June 2018 and 7 July 2018 were selected for the study. The Sentinel-2B satellite provides data in 13 spectral bands with a varying spatial resolution (Zhang et al., 2017). Two different multispectral images measuring 10 m and 20 m are generated by stacking the images of respective spectral bands. A 10 m visible/near-infrared (VNIR) imagery is produced by combining blue (band 2: 490 nm), green (band 3: 560 nm), red (band 4: 665 nm) and NIR (band 8: 842 nm) bands. A 20 m short wave infrared (SWIR) imagery is also produced by combining vegetation red edge band (Band 8a: 865 nm), a SWIR band (Band 11: 1610 nm) and another SWIR band (Band 12: 2135.7 nm). Further, we improved the spatial

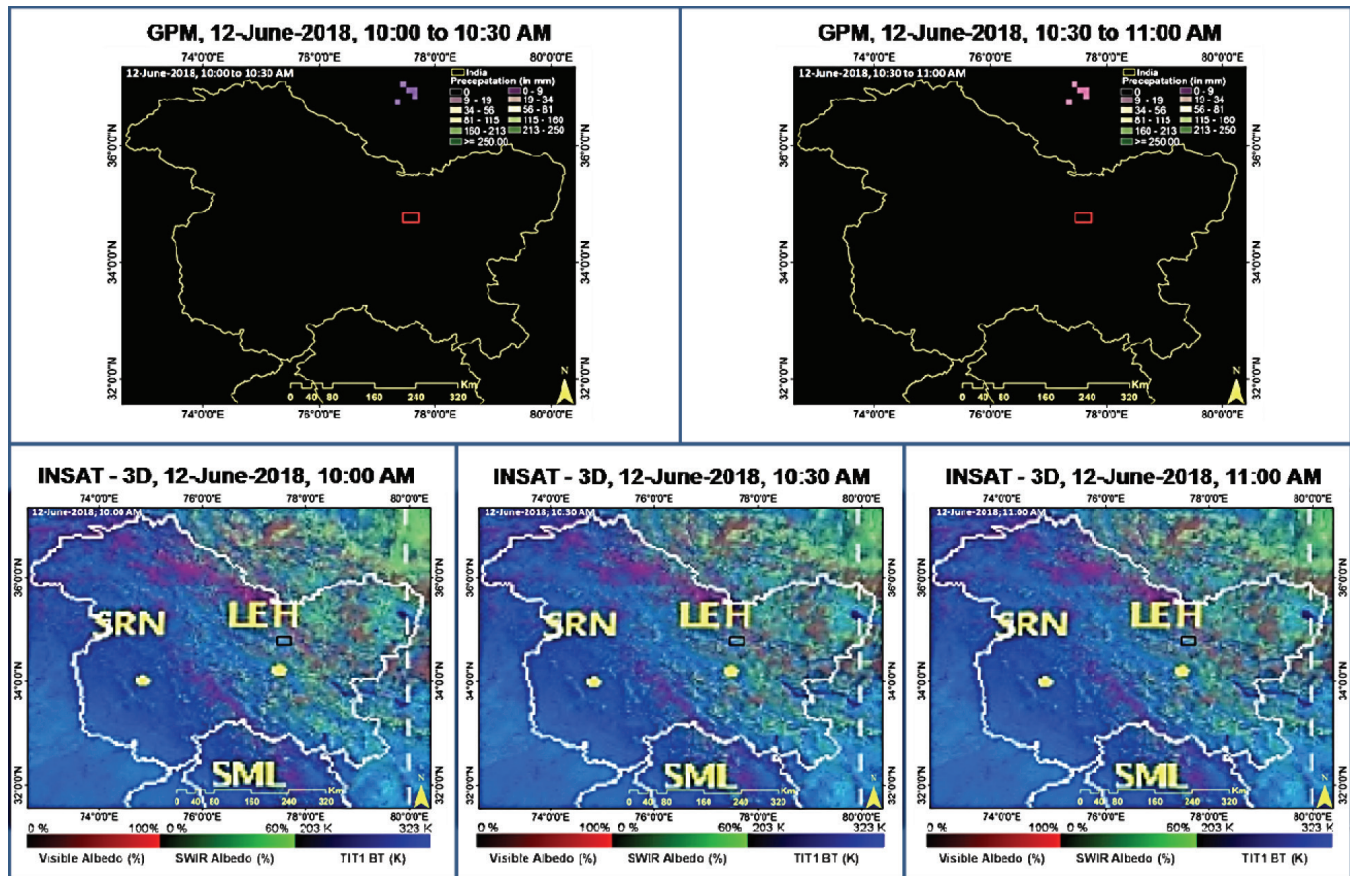


Figure 2: GPM and INSAT-3D images of the 12 June 2018 covering the study catchment in Nubra valley. Both images are unable to capture any precipitation or formation of clouds over the study area.

Table 1: Details of satellite data used in the study

S. No.	Date of acquisition (DD-MM-YYYY)	Satellite/Data name	Acquisition time (UTC)	Spatial resolution	Remarks
1.	12-06-2018	GPM	05:36:41	0.1°	No evidence of precipitation may be because of poor spatial resolution
2.	12-06-2018	INSAT-3D	4:00 to 6:30	0.1°	No dense cloud is visible over the study area
3.	07-06-2018 to 07-07-2018	SENTINEL-2B	~5:30	10 m	Cloud is visible on the upper ridges of the study area. Flood water in the stream is also visible

Details of Sentinel – 2B satellite data used for the study

S. No.	Date of acquisition (DD-MM-YYYY)	Platform	Orbit direction	Orbit number	Tile number	Acquisition time (UTC)
1.	07-06-2018	SENTINEL-2B	Descending Orbit	5	T43SGU	05:36:41
2.	12-06-2018			5		05:36:39
3.	14-06-2018			105		05:26:51
4.	07-07-2018			5		05:36:41

resolution of 20 m SWIR image to 10 m by fusing 20m image with the NIR band by applying high-pass filter (HPF) resolution merge (Gangkofner et al., 2007) for enhancing the moisture distribution. The data taken on

7 June 2018 show a small supraglacial lake over the lone glacier in the catchment (Figure 3). Images dated 14 June 2018 (Figure 4) show clouds over that particular location (supraglacial lake). A cloud-free image dated

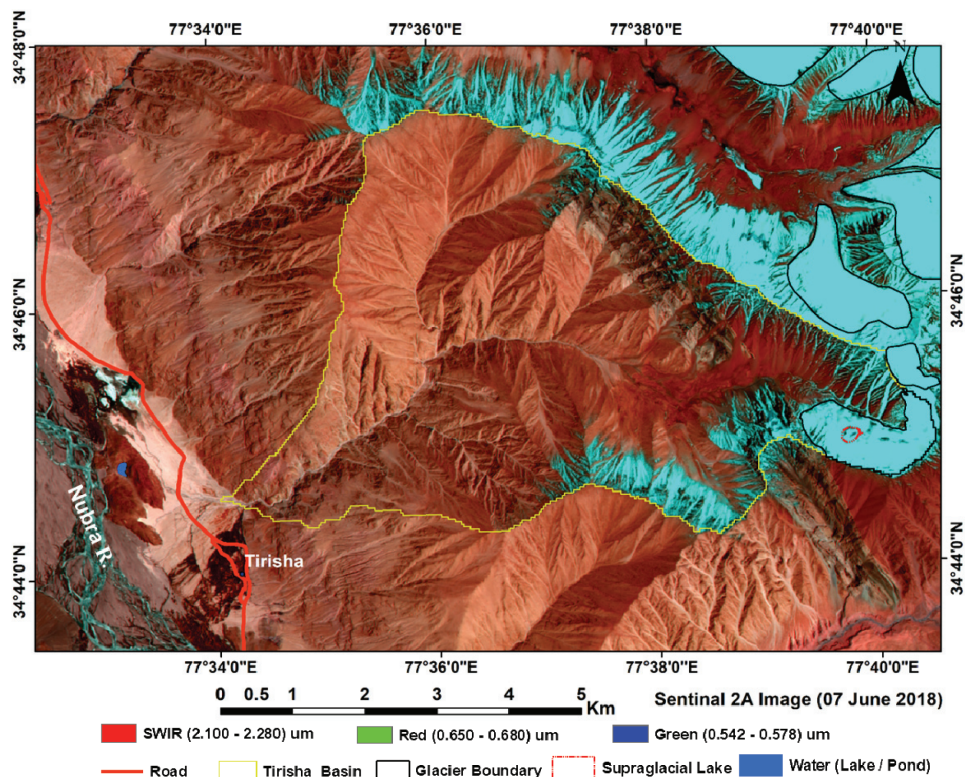


Figure 3: Pre-flood imagery of 7 June 2018 showing the snow distribution and channel morphology. The flood catchment is marked in yellow. A small supraglacial lake in the catchment is marked by a blue circle.

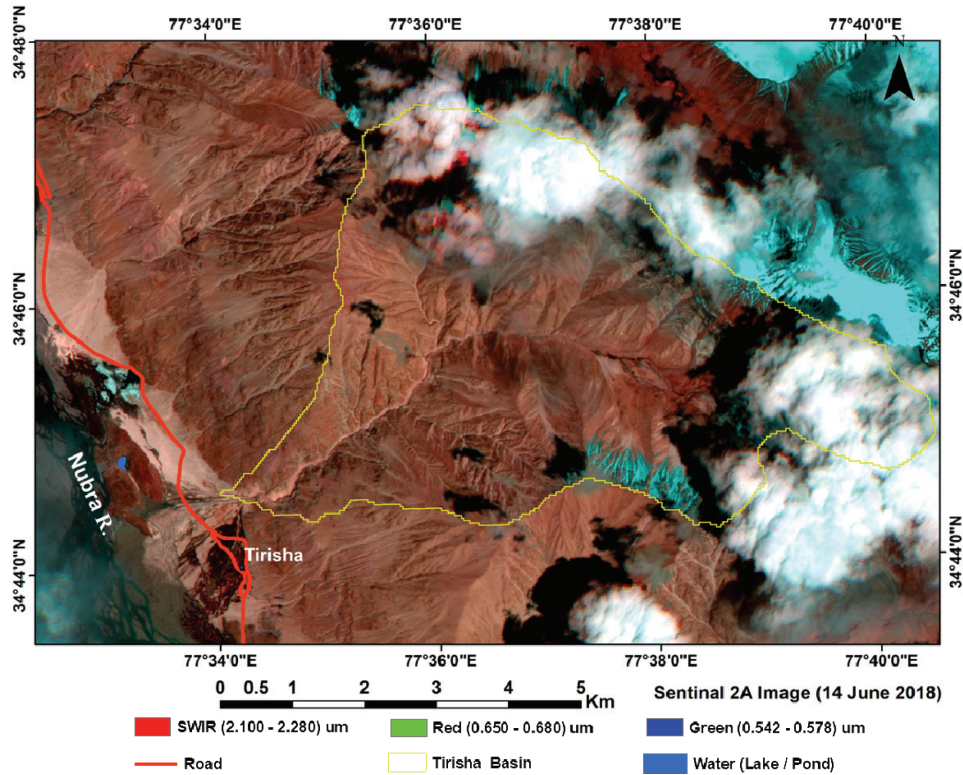


Figure 4: Post-flood imagery of 14 June 2018 showing cloud over supraglacial lake in the catchment.

07 July 2018 also analysed any modification in the location of lake area. But this lake did not show any sign of breach in the post-flood imagery dated 7 July 2018. Field photograph of the flood impact area is used to illustrate the ground situation as compared to the post-flood satellite imagery. Furthermore, the study discusses temperature lapse rates of Leh valley (Thayyen and Dimri, 2014) to show the prevailing atmospheric instability in the region during summer months, which is forced by local heating of the barren and arid land surface.

Results and Discussion

The Sentinel-2B satellite imagery of 11:06:39 hrs (IST) on 12 June 2018 probably settled the question of flash flood source as it revealed an impressive image of a spatially constrained cumulonimbus (Cb) cloud over the mountain ridge and floodwater in streams (Figure 5). The image clearly shows the floodwater in the stream suggesting that the cloudburst was in progress at the time of image acquisition and the time matches very well with feedback given by the local people as the time of flood occurrence (~1100 hrs). We have no further means of ascertaining the cloud characteristics due to

the unavailability of data as mentioned earlier. The pre-flood image taken on 7 June 2018 shows the undisturbed landscape (Figure 6a) and the post-flood image taken just 2 days after the event on 14 June 2018 (Figure 6b) shows a dry riverbed with a widened stream course as compared to the pre-flood image. Measurement of cloud top dimension from manually digitised cloud top boundary suggests of this particular Cb cloud was spread around 2.97 km². It is a rare coincidence that the image captured an active cloudburst event while the surrounding areas remained cloud-free, facilitating the view of the floodwater in the stream. A further look into the post-flood imageries of 14 June 2018 show partial cloud cover along the ridges (Figure 6b). The figure shows visible changes in the channel morphology close to the Cb boundary. Morphological changes are visible in the cloudburst impact zone at 5200 m a.s.l. as in the imagery from 7 July 2018 (Figure 6c). Morphological changes between pre-Cb events can be identifiable from the pre-event image (07 June 2018) and post-event image (14 June 2018) and these morphometric changes are shown in Figure 7a. The cloudburst impact zone is visible as the snow from this small area has melted away as compared to the surrounding area. There are morphological changes visible in the area.

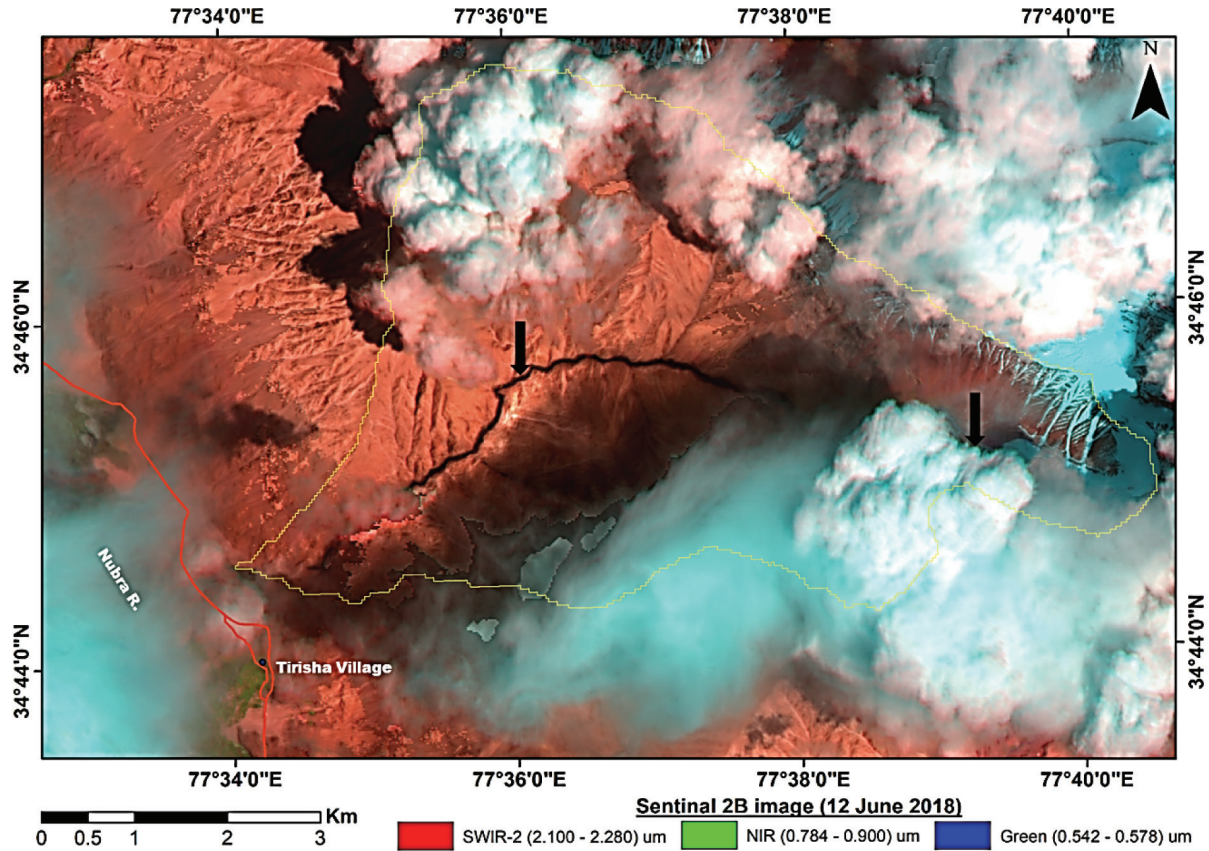


Figure 5: Sentinel-2A imagery of 12 June 2018 showing the cumulonimbus cloud (Cb) producing the cloudburst and floodwater flowing in the stream below at around 1120 hrs in the study catchment near Tirisha village, Nubra valley.

The cloudburst impact zone has a snow washout area of 0.36 km^2 . These images provide irrefutable proof of constrained spatial coverage of some of the cloudburst events in the Himalayas as conceived in our earlier study (Thayyen et al., 2013). We have suggested the possibility of the small impact area of cloudburst (<1.0 to 2.5 km^2) with very high-intensity rainfall in the range of $200 - 320 (\pm 35\%) \text{ mm}$ precipitating during the short time interval of 8 to 12 minutes over the selected study sites during 2010 Leh cloudbursts (Thayyen et al., 2013). The imagery shown here stands testimony to our earlier observation and illustrates the challenges involved in monitoring the cloudburst event in the remote mountainous region. It was observed that there is very little chance of ground-based in-situ rainfall measuring stations to capture the cloudburst events. Instances have also been reported where both satellite observation (TRMM) and dynamical weather models or the ground stations could not capture some of these events as experienced for 23-24 June 2005 event (Dimri et al., 2017). Studies so far focussed on

the mesoscale atmospheric processes linking cloudbursts with moisture inflow from surrounding regions into the Ladakh region (Kumar et al., 2012; Rasmussen and Houze, 2012). While there is no ambiguity of such processes operating in the region, Dimri et al. (2017) suggested that the convective initiation followed by orographic locking is imperative for cloudburst occurrences. Several standalone cloudburst events in the region including the present one strongly suggest that the occurrences of cloudburst independent of large-scale circulation are also possible in the region. Only two cloudburst events in June (23-24 June 2005 and the present one) are reported so far from the region, probably due to the local origin and extremely constrained impact area. It is also pertinent to point out that these events in June are the ones which are not registered by the meteorological satellites and are facing problems with simulation as shown by Dimri et al. (2017). This highlights the challenges faced in improving monitoring and modelling capabilities to identify and study such events.

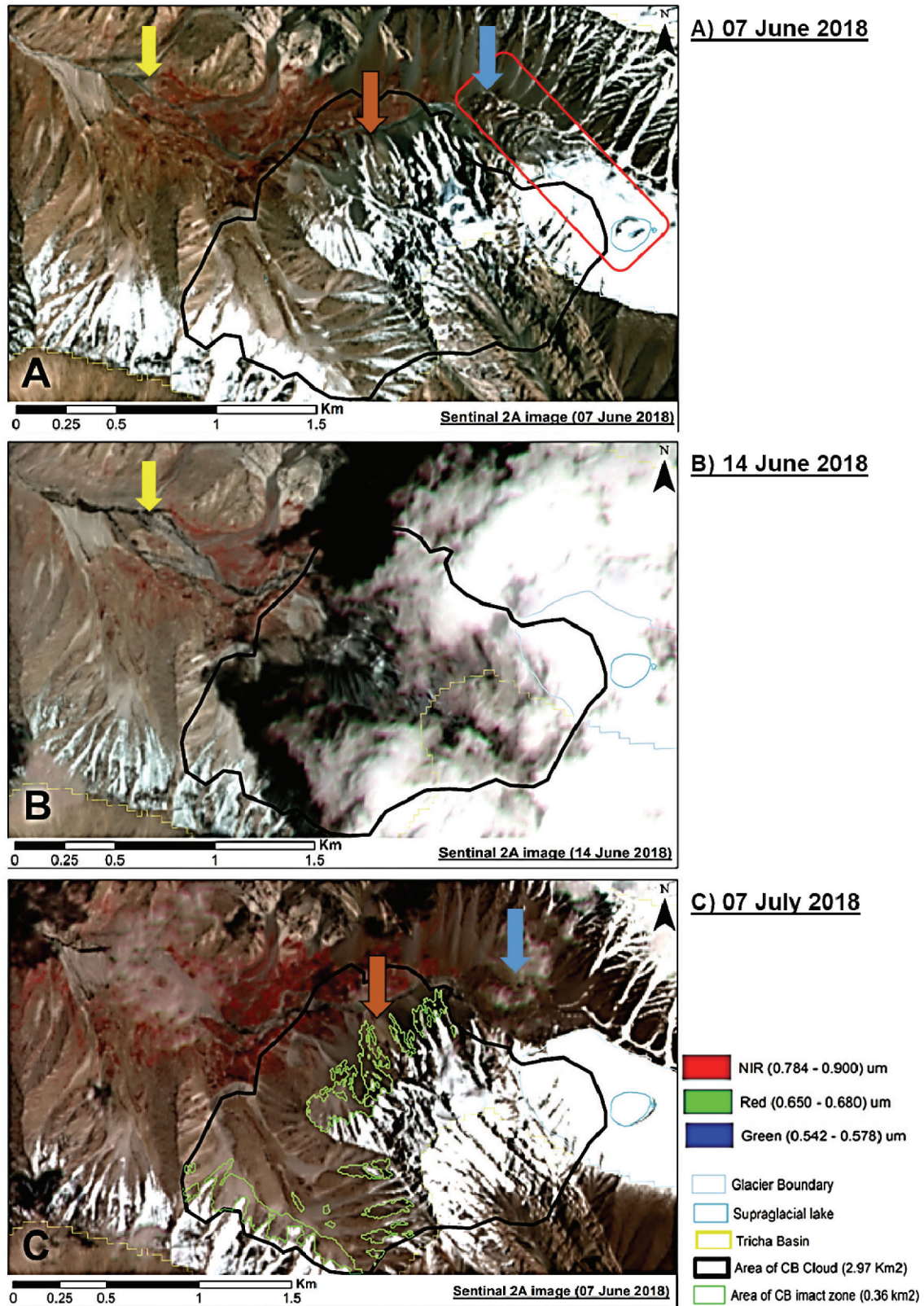


Figure 6: (A) Pre-flood (7 June 2018); (B) post-flood (14 June 2018) and (C) (7 July 2018) images of cloudburst impact zone. The area covered by the Cb cloud is shown by the black line. Morphological changes in the stream (yellow arrow) close to the cloud margin is shown in B. Cb impact area (saffron arrow) is shown by green lines and proglacial stream without any morphological changes is marked by a blue arrow.

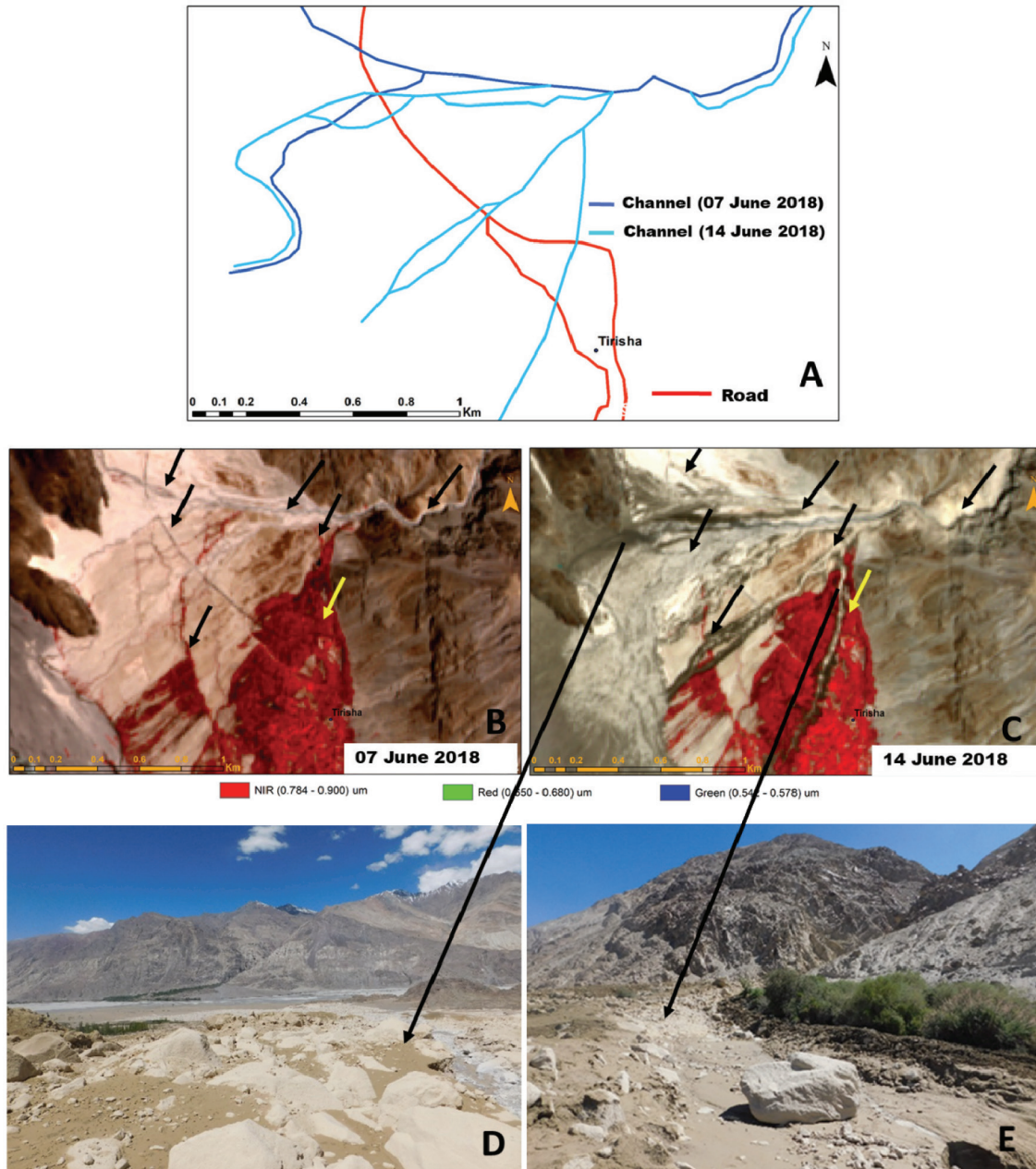


Figure 7: (a) Change in morphometry between pre (07 June 2018) and post-incident (14 June 2018) dates. (b) Pre-flood imagery of 7 June 2018 showing the road and vegetation; (c) Post-flood imagery of 14 June 2018 showing morphological changes caused due to the flood and (d) and (e) are field photographs taken on 13 June 2018.

The present event also suggests a clear danger of cloudburst occurring over the snow and glacier regions, which could exacerbate the flood magnitude. The most recent vivid example of extreme rain on snow event was the Kedarnath event on 16-17 June 2013 in the state of Uttarakhand (Sati and Gahalaut, 2013; Allen et al., 2016), which was further worsened by the bursting of a moraine-dammed lake. The comparison of pre- and post-flood image (Figure 6a, c) shows that the present

event occurred over a snow-covered area very close to the glacier in the catchment. The post-flood image on 7 July 2018 clearly shows the impact zone without snow cover. Cloudbursts on snow certainly could have enhanced the flood severity and resulted in prolonged flow in the stream till 1500 hrs. Fortunately, the event did not happen over the nearby glacier catchment with glacial lakes, which is hardly 200 m away from the current impact site. We could also locate a small

supraglacial lake over the glacier in the catchment, which remained intact after the flood event as there is no change in the channel morphology from glacier snout to 300 m below. (Figure 6a, c). It suggests that the flood has no connection with the glacial system. But the present flood event is strongly indicative of the high probability of cloudburst triggered GLOF in the region. This should be a concern while designing flood estimates for roads, bridges, and culverts in the area. The flood impacted the area near Tirisha village in the foothill and destroyed 100 meters of a crucial stretch of the mountain road. The impact is clearly distinguished by the satellite data of 14 June 2018 (Figure 7c) as compared to the pre-flood image of 7 June 2018 (Figure 7b). Corresponding field photographs are shown in Figure 7d, e. It is also pertinent to note that a similar event reported by local villagers of Murgi village in the same valley in July 2019, which is about 5 km from the current location. This suggests a clear repeated danger for such extreme events in the valley.

Ziegler et al. (2016) explained why “Ladakh is an ideal location where intense rainfall events turn into deadly flash floods and debris flows”. But we believe that Ladakh is an ideal location for cloudbursts in the first place. In Ladakh, the slope environment lapse rate (SELR) (Thayyen and Dimri, 2014) showed a super

adiabatic condition of $> 9.8 \text{ K/km}$ for several days that is from 42 to 70 days. The tenure for this adiabatic condition was seen in March to September (summer seasons) for the years 2011 to 2013 between the valley bottom station (3256 m a.s.l.) and a station located at 4700 m a.s.l. This led to absolute instability for many days followed by conditional instability for most of the summer period (Figure 8). This instability generated due to the local warming of the arid valley bottom is possibly one of the reasons facilitating convective triggering of the cloudbursts in the region. The orographic locking due to local convection is considered as a key feature of cloudburst in the Indian Himalayan Region (Chevuturi et al., 2015; Dimri et al., 2017). In the arid lands of Ladakh, this orographic locking is easily achieved by the prevailing unstable conditions. If the moisture comes in either through mesoscale processes or through local evaporation, the local atmosphere is well prepared for convective triggering to form deadly Cb cells along its mountain ridges. Once the Cb cell is orographically locked, it can't flow in large-scale circulations due to the mountainous terrain. Out of 12 cloudburst events reported from the region since 2005 (Table 2), eight of them occurred in August and two each in June and July, respectively. All these events occurred during summer instability as shown in Figure 8. The events

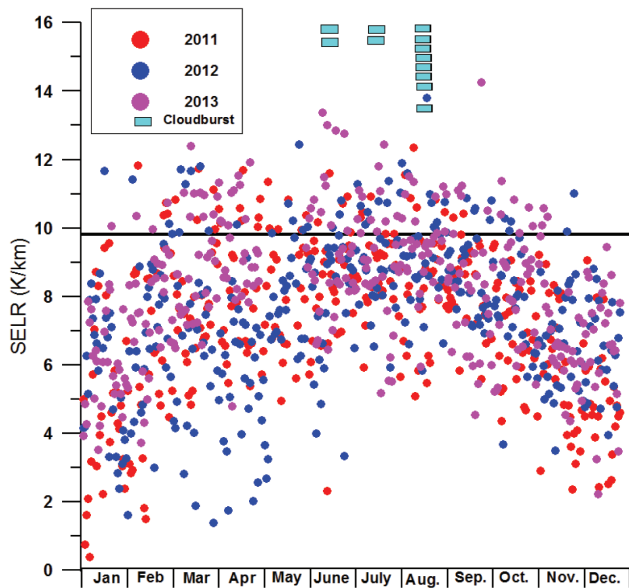


Figure 8: Daily temperature lapse rate of $>9.8^\circ\text{C/km}$ for the Leh region suggests higher atmospheric instability during summer months facilitating the development of local convective trigger facilitating cloudbursts. All of 12 cloudburst record available from 2015 to 10 August 2018 happened during a highly unstable period of June (2), July (2) and August (7) months.

Table 2: Reported cloudburst events in the Ladakh region since 2005

	<i>Cloudburst events</i>	<i>Location of flash flood</i>
1	23-24 June 2005	Leh stream (Ganglass)
2	July 2005	Phyang stream
3	30-31 July 2006	Leh & Igu streams
4	01 Aug. 2006	Phyang streams
5	09 August 2008	Ulle top
6	04-06 August 2010	Sabu and many other streams
7	06 August 2014	Gya village (Cloudburst or GLOF?)
8	04 August 2015	Leh stream
9	August 2015	Before Tirisha, Nubra Valley
10	09 August 2016	Tangtse- Pangong Lake road
11	04 August 2017	Achinathang, Leh-Kargil road
12	12 June 2018	Tirisha Village, Nubra Valley
13	08 August 2018	Sabu and Shey Villages
14	July 2019	Murgi Village, Nubra Valley

occurring in June is particularly interesting, as it is facilitated by local moisture rather than monsoon activity, most probably linked to the snowmelt period. However, further studies need to be done to better understand the phenomena. A common question often asked by the administrators, media and public to the researchers working in the field is about the perceived increase in the incidents of cloudburst events in the region. However, in the absence of a robust monitoring programme, this question remains unanswered so far. An increase in extreme events is identified as one of the key indicators of climate change. Hence, it is high time that appropriate instrumentation is put in place to monitor all such events. This will not only help for enhancing our knowledge about the processes leading to such events but also help building effective adaptive strategies to reduce the risk and vulnerability of the mountain people.

Conclusions

This study presents a rare satellite image of a cloudburst at the time of its occurrence with cumulonimbus cloud (Cb) and floodwater in a stream in the Nubra valley of Ladakh. The imagery provides first visual evidence of spatially constrained Cb cloud covering a limited area of 2.97 km² and corresponding cloudburst impact zone of <1km² area. The study highlights the challenges involved in monitoring such high-intensity events in the remote mountain areas. It is suggested that warming of arid valley bottom in summer months produces absolute instability conditions in the region for more than 40 days in a year with a SELR >9.8 K/km leading to aggressive convective activity, which could increase the chance of cloudburst occurrence in the region. There are limitations in the existing observation and modelling tools to capture such standalone events and possible implications of such extreme events for the local people and downstream infrastructure in a transboundary basin, hence, research should emphasise on the need of robust monitoring systems for the region.

Acknowledgement

The authors thank Dr. Sharad K Jain, Director, NIH and Dr. Sanjay K. Jain, Head, WRS division for their constant encouragement and support. Financial support from Ministry of Environment, Forest and Climate Change (MoEF & CC), under National Mission on Himalayan Studies (NMHS/LG-2016/006/8511-6) and Council of Scientific and Industrial Research (CSIR) (No. 23/0031/16 EMR-II) is duly acknowledged.

References

- Allen, S.K., Rastner, P., Arora, M., Huggel, C. and Stoffel, M., 2016. Lake outburst and debris flow disaster at Kedarnath, June 2013: Hydrometeorological triggering and topographic predisposition; *Landslides*, **13**(6): 1479-1491. <https://doi.org/10.1007/s10346-015-0584-3>
- Ashrit, R., 2010. Investigating the Leh 'cloudburst'. National Centre for Medium Range Weather Forecasting, Ministry of Earth Sciences, India. https://www.ncmrwf.gov.in/Cloudburst_Investigation_Report.pdf
- Chevuturi, A., Dimri, A.P., Das, S., Kumar, A. and Niyogi, D., 2015. Numerical simulation of an intense precipitation event over Rudraprayag in the central Himalayas during 13–14 September 2012. *The Journal of Earth System Science*, **124** (7): 1545-1561. <https://doi.org/10.1007/s12040-015-0622-5>
- Das, S., Ashrit, R. and Moncrieff, M.W., 2006. Simulation of a Himalayan cloudburst event. *The Journal of Earth System and Science*, **115**(3): 299-313. <https://doi.org/10.1007/BF02702044>
- Dimri, A.P., Chevuturi, A., Niyogi, D., Thayyen, R.J., Ray, K., Tripathi, S.N., Pandey, A.K. and Mohanty, U.C., 2017. Cloudbursts in Indian Himalayas: A review. *Earth-Science Reviews*, **168**: 1-23. <https://doi.org/10.1016/j.earscirev.2017.03.006>
- Dimri, A.P., Thayyen, R.J., Kibler, K., Stanton, A., Jain, S.K., Tullos, D. and Singh, V.P., 2016. A review of atmospheric and land surface processes with emphasis on flood generation in the Southern Himalayan rivers. *Science of the Total Environment*, **556**: 98-115. <https://doi.org/10.1016/j.scitotenv.2016.02.206>
- Gangkofner, U.G., Pradhan, P.S. and Holcomb, D.W., 2007. Optimizing the high-pass filter addition technique for image fusion. *Photogrammetric Engineering and Remote Sensing*, **73**(9): 1107-1118. <https://doi.org/10.14358/PERS.73.9.1107>
- Hobley, D.E., Sinclair, H.D. and Mudd, S.M., 2012. Reconstruction of a major storm event from its geomorphic signature: The Ladakh floods, 6 August 2010. *Geology*, **40**(6): 483-486. <https://doi.org/10.1130/G32935.1>
- Kumar, M.S., Shekhar, M.S., Krishna, S.R., Bhutiyan, M.R. and Ganju, A., 2012. Numerical simulation of cloud burst event on August 05, 2010, over Leh using WRF mesoscale model. *Natural Hazards*, **62**(3): 1261-1271. <https://doi.org/10.1007/s11069-012-0145-1>
- Rasmussen, K.L. and Houze, Jr., R.A., 2012. A flash-flooding storm at the steep edge of high terrain: Disaster in the Himalayas. *Bulletin of the American Meteorological Society*, **93**(11): 1713-1724. <https://doi.org/10.1175/BAMS-D-11-00236.1>
- Sati, S.P. and Gahalaut, V.K., 2013. The fury of the floods in the north-west Himalayan region: The Kedarnath tragedy. *Geomatics, Natural Hazards and Risk*, **4**(3): 193-201. <https://doi.org/10.1080/19475705.2013.827135>

- Thayyen, R.J. and Dimri, A.P., 2014. Factors controlling slope environmental lapse rate (SELR) of temperature in the monsoon and cold-arid glacio-hydrological regimes of the Himalaya;. *Cryosphere Discussion*, **8(6)**: 5645-5686. <https://doi.org/10.5194/tcd-8-5645-2014>
- Thayyen, R.J., Dimri, A.P., Kumar, P. and Agnihotri, G., 2013. Study of cloudburst and flash floods around Leh, India, during August 4–6, 2010. *Natural Hazards*, **65(3)**: 2175-2204. <https://doi.org/10.1007/s11069-012-0464-2>
- Zhang, T., Su, J., Liu, C., Chen, W.H., Liu, H. and Liu, G., 2017. Band selection in Sentinel-2 satellite for agriculture applications. *In*: 23rd International Conference on 'Automation and Computing (ICAC)'. Huddersfield, United Kingdom.. IEEE. <https://doi.org/10.23919/IconAC.2017.8081990>
- Ziegler, A.D., Cantarero, S.I., Wasson, R.J., Srivastava, P., Spalzin, S., Chow, W.T. and Gillen, J. 2016. A clear and present danger: Ladakh's increasing vulnerability to flash floods and debris flows. *Hydrological Processes*, **30(22)**: 4214-4223. <https://doi.org/10.1002/hyp.10919>