

Analysis of Recent Cloudburst Events in Himachal Pradesh

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KEYWORDS

ABSTRACT

Cloudburst,
Optical Datasets,
Cloud Pattern,
Meteorological
Parameters

The recent cloudbursts in hilly terrain of himalayan region is challenging task as they pose significant threat to inhabitant lives and causes serious destruction of property. This study deeply focuses on various meteorological and geographical parameters. This research will include historical weather data ,temperature ,humidity, cloud pattern, topographical features, and satellite imagery to create a comprehensive datasets. The study will focus on several cloudbursts and finding common parameters for analyses. On completion of this research we will be able study about the various aspects of recent cloudbursts events and by the use of result we will able assess the situation during cloudbursts. A brief overview of overall thesis is discussed in below lines as total cloudburst and landslide of 170 incident cumulatively took place across Himachal Pradesh since monsoon hit on 24th June 2023. But as of records major 25 cloudburst list in inventory and out of 25 only 7 were taken to study and analyse their deep effect over the state. Optical data taken various websites were collected to observe the change.

1. INTRODUCTION

In recent decades, instances of 'cloudburst' occurrences have become increasingly regular in and around the southern rim of the Indian Himalayas. Many of these incidents are due to unforeseen high rains[1]. The rough and unstable topography of the Himalayas provides an excellent setting for such cloudburst events to result in flash floods or landslides[1]. Anticipating the location, intensity, and scale of these catastrophic occurrences beforehand remains a major challenge[1]. Modelling initiatives have revealed insights into cloudburst events and their dynamic interplay with the region's terrain[1].

Most of these events in mountainous regions are associated with cumulonimbus or thunder clouds[1]. In a very short time span over a localized area, heavy downpour ranging from 200 to 1000 mm/h occurs in these events[2]. Corresponding droplet size ranges from approximately 4–6 mm with a fall speed of around 10 m/s[3]. Cloud bursts, characterized by intense, concentrated rainfall over a narrow area for a short duration, offer substantial threats such as flash floods, landslides, and infrastructure damage, particularly in hilly regions like Himachal Pradesh (HP) during the southwest monsoon season[1], [4]. While the precise causes of cloud burst creation are not entirely known, scientific literature suggests they emerge from powerful vortices generating convective currents, leading to the fast development of cumulonimbus clouds [1], [4]. The orographic features of HP contribute to the vertical uplift necessary for these clouds to form.

Despite their catastrophic potential, predicting cloud bursts remains problematic due to their tiny scale and the cost of building precision radar networks. However, identifying places and meteorological conditions susceptible to cloud burst development is crucial for reducing damage and loss of life[1]. Historical data, especially reported landslides in HP, provide vital insights into hazardous places. Factors such as steep topography, climatic patterns, geology, and hydrology play key roles in determining vulnerability to cloudbursts[1]. Leveraging remote sensing and GIS technologies can aid in mapping high-risk areas and guiding disaster preparedness and mitigation measures to lessen the repercussions of future catastrophes[1].

The primary goal of this study is to give a general overview of the Topology (located in Himachal Pradesh) and to do Cloudburst events prioritization of the Himachal region, as well as to evaluate the different meteorological parameters to determine characteristics using ARCGIS tools.

The specific objectives are:

- To prepare the inventory of all the cloudburst events that have taken place over Himachal region and select the events on which analysis can proceed.
- To study the following meteorological parameters and analyse the Precipitation Index, Elevation Profile, and Cloud Water Content and Cloud Top temperature.

2. STUDY AREA

Himachal Pradesh, nestled in the western Himalayas of India, is a state renowned for its stunning landscapes, rich cultural heritage, and unique biodiversity. Spread over approximately 55,673 square kilometres, Himachal Pradesh encompasses a diverse range of topographical features, from snow-capped peaks to lush valleys and deep gorges. Himachal Pradesh is characterized by its diverse topography, which includes high-altitude mountain ranges, such as the Great Himalayas and the Pir Panjal, as well as lower foothills and valleys. The state's elevation ranges from around 350 meters above sea level in the foothills to over 6,000 meters in the Himalayan ranges[1]. Himachal Pradesh is crisscrossed by several major rivers, including the Satluj, Beas, Ravi, Chenab, and Yamuna, which originate from the Himalayas and flow through the state's valleys. These rivers not only provide water for irrigation and hydroelectric power generation but also shape the region's landscape through erosion and sedimentation processes. The climate of Himachal Pradesh varies from subtropical in the southern lowlands to alpine in the higher elevations. The state experiences four distinct seasons: summer, monsoon, autumn, and winter. While summers are generally mild and pleasant, with temperatures ranging from 15°C to 30°C, winters can be cold and snowy, especially in the higher reaches[5]. In Himachal Pradesh, major districts: Kullu, Mandi, Shimla, Sirmour and Chamba. Lahaul and Spiti is the largest district in Himachal Pradesh, making up roughly 22% of the state's total area. Chamba is next, making up about 15% of the total landmass, and is distinguished by its varied topography and rich cultural legacy. Kinnaur, which makes up about 12% of the state, is known for its breathtaking scenery and distinctive customs. As we move down the list, Sirmour, Kangra, and Shimla all make major contributions to the state's allure thanks to their unique qualities. Mandi and Kullu have comparable sizes, which reflects their significance as commercial and tourist hubs. Even though they are smaller, Bilaspur, Hamirpur, Una, and Solan are nevertheless vital to the growth and cultural fabric of Himachal Pradesh[6].

2.1 Cloudburst Inventory Of The Study Areas Event Occurred During 2023

Total 170 incidents have been recorded out of which 15 were found through online sources and only 7 were used in study area as rest of events data is missing.

DATE	LOCALITY	DISTRICT & LAT/LON	SOURCE	DAMAGES
25-06-23	Rampur	Shimla & (31.45,77.63 0)	https://www.tribuneindia.com/news/	A school, Five houses and Agricultural land
10-07-23	Thunag Area	Mandi & (31.552,77.1 65)	https://www.india.com/news/	14 lives lost, Roads filled with debris and mud
17-07-23	Kais Village	Kullu & (31.957,77.1 09)	https://timesofindia.indiatimes.com/city	1 dead,3 injured, and 9 vehicles damaged
20-07-23	Salooni Sub-division	Chamba & (32.752,75.9 8)	https://timesofindia.indiatimes.com/city/	8 pucca houses, 11 kutcha houses, 4 shops and 16 cowsheds were damaged
22-07-23	Rohru Village	Shimla & (31.197,77.6 57)	https://www.outlookindia.com/national	2 people died and 1 missing during Cloudburst in Shimla
26-07-23	Bharmour Town	Chamba & (32.441,76.5 35)	https://www.hindustantimes.com/	1 person lost his life
14-08-23	Kandaiwala Village (Nahan)	Sirmaur & (30.575,77.2 2)	https://www.livemint.com/news/	1 cowshed along with 3 cattles washed away

Table 2.1 Showing Cloudburst Inventory Of Study Areas

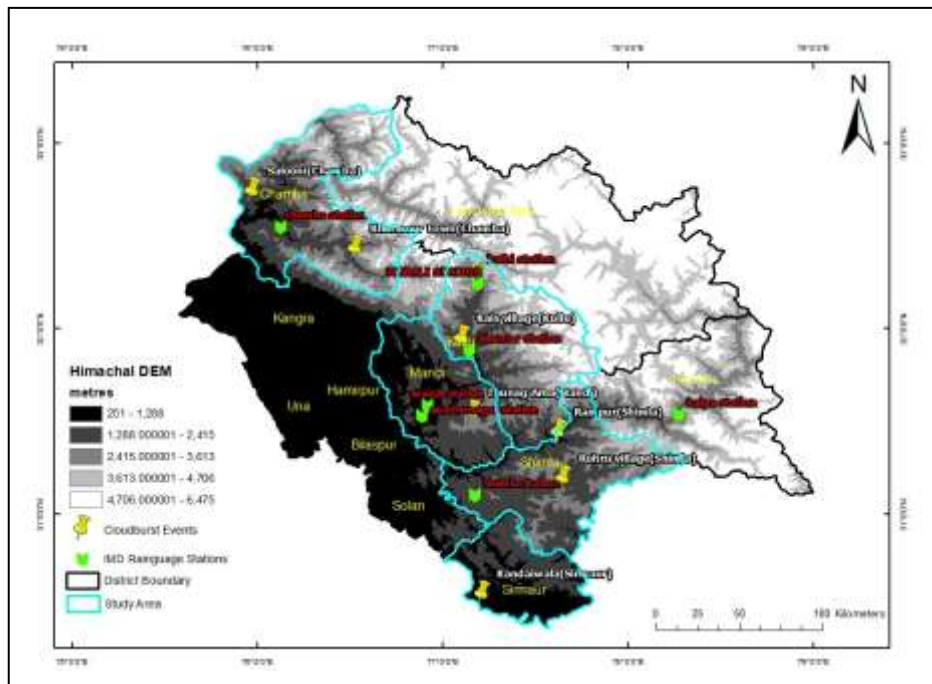


Figure 2.1 Study Area of Himachal Pradesh

3. MATERIAL AND METHODS

In this study the work done is divided into two parts. In the first part of the analysis, two parameters elevation & precipitation and the next two parameters include cloud top temperature & cloud water content.

3.1 Evaluation of Meteorological parameters

These are the necessary steps for estimating meteorological parameters depending on the requirements. Raw optical images obtained from United States Geological Survey website. In ArcGIS, WGS 1984 > UTM 45 zone was applied to all coordinate systems in order to standardize them. The flow chart as shown below depicts the basic steps used to carry out the current study for both parts discussed above. The methodology used below in flowchart format is described as raw data downloaded from USGS website as an optical image from level-2 and collection-2 Landsat 8/9 image from which precipitation data is extracted.

Elevation, Cloud water content and Cloud top temperature parameters are downloaded from other datasets and raw data is downloaded in .tiff and NetCDF format then they are converted to graphical as well as .CSV format. This data is processed using ARCMAP software. Then after this data is processed result are represented in graph form using OriginPro software.

3.2 Data Collection

The necessary data were gathered from various sources in order to conduct the present study. Satellite imagery data (SRTM DEM) is considered in the evaluation of morphometric parameters.

In this study, data from satellite imagery (SRTM DEM) with a spatial resolution of 30 meters was utilized, and it was obtained from the US Geological Survey (USGS). All the above data was analyzed by employing the Arc Hydro tool and the spatial Analyst tool from the ArcGIS.

3.3 Meteorological Parameters

There are 4 parameters on which analyses of cloudburst events based on-

- **ELEVATION** - The Digital Elevation Model (DEM) Map is very helpful in finding out the elevation of the study area. It plays a very deciding role in intensity of cloudburst events. Generally during traditional times the cloudburst occur at elevation of 1000-1500 m but now in recent events cloudburst are occurring at elevation below 500 m[1].
- **PRECIPITATION(PPT)** - Gridded rainfall data from various datasets are very resourceful in early progress of this research study. Datasets like- GPM, TRMM, CHIRPS AND CHRS PORTAL where very helpful in collecting precipitation data for the study. [7], [8], [9]
- **CLOUD TOP TEMPERATURE(CTT)** - Cloud top temperature is a crucial parameter for understanding the vertical structure and thermodynamic properties of clouds, serving as a proxy for cloud height and intensity[10].
- **CLOUD WATER CONTENT(CWC)** - Cloud water content, a remote-sensing data product derived from measurements of clouds optical thickness and cloud particle radius collected by the Moderate resolution Imaging Spectroradiometer (MODIS) instrument aboard NASA's Terra and Aqua satellites[11].

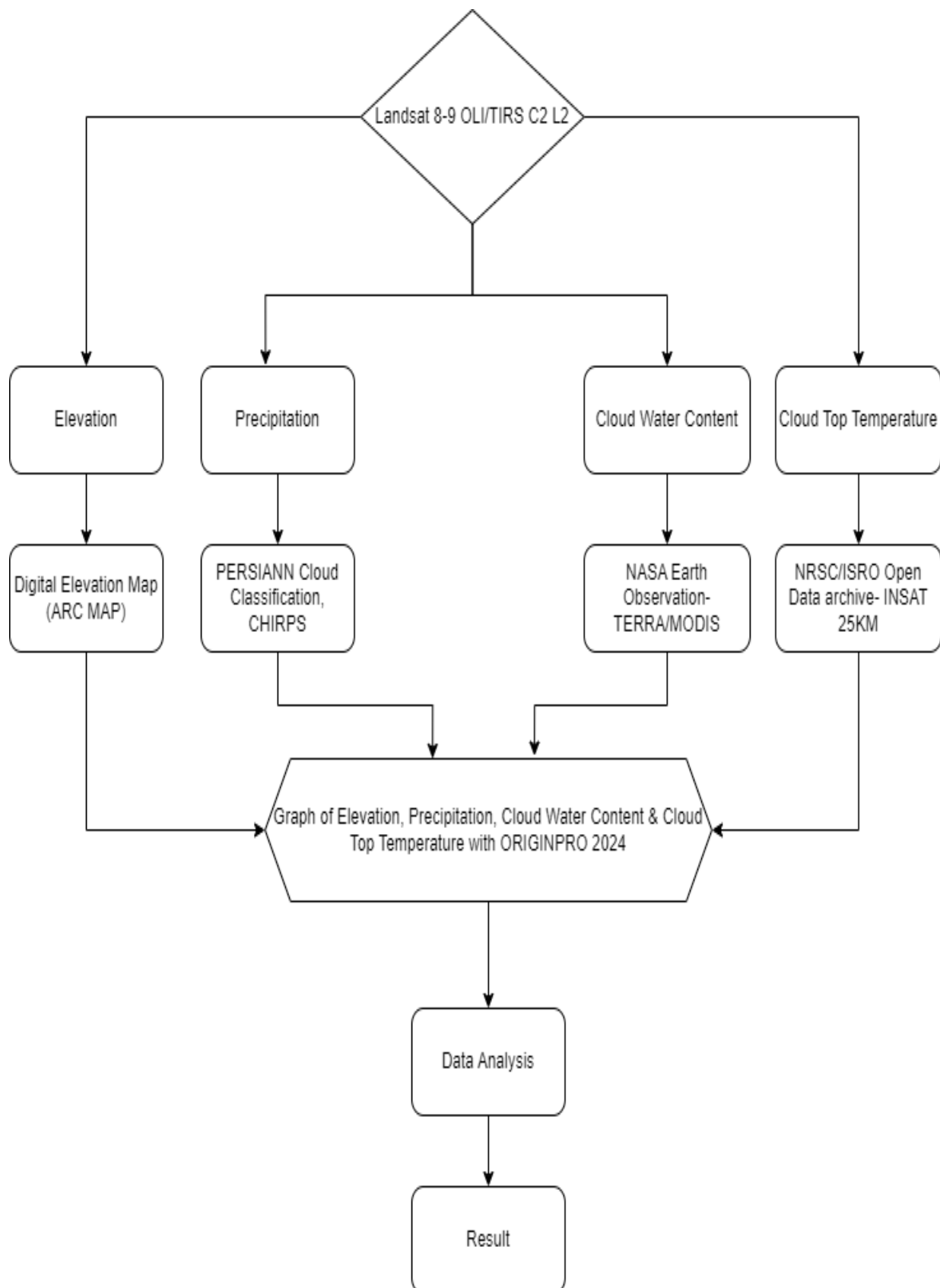
3.4 Observational Datasets Used

Local cloudburst events information is collected from various printed blogs and media reports in newspaper articles and events time and exact location is still not truly confirmed because sources can't be verified. The station gauges are sparse and lack of data on the day of events is sore truth, so various global observational datasets are used in this study. The observational datasets include:

1. Climate Hazards Group Infrared Precipitation with Station data (CHIRPS) is a 30+ year quasi-global rainfall dataset. CHIRPS incorporates 0.05° resolution satellite imagery with in-situ station data to create gridded rainfall time series for trend analysis and seasonal drought monitoring[8]. The data is available from 1981 to onwards.
2. PERSIANN-Cloud Classification System (PERSIANN-CCS) is a real-time global high resolution (0.04° x 0.04° or 4km x 4km;) satellite precipitation product developed by the Center for Hydrometeorology and Remote Sensing (CHRS) at the University of California, Irvine (UCI). PERSIANN-CCS system enables the categorization of cloud-patch features based on cloud height, areal extent, and variability of texture estimated from satellite imagery[7].
3. ERA 5 land dataset provides data in gridded form with global coverage and projection is regular latitude-longitude grid. The resolution is 0.1° x 0.1° and native resolution is about 9km. The temporal coverage is from 1950 to onwards. The temporal and spatial resolutions of ERA5-Land makes this dataset very useful for all kind of land surface applications such as flood or drought forecasting[12].
4. Clouds with comparatively low water content—100 grammes per square metre or less—are particularly significant in terms of climate. This group includes stratus, cumulus, and mixed-phase clouds, among other cloud types. Only roughly 3% of Earth is covered by deep convective clouds, despite the fact that clouds cover nearly 69% of the planet at any given time. Thus, low-water-content clouds dominate in terms of extent. Because lower atmosphere clouds are usually warmer, they are primarily made of liquid water droplets. These clouds of low- and mid-level liquid water cover roughly 47% of the planet and have a density of 51–60 grammes per square metre. Furthermore, about 80% of the Arctic's liquid

droplet clouds are below the 100 grams per square meter threshold. Thus, these maps provide an excellent basis for quantifying the roles of clouds in Earth's energy budget on a global scale[11].

5. Hourly observation precipitation records are taken from Self Recording Rain Gauge (SRRG) stations of IMD, India.
6. The Global Climate Observing System (GCOS) has classified cloud top temperature (CTT) as an Essential Climate Variable (ECV). For studies on climate change, precise data on CTT and its temporal and spatial variations is crucial. The Indian national geostationary satellite, INSAT-3D, offers a rare chance to continuously observe at 4 km spatial resolution and 30 min temporal resolution over the Indian subcontinent and surrounding areas. Studies on the evolution and variation of clouds and their properties frequently make use of the datasets from the INSAT satellite series[10].
7. The Integrated Multi-satellite Retrievals for GPM (IMERG) IMERG is a NASA product estimating global surface precipitation rates at a high resolution of 0.1° every half-hour beginning 2000[13]. It is part of the joint NASA-JAXA Global Precipitation Measurement (GPM) mission, using the GPM Core Observatory satellite as the standard to combine precipitation observations from an international constellation of satellites using advanced techniques. Merged satellite-gauge precipitation estimate - Final Run (recommended for general use) (GPM_3IMERGM v07)[9].

**Figure 3.1 Process Flowchart for Methodology**

4. RESULT AND CALCULATION

4.1 Study Area's Elevation Analysis

- Rampur(Shimla) - Bushahar's winter capital was Rampur, a small township on the left bank of the Sutlej, at an elevation of 1,005 meters. The coordinates of Rampur are 31.45°N 77.63°E. It is located at an average elevation of 4429 feet, or 1021 metres. The elevation profile is done using ARCGIS software, first SRTM DEM(.tiff) tile downloaded from USGS site using SHAPEFILE which is developed by GOOGLE EARTH PRO by marking polygons of the area. In next step, this .tiff file masked out from the SHAPEFILE of the study area.
- Thunag(Mandi) - The village of Thunag is situated in the Mandi district's Thunag tehsil in Himachal Pradesh, India. It is located 75 kilometers from Thunag, the district headquarters. The village of Thunag is home to the subdistrict headquarters. The village's entire land area is 97.65 hectares.
- Kais Village(Kullu) - In the Indian state of Himachal Pradesh, Kais village is situated in the Kullu district's Kullu tehsil. It is located 7 kilometers from Kullu, which serves as Kais Village's district and subdistrict headquarters.
- Salooni Sub-Division(Chamba) - Salooni is the sub-division and tehsil headquarters in the Indian state of Himachal Pradesh's Chamba district. Salooni, 56 kilometers from Chamba and at an elevation of 1829 meters.
- Rohru Village(Shimla) - Himachal Pradesh, an Indian state, has the town and municipal committee of Rohru located in the Shimla district. Situated on the Pabbar River's banks, it is roughly 115 km away from Shimla. At 31.202°N 77.7519°E is Rohru. The average elevation is 5,003 feet, or 1,525 meters.
- Bharmour Town(Chamba) - Bharmour is small town located in south-east with distance of 64km from district HQ. The altitude of bharmour town is about 2100 metres.
- Kandaiwala Village(Sirmaur) - The village of Kandaiwala Dakra is situated in the Nahan tehsil of the Sirmaur district in the Indian state of Himachal Pradesh. It is located 18 kilometers from Nahan, which serves as Kandaiwala Dakra village's district and subdistrict headquarters.

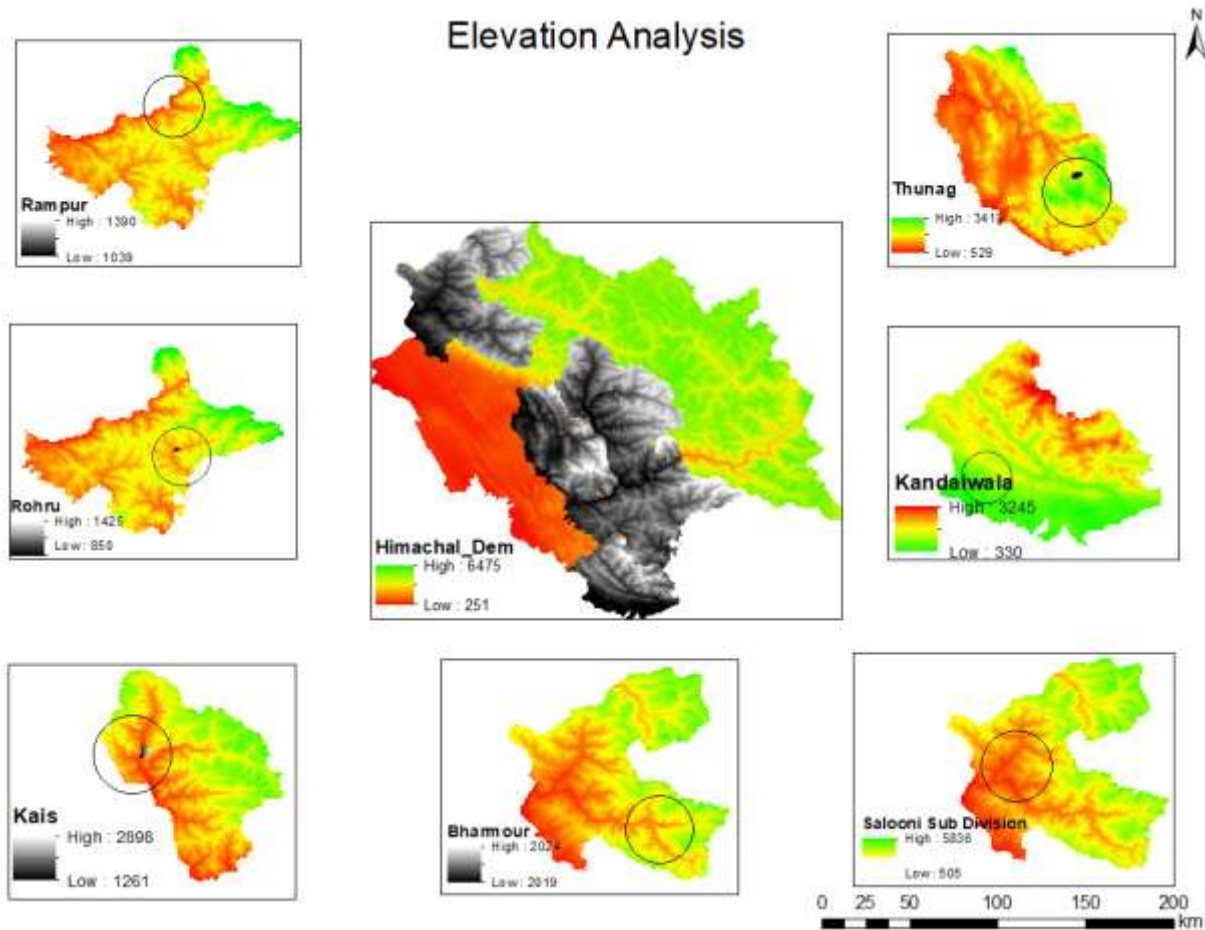


Figure 4.1 Elevation Analysis of the study area

4.2 Study Area's Precipitation Analysis

- Rampur(Shimla) - Precipitation analysis is done ARCGIS software using optical data various datasets. Two dates are taken-
 Cloudburst Day Date(25/06/2023) – Precipitation ranges between 75-105 mm.
 Before Cloudburst(17/06/2023) – Precipitation ranges between 15-30 mm.
 From the figure shown below clearly represents the above data as described above. The process of precipitation involves the file received from datasets in NetCDF format which is converted to raster format using ARCMAP software.
- Thunag(Mandi) – Cloudburst Day Date(10/07/2023) - Precipitation ranges between 105-150 mm.
 After Cloudburst Day Date(11/07/2023) - Precipitation ranges between 30-45 mm.
- Kais Village(Kullu) – Before Cloudburst Day Date(11/07/2023) - Precipitation ranges between 105-150 mm.
 After Cloudburst Day Date(19/07/2023) - Precipitation ranges between 45-60 mm.

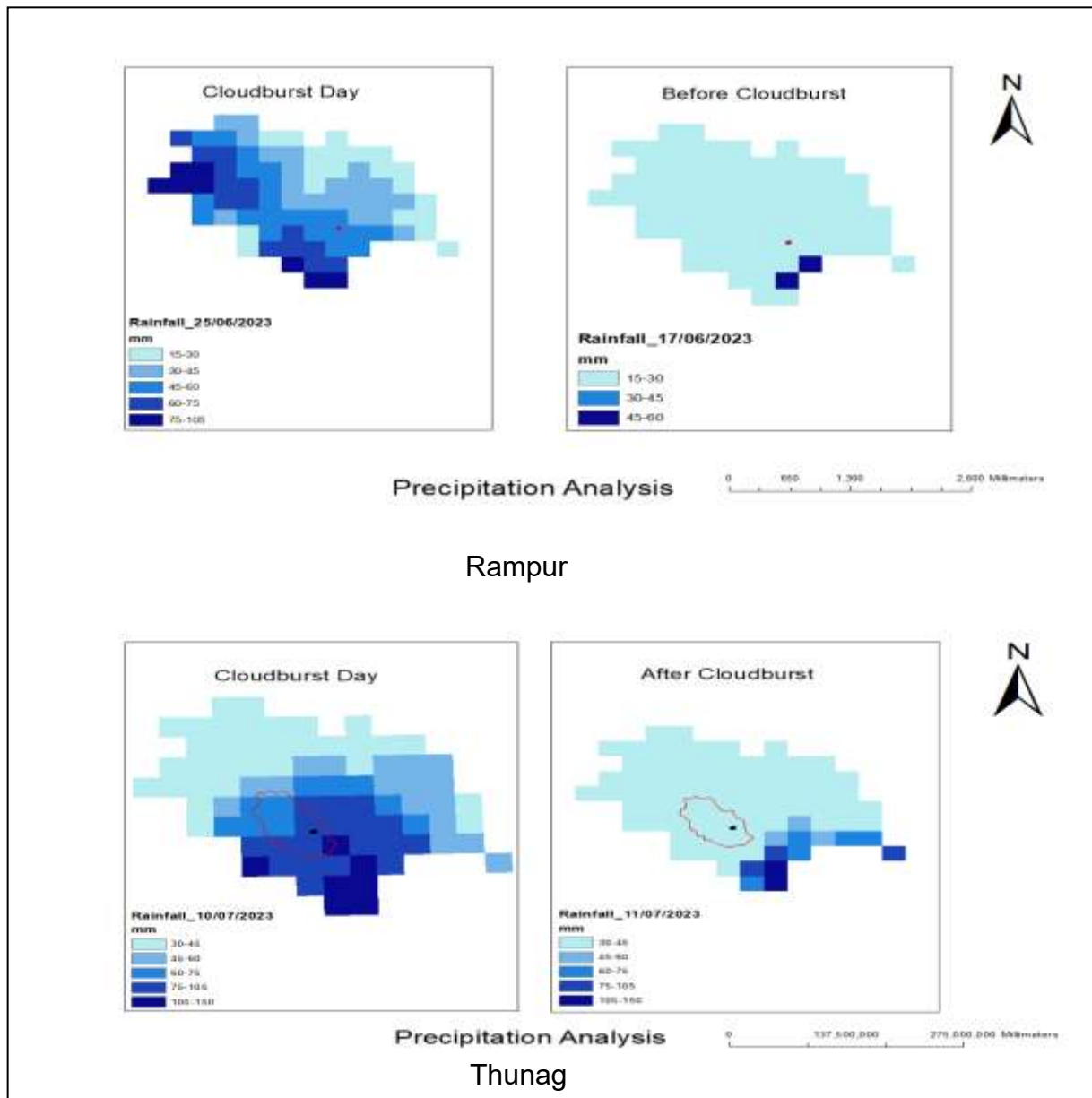


Figure 4.2 Precipitation Analysis of Rampur(Shimla) & Thunag(Mandi)

➤ Salooni Sub-Division(Chamba) – Before Cloudburst Day Date(19/07/2023) - Precipitation ranges between 75-105 mm.

After Cloudburst Day Date(22/07/2023) - Precipitation ranges between 45-60 mm.

➤ Rohru Village(Shimla) – Before Cloudburst Day Date(11/07/2023) - Precipitation ranges between 75-105 mm.

After Cloudburst Day Date(28/07/2023) - Precipitation ranges between 45-60 mm.

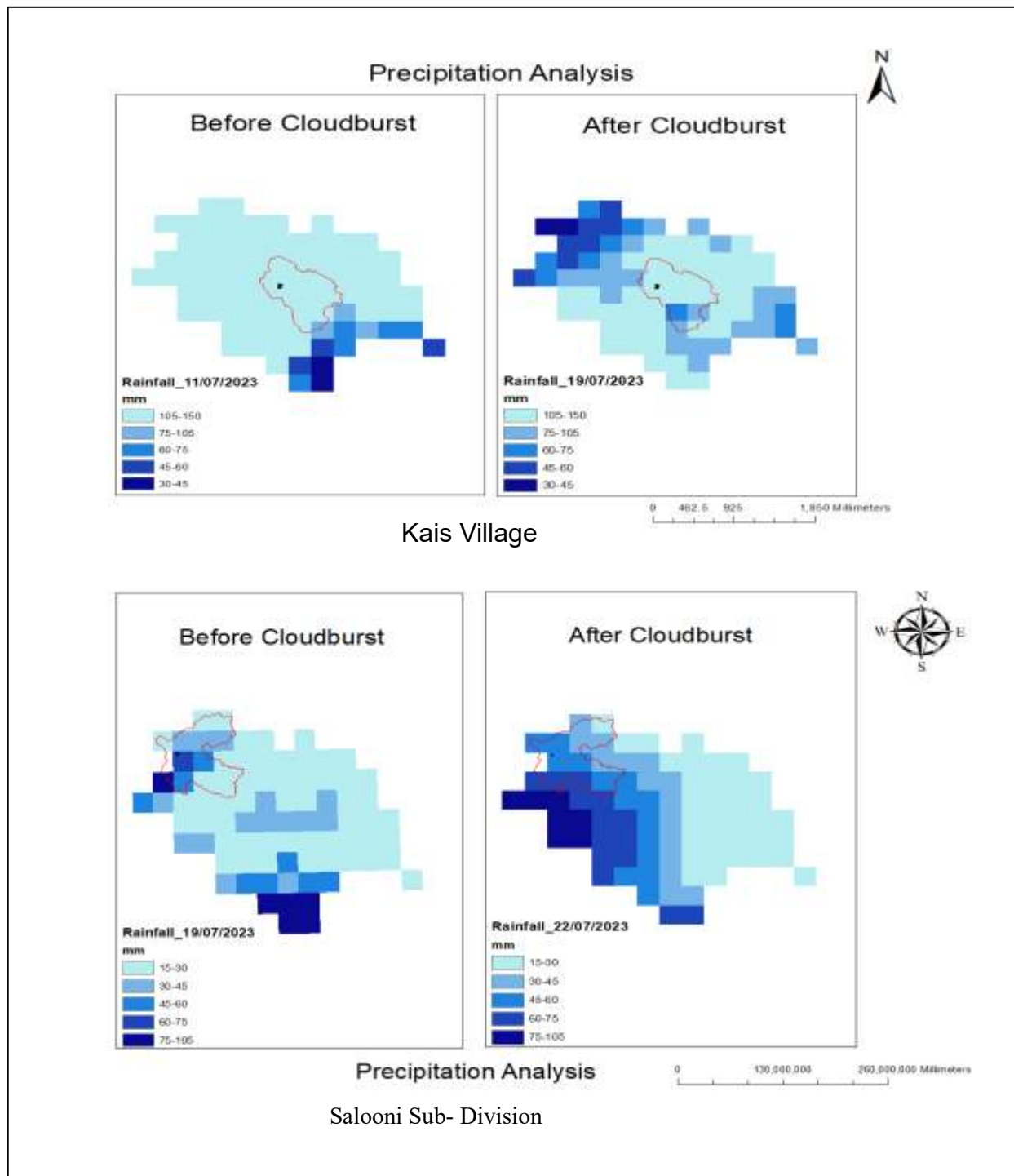


Figure 4.3 Precipitation Analysis of Kais(Kullu) & Salooni(Chamba)

➤ Bharmour Town(Chamba) – Before Cloudburst Day Date(11/07/2023) - Precipitation ranges between 75-105 mm.

After Cloudburst Day Date(11/07/2023) - Precipitation ranges between 75-105 mm.

➤ Kandaiwala Village(Sirmaur) - Before Cloudburst Day Date(11/07/2023) - Precipitation ranges between 105-150 mm.

After Cloudburst Day Date(11/07/2023) - Precipitation ranges between 30-45 mm.

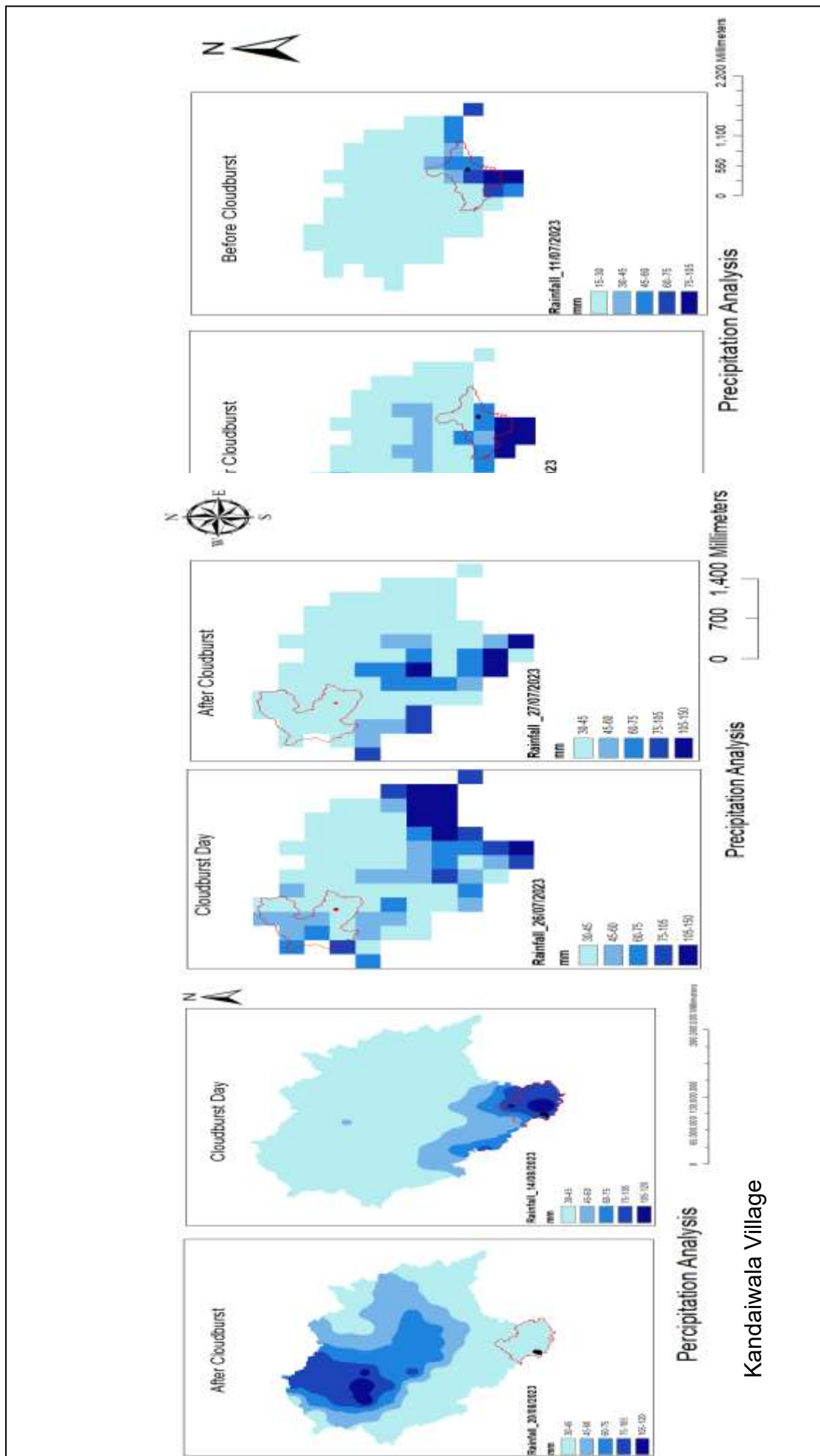


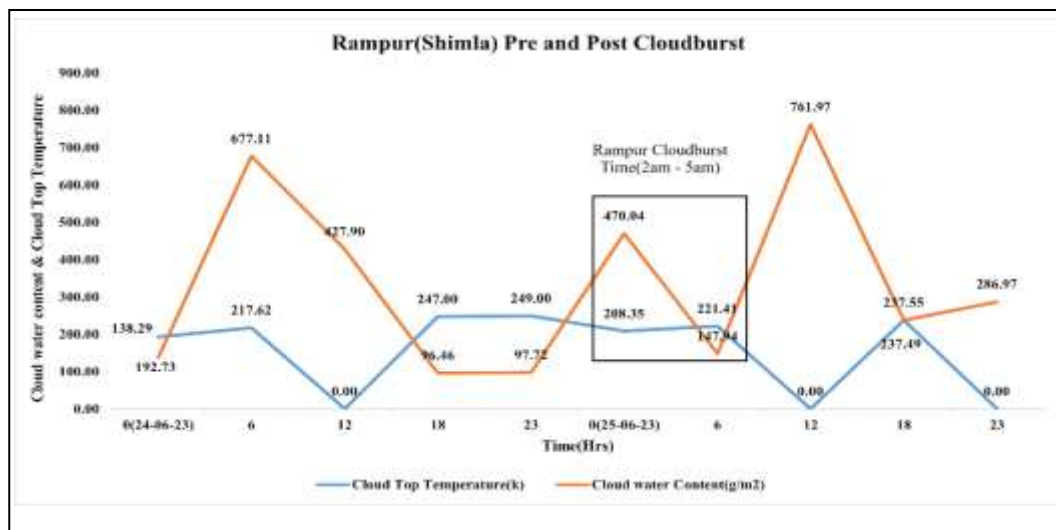
Figure 4.4 Precipitation Analysis of Rohru(Shimla), Bharmour(Chamba) & Kandaiwala(Sirmaur)

4.3 Study Area's Cloud Water Content & Cloud Top Temperature Analysis

1. **Cloud Water Content(CWC)** - Cloudburst events' frequency and intensity are significantly influenced by the water content of the clouds. It represents the amount of water vapour that clouds condense into liquid, which has a direct impact on precipitation formation. Cloudbursts release substantial amounts of precipitation quickly and are marked by brief but intense downpours. They are caused by clouds that contain more water than usual. Variations in cloud water content are driven by atmospheric dynamics, such as temperature and humidity, and are amplified by topographical features, such as mountains, which promote the formation of cloudbursts. Because of the increased water content, drainage systems are overloaded, and slopes become unstable, making hazards like flash floods and landslides worse. Forecasting, impact mitigation, and improving resilience to cloudbursts all depend on an understanding of the dynamics of cloud water content[11].

2. **Cloud Top Temperature(CTT)** - Cloud top temperature is a crucial factor in understanding cloudburst events because it provides information about the intensity and characteristics of convective cloud systems, which frequently produce heavy rainfall. Cloudbursts are caused by these convective clouds, which are usually cumulonimbus clouds because of their strong updrafts and quick development. The strength and vertical extent of convective activity can be determined by measuring the temperature at the top of the clouds. Higher cloud tops and more vigorous convection are indicators of warmer cloud top temperatures, which raises the possibility of heavy precipitation. On the other hand, lower cloud top temperatures indicate more vertical development and instability, both of which can result in heavy precipitation events. Through monitoring variations in cloud top temperatures, meteorologists are able to predict when cloudbursts will occur and can promptly warn people to reduce the risk and minimize impacts. Additionally, cloud top temperature data is integrated into weather forecasting models to improve the accuracy of cloudburst predictions, aiding in disaster preparedness and response efforts[10].

Figure 4.5 Graph between CWC & CTT Vs Time of Rampur Pre & Post Cloudburst(6hrs interval)



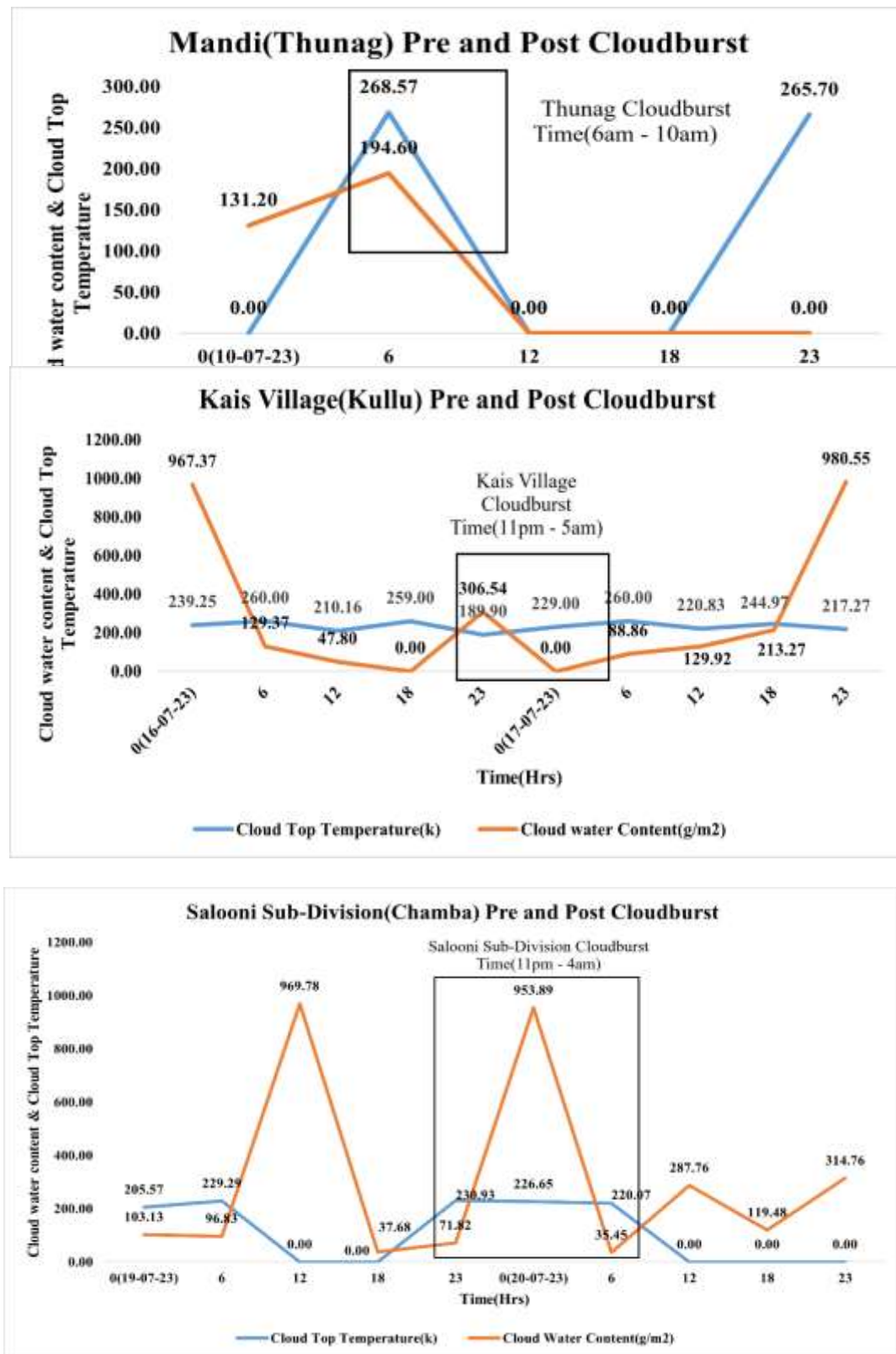


Figure 4.6 Graph between CWC & CTTVs Time of Thunag, Kais & Salooni Pre & Post Cloudburst(6hrs interval)

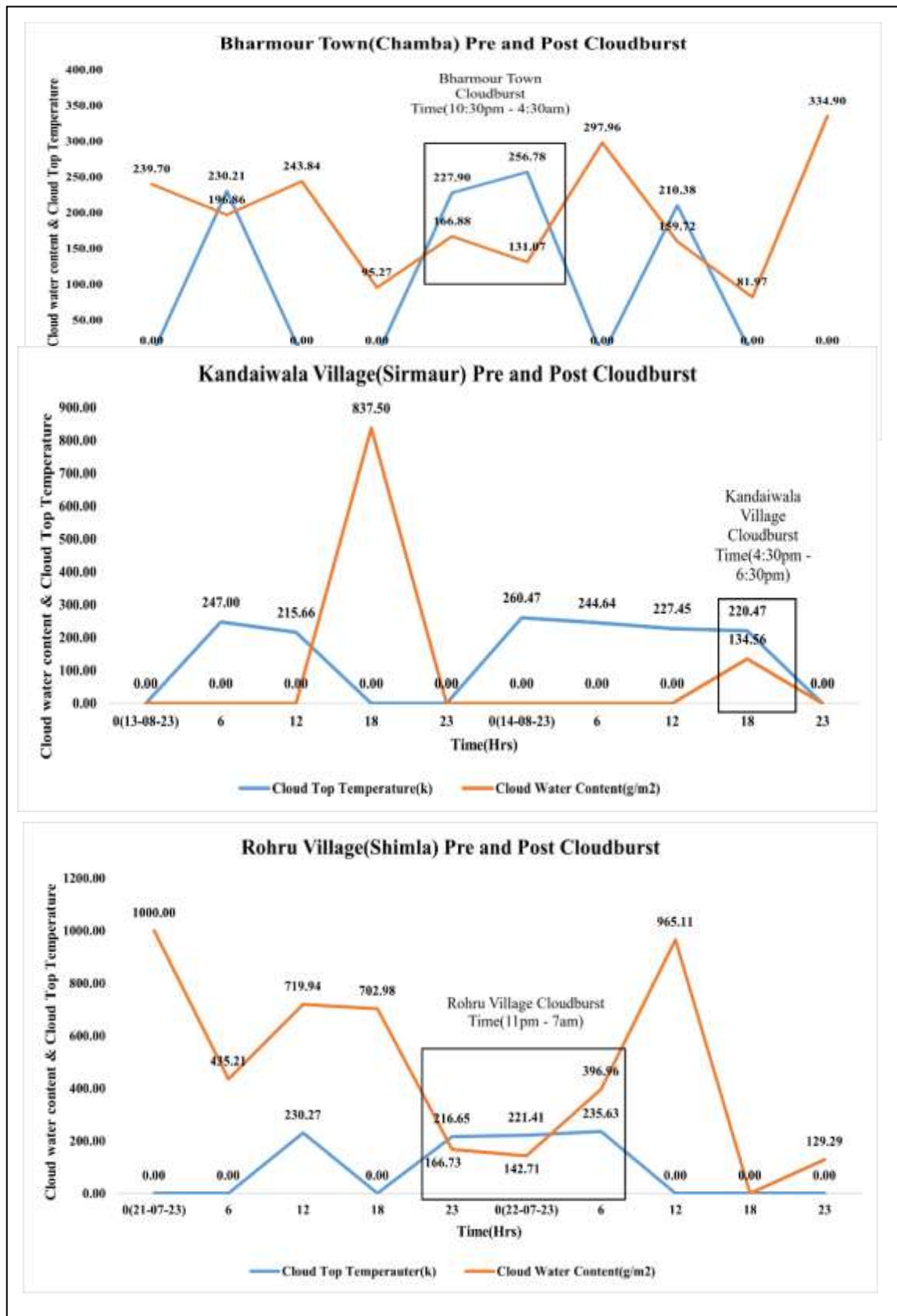


Figure 4.7 Graph between CWC & CTT Vs Time of Bharmour, Kandaiwala & Rohru Pre & Post Cloudburst(6hrs interval)

5. FINAL DISCUSSION

From the above graph it is concluded that 24hr period before the cloudburst occurrence and 24hr post cloudburst window is studied. It was founded that there is initial buildup of Cloud water content(g/m²) between 300-500 g/m² and Cloud top temperature(k) between 200-330k is seen just before the cloudburst sudden peak and this is represented by graph which shows the occurrence of cloudburst event.

Finally the parameters is concluded in the table form to easily understand robust data structure displayed in above pages. Some of data values are missing so N.A is shown in place of them. Cloudburst events are marked with Latitude and Longitude position and Time is taken local blog or locally available newspaper(sandrp).

Below table shows 24hr pre cloudburst time so we can understand the situation that which additional factors are responsible for the occurrence of this event.

Table 5.1 Final parameters values

DATE	TIME	LOCATION	LAT/LONG	ELEVATION (m)	PRECIPITATION (mm)	CWC (g/m ²)	CTT (k)
24-06-23		Rampur	31.45,	1039-1390		71	201.175
25-06-23	2am-5am	(SHIMLA)	77.630		75-105	154	
09-07-23		Thunag	31.552,	1877-2376		N.A	
10-07-23	6am-10am	(MANDI)	77.165		105-150	1000	N.A
16-07-23		Kais Village	31.957,	1251-2877		N.A	269.76
17-07-23	11pm-5am	(KULLU)	77.109		75-105	N.A	
19-07-23		Salooni Sub-	32.752,	1408-1633		295	245.99
20-07-23	11pm-4am	Division (CHAMBA)	75.98		75-105	N.A	
21-07-23		Rohru Village	31.197,	1564-1622		N.A	246.68
22-07-23	11pm-7am	(SHIMLA)	77.657		75-105	874	
25-06-23		Bharmour	32.441,	2091-2042		N.A	245.31
26-07-23	10:30p m-4:30a m	Town (CHAMBA)	76.535		75-105	110	
13-08-23	4:30p	Kandaiwala	30.575,	413-692		67	250
14-08-23	m-6:30p m	Village (SIRMAUR)	77.22		105-120	134	

5.1 Graph Elevation Vs Precipitation

The relationship between elevation and precipitation is depicted in the above graph. A cloudburst event is most likely to occur in conditions where elevation is between 1500 and 2500 m and precipitation is between 100 and 150 mm.

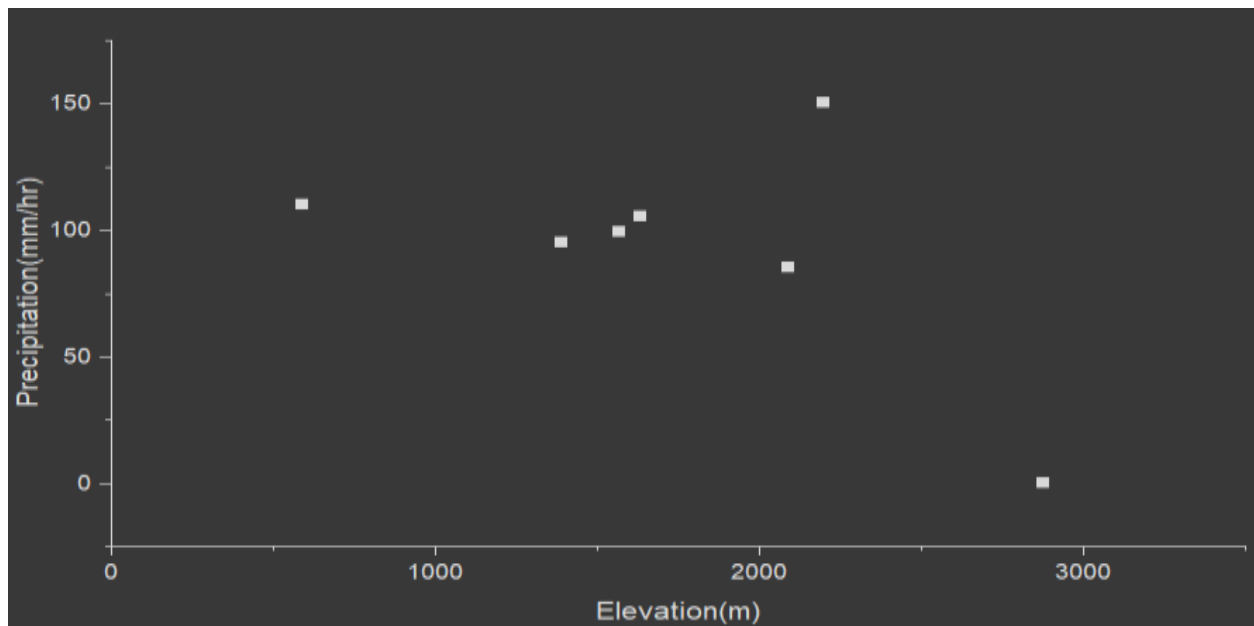


Figure 5.1 Graph(dot indicates the Cloudburst events at 7 different dates)

5.2 Graph Cloud Water Content(CWC) Vs Cloud Top Temperature(CTT)

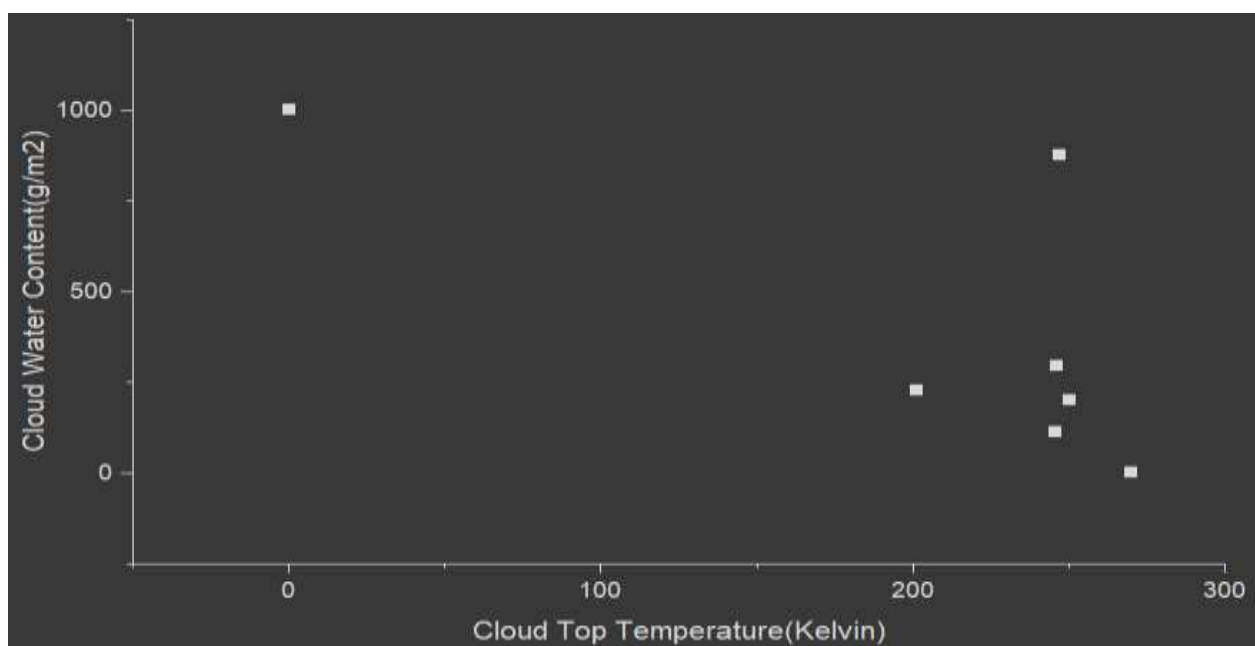


Fig 5.2 Graph(dot indicates the Cloudburst events at 7 different dates)

From the above graph we can conclude that -

- Because of orographic lifting, which causes moist air to rise, cool, and condense, higher elevations usually receive more precipitation.
- Higher elevations may have cooler temperatures, allowing water vapor to condense into cloud droplets.

- Higher altitudes and possibly more intense convective activity are generally indicated by colder cloud tops. Stronger convective cells and more intense updrafts are frequently associated with colder cloud tops, and these conditions can result in heavy precipitation, including cloud bursts.
- The amount of precipitation that a cloud can produce is directly correlated with its water content. In general, higher cloud water content means a higher chance of rain.
- An increase in cold tropopause temperatures may be a factor in the emergence of extreme weather events that occur more frequently like cloudburst.

6. CONCLUSION

The primary purpose of the current study is to conduct an analysis of the meteorological characteristics of the vulnerable region in Himachal Pradesh.

The following noteworthy characteristics of cloud bursts in Himachal Pradesh during the monsoon season have been identified.

- July and August have a higher frequency of cloud burst occurrences than June and September do[4].
- The districts of Kullu, Shimla, Chamba, Sirmaur, Kangra, and Mandi are the most susceptible to these occurrences. Particular care must be taken in these areas during the monsoon season[4].
- It has been discovered that cloud bursts have the least impact on the districts of Lahul & Spiti, Solan, Kinnaur[4].
- Despite this knowledge, additional modelling research involving numerous events and radar observations throughout the area are necessary to gain a deeper understanding of the entire range of these deep convective events over the region. Furthermore, a review of the definition based on the precipitation threshold in accordance with regional differentiation is necessary[1].
- Reevaluating and revising the IMD definition of associated precipitation of cloudburst from "N100mm/h over a geographical region of approximately 20–30 km²" to "N100 mm/15 min over a geographical region of approximately 20–30 km²" is the appropriate course of action[1]. It also takes navigating through multiple cloudburst cells within the event to produce spell precipitation[14].
- Flash floods and debris flows caused by cloudbursts are examples of natural disasters that occur in mountainous areas, particularly the Himalaya. There is no controlling them; they just happen. Consequently, there will be environmental losses.
- The monetary loss brought on by their occurrences, however, can be reduced. According to the study, the location was a major factor in the economic and human losses caused by the current disaster. Their towns and fertile land are situated on both sides of the rivers. In addition, the land is unstable and has a steep gradient. For the whole Himalayan region, this is the. Large-scale out-migration has resulted from the psychological shocks caused by disasters.

References

- [1] A. P. Dimri *et al.*, "Cloudbursts in Indian Himalayas: A review," May 01, 2017, *Elsevier B.V.* doi: 10.1016/j.earscirev.2017.03.006.
- [2] B. Deoja, M. R. Dhital, B. Thapa, and A. Wagner, *Mountain Risk Engineering Handbook: Vol I*. International Centre for Integrated Mountain Development (ICIMOD), 1991.
- [3] G. S. Singh and K. K. Sen, "Causes and Consequences of Cloudbursts at Kullu districts in the Himachal Himalaya," *Himalaya Paryavaran*, vol. 4, no. 1, pp. 13–16, 1996.

- [4] S. C. Bhan, S. Paul, and K. L. Kharbanda, "Cloud bursts in Himachal Pradesh," *Mausam*, vol. 55, no. 4, pp. 712–713, 2004.
- [5] S. Mueller *et al.*, "Disaster scenario simulation of the 2010 cloudburst in Leh, Ladakh, India," *International Journal of Disaster Risk Reduction*, vol. 33, pp. 485–494, Feb. 2019, doi: 10.1016/j.ijdrr.2018.09.004.
- [6] V. P. Sati and S. K. Dubey, "Environmental and Economic Impact of Cloudburst Triggered Debris Flows and Flash Floods in the Himalaya: A Case Study," 2021, doi: 10.21203/rs.3.rs-924043/v1.
- [7] P. Nguyen *et al.*, "The CHRS Data Portal, an easily accessible public repository for PERSIANN global satellite precipitation data," *Sci Data*, vol. 6, no. 1, pp. 1–10, 2019.
- [8] C. Funk *et al.*, "The climate hazards infrared precipitation with stations—a new environmental record for monitoring extremes," *Sci Data*, vol. 2, no. 1, pp. 1–21, 2015.
- [9] G. J. Huffman, E. F. Stocker, D. T. Bolvin, E. J. Nelkin, and J. Tan, "GPM IMERG final precipitation L3 1 day 0.1 degree× 0.1 degree V06. Goddard Earth Sciences Data and Information Services Center (GES DISC)," 2019.
- [10] A. Lima, "NATIONAL REMOTE SENSING CENTRE REPORT / DOCUMENT CONTROL SHEET 1. Security Classification Unclassified 2. Distribution Through soft and hard copies Title Cloud Top Temperature (CTT) from INSAT-3D Originating unit NICES (National Information system for Climate and Environment studies)," 2020.
- [11] L. M. Olsen *et al.*, "Nasa/global change master directory (gcmd) earth science keywords," *Version*, vol. 6, no. 0.0, p. 0, 2007.
- [12] J. Muñoz-Sabater *et al.*, "ERA5-Land: A state-of-the-art global reanalysis dataset for land applications," *Earth Syst Sci Data*, vol. 13, no. 9, pp. 4349–4383, 2021.
- [13] P. Jena, S. Garg, and S. Azad, "Performance analysis of imd high-resolution gridded rainfall (0.25° X 0.25°) and satellite estimates for detecting cloudburst events over the Northwest Himalayas," *J Hydrometeorol*, vol. 21, no. 7, p. 1549, Jul. 2020, doi: 10.1175/JHM-D-19-0287.1.
- [14] P. Vijaykumar *et al.*, "Kerala floods in consecutive years - Its association with mesoscale cloudburst and structural changes in monsoon clouds over the west coast of India," *Weather Clim Extrem*, vol. 33, Sep. 2021, doi: 10.1016/j.wace.2021.100339.