Hydrogeography of Cloudburst Flooding in the Himalaya

by
Sonja Michelsen

A PROJECT

Submitted to

Oregon State University

University Honors College

in partial fulfillment of
the requirements for the
degree of

Honors Baccalaureate of Science in Ecological Engineering

(Honors Scholar)

Presented May 26, 2015
Commencement June 2015

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Sonja Michelsen for the degree of Honors Baccalaureate of Science in Ecological Engineering presented on May 26, 2015. Title: Hydrogeography of Cloudburst Flooding in the Himalaya.

Abstract approved:

Desirée Tullos

Even though cloudburst events in high mountain areas can be highly destructive and result in significant losses of life, little is known definitively about these flood events. An exact understanding of the driving processes, typical precipitation rates, and impacts of cloudburst events remain uncertain. This study seeks to advance knowledge on the hydrology, spatial aspects, and impacts of cloudburst events through compiling a list of reported cloudburst events, investigating five case studies of cloudburst events to identify trends, and providing direction for future research. Information was collected from news articles, publications, government records, and remotely-sensed data. Major similarities across the five assessed events included occurrence during the monsoon and at night, impacted villages at elevations between 1600 and 2100 meters, lack of rainfall signatures in remotely-sensed precipitation data, occurrence of landslides with cloudburst events, catchments consisting of a majority of landslide hazard slopes, village access blockades, migrant workers as a large fatality group, and damages to hydropower. Further study on cloudburst events within larger atmospheric-landscape processes and the underlying hydrology would be helpful to plan for and respond to the flood hazards resulting from these events.

Key Words: hydrology, spatial, cloudburst, cloud burst, flooding, India, Himalaya

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APPROVED:

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I understand that my project will become part of the permanent collect of Oregon State University, University Honors College. My signature below authorizes release of my project to any reader upon request.

Sonja Michelsen, Author

Abstract

Even though cloudburst events in high mountain areas can be highly destructive and result in significant losses of life, little is known definitively about these flood events. An exact understanding of the driving processes, typical precipitation rates, and impacts of cloudburst events remain uncertain. This study seeks to advance knowledge on the hydrology, spatial aspects, and impacts of cloudburst events through compiling a list of reported cloudburst events, investigating five case studies of cloudburst events to identify trends, and providing direction for future research. Information was collected from news articles, publications, government records, and remotely-sensed data. Major similarities across the five assessed events included occurrence during the monsoon and at night, impacted villages at elevations between 1600 and 2100 meters, lack of rainfall signatures in remotely-sensed precipitation data, occurrence of landslides with cloudburst events, catchments consisting of a majority of landslide hazard slopes, village access blockades, migrant workers as a large fatality group, and damages to hydropower. Further study on cloudburst events within larger atmospheric-landscape processes and the underlying hydrology would be helpful to plan for and respond to the flood hazards resulting from these events.

1.0 Introduction

Floods are one of the most frequent and destructive natural disasters globally (Noji & Lee, 2005) and are the most frequent of all natural disasters in Asia, estimated to have affected 2.2 billion people between 1975 and 2000 (*20th Century Asian Natural Disasters Data Book*, 2002). Vulnerability to flooding in the Himalaya and downstream basins is associated with 1) a lack of basic data that leads to limited knowledge of the hydrology (Shrestha, Wake, Dibb, & Mayewski, 2000), 2) water resources management that achieves short-term development goals but lacks long-term sustainability (Gupta, Pahl-Wostl, & Zondervan, 2013), 3) a broad suite of other socio-economic, environmental, and geopolitical factors (Ives & Messerli, 1989); 4) increasing precipitation intensity associated with changing monsoonal rains (Li, Liu, Qiu, An, & Yin, 2013), and 5) increasing prevalence of highly destructive Glacial Lake Outburst Floods (GLOFs) (Bajracharya, Mool, & Shrestha, 2007) and cloudburst events (Devi, 2015) and the subsequent geophysical flows. This study focuses on cloudburst events due to the limited knowledge surrounding them and their devastating impacts, with recognition that many of these factors contributing to vulnerability to floods are highly interactive.

Cloudburst flood events in the Himalaya are one of the least understood weather systems (Das, Ashrit, & Moncrieff, 2006) because there is confusion around the definition of cloudbursts and basic data is not available about the events. In reports from Utah in the early 20th century, the lack of understanding around Utah cloudburst events is expressed repeatedly, and cloudbursts and thunderstorms are used interchangeably (*Engineering News-record*, 1922; Woolley, Marsell, & Grover, 1946). Additional confusions stems from lack of understanding by the Indian public or media. For example, some reported the widespread flooding in Uttarakhand that occurred over three days in June 2013 as a cloudburst event (Varghese & Jose Paul, n.d.) while experts claimed it did not fit the criteria (Gulati, 2013). Cloudbursts are also difficult to study in the Himalaya because most of the region does not have rain gauges, events often occur on remote mountain slopes, and usually events are only recorded if lives are lost (Thayyen, Dimri, Kumar, & Agnihotri, 2013).

It is known that cloudbursts consist of very intense rainfall events over a very short period of time and small spatial scale, though the mechanisms that generate them are not fully understood. These events have been quantified with a minimum rainfall rate of 100 mm per hour over an area less than 30 km^2 (Dasgupta, 2010; Das et al. 2006; Thayyen et al., 2013), though the range of precipitation intensities can greatly vary and no single criterion for identifying cloudbursts has been widely established. Some authors define cloudburst events based on the hydrometeorological conditions that generate them (Section 2). One feature that is common regardless of how they are defined it the associated of cloudbursts with flash floods and debris flows in mountainous regions (*Engineering News-record*, 1922; Woolley et al., 1946).

Thus, this study seeks to advance knowledge on the hydrogeography of cloudburst events through compiling a list of reported cloudburst events, investigating five case studies of cloudburst events to identify hydrogeographic and impact trends, and providing a direction for future research.

2.0 Hydrometeorology of Cloudbursts

Based on existing literature (Das et al., 2006; Thayyen et al., 2013) and generalized assumptions on the hydrological conditions required for rainfall and flooding (Hendriks, 2010), an outline of the physical processes that lead to cloudburst events was developed (Fig. 1), acknowledging that the specific processes required for cloudbursts are not agreed upon.

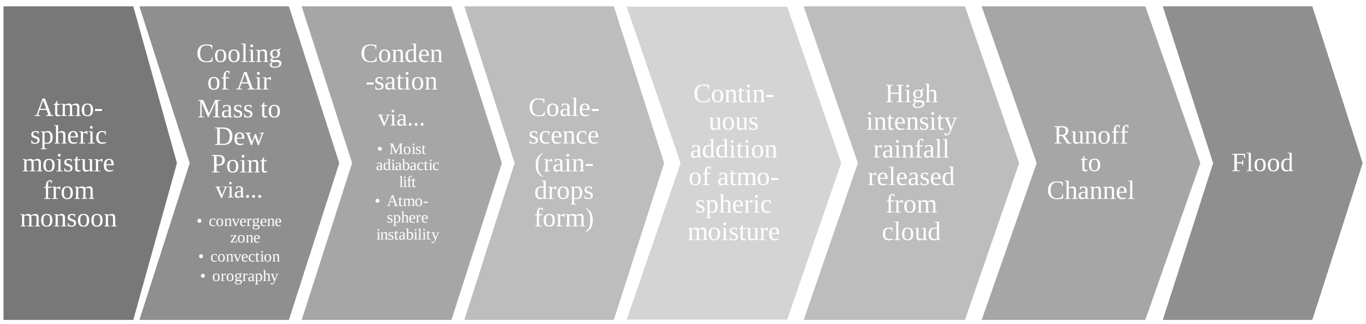

Fig 1: A generalized understanding of the physical processes leading to a cloudburst flood event.

While the exact mechanisms for the formation of cloudburst events are not well understood, they appear to be associated with interactions between the atmosphere and the landscape, and particularly between convection and orography (Thayyen et al., 2013). Convection within cumulonimbus clouds associated with cloudbursts can rise to 15 km, with atmospheric instability and strong up and down drafts from orographic forcing (Thayyen et al., 2013). The convective energy may be provided at night from evapotranspiration of vegetation, convergence on windward valley slopes, and evaporative cooling of rainfall as seen in other places in the Himalaya (Barros et al. 2004). A potential alternate atmospheric mechanism related to cloudbursts is the collisions of two clouds systems (Srivastava and Bhardwaj, 2013). Other clues regarding mechanism of cloudburst hydrogeology are occurrence between 1600 to 2200 meters and reoccur in the same location (Asthana & Asthana, 2014; Sharma, 2011).

The hydrograph of cloudburst events is assumed to be flashy, since the cloudbursts occur over small areas and short periods of time (Thayyen et al., 2013). A hydrograph (Fig. 2) for a cloudburst event in 2010 was hindcasted based on Manning’s equation, step-backwater model with multiple cross sections, and a two-dimensional depth-averaged hydraulic model (Thayyen et al., 2013).

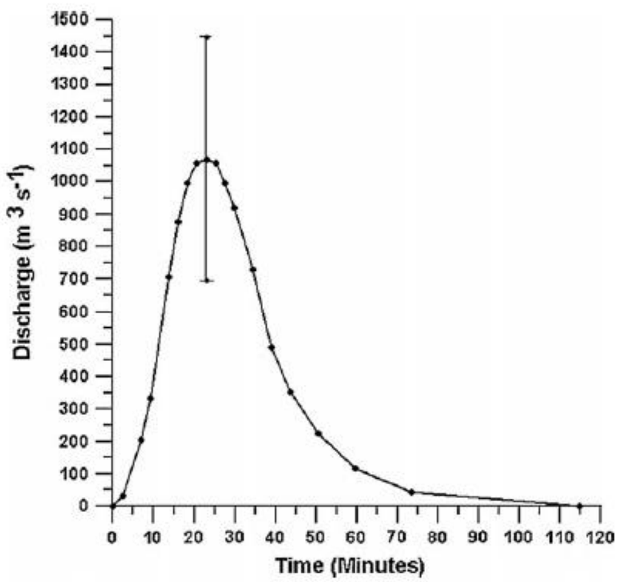

Fig 2: Estimated flood hydrograph from cloudburst event in the Chonglamsar area in Leh in 2010 with ±35% error from analysis methods (Thayyen et al., 2013).

Cloudbursts may also include hail, lightning, and windstorms, which can make it difficult to differentiate cloudbursts from thunderstorms (Das, 2005; Srivastava & Bhardwaj, 2013). Despite overlaps between cloudburst events and other weather phenomenon, the quantity of literature differentiating cloudbursts from other flash floods (Dasgupta, 2010; Das et al., 2006; Devi, 2015b; Srivastava & Bhardwaj, 2013; Thayyen et al., 2013; and more), as well as the large gap in hydrometeorology knowledge in the Himalaya (Shrestha et al., 2000), support the discretization of cloudbursts as unique weather phenomenon from thunderstorms or hailstorms. This differentiation is important for scientific understanding of weather patterns within the Himalaya, as well as managing and forecasting potentially fatal cloudburst events.

3.0 Methods

3.1 Study Area

The Himalayan Mountains span across Northern India, Nepal, Bhutan, China, Afghanistan, and Pakistan and run 2,400 km from east to west (Jain, Agarwal, & Singh, 2007b). The elevation ranges from 100 meters to over 8,000 meters above sea level (Nature, 2011). Five major Southeast Asian rivers, the Indus, Ganges, Brahmaputra, Yangtze, and Yellow, drain from the Himalaya Mountains and provide water to over 1.4 billion people, 20% of the global population (Immerzeel, Beek, & Bierkens, 2010). Cloudburst events are most frequent in northwestern Himalaya (Das et al., 2006; Jain, Agarwal, & Singh, 2007c), occurring especially in the states of Himachal Pradesh and Uttarakhand, (Fig. 3).

Cloudburst Hazard States

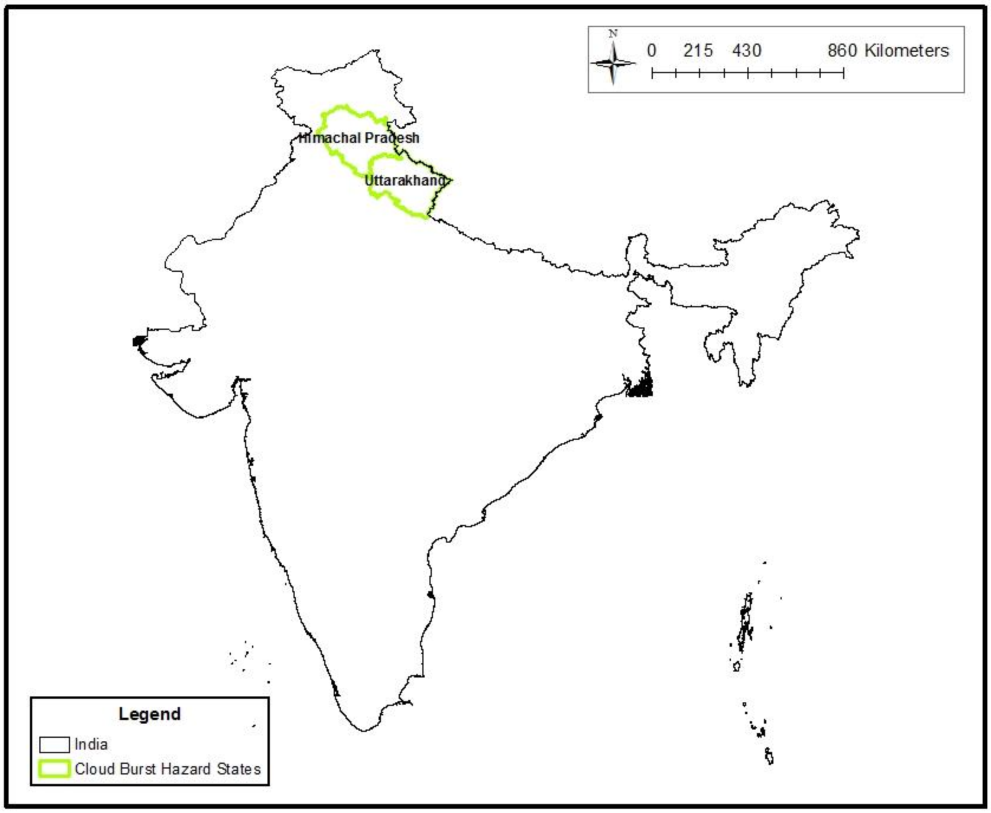

Fig. 3: States that are especially at risk for cloudburst flooding (Das et al., 2006; Jain et al., 2007c).

3.2 Cloudburst Case Studies

Instances of flooding attributed to cloudbursts were compiled from news media, post-hazard government publications, and scientific literature to develop a list of events and select five cloudburst events for further analysis. The sixteen cloudbursts compiled (appendix Table 4) are not representative of all cloudburst events between 1997 and 2013 in the region, but reflect some of the events found through online searches of "cloudburst", "cloud burst" and "floods" and an examination of peer-reviewed literature and news reports. The distribution of sources is shown in Table 4 in the appendix. Five events that were reported by both literature and news reports were selected for further analysis. These events represent those with the largest quantity of peer reviewed articles and news stories, resulting in the most reliable source of information. Since cloudbursts are defined variably throughout sources, using events with multiple reports calling them “cloudbursts” was important to attempt to reflect “true” cloudburst events. Finally, these events were chosen for their wide distribution across the last 18 years and spatial range across Himachal Pradesh and Uttarakhand (Fig. 4).

Each of the five selected events were assessed for similarities based on temporal, spatial, hydrological, and human conditions (Table 1, 2, and 3).

Temporal information, including date and time, was verified across reports (Table 1). Some discrepancies between days and times were found, largely due to irregular reporting and the cloudburst's occurrence within larger flood events. The times and dates reported in this study were the ones most commonly stated, and information found in government reports and articles was assumed to be more credible.

Spatial information for the cloudbursts included the location of the impacted village and elevation of the village and rainfall catchment (Table 1 and 3). The impacted village locations were determined from reports that mentioned village, topographical, or road landmarks. These landmarks were then found on Google maps and ESRI maps to determine the latitude and longitude coordinates. The elevation of the village and catchment was determined from a global digital elevation model, ASTER-GDEM (METI and NASA, 2011), with 1 arc-second (~30 m) raster pixels. Additionally, the closest river and the slopes of the land surrounding the event were investigated (Table 3). The closest river was determined with Google Maps data and ESRI's topographic map to specify the catchment in which the cloudburst occurred within and provide additional information for location. The valley hillslopes within the catchment were calculated with the ArcGIS slope tool and elevation data (Table 6 in appendix) to compare landslide hazard conditions within each event. To calculate the percent of the area covered with a hazard slope, slopes above 20 degrees were assumed to be areas of high landslide hazard (Harp, Michael, & Laprade, 2008).

To study hydrological conditions, the catchment, stream order, and precipitation data,each cloudburst was assessed with ASTER-GDEM elevation data and remotely sensed precipitation data (Table 3). The catchment area above the impacted village was delineated in ArcGIS with ArcHydro tools and GDEM data, applying the assumption that the upstream catchment includes the location where the cloudburst occurred. Stream orders were calculated within ArcGIS using GDEM data and ArcHydro with the assumption that a drainage area of 4.5 km^2 constituted a stream. The precipitation data were collected by remote precipitation data from the Tropical Rainfall Measuring Mission (TRMM) which produces 3 hourly remote precipitation measurements at 0.25 degree (~30 km) raster pixels. TRMM 3B43 data were downloaded for a range of time periods including prior and post the reported event time. The highest rainfall rate within the catchment during that time period was reported (Table 3 and 6 in appendix).

Human aspects of flooding include damages, deaths, emergency response, and political responses (Table 2) reported in the news reports, post-hazard government publications, and peer-reviewed literature.

4.0 Case Studies

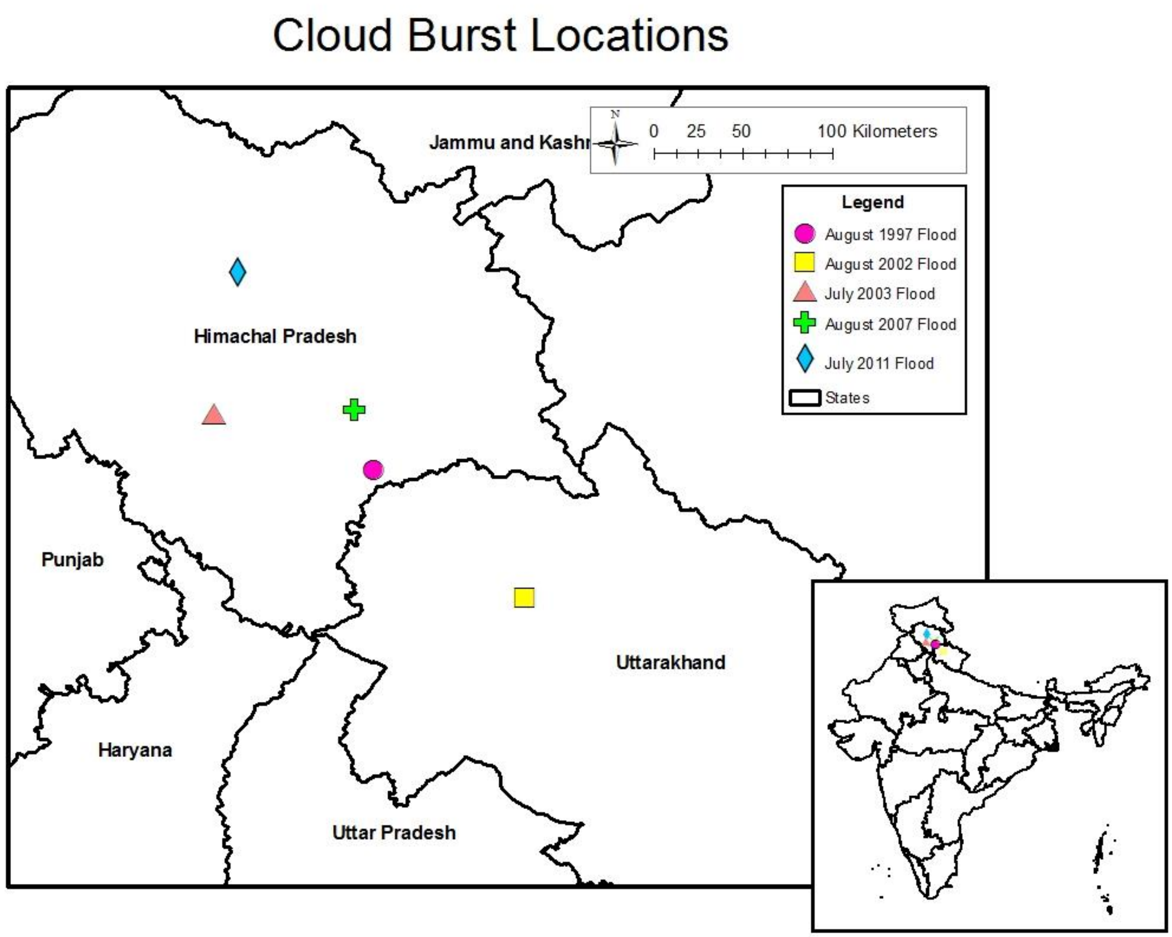

Fig 4: Villages impacted by cloudburst events for case study.

Table 1: Spatial and temporal information for cloudburst events

Date	Time	State	District	Village in Case Study
August 11, 1997	8:30 pm IST	Himachal Pradesh	Kinnaur, Mandi, Chamba, Kullu, Una, Shimla	Chirgaon
August 11, 2002	~ 9pm - 2 am IST	Uttarakhand	Tehri Garhwal	Marwari and Agunda
July 16, 2003	3 am - 4 am IST	Himachal Pradesh	Kullu	Shillagarh
August 14, 2007	unkwn	Himchal Pradesh	Shimala	Bhavi
July 20, 2011	12:30 am	Himachal Pradesh	Kullu	Manali

4.1 August 1997

On August 11th, 1997 at 8:25 pm IST, the Andhra River was reported as "violent" due to a cloudburst over higher reaches (Sharma, 2006). Heavy flooding occurred in the state of Himachal Pradesh in the districts of Shimla, Kinnaur, Mandi, Chamba, Kullu, and Una (Sharma, 2006). One of the most devastated locations was the village of Chirgaon in the Shimla District (Fig. 5), near the confluence of the Andhra and Pabbar Rivers (Chand, 2014).

August 1997 Cloudburst Location

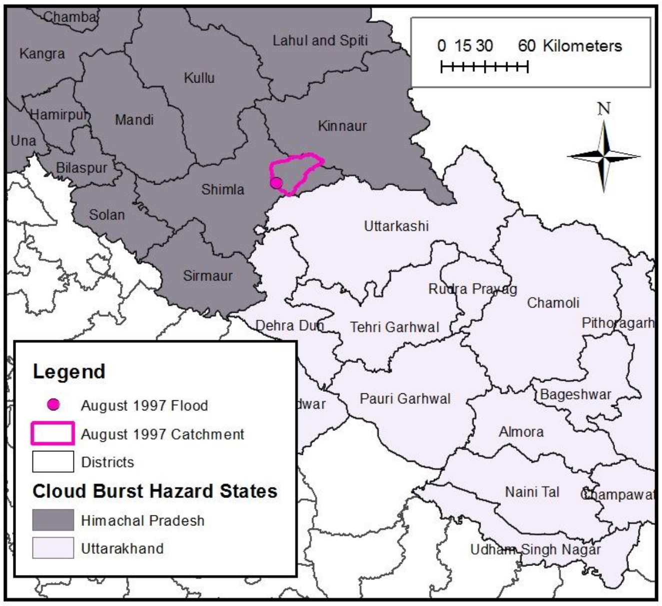

Fig 5: Map of the impacted village and probable catchment area for August 1997 cloudburst.

The exact cloudburst location is disputed, but it appears the event impacted two river basins. Some reports stated the cloudburst occurred on the snow covered ridge on Shatlu Dhar of Rohal Parbat (Chand, 2014) and others claim the Shatul Ghati glacier (Pirta, 2001; Yogendra, 1999). With available data, the potential cloudburst locations could not be found. Flooding occurred in both the Andhra and Sutlej River basins, so this provides some basis for the claim the cloudburst occurred on a ridge between the two catchments (District Disaster Management Authority Shimla, 2012). However, the village of Chirgaon in the Andhra catchment will be the focus of this study.

Regardless of origin, the event caused flooding, landslides, and debris flow, which damaged infrastructure and agricultural land (Sharma, 2006). The cloudburst caused three major blockades with previously-uprooted trees and numerous landslides between Rohal and Chirgaon villages. It also created temporary dams that blocked debris until they collapsed and caused intense flooding downstream (Yogendra, 1999). The Andhra River changed course in the flooding as well (Chand, 2014).

In Chirgaon, the main bazar, fish farm, temple, school, police post, roads, water supply works, and residential buildings were destroyed (Chand, 2014; Sharma, 2006). Debris, mud, and boulders were left behind (Sharma, 2006). Based on reports from an eye witness in Chirgaon, “a major part of the town was buried under several feet of debris” (Fig. 6) (Chand, 2014).

Agricultural land along the bank of the Andhra and Pabbar Rivers was swept away (Chand, 2014) and the Andhra hydroelectric power house and the Nogli power house were damaged (Jain, Agarwal, & Singh, 2007a). Flooding in other districts was associated with landslides and flashfloods during the larger rainfall event. An eyewitness, Tapesh Chauhan, claimed that the river rose “30 to 50 meters above normal levels” (Yogendra, 1999).

Reports list 124 (Sharma, 2006) to 140 fatalities, but an additional 160 migrant workers could not be found and were possibly killed (Chand, 2014). Livestock losses are estimated at 456 cattle (District Disaster Management Authority Shimla, 2012).

Fig 6: Photo of damages from August 1997 flood in Chirgaon (“State Strategy & Action Plan on Climate Change, Himachal Pradesh,” 2012).

Vegetation may play important role in both exacerbating and reducing flood impacts. Overharvest of medicinal "dhoop roots" near Chirgaon appeared to contribute to the landslides, slumping and soil erosion (Yogendra, 1999). These roots are harvested by digging 0.5 m trenches, which are left open (Yogendra, 1999). This is an example of the connection between land use and flood damages. Conversely, Alnus trees are attributed to saving a row of houses in Chrigaon by bearing the water's force and diverting boulders (Chand, 2014).

Some local communities feel there has not been support from institutions, government, political party, or other organization for the affected people (Yogendra, 1999). Another source stated “the administration in our towns neglect the essential services, especially the drainage system” and infrastructure including water supply, solid waste disposal and drainage, is “the last priority" (Nandy, 2005). These claims imply that inadequate disaster response and city planning may contribute to the extensive damages.

4.2 August 2002

On August 10, 2002, a cloudburst was reported in the district of Tehri Garhwal in Uttarakhand (Sah, Asthana, & Rawat, 2003). The cloudburst event occurred in the northern section of Tehri Garhwal in the Medha Gad and Dharam Ganga River valleys (Fig. 7) (Sah et al., 2003). Two of the impacted villages were Marwari and Agunda, which were used in this assessment (Sah et al., 2003).

August 2002 Cloudburst Location

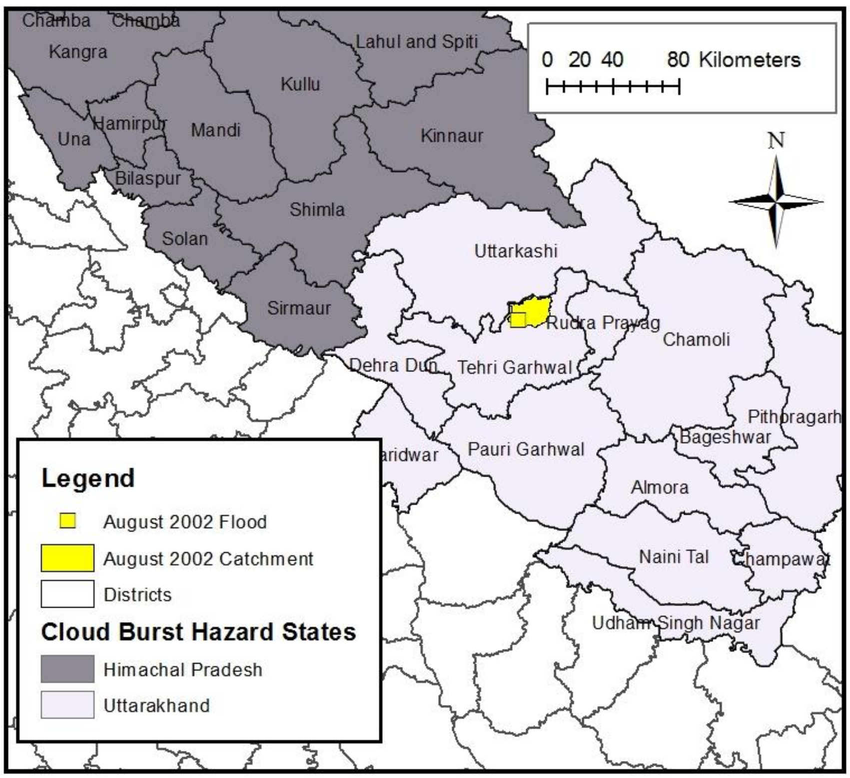

Fig 7: *Map of the impacted village and catchment area for August 2002 cloudburst near Marwari and Agunda.*

The time that the cloudburst occurred is disputed, though it is clear the event occurred at night. Villagers in Marwari and Agunda report that it began between 9pm-11pm (Sah et al., 2003). Other report that it occurred "in late hours" (Asthana & Asthana, 2014), while the Deputy Inspector General, Anil Ratuir, claimed it struck at 2am (The Hindu, 2002).

More than 17 villages and 1200 people were impacted by this event (Asthana & Asthana, 2014). Damages included fatalities, property, landslides, debris flows, and mass movement. There were 14 landslides, debris flows, and debris slides in the region, and some damage to 151 houses. Additionally, a micro hydro power plant at the Medh Gad-Balganga confluence was damaged. (Sah et al., 2003) The death estimate for this event ranged between 28 (Sah et al., 2003) to 33 people (The Hindu, 2002).

4.3 July 2003

During the early morning of July 16th, 2003, a cloudburst flood reportedly occurred in the Kullu district in Himachal Pradesh (Garg, Gujral, Sharma, & Gupta, 2006). The event impacted the village of Shillagarh (Das et al., 2006) which is along the Sarari Khad, Parbali, and Beas Rivers. The village of Shillagarh was not easily located, but based on a map in a paper about the event, the rough village location was determined (Fig. 8) (Das et al., 2006).

July 2003 Cloudburst Location

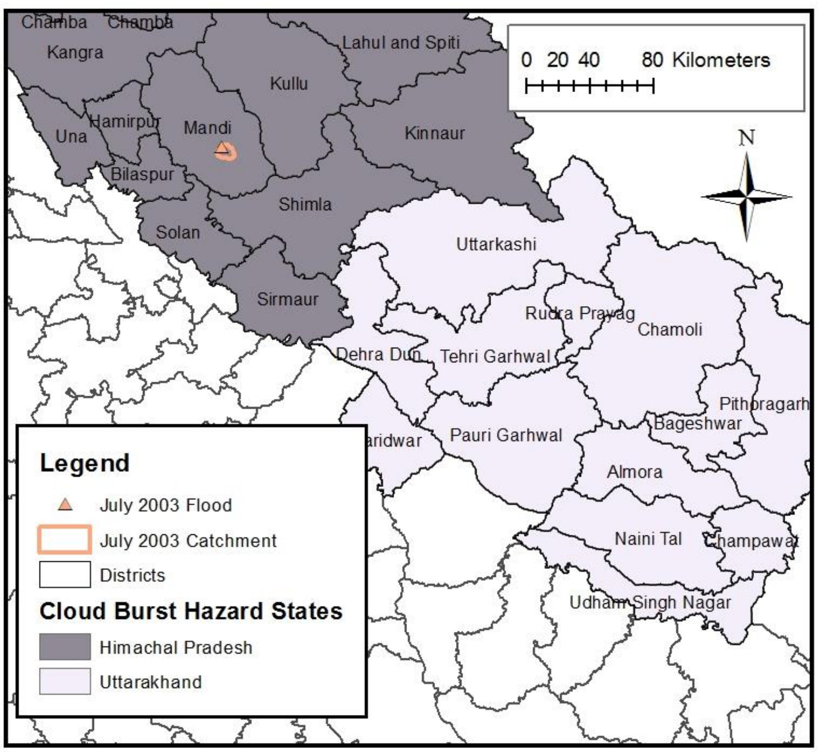

Fig 8: Map of the impacted village and catchment area for July 2003 cloudburst at Shillagarh.

According to one report, the cloudburst occurred between 3 am and 4 am IST (Das et al., 2006). The cloudburst event destroyed roads, communication systems, power supplies, and property (Das et al., 2006) in Shillagarh, but losses weren't reported in nearby Manihar and Nanja villages (Yogendra, 2003). An eye witness explained that some people evacuated their houses and moved uphill, but not everyone could escape (Reuters, 2003). The death count is estimated between 35 (Das et al., 2006) and 150 (Garg et al., 2006). This discrepancy may stem from the fact many of the victim were migrant workers working on a power project and living in shacks (Reuters, 2003). These laborers were from other parts of India and from Nepal (Yogendra, 2003).

Rescue operations and communications after the event were complicated due to the heavy rains following the event. One victim reported that the government "has given us a blanket and bed but nothing to eat" (Yogendra, 2003). The prime minister, Shir Atal Bihari Vajapyee, acknowledged the event and "expressed his heartfelt sympathies with the members of the bereaved families and wished early recovery to those injured" (Vajpayee, 2003).

4.4 August 2007

On August 14, 2007, a cloudburst event occurred near Ghanvi in the Shimla district of Himachal Pradesh (Fig 9) (Yogendra, 2007)near the Sutlej River. The village of Bhavi, population 52, was most impacted. (Yogendra, 2007). While Bhavi was hardest hit, the nearby village of Ghanvi was used for most assessment because it could be found on maps.

August 2007 Cloudburst Location

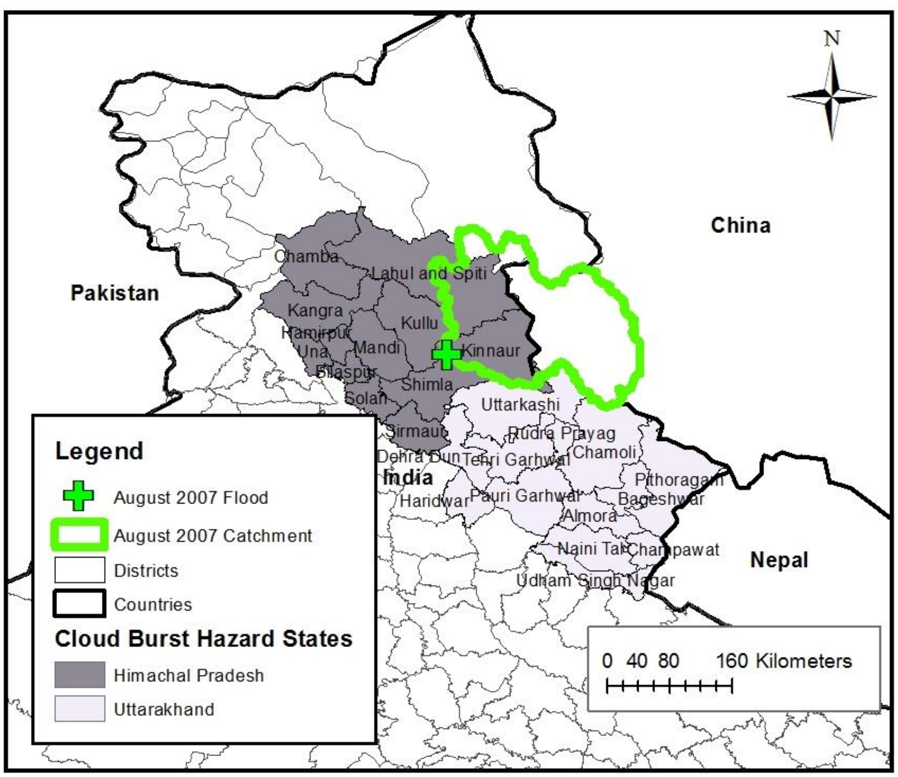

Fig 9: Map of the impacted village and catchment area for August 2007 cloudburst near Bhavi.

The cloudburst event is assumed to have occurred at night, but there was not a clear time reported for the event. One report discussed relief operations that started in the morning of August 15th, 16 hours after the event (Lohumi, 2007). It was assumed that the rainfall event occurred between 4 pm and 7 am (Asthana & Asthana, 2014).

The event included large debris movement, landslides, and, possibly, a temporary lake. Residents reported hearing a "thunder-like sound as the rubble moved" and when the cloudburst occurred, a "huge mass of slush and rubble" was reported to move toward the village without warning. There has been speculation that the debris flood was caused by both a temporary lake formed by a landslide and a landslide from another side (The Tribune, 2007).

The flood event is estimated to have killed over half of the village's population and caused substantial damage (The Tribune, 2007). In the village of Bhavi, the Chief Minister, Virbhadra Singh, reported that at least 15 houses, a health center, a school building, and apple orchards washed away in the cloudburst event (Yogendra, 2007). Debris and mud (Fig. 10) were reported up to 20 feet deep in some parts of the village (Lohumi, 2007). Additionally, all roads (Fig. 11) to the village were blocked with reports of landslides over 18 locations (Lohumi, 2007). Power and the water supply were also washed out (Lohumi, 2007). The death toll was reported between 52, including 10 children. (Yogendra, 2007) and 58 (State Centre on Climate Change, 2014).

Fig 10: Aerial image of destruction from August 2007 cloudburst near Bavi. (The Tribune, 2007)

Fig 11: Bridge in Ghanvi village that collapsed due to August 2007 cloudburst (Lohumi, 2007).

Relief operations began the morning following the cloudburst. Rescue operations were hampered due to initial lack of earth moving equipment and difficulty accessing the village because all roads were blocked by landslides (Lohumi, 2007). The army, Indo-Tibetan Border Police, Armed Border Force (Sashastra Seema Bal, SSB), Central Industrial Security Force, home guards, and police were involved in rescue efforts. In nearby at-risk villages, the administration moved 14 families and provided blankets, tarpauline, and food grains (Lohumi, 2007).

Monetary relief was also provided to families. It was reported that Rs 10,000 was given to all affected people (The Tribune, 2007), and next of kin to those killed were given Rs 100,000. Survivors with destroyed houses were given Rs 50,000 (Lohumi, 2007). As of August 16, Rs 2,600,000 was distributed to affected families and a common kitchen available to all, called a "langar", was established. Additionally, the army put up tents, and a medical team was stationed nearby (The Tribune, 2007). Officials, including Chief Minister Virbhadra Singh, claimed rehabilitation would be carried out for the area, possibly including providing alternative land to families and replanting forests (Yogendra, 2007).

4.5 July 2011

On July 20, 2011, the town of Manali, near the Beas River, in the district of Kullu in Himachal Pradesh was allegedly hit by a cloudburst flood (Fig 12) (Sharma, 2011). Reports claim the cloudburst event occurred near the south portal of the Rohtang Tunnel (Sharma, 2011).

July 2011 Cloudburst Location

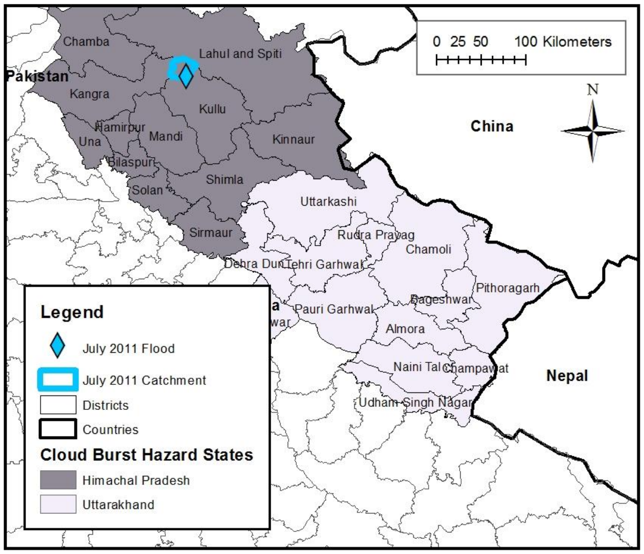

Fig 12: Map of the impacted village and catchment area for July 2011 cloudburst near Manali.

According to Balbir Thakur, the Manali sub-divisional magistrate, the flood started around 12:30 am IST. Witnesses say that they “heard a loud sound of flowing water and debris" (Fig 13) (Sharma, 2011). Many of the affected were laborers working on the approach road to the Rohtang tunnel (Fig 14). These laborers were working on the site until 11:30pm so the disaster could have been much worse if the flood had occurred earlier (Sharma, 2011). The cloudburst injured 22 laborers and killed 2 (Sharma, 2011) to 8 people (Ray, Doshi, Alag, & Sreedhar, 2011).

Fig 13:Damages from July 2011 cloudburst near Manali (Himachal, n.d.) .

Figure 14: Damages from July 2011 cloudburst near Rohtang tunnel ("Himachal Vacation Travel Guide," n.d.).

Search and rescue was carried out by the Indo Tibetan Border Patrol, SSB, Snow Avalanche Study Establishment, Border Roads organization, some private construction companies, and Atal Bihari Vajpayee Institute of Mountaineering and Allied Sports (Sharma, 2011).

Kullu deputy commissioner BM Nanta said there was a strong possibility of cloudburst, but there was also "a huge broken part of a glacier above the region which could have made the disaster" (Sharma, 2011). Additionally, a newspaper stated the event was not a cloudburst event because nearby precipitation measurements in Udaipur and Fingri were 24mm and 73 mm, respectively, for the day (Lohumi, 2011).

5.0 Results and Discussion

Table 2: Reported impacts of studied cloudbursts.

Year	Village in Case Study	River	Related Events	Damages	Deaths	Responses
1997	Chirgaon [1]	Andhra, Pabbar, Sutlej	·landslides ·debris flows ·stream changed course ·blockades ·temporary dams [1–3]	· main bazar · fish farm · temple · school · police post · roads · water supply works · residential buildings · Andhra/Nogli power houses · livestock [1,2,4]	124-300 people (possibly 160 more migrant laborers) [1,2]	· town unprepared · caused by denuding hills for roots [3,5]
2002	Marwari and Agunda [6]	Medha Gad, Dharam Ganga [6]	·landslide ·debris flow ·mass movement [6]	· 151 houses · micro hydro power plant · 17 villages · 1200 people [6,7]	28 – 33 people [6,8]	
2003	Shillagarh [9]	Dal Khad		· Roads · communication systems · power supplies · property [9]	35 – 150 people (many migrant workers) [9,10]	· provide blanket and bed · prime minister acknowledged damages [11,12]
2007	Bhavi and Ganvi	Sutlej	·landslides ·debris flow [13]	· houses · school · medical facility · roads · apple orchards · power and water supply [14,15]	52 – 58 people [14,16]	· lack of earth moving equipment at first · difficult to access · search and rescue 14 families moved · provided blankets tarpauline, food · monetary relief [13,15]
2011	Manali [17]	Beas River	·debris flow [17]		8 people (including laborers) [18]	· Search and rescue [17]

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Table 3: Site characteristics for cloudburst flood events.

Year	Village in Case Study	Stream Order	Area of Catchment with Landslide Hazard Slope	Peak TRMM Rainfall in Catchment	Elevation of Village	Catchment Elevation Range
1997	Chirgaon	1st – 3rd Order	76%	N/A	1900m	1740 to 5220 m
2002	Marwari and Agunda	1st – 3rd Order	77%	14.2 mm/hr	1820m and 2000m	1300 to 4830 m
2003	Shillagarh	1st – 2nd Order	75%	5.33 mm/hr	2100 m	1650 to 3200 m
2007	Bhavi and Ganvi	1st – 7th Order	57%	1.74 mm/hr	1750 m	1170 to 7170 m
2011	Manali	1st – 4th Order	76%	1.84 mm/hr	1800 m	1810 to 5880 m

5.1 Similarities

Temporal, spatial, hydrological, and damage similarities occur across the five events.

Temporally, all of the cloudburst events occurred during the monsoon season, between July and August (Table 1). This is likely because 90% of the precipitation in India occurs during the monsoon season (Jain et al., 2007c). Additionally, all of the events occurred at night, roughly between 8 pm and 4 am (Table 1), which is consistent with previous studies (Asthana & Asthana, 2014). Studies have indicated that the Northern India Convergence Zone, which includes the Himalayan range, has strong convective night-time activity, especially between 1:00 and 3:00 am (Barros et al., 2004). The night time rainfall pattern has been hypothesized to result from low level convergence on windward valley slopes due to downslope flow, evaporative cooling of rainfall, and evapotranspiration (Barros et al., 2004). Assuming cloudburst events are associated with convective currents, these processes could explain the prevalence of nocturnal cloudburst events.

Spatially, the elevations for the impacted villages ranged between 1,600 and 2,100 meters (Fig 15). This is consistent with the maximum elevation of 2,400 meters expected from cloudbursts in Utah (Woolley et al., 1946). It is unclear if this elevation range is where cloudbursts exclusively occur or if it is the elevation range that people live in within the Himalaya.

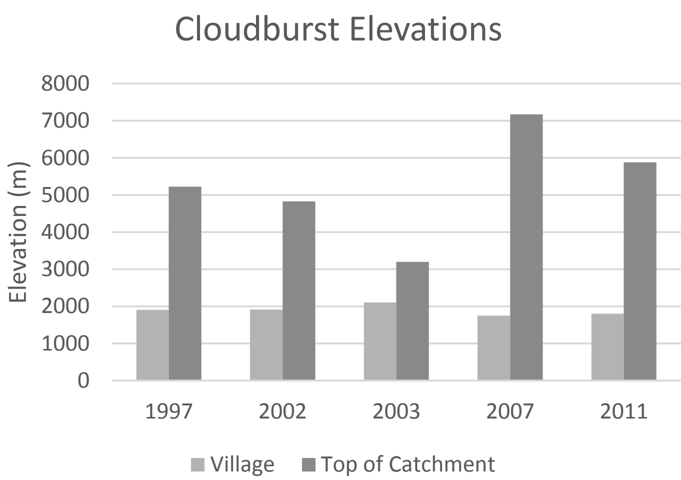

Fig 15: Elevation of villages impacted by cloudburst flood and the elevation of the top of the catchment which is assumed to includethe cloudburst event.

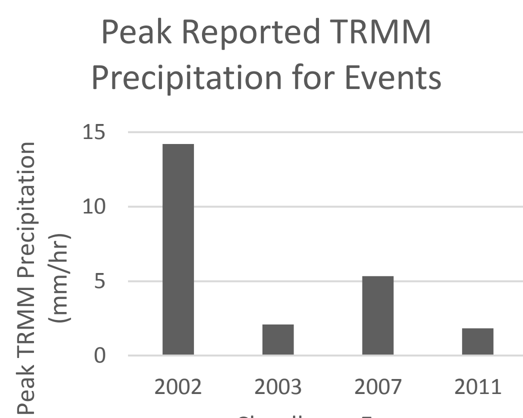

Fig 16: Peak precipitation (mm/hr) reported from gridded Tropical Rainfall Monitoring Measurements (TRMM) for cloudburst events.

Across all of the events, the TRMM signature was substantially lower than the definition of cloudburst precipitation intensities over 100 mm/hr (Fig 16 and 17). The lack of a precipitation signature is likely due to the coarse spatial and temporal TRMM 3B43 data. TRMM data used in this study is processed into a 30 km by 30 km pixel grid. The spatial resolution of TRMM measurements makes cloudburst detection difficult since the events are less than 30 km^2 compared to 900 km^2 pixels (Das et al., 2006). Additionally, the moisture measurement in TRMM is prone to underestimating precipitation because precipitation is averaged over the whole pixel area. The temporal resolution for TRMM data is coarse as well because the satellite's orbit allows measurements every 91.3 minutes (Lin, Fowler, & Randall, 2002). Each TRMM precipitation rate is derived from 2 measurements taken 1.5 hours apart and since cloudburst events happen over a period of less than one hour (Thayyen et al., 2013; Woolley et al., 1946), it is possible the sensor entirely misses events. Alternative data sets, including total lightning data, may be an alternate way to remotely sense cloudburst events.

2011 Remote Sensed Precipitation

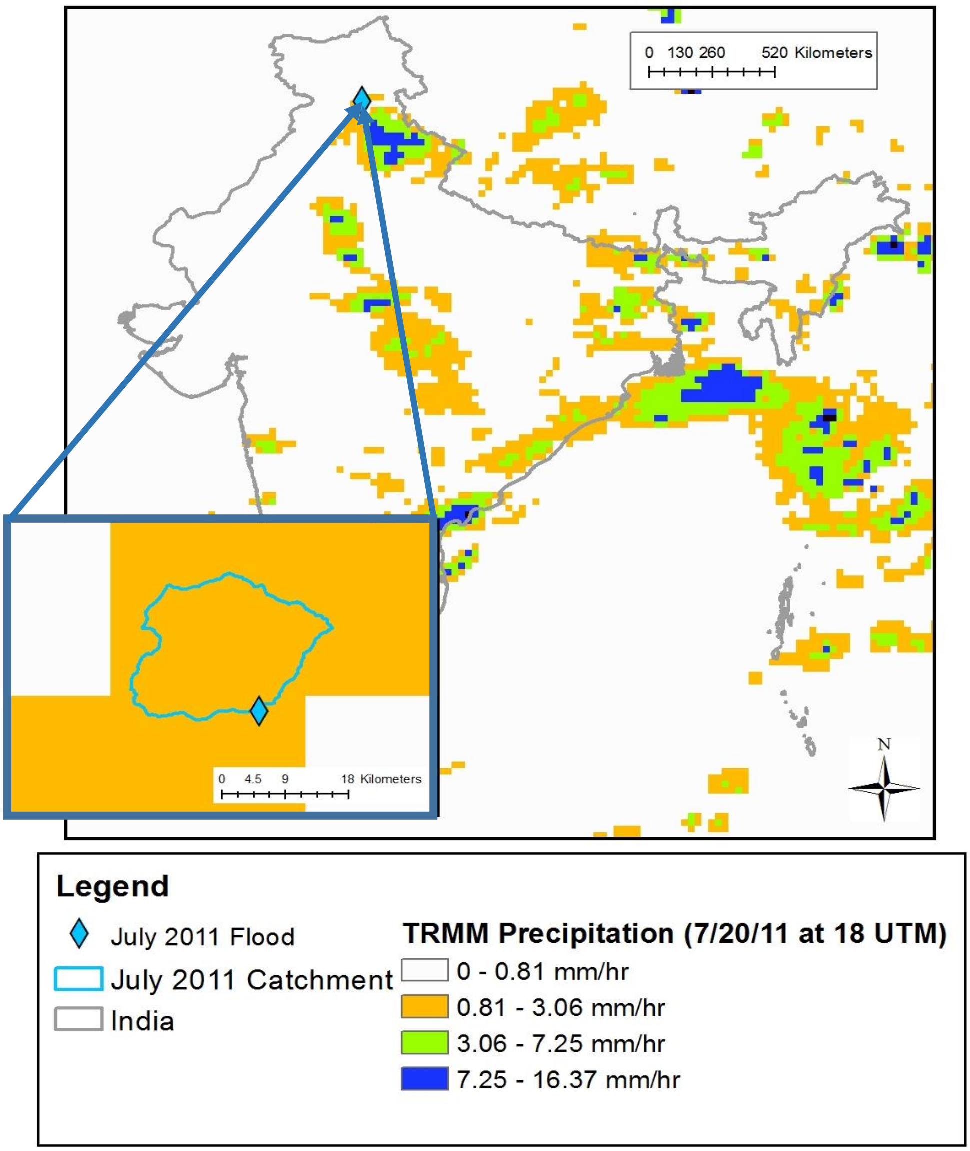

Fig 17: TRMM precipitation on July 20th, 2011 at 18:00 UTM. The pop-out box shows the catchment for the July 2011 cloudburst event. Based on this data, the peak rainfall at the cloudburst location was between 0.81 and 3.06 mm/hr, significantly lower than the cloudburst threshold. The lack-of a cloudburst signature in the TRMM data was true for all cloudburst events that were studied.

Hillslope is a factor in land movement and landslides, and it was similar across cloudburst areas. Land movement in the Himalaya is related to the geology, structure, geomorphology, moisture antecedent conditions, and intense precipitation (Caine, 1980; Rahardjo, Li, Toll, & Leong, 2001; Varnes & others, 1984). It has already been established that cloudburst events help facilitate land movement because they occur during the monsoon season, where there is ample antecedent moisture from monsoonal rains, and the intensity of cloudburst events have the potential to be well above estimated landslide thresholds (Caine, 1980). A 20 degree threshold for landslide hazard slopes was assumed (Harp, Michael, & Laprade, 2008) and it was that all five of the events occurred in catchments where over half of the area was at risk for landslides based on slope (Fig 18).

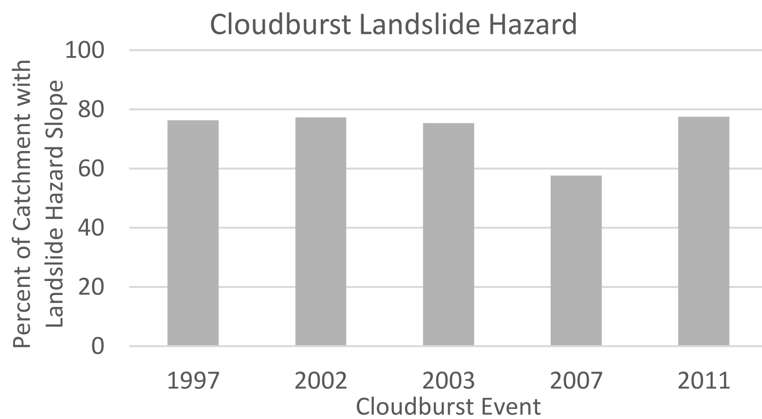

Fig 18: The percent of each catchment with slopes greater than 20 degrees, which is established as the landslide hazard threshold.

Landslides and debris flows caused the most substantial damage in all the studied cloudburst events, as reported in the literature and media. The flow related to a cloudburst event is very muddy and turbulent and usually carries trees, debris, bed load, and boulders (Woolley et al., 1946). It is important to note that there is a selection bias in this study as only cloudburst events associated with damages to human impacts are reported (Fig 19). This could impact the types of events studies and create a bias toward destructive, debris-flow-centric events.

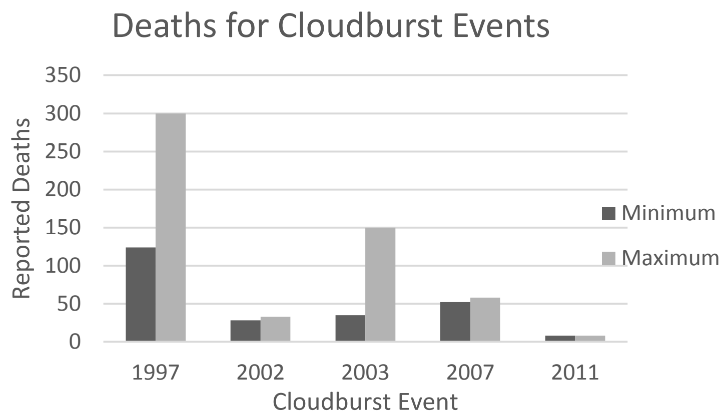

Fig 19: Minimum and maximum reported fatalities for cloudburst events.

Other trends emerged regarding indirect effects of the cloudburst events. First, a common effect of the debris flows and landslides in cloudburst events is making villages inaccessible by blocking or washing away roads. This could be due to cloudbursts occurring in geographically vulnerable areas that may only have one access point, and it underscores a key concern with cloudburst events; rescue and aid operations are incredibly difficult. Next, two of the flood events (in 1997 and 2002) damaged hydropower operations, likely due to the location of hydropower stations in steep, mountainous systems near people. Finally, there is a consistent trend in high fatalities among migrant workers for three of the events, in 1997, 2003, and 2011.

5.2 Uncertainties

There is substantial uncertainty surrounding the exact location of cloudbursts, which leads to uncertainty in trends across precipitation regimes, orientation, and stream order. The TRMM data do not capture the unique event signature (Fig 16 and 17). In addition, there is limited gauging, and radar information is not available to determine the location or the precipitation regime. Patterns across the slope orientation could not be assessed. Although precipitation gradients have been observed at altitudes, between ridge zones, and within ridges and valleys (Barros et al., 2004), this study could not assess variation or patterns in spatial arrangement of topography. Finally, stream orders were determined across each region, but patterns between stream orders and rainfall events could not be determined without the cloudburst's exact location.

5.3 Limitations and future research

All of the data have errors associated with inconsistent reporting, lack-of-information, and circulation of unreliable information. The information contained in this study reflects the best available, but is likely to have errors. These discrepancies could be corrected with site visits, additional interviews, or more detailed government records. The lack of information also reflects the recurring difficulties with study in the Himalayas, especially surrounding hydrology. Due to the discrepancies, considerable caution should be used with cloudburst reporting.

This study focused only on the cloudburst event, but they usually occur in conjunction with landslide lake outburst floods or heavy rainfall. The embedded nature of cloudburst events is a large factor in the difficulty in measuring or predicting the events. Separating the small scale cloudburst event from the larger precipitation event is problematic due to data limitations with rainfall measurements, reporting, and public understanding. Further research on the hydrology of specific cloudburst events, especially the precipitation regime, stream discharge, and atmospheric conditions, would improve scientific understanding which would enable researchers to better distinguish cloudburst events and improve planning and disaster management.

Some of the cloudburst reports discussed relief operations, but the information was not comprehensive so it is not possible to draw conclusions about quantity or quality. This is an important part of disaster management, and additional study should emphasize the most effective strategies for reducing losses associated with cloudburst events.

Finally, future research could attempt to verify, disprove, or explain the trends that were found in this study or those reported elsewhere. This study intended to shed light on potential temporal aspects, geographic location, and impacts, but five studies are not enough to make statistically significant statements.

6.0 Conclusion

The Himalayan region is vulnerable to flooding events, some of which one of which are not well understood, including cloudburst rainfall events. This study investigated the similarities in temporal, spatial, hydrologic, and damage characteristics of five cloudbursts events in the northwestern Himalayan region. Trends were found in impacted village elevation, occurrence during the monsoon and at night, lack of precipitation signature in remotely sensed data, damage from landslides, migrant workers as major fatality, and impacts to roads and hydropower power. These similarities demonstrate common patterns across cloudburst events and the potential for better defining the events to improve forecasting and reduce fatalities. Limitations in data and uncertainty surrounding cloudburst events, including cloudburst location, precipitation regime, and presence in weather patterns, underscore the difficulties in current study. Without greater understanding around the listed uncertainties, it is impossible to fully understand cloudbursts as a unique and independent precipitation event, and prediction and management is difficult.

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Appendix

Table 4: Sixteen cloudburst events between 1997 and 2013 found with literature reviews, newspaper articles, and governmental records. The five highlighted events were selected for further assessment of trends based on the quality and quantity of sources, and the distribution across space and time.

Date	State	Locations Mentioned	Scientific Literature		Newspaper Sources			Count of Sources
August 11, 1997	Himachal Pradesh	Shimla District	Sharma. (2006). Floods and Flash Floods in Himachal Pradesh: A Geographical Analysis.	Chand, J. (2014). Mechanism of Landslides of National Highway-22 in Himachal Pradesh. International Referred Online Research Journal.				2
July 29-30, 2001	Himachal Pradesh	Chhota Bhangal and Baijnath Sub Division of Kangra District	Pandey, V., Mishra, A., Mishra, S. Jan 2015. Climate Change And Mitigation Measures For The Hydrometerological Disaster In Himachal Pradesh, India- In Light Of Dams.					1
August 21-22, 2001	Himachal Pradesh	Ani Sub Division, Kullu District	Pandey, V., Mishra, A., Mishra, S. Jan 2015. Climate Change And Mitigation Measures For The Hydrometerological Disaster In Himachal Pradesh, India- In Light Of Dams.					1
July 23, 2001	Himachal Pradesh	Kullu	Pandey, V., Mishra, A., Mishra, S. Jan 2015. Climate Change And Mitigation Measures For The Hydrometerological Disaster In Himachal Pradesh, India- In Light Of Dams.					1
August 10, 2002	Uttarakhand	Tehri Garhwal	Sah, M. P., Asthana, A. K. L., & Rawat, B. S. (2003). Cloud burst of August 10, 2002 and related landslides and debris flows around Budha Kedar (Thati Kathur) in Balganga valley, district Tehri. Him. Geol, 24(2), 87–101.	Asthana, A. K. L., & Asthana, H. (2014). Geomorphic Control of Cloud Bursts and Flash Floods in Himalaya with Special Reference to Kedarnath Area of Uttarakhand, India. INTERNATIONAL JOURNAL OF ADVANCEMENT IN EARTH AND ENVIRONMENTAL SCIENCES, 2(1), 16–24.	12 Aug 2012. "33 killed in cloudburst". The Hindu.			3
July 16, 2003	Himachal Pradesh	western Himalayas, about 50 km from Shimla and 35 km from Mandi, Gharsa valley in Kullu District	Simulationg of Himalayan Cloudburst Event		18 Jul 2003. "India: At Least Forty People Believed Dead and about Thirty Missing After Torrential Rains". Reuters.	Yogendra, Kanwar. 17 Jul 2003. "Himachal cloudburst: bodies yet to be recovered". The Hindu.	Yogendra, Kanwar. 17 Jul 2003. "40 killed in Himachal cloudburst, flash floods". The Hindu.	4
July 6, 2004	Uttarakhand	near Badrinath shrine area Chamoli			6 Jul 2004. "17 killed as cloudburst hits Badrinath area". Outlook.			1
August 16, 2007	Himachal Pradesh	Bhavi village in Ghanvinear sutlej river, upstream of Rampur gauge	Asthana, A. K. L., & Asthana, H. (2014). Geomorphic Control of Cloud Bursts and Flash Floods in Himalaya with Special Reference to Kedarnath Area of Uttarakhand, India. INTERNATIONAL JOURNAL OF		16 Aug 2007. "52 casualties confirmed in Ghanvi cloud burst". The Hindu.	Lohumi, R. 16 Aug 2007. "Identity of 28 missing established Ghanvi: 5 bodies recoevered". The Tribune.		3

(Table 4 continued)

Date	State	Locations Mentioned	Scientific Literature	Newspaper Sources	Count of Sources
August 7, 2009	Uttarakhand	Pithoragatrh		Khanna, Rajeev. 8 Aug 2009. "38 die in Pithoragarh cloudburst, rescue works on". The Indian Express.	1
Aug 6-10, 2010	Jamu and Kashmir	Leh and Ladakh	Thayyen, R. J., Dimri, A. P., Kumar, P., & Agnihotri, G. (2013). Study of cloudburst and flash floods around Leh, India, during August 4–6, 2010. Natural Hazards, 65(3), 2175–2204.		1
August 20-21, 2011	Himachal Pradesh	Manali, South Gate of Rohtang Tunnel	Ray, M., Doshi, N., Alag, N., & Sreedhar, R. (2011). Climate Vulnerability in North Western Himalayas. Environics Trust.	Sharma, Suresh. 21 Jul 2012. "Cloudburst in Manali: 2 dead, many missing". The Times of India	2
August 12, 2011	Himachal Pradesh	Manali, Chhaki, Pulag, Shoran, and Rumsu villages		Sharma, Suresh. 12 Aug 2011. "Cloudburst in Chhaki village of Kullu, nocasualties". The Times of India.	1
August 16, 2011	Himachal Pradesh	Mandi, Kullu, Lahaul, Sirmour, Solan, Manali; near Rani Nullah		17 Aug 2011. "Rain wreaks havoc in state; 14 killed". The Tribune.	1
June 9, 2011	Jammu and Kashmir	135 from Jammu, Doda-Batote highway		Jun 10, 2011. "Doda cloudburst: 4 feared dead, several stranded". NDTV.	1
September 14, 2012	Uttarakhand	Rudraprayag district in UK		Kumar, Suresh. 17 Sep 2012. "Fresh landslides in Uttarakhand, toll 39". The Times of India.	1
June 15-17, 2013	Himachal Pradesh	Kinnaur District	Pandey, V., Mishra, A., Mishra, S. Jan 2015. Climate Change And Mitigation Measures For The Hydrometerological Disaster In Himachal Pradesh, India- In Light Of		1

Table 5: TRMM Rainfall quantities for each cloudburst event.

2002

Date	UTM Time	IST Time	Within Catchment (mm/hr)		Nearby Catchment (mm/hr)			
10-Aug-02	15	20.5	12.55	8.96	13.28	12.87	0	0
10-Aug-02	18	23.5	14.2	13.7	12.9	24.13	15.03	13.55
10-Aug-02	21	26.5	0	0	7.2	0	0	0
11-Aug-02	0	5.5	0.31	0	4.4	0	0	0
11-Aug-02	3	8.5	0	0	0	0	0	0

2003

Date	UTM Time	IST Time	Within Catchment (mm/hr)		Nearby Catchment (mm/hr)			
15-Jul-03	21	2.5	1.73	5.33	11.18	2.52	3.25	5.96
16-Jul-03	0	5.5	0	1.68	1.60	1.08	3.44	1.92

2007

Date	UTM Time	IST Time	Within Catchment (mm/hr)		Nearby Catchment (mm/hr)			
14-Aug-07	12	17.5	1.58	0	0.9	2.3	3.04	0.902
14-Aug-07	15	20.5	0	0	0	0	0	0
14-Aug-07	18	23.5	0	0	0	0	0	0
14-Aug-07	21	2.5	0.86	0.9	1.54	1.7	0	0
15-Aug-07	0	5.5	1.74	0.62	0	0	0	0

2011

Date	UTM Time	IST Time	Within Catchment (mm/hr)		Nearby Catchment (mm/hr)			
20-Jul-11	18	23.5	1.84	1.35	1.92	1.55	0	0
20-Jul-11	21	2.5	0	0	0	0	0	0
21-Jul-11	0	5.5	1.28	2.02	1.65	2.24	0	0
21-Jul-11	3	8.5	0	1.46	0	0	0	0

Table 6: Landslide hazard slope measurements for all cloudburst events.

Cloudburst Event	Catchment Area (km^2)	Hazard Slope Area (km^2)	Percent of Catchment in Hazard Slopes
1997	644.56	491.56	76.3%
2002	411.38	318	77.3%
2003	77.55	58.5	75.4%
2007	42695.07	24608.79	57.6%
2011	491.77	381.11	77.5%