ANSF
APPLIED AND NATURAL SCIENCE FOUNDATION

*Journal of Applied and Natural Science*
16(2), 534 - 542 (2024)
ISSN : 0974-9411 (Print), 2231-5209 (Online)
journals.ansfoundation.org

*Research Article*

# Application of Satellite and Geospatial technology for flash flood mapping over Himalayan with reference to Dharamshala in Himachal Pradesh, India during July 2021

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***Article Info***
https://doi.org/10.31018/jans.v16i2.5436
Received: January 22, 2024
Revised: April 9, 2024
Accepted: April 15, 2024

***How to Cite***
Nagamani, K. *et al.* (2024). Application of Satellite and Geospatial technology for flash flood mapping over Himalayan with reference to Dharamshala in Himachal Pradesh, India during July 2021. *Journal of Applied and Natural Science*, 16(2), 534 - 542. https://doi.org/10.31018/jans.v16i2.5436

**Abstract**
Floods have devastating consequences for human life and economies worldwide. The present study focuses on flash flooding in the Himalayan environment, specifically in Dharamshala, Himachal Pradesh, India. In July 2021, a low-pressure system developed in the area, intensifying into a deep depression and resulting in extreme rainfall on July 12, 2021. This extreme rainfall event resulted flash flooding, landslides, and extensive damage in Dharamshala. Utilizing satellite observation and geospatial technology, this study examined the heavy rainfall events and the vulnerability of the geology of Dharamshala to flash flooding. The area received a cumulative rainfall of more than 370 mm, with over 35 mm recorded at 09:00 Universal Time Coordinated (UTC). The steep slopes of the region, combined with sudden heavy downpours from multiple extreme rainfall events, contributed to flash flooding and landslides. The consequences were severe, resulting in the loss of seven lives and impacting thousands of people in the study area. The research findings emphasize the significance of satellite-borne remote sensing applications and geospatial technology for real-time short-lived localised rainfall events in the study area. The study also highlights the role of Bhagsu Nala in exacerbating flood risks. This research provides a valuable model for implementing effective disaster mitigation measures. Moreover, it contributes to global efforts to reduce the risk of natural catastrophes, particularly in Himachal Pradesh. The findings offer valuable insights into disaster management and mitigation strategies.

**Keywords:** Cumulative rainfall, Disaster mitigation, Flash flooding, Meteosat-8, Steep slope

## INTRODUCTION

A growing body of scientific evidence suggests that human-induced climate change has had harmful effects on the natural world (Perkins *et al*., 2022; Stone *et al*., 2021; Wakatsuki, 2023). These effects are observed in the form of floods and excessive precipitation. In recent decades, frequent floods and extreme precipitation have occurred in various regions, particularly in South Asia and the Himalayan region of India, causing significant devastation (Samantarayand Gouda,2023; Dimri*et al*., 2017; Mirza, 2015; Thomas and Lopez, 2015; Kumar *et al*., 2014; Houze, 2012). Substantial precipitation events in the Himalayan region are closely linked to its unique geography (Krishnan*et al*., 2019; Wester *et al*., 2019; Das *et al*., 2006). The delicate natural environment of the Indian Himalayas, compounded by complex mountain structures and human activities, makes it more vulnerable to catastrophic disasters like floods and landslides (Genelettiand Dawa, 2009; Gupta *et al*., 2022). These calamities, including flash floods and landslides, have adverse consequences for natural resources, economic assets, and people's livelihoods (Pham *et al*., 2020; Rawat, 1995; Tucker, 1982, 1983, 1988; Arnold and Guha, 2001; Nüsser, 2000).

Flash floods typically result from a combination of steep slopes, meteorological conditions, and the geomorphology of the drainage basin (Chaithong 2022; El Kharraz, 2012; Youssef, 2009; Abdel-Fattah *et al*., 2017; Costa, 1987).Past research has predominantly focused on basin studies and traditional geomorphological methods, such as analyzing geometry and relief to comprehend and manage flash floods (Abdelkareem, 2017;Wheater, 2002; Horton, 1945; Strahler, 1964). However, advancements in geospatial technology, including satellite remote sensing and GIS, are now utilized to obtain geomorphological information for flood mapping, monitoring, and hazard assessment (Bisht *et al*., 2016; Sanyal and Lu 2004; Smith, 1997). Satellite remote sensing allows for estimating losses and damages caused by natural disasters like floods, hurricanes, and earthquakes. Synthetic Aperture Radar (SAR) data derived from satellites can effectively map flood damage, while optical satellites can assess flood damages by detecting changes in vegetation cover before and after a flood (Tay*et al*., 2020; Uddin and Meyer, 2019; Tavus*et al*., 2022; Chakraborty *et al*., 2021). Over time, researchers have developed mathematical models that consider physical processes in a river basin and the stage-damage relationship for different land use features to estimate flood losses and quantify economic damages (Dutta *et al*., 2003). This has led to the development of the Disaster Vegetation Damage Index (DVDI), which specifically maps crop-related damage immediately following a flood event (Dutta *et al*., 2003).

An increasing body of scientific evidence suggests that human activity is the primary cause of climate change. This has resulted in severe ecosystem consequences and endangered global food supplies (Perkins *et al*., 2022; Stone *et al*., 2021; Wakatsuki*et al*., 2023). Floods and other extreme events have become more frequent in South Asia and worldwide, leading to significant losses and damages (Thomas and Lopez, 2015). Particularly in India, the impact of these natural disasters has been devastating. Due to heavy monsoon rainfall in July and August, major floods have occurred almost every decade or even more frequently. These floods have resulted in numerous human casualties, agricultural losses, infrastructure damage, property destruction, and economic setbacks.

In recent years, countries like India, Pakistan, and Nepal have faced a series of floods. The most recent disaster, known as the "2022 Pakistan floods," affected over 33 million people, claimed the lives of nearly 1500 individuals, and caused substantial damage to vital infrastructure, agricultural land, and properties. In August 2022, the Sindh province in Pakistan experienced rainfall of 726% above the average for that month, while Balochistan received rainfall of 590% higher than the normal level (PMD, 2022). According to the findings of the World Weather Attribution group, the Indus River basin had 75% more intense rainfall over a sixty-day period. Multiple studies are currently being conducted using a multi-satellite/sensor framework to assess the impacts of flooding, waterlogging, torrential/incidental rainfall, and their effects on seasonal crops. These studies emphasize the role of satellite data in analyzing and projecting economic conditions (Qamer *et al*., 2022).

The Himalayan region is susceptible to various hazards and disasters, including landslides, flash floods, and cloud bursts (Prasad *et al*., 2016; Rawat, 2013). The unique geological features, terrain, and seasonal hydro -meteorological conditions of Himachal Pradesh increase its vulnerability to natural disasters, particularly due to significant surface runoff within short time periods (Sah *et al*., 1996; Sah and Mazari, 1998; Nibanupudi and Shaw, 2015; Sah and Bist, 1988; Shaw, 2015). Moreover, human activities such as land degradation, population growth, deforestation, and economic development further contribute to the region's proneness to disasters (Rawat *et al*., 2010, 2012; Rawat and Pant, 2007; Pandey, 2002; Pandey, 2014; Bhasin *et al*., 2002). These human-induced factors have significant scientific implications. The present study focused on on Dharamshala (Himachal Pradesh), evaluating the instances of intense rainfall in conjunction with the local terrain, which subsequently contributed to flash floods. A distinctive aspect of this study was its emphasis on short-lived localized rainfall events.

## MATERIALS AND METHODS

### Study area

Dharamshala, located at approximately 32.219044° N latitude and 76.323402° E longitude, emerges as a pivotal municipality in Himachal Pradesh, strategically positioned just 11 miles from Kangra (Fig. 1). Himachal Pradesh, in northern India, comprises 12 districts: Shimla, Kangra, Hamirpur, Mandi, Chamba, Bilaspur, Una, Lahul and Spiti, Sirmaur, Kullu, Solan, and Kinnaur. The state capital is in the Shimla district. The region consists of two parts, lower Dharamshala and upper Dharamshala. Lower Dharamshala serves as the city's commercial center, bustling with markets, courts, and the famous Kotwali Bazaar. Upper Dharamshala is characterized by its colonial era buildings, including the notable Mcleodganj. Each area offers its own unique attractions and experiences, providing tourists with the opportunity to unwind and enjoy the surroundings. Despite its location in the high and cold mountains, Dharamsala does not always have a snow-covered landscape. Occasionally, even at lower elevations, solid rainfall occurs during the cold weather, adding to the diversity of the environment (https://hpkangra.nic.in).

**Weather pattern**

The geographical features of Dharamshala in Himachal Pradesh contribute to its unique weather patterns. The area experiences significant variations in elevation, leading to distinct climatic characteristics. The spatial altitude above sea level influences temperature fluctuations within Himachal Pradesh. It is well-known that temperature decreases with an increase in height, following the lapse rate (Romshoo*et al*., 2017). During the summer season (April to June), the average temperature in Himachal Pradesh is around 28°C, while in winter (late November to mid-March), it drops to an average of 7°C. The region's topography, as depicted in Fig. 2a (elevation), Fig 2b (slope), Fig. 2c (aspect), and Fig. 2d (curvature), is characterized by rugged terrain. These topographical features result in substantial snow cover, particularly during winter when temperatures consistently remain below freezing. The rainy season follows the summer period, typically lasting from July to September. However, certain northern districts of Himachal Pradesh, such as Lahaul and Spiti, receive minimal rainfall and remain cold throughout the year. Dharamshala, on the other hand, has a subtropical climate that becomes humid during the monsoon season. In comparison to other regions in Himachal Pradesh, the city experiences relatively higher levels of precipitation, making it one of the wettest areas in the state.

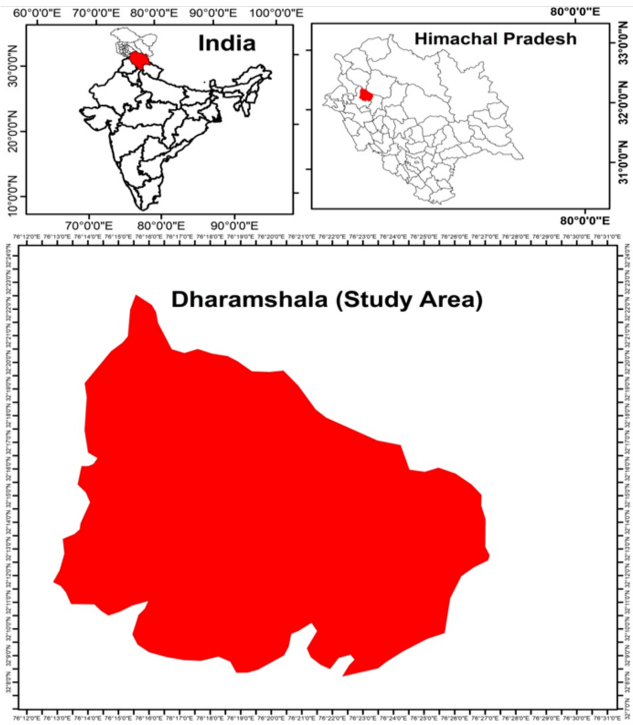


**Fig. 1.** *Showing study area Dharamshala, Himachal Pradesh*

**Methodology**

Radar serves as a remote means of collecting rainfall data, whereas rain gauges on the ground offer a conventional method to record rainfall depth in millimeters. These two methods, radar systems and rain gauges, are widely used for tracking significant rainfall events. However, accurate rainfall monitoring requires a widespread and uniform network of rain gauges, which, unfortunately, is lacking in Dharamshalla, Himachal Pradesh and other parts of India. The diverse topography of Dharamshalla, makes it particularly challenging to achieve accuracy when using radar and rain gauge stations to observe extreme rainfall events. As a result, satellite observation stands as the sole tool available for monitoring such events.

The extreme rainfall event over Dharamshalla, Himachal Pradesh, was monitored using hourly measurements of rainfall obtained from the Meteosat-8 geostationary satellite. By integrating observations from the Meteosat-8 satellite with space-borne precipitation radar (PR) data from the tropical Rainfall measuring mission (TRMM), the study estimated hourly rainfall at a resolution of five kilometers. To carry out this estimation, the rain index-based technique developed by Mishra (2012), utilizing the Infrared (IR) and water vapor (WV) channels of Meteosat-8 at a 5 km resolution was employed. The technique incorporated data from TRMM, space-borne precipitation radar (PR), and Meteosat-8 multispectral satellite data to comprehensively analyse rainfall. Specifically, the infrared and water vapor observations from Meteosat-8 on July 12$^{th}$, 2021, were utilized to calculate a new rain index (RI). The procedure for computing the rain index is outlined in equation (1). It involves filtering out non-rainy clouds using a spatial and temporal gradient approach and calculating the brightness temperature from thermal Infrared (TIR) and WV channels with Rainfall data from the precipitation radar (PR) to establish non-rainy thresholds for these channels. Subsequently, the TIR and WV rain coefficients were determined by dividing the brightness temperature values by the non-rainy thresholds. The product of these coefficients, the TIR and WV rain coefficient product, is defined as the rain index (RI). The RI was then collocated with Rainfall data from PR to develop a relationship between Rainfall and RI, utilizing extensive datasets of heavy rainfall events during multiple monsoon seasons.

The resulting equation establishes a correlation between rain rate (RR) and RI, offering a valuable tool for assessing and quantifying rainfall :

$$RR = a + (b \times RI^c) \qquad \text{Eq. 1}$$

Finally, the equation (1) is utilized to calculate the rate of rainfall (RR). Specifically, for the Indian subcontinent, the values of a, b, and c are determined as follows: a =

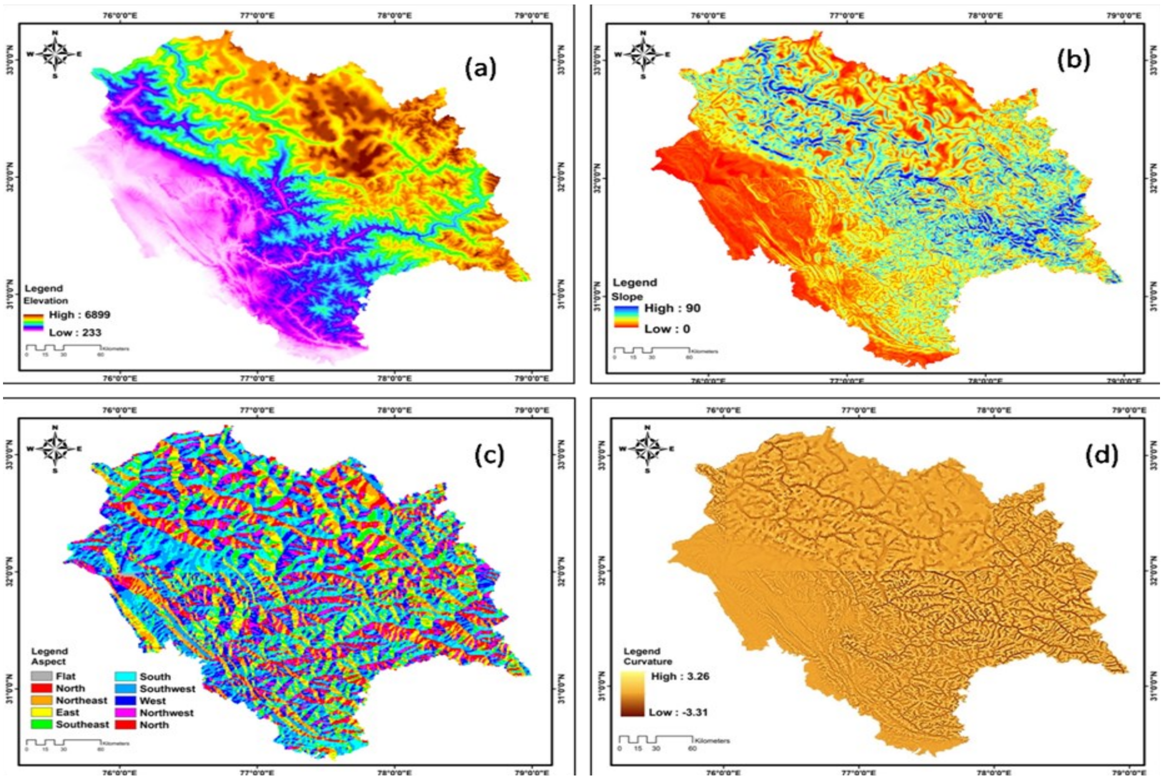


**Fig. 2.** *Showing (a) Elevation (b)Slope (c) aspect (d) curvature of the Himachal Pradesh*

8.4969, b =2.7362, and c = 4.27. By employing the rain index (RI) generated from Meteosat-8 measurements, this model can be utilized to estimate hourly rainfall. The validity of the current equation (1) was confirmed by comparing it to observations from a robust network of ground-based rain gauges. During the southwest monsoon season in India, hourly readings from rain gauges demonstrated a correlation coefficient of 0.70, a bias of 1.37 mm/h, a root mean square error of 3.98 mm/h, a chance of detection of 0.87, a false alarm ratio of 0.13, and a skill score of 0.22 (Mishra, 2012). The method developed by Mishra (2012) outperformed other techniques in assessing the diurnal aspects of heavy rain in India when compared to existing global rainfall statistics. Suppose the spectral responses of both satellites to the channels utilized for generating the rain signatures are similar. In that case, the equation established for estimating rainfall using the rain signature from one satellite can also be applied to estimate rainfall using the rain signature from another satellite. The present study employed Meteosat-8 Second Generation (MSG) observations to examine precipitation characteristics at relatively fine spatial and temporal scales. Additionally, topography data was analyzed and assessed within a remote sensing and GIS environment. The impact of topography was connected to the corresponding time series of heavy rainfall and flash flooding over the Bhagsu Nag Nala. Ultimately, the implications of this study are discussed concerning planning, policymaking, and disaster mitigation for the preservation of life and livelihoods. The present technique measured extreme rainfall events in Jammu & Kashmir, Kedarnath, Kerala, Bihar, Assam, Rajasthan, Tamil Nadu and Kerala (Mishra, 2015, 2016, 2019, 2021,2024 and in Uttarakhand (Nagamani 2024).

## RESULTS AND DISCUSSION

Data from the Meteosat-8 second generation (MSG) satellite employed to estimate rainfall with a resolution of 5 km heavy rainfall in Dharamshala, Himachal Pradesh, on July 12th, 2021. These intense rainfall events subsequently led to flash flooding in the region. Dharamshala, Himachal Pradesh, is characterized by steep, hilly terrain slopes (Fig. 2 (a, b, c, d)). Such pronounced slopes render the area highly susceptible to flash flooding and landslides (Gupta *et al*., 2022). On July 12th, 2021, the cumulative rainfall in the region reached 300mm due to the occurrence of multiple with extream rainfall events, resulting in widespread flash flooding over the study (Fig. 3).

Fig. 4(a) provides a detailed representation of the temporal distribution of hourly accumulated rainfall over the study area. The graph depicts the variations in rainfall intensity over time. Specifically, at 0630 UTC on July 12th, the area experienced a high hourly rainfall rate of 35mm/hr. This intense rainfall persisted until 1030 UTC, resulting in a prolonged period of heavy with extreme rainfall. These rainfall episodes exhibited characteristics similar to cloud burst events, which are characterized by sudden and intense downpours. Further spikes in rainfall were observed at 1230 UTC, with rainfall rates reaching approximately 34mm/h. These notable rainfall peaks contributed to the cumulative rainfall for July 12th, exceeding 300mm, as shown in Fig. 4(b). The combination of the region's hilly terrain and steep slopes, along with the occurrence of intense and abrupt rainfall, played a significant role in triggering flash flooding in the study area. The topography, characterized by elevated areas and rapid descent, facilitated the rapid runoff of water. As a result, the water level in Bangsunag Nalla, a local watercourse, rose significantly due to the multiple with extreme instances of heavy rainfall. Consequently, the main Dharamshala area became submerged under the rising floodwater. The findings presented in Fig. 4 provide valuable insights into the temporal characteristics of the rainfall events and their impact on the hydrological dynamics of the area, contributing to a better understanding of the flash flooding phenomenon.

Fig. 5 is a visual representation that provides important information about the geography and elevation of Bhagsu Nag Nala of Dhrmshalla, a region that experienced flash flooding. Fig. 5 highlights the specific areas that were approximately affected by the flooding, emphasizing the impact on the upper Dharamshala and lower Dharamshala regions. These areas are shown to have been significantly affected by the flash flooding events. The findings indicate that flash flooding in certain terrain areas can be attributed to multiple episodes of intense rainfall (Santangelo *et al*., 2021).This suggests that the heavy rainfall experienced in the region played a crucial role in triggering the flash flooding. The consequences of the flash flooding were devastating, particularly for the livelihood along the BhagsuNag Nala (https://www.downtoearth.org.in/news/climate-change/flash-floods-in-dharamshala-after-heavy-rains-in-kangra-district-77894). Unfortunately, the flash flooding event had severe human consequences. Seven lives were lost as a result of the disaster, highlighting the tragic impact on the affected population. The flooding and its aftermath affected thousands of people in the region, causing significant disruptions and hardships. Overall, Fig. 5 serves as a visual aid to demonstrate the geography, elevation, and areas affected by flash flooding in Bhagsu Nag Nala.The Bhagsu Nag Nala experiences recurrent flooding annually, necessitating a thorough examination of its hydrological aspects and the longitudinal profile (Gupta *et al*., 2022). This study aims to enhance flood forecasting capabilities. By understanding the dynamics of Bhagsu Nag Nala, we can visualize the extent of flooding and its potential consequences. Many reports suggest that changes in the physical dynamics of Bhagsu Nag Nala incline the number of major flooding episodes over the area. So, it is urgent to study the change in the dynamics of Bhagsu Nag Nala (Gupta, *et al*., 2022; https://www.ndtv.com/india-news/cloudburst-triggers-flash-floods-in-dharamshala-s-bhagsu-nag-area-2484548).

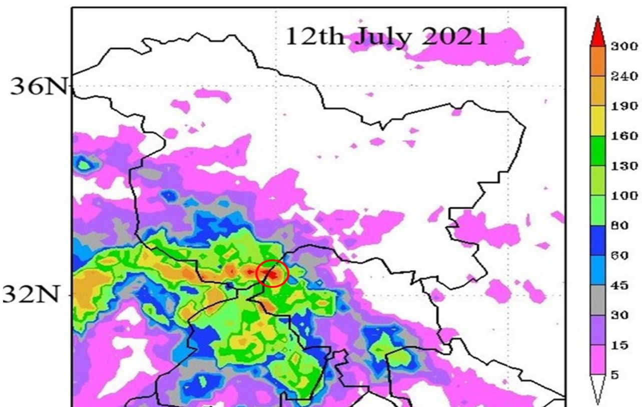


**Fig. 3.** *Showing rainfall distribution over the study area (Daramshala) on 12$^{th}$ July 2021*

The present study also evaluates the hydrological properties, longitudinal profile and anthropogenic intervention of the Bhagsu  Nag Nala.This underscores the importance of implementing effective measures to mitigate the risks associated with these events in the future (https://www.downtoearth.org.in/news/climate-change).

**Hydrological properties, longitudinal profile and anthropogenic intervention of BhagsuNag Nala**

The Bhagsu Nag Nala (Fig. 5), located in the reserved area between Chakban and Dharamshala in Himachal Pradesh, is a significant watercourse that plays a crucial role in the occurrence of flash flooding in the region (Wescoat 2019). It originates at 3,320 meters above mean sea level and is primarily fed by rainfall and springwater sources. The upstream watershed area of the Bhagsu Nala covers approximately 2.8 square kilometers, contributing to its flow and water volume. In its upper reaches, the width of the watercourse ranges from 10 to 20 feet, indicating its capacity to carry substantial amounts of water. By documenting the characteristics and infrastructure along the Bhagsu Nala, this study provides valuable insights into the area's hydrological dynamics and flood vulnerability. The study emphasized the importance of considering various factors, such as elevation, stream width, road connectivity, and culvert construction, when assessing the potential impact of flash flooding and formulating appropriate mitigation measures. Understanding the interactions between natural features and human-made infrastructure is crucial for effectively managing and mitigating the region's flash flooding risk (Da Silva and  Wheeler, 2017).

Over the study area, human activities harm the carrying capacity and flow dynamics of the Bhagsu Nag Nala. As a result of human interventions, the width of the

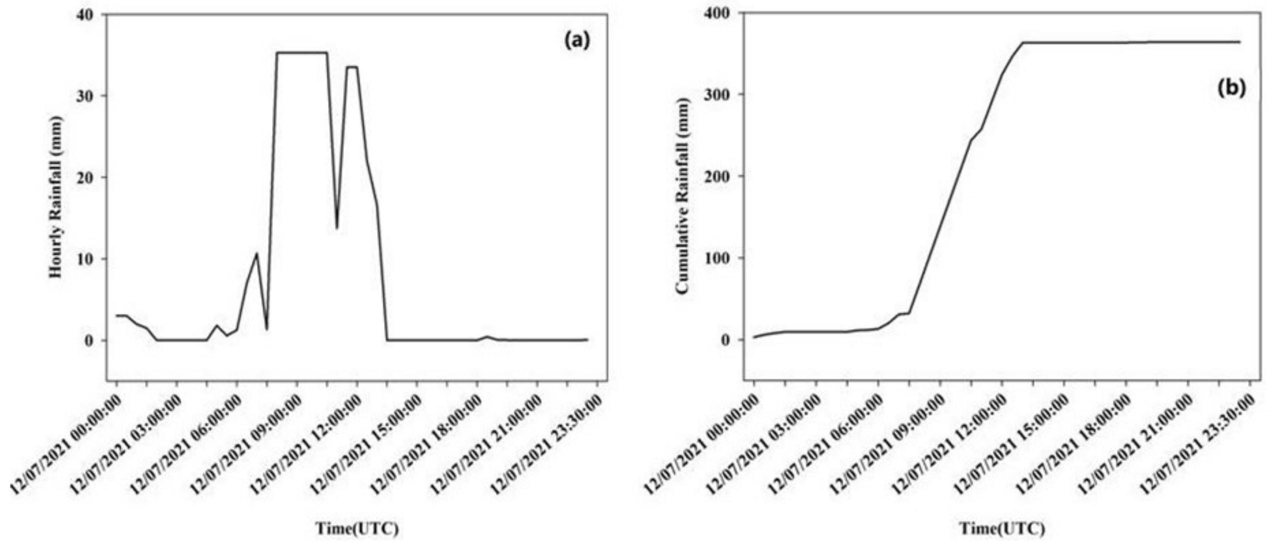


**Fig. 4.** *Showing hourly rainfall during 12th July 2021*

Bhagsu Nag Nala has been significantly reduced and altered downstream. Previously, the Bhagsu Nala had a wider width, allowing for the efficient water transport. However, the average width has now dwindled to a range of 6-8 feet in some areas; it has been reduced to a mere 2-3 feet. The diminished width of the BhagsuNag Nala has profound consequences on its ability to handle water flow effectively. The restricted width hampers the Bhagsu Nag Nala's capacity to accommodate large volumes of water during heavy rainfall or flash flooding events. This reduction in carrying capacity increases the risk of overflow and exacerbates the potential for flood-related damages, further complicating the Bhagsu Nag Nalas carrying capacity. By repurposing the nala for non-natural functions, such as accommodating a road, the watercourse's ability to convey water has been severely impeded. This encroachment on the Bhagsu Nag Nala's natural course exacerbates the constraints imposed by the reduced width and amplifies the risk of flooding. In summary, human activities have severely affected the carrying capacity of the BhagsuNala, leading to a significant reduction in width downstream. This constrained width, sometimes as narrow as 2-3 feet, impedes the Bhagsu Nag Nala's ability to efficiently handle water flow efficiently, increasing the likelihood of flooding. Additionally, the transformation of the lower sections of theBhagsu Nag Nalainto a road highlights the extent to which human interventions have compromised the natural functioning and capacity of the watercourse. These alterations underscore the urgent need to consider sustainable management practices and mitigate the adverse impacts of human activities on the hydrological dynamics of the Nala.

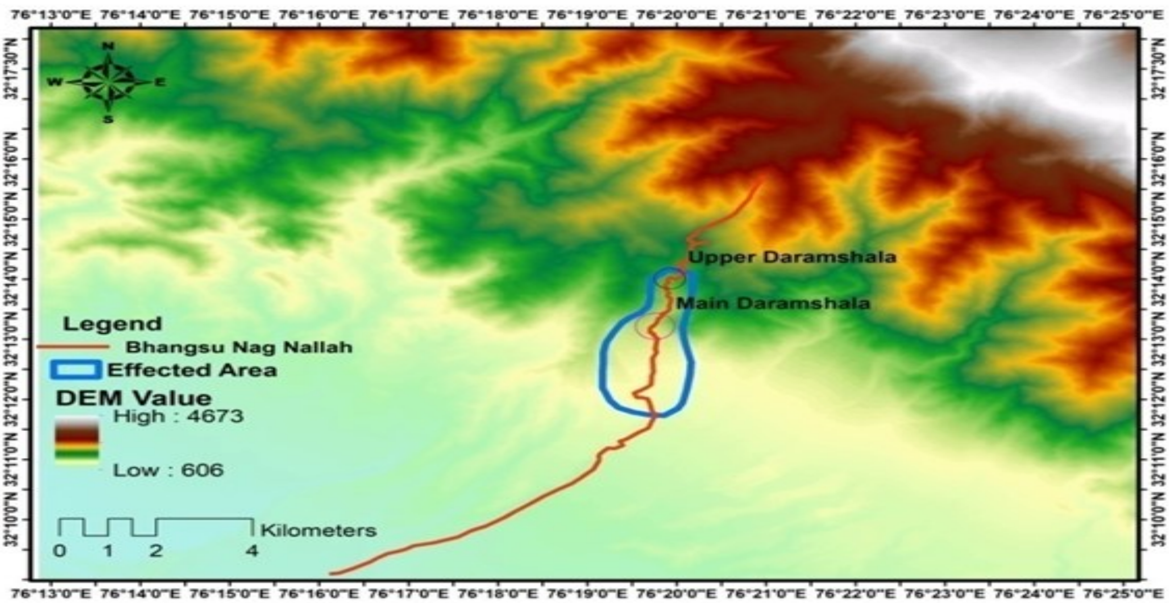


**Fig. 5.** *Showing the area affected on the Digital Elevation map (DEM) map*

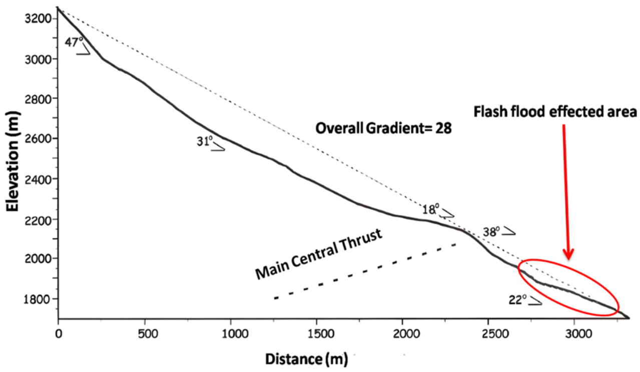


**Fig. 6.** *Longitudinal profile of the Bhagsu nala indicating general concavity in the overall gradient (Slope break is marked by a knick point where the main central thrust cut across the channel, and a flash flood affected the area at the outlet of theBhagsu Nag Nala catchment)*

The circularity of the catchment plays a significant role in determining the characteristics of peak flow during rainfall events. A circular catchment tends to generate high peak flow for a shorter duration, while an elongated and low circular catchment results in lower peak flow but for a longer duration. In the case of BhagsuNag Nala, both the drainage density (the extent of stream channels in the catchment) and the shape of the catchment favor peak discharge for a shorter duration. This characteristic of the catchment contributes to the occurrence of flash floods in the area, where a sudden surge of water recedes quickly.The longitudinal profile of the Bhagsu Nag Nala provides additional insights into the topography of the area. The overall gradient of the Bhagsu Nag Nala, as depicted in Fig. 6 (Gupta *et al.,* 2022), is 28° across the entire study area. The gradient is steeper (50°) in the upper part of the nala and gradually decreases downstream. At an elevation of approximately 2100 m, there is a notable feature known as a knick point, which is characterized by a convexity in the longitudinal profile (Fig. 6). This knick point is associated with a major thrust called the 'Main Central Thrust.' It marks a significant change in gradient from 18° to 38°. Further downstream towards the lower end of Bhagsu Nala, the gradient is approximately 22°.The drainage density of the Bhagsu Nala watershed is calculated to be 6.36 $km^2$, indicating that the watershed responds rapidly to rainfall events. This means that the flow generated by rainfall reaches the stream channels quickly, contributing to an increase in flow (Nicholson *et al*., 2020; Cheng and Chau, 2004; Horton, 1932).The catchment form factor, which is the ratio of the catchment's area to its length squared, also influences the hydrological characteristics of the watershed. In the case of Bhagsu Nag Nala, the form factor is 0.53, suggesting that the shape of the catchment is approximately circular. This circular shape, though not perfectly circular (0.786), further contributes to the swift response of the watershed to rainfall events and the potential for flash flooding.In conclusion, the circular shape of the Bhagsu Nala catchment, along with its drainage density and longitudinal profile, contributes to the occurrence of flash floods in the area. The circularity promotes high peak flow for shorter durations, while the swift drainage density allows for rapid response to rainfall events. The presence of a knick point and changes in gradient along the Bhagsu Nala further affect the flow dynamics. Understanding these characteristics is crucial for assessing and mitigating the risks associated with flash flooding in the Bhagsu Nala region.

## Conclusion

The present study highlighted the application of remote sensing and GIS for analyzing flash flooding in Dharamshala, Himachal Pradesh, by measuring short-lived localized rainfall events. By integrating satellite data into flood monitoring systems, authorities gained timely and accurate information, enabling prompt responses to mitigate impacts on communities and infrastructure. This study also examined the hydrological dynamics and flood vulnerability of Bhagsu Nag Nala in Dharamshala, emphasizing key factors like elevation, stream width, road connectivity, and culvert construction. Human activities, particularly downstream alterations, and road development, reduced the *nala's* carrying capacity, highlighting the need for sustainable management. The research underscored the importance of understanding these features for effective risk assessment and mitigation strategies over the study area.


## ACKNOWLEDGEMENTS

We acknowledge the funding support from HRDG CSIR through Grant Number 23(0034)/19/EMR-II.


### Conflict of Interest

The authors declare that they have no conflict of interest.

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