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Orographic and Tectonic Control on Extreme Events with Special Reference to Uttarakhand Disaster of June 2013 in the Mandakini Valley, India

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Abstract

This study deals with the climate change and its impact on changing precipitation behaviour, consequent events of extreme rainfall (cloudburst), landslides and flash floods. In this work, TRMM (Tropical Rainfall Measuring Mission) 3B42RT(real time) precipitation data for 16 (1998-2013) years was utilized to understand the present variation of precipitation and extreme events such as cloudburst, flash floods, and landslides in Western Himalaya. It was observed that the extreme events are mainly restricted to the south of higher Himalaya, coinciding with high precipitation. Since, the higher Himalaya is bounded by MCT (Main Central Thrust), it could be envisaged that this zone has been acting as orographic barrier hence most of high precipitation and extreme events are confined below the area. This orographic barrier plays a significant role in controlling the expectancy and extent of high rainfall and thus triggering of the associated hazards like landslides. A case of Mandakini valley where Kedarnath disaster of June 2013 has caused loss of over five thousand lives and properties worth billions has been studied.

Keywords: Extreme events; Landslide; Rainfall; Uttarakhand; TRMM (Tropical Rainfall Measuring Mission); Mandakini valley; Orographic barrier

Introduction

The changing pattern of climate is one of the prime concerns of today's world. Every area of the earth is facing brutal consequences of climate change but the impact of change is not distributed evenly across the world. Mountain ecosystems are more sensitive to the habitat and climate change due to interaction of tectonic, geomorphic, ecological and climate agents [1]. However, apart from nature's fury, human intrusion in search of life and prosperity has enhanced these catastrophic events in the Himalayan region. Water and climatic hazards include cloudburst, landslide, floods, glacial lake outburst Flow, and drought. Of all the hazards, landslide is common in both geological and climatic hazards. The tectonic activities coupled with high precipitation and anthropogenic activities have played a vital role in triggering the majority of landslides in this area. The great Himalaya is one of the world's most sensitive areas to the climate change. High precipitation throughout the Himalaya has resulted into disastrous events like landslides, cloudbursts, bank erosion flash floods etc. Heavy rainfall is one of the major climate challenges that Himalayan range faces due to its steep and fragile topography. Among all the Himalayan states, Uttarakhand region is the most affected by extreme events like landslides. Along the southern Himalayan front, rainfall for up to several meters per year has resulted into erosion and heavy flooding [2-4].

For better understanding and analysis of precipitation, TRMM (tropical rainfall measuring mission) satellite was launched in November 1997 [5]. TRMM gives real time (RT) rainfall data annually, monthly and three hourly. TRMM is a joint mission of NASA and Japan Aerospace Exploration Agency (JAXA) satellite for precipitation records [6]. TRMM 3B42RT data was used for the study because of its continuous availability, accuracy, resolution and also lack of the Indian Meteorological Department (IMD) rain gauges above 3500 metres. Relationship of precipitation with the Himalayan topography is poorly defined [7]. Presence of mountainous topography influences the direction of wind and disturbs the vertical stratification of atmosphere by acting as a physical barrier [8]. So if the spatial pattern of precipitation is understood over a region then it can give the development of landscape, rate of erosion and its interaction with the precipitation. Spatial variation in precipitation so far has received very less attention for the study of relation in between climate, tectonics and erosion [7,13]. The study of spatial variability of extreme rainfall events helps to identify the zone of high and low value of extreme rainfall events [9]. Data of extreme events have been collected from year 1951-2014 to understand the changing trend of extreme events with changing behaviour of precipitation in western Himalayan region. Hence this paper mainly focuses on the interaction of the TRMM precipitation with topography/relief in the Western Himalayan region which is further checked on a watershed of Mandakini Valley. The case study of Mandakini valley with respect to Uttarakhand disaster of June 2013, which was initiated by an extreme event of precipitation, shows the importance and concerns on the climatic effects avoiding which can lead to widespread disasters. The area is inherited by great variability in lithology and has structural controls. The presence of tectonically active MCT (Main Central Thrust), highly sheared and fractured rocks makes the area vulnerable to mass movements in case of extreme events like unprecedented rain or cloudbursts occurs. It was one of the main factors which has caused hundreds of landslides, consequent damming of river, flash flood etc. during the disaster of June 2013 [10].

Study Area

Spatial variation in precipitation was studied for the western

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Himalayan region extending from 73⁰ E to 81⁰E. The rainfall map has been generated to cover geological settings having various major faults like MBT, MCT, ITSZ etc. For precipitation variation and its changing pattern with reference to relief change along these major thrusts in the western Himalayan region. For extreme events study, main emphasis was given to Uttarakhand region particularly south of MCT because of its higher degree of proneness to mass movements mainly landslides in relation to extreme events/high precipitation and its fragility due to tectonic and anthropogenic mismanagement.

Methodology

TRMM has provided real time rainfall data for last sixteen years i.e., from 1998 to 2013. TRMM RT precipitation data was downloaded and used for calculation of average annual rainfall of each year section wise. Precipitation maps on the basis of temporal variation, as Pre-monsoon (February–May), Monsoon (June-September) and Post Monsoon (October-January) using Arc GIS 9.3 version were prepared. The statistical analysis for average annual precipitation was done for each year. On the basis of maximum, minimum and mean precipitation, three years of average annual rainfall data 1998, 2005 and 2010 was selected to understand the behaviour of the precipitation over western Himalayan region. Also, for Uttarakhand region, data on extreme events was collected for last 63 years to understand the long term effect of precipitation on extreme events such as cloudburst, flash flood and landslide. The graph has been plotted keeping the frequency of occurrences on x axis while the year of occurrence of extreme events on y axis.

Results and Discussion

In western Himalayan region, the precipitation is sparsely varied as it responds to both monsoon moisture from Bay of Bengal and westerly winds moisture [7,11,12]. There are two rainfall gradient along the Himalayan region, firstly an east west gradient with rainfall occurring closer to moisture source i.e., Bay of Bengal and secondly the north south gradient which is from rain drenched southern flank to semi-arid Tibetan plateau [3,7,13-15]. The east west gradient rainfall is mainly confined to eastern and central Himalayan region while the western Himalayan region is mostly influenced by the north south gradient [7]. The north south gradient is a consequence of orographic rainfall i.e., rising topography in the face of prevailing winds which causes lifting of humid air, cooling, condensation and precipitation [3,7,8,16]. An analysis on annual average TRMM precipitation (mm) for year 1998, 2005 and 2010 has been done (Figure 1 indicates only for year 2005 and for the rest of two years Figures are not given as there wasn't enough space in the paper, however following analysis will give the clear picture of precipitation variation during the Pre-monsoon, Monsoon and Post-monsoon. It is observed in Figure 1 that intense pre monsoon precipitation can be seen in the Northern section of the western Himalaya (Kashmir Nappe) which is a relief, stopping the moist air to cross.

In the southern flank, most of the precipitation is constrained around MCT, which is a result of western disturbances i.e., north south gradient, while during the monsoon season the precipitation is dominant in the southern part of the western Himalaya (Rampur Window, Chail Nappe). Also the precipitation has shifted from north during the Pre-monsoon season to south in Monsoon season and during the Post-monsoon season; rainfall is mostly dominant in southern part of the western Himalaya (Garhwal, Pithoragarh). The areas receiving high rainfall are the areas having a change in relief which results into change in rainfall. The higher Himalaya has received a lot of significance in terms of receiving high precipitation near its toe [7,17]. The data analysis done for year 1998-2013, shows prolong extend of high precipitation along the southern edge of Lesser Himalaya (Figure 1) as noticed by Bookhagen and Burbank, for the study of TRMM data for Himalayan region for 1998-2005. It is quite conspicuous that this rainfall has basically been triggered due to topography change hence blocking the moist air to pass by Haselton, Bookhgen and Burbank. But still, the control of relief/ topography is poorly defined.

High precipitation is mainly confined to south of highest reliefs are for tens of kilometres after which the precipitation drastically changes as observed in the Figure 1 [7]. As observed from the Figure 1, it is quite evident that the precipitation along the western Himalayan region is continuous and changes drastically with change of relief which was also observed by Bookhagen and Burban.

The average annual precipitation rate, standard deviation, and relief profile, indicates that the change in relief (around klippes and nappes, windows), near MCT (lesser Himalayan section), sudden change in topography at the toe of higher Himalayan section, near Indo-Gangetic plains and lesser Himalaya is one such factor swinging moist air around the reliefs and resulting into high precipitation. It is observed that the heavy precipitation in western Himalayan region is mainly confined below the MCT zone which acts as a physical/orographic barrier [10]. It has also been noticed that on moving from west to east along the western Himalayan section, precipitation changes for pre monsoon, monsoon and post monsoon. From west to east, precipitation shows a decreasing behaviour. It is important to mention here that though the higher Himalaya are more tectonically active, more exposed to erosion

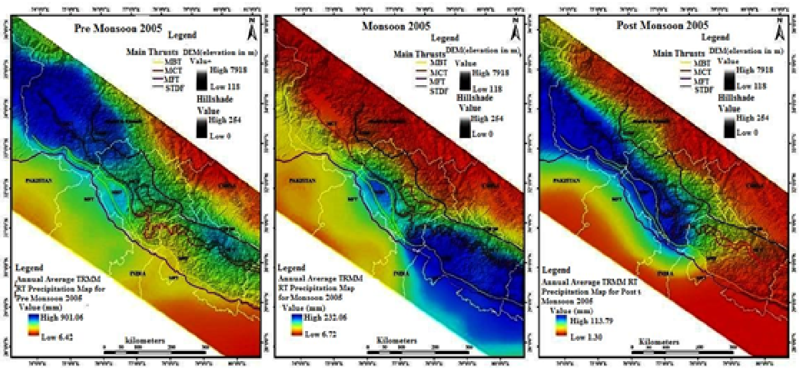

Figure 1: Showing the western section of Himalayan region for year 2005.

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and lithologically fragile, most of the landslides have been reported from lesser Himalaya section. Precipitation is one major factor which has made these areas more prone to landslides than the higher Himalaya. Analysis of extreme for last 63 years done on a decadal basis exhibits an increasing trend in natural hazards mainly cloud burst, flash floods and landslides (Figure 2). Also when extreme events for last 16 years were plotted on Arc GIS (Figure 3), the map shows that most of the extreme events are confined below the MCT zone, where the precipitation is very high as a result of change in relief. The 16 years precipitation graph does not exhibit any specific trend but it does show that in recent years, precipitation has been more prominent and has increased (a liner trend line was drawn) as compared from the past and so has the extreme events, indicating that with increase of precipitation, extreme events have increased for western Himalayan region.

From Figure 2, years which have witnessed high frequency of cloudburst are the years having highest numbers of landslides in the Uttarakhand region. Flash floods though have increased with years but they aren't that prominent. An increasing trend in the extreme events as a result of intense precipitation is observed for the Uttarakhand region. Trend line drawn for cloudburst, landslide, and flash flood shows an increasing trend for extreme events from year 1951-2014. From the TRMM data it is quite interesting to note that though the intensity of rainfall has increased in this region, number of rainy days has decreased and the total annual precipitation has increased. Also one day extreme rainfall during the monsoon season has increased as noticed in the TRMM precipitation data which was further cross

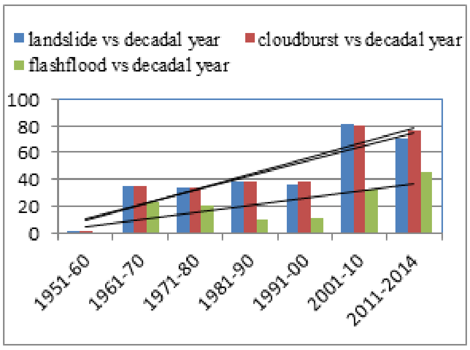

Figure 2: Extreme event pattern change on decadal basis from the year 1951 to 2014 for Western Himalayan region.

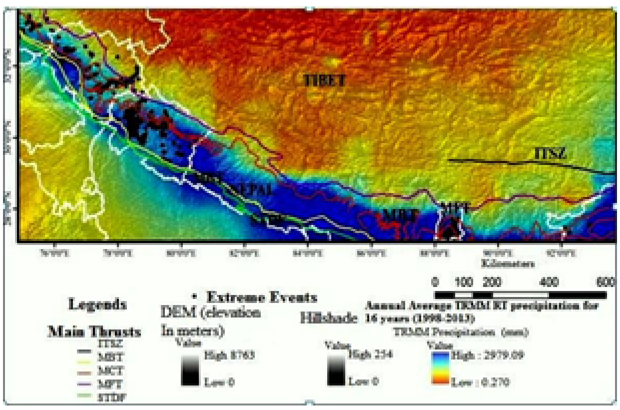

Figure 3: Extreme events along the Himalayan region for 16 years (1998-2013).

checked with the Indian meteorological data available for western Himalayan section, as few days record rainfall greater than 300 mm in just 12 hours. The intensity of rainfall has increased in this area and so has the frequency of extreme events as maximum have been witnessed during these last 16 years as compared to extreme events data of 50 years which is evident from the graph (Figure 2).

Case Study of Mandakini Valley

An example of unprecedented precipitation followed by flash floods and landslides events during June 2013 has been selected to study the impact of orographic barrier in controlling the precipitation and extreme events.

Mandakini basin covering 2439 kms lies between latitude 30°19′00″ and 30°49′00″ N and longitude 78°49′ and 79°21′13″ E. Mandakini River is one of the major tributaries of Alaknanda River and joins it at Rudraprayag (Figure 4). The area severely affected by landslides in the past including the disastrous event of June 2013 when unprecedented precipitation as a result of cloud burst, followed by flash flood and landslides all over the valley killed over 5000 people and destroyed property of billions. The kind of damage that occurred during the disaster will take many years to put back the area into normalcy. The area is highly susceptible to landslides and like processes because of fragile geological formations traversed by MCT zone which forms 10-12 km NNE dipping zone in Garhwal Himalaya [18,19].

The precipitation pattern has been studied using TRMM 3B42RT satellite data for the monsoon period. ASTER DEM of Mandakini watershed was utilized on Arc GIS platform for making precipitation map using krigging. The landslide event was super imposed on this map. These events were plotted to study the trend of landslides and correlation analysis with various morphometric parameters such as, stream segments, basin length, basin parameters, basin area, altitude, volume, slope, and profiles, indicating towards the nature of the development of the basin. Geomorphic indices have been used as a measure of active tectonics. The knick points were located along the slope length gradient index with longitudinal profile. 15 morphometric parameters have been used to prioritize the sub watershed basin to understand the degree of instability due to tectonic activities based on relief, linear and basin network. On account of tectonic activities each sub basin has been divided with stable, moderate and active watershed (Figure 4a).

All the prioritization maps have been combined to form a composite map of all 14 sub watershed basin (Figure 4a). The precipitation map for complete watershed along with landslides and knick points (Figure 4b) indicates the high concentration of the rainfall south of MCT. This indicates that during south west monsoon, winds are majorly restricted south of MCT zone which acts as an orographic barrier and causes high rainfall at lower elevation on lesser Himalaya than on higher Himalaya.

The watershed prioritization map (Figure 4b) of study area reveals that the higher Himalayan region is comparatively more tectonically active than the Lesser Himalaya. However, the frequency of extreme events, intense anthropogenic activities and fragile lithology coupled with high rainfall makes the Lesser Himalaya more prominent to natural hazards. High precipitation on the lesser Himalaya during monsoon also increases infiltration and consequent pore pressure resulting in instability in the area.

Conclusion

The analysis done on TRMM 3B42RT data of western Himalaya

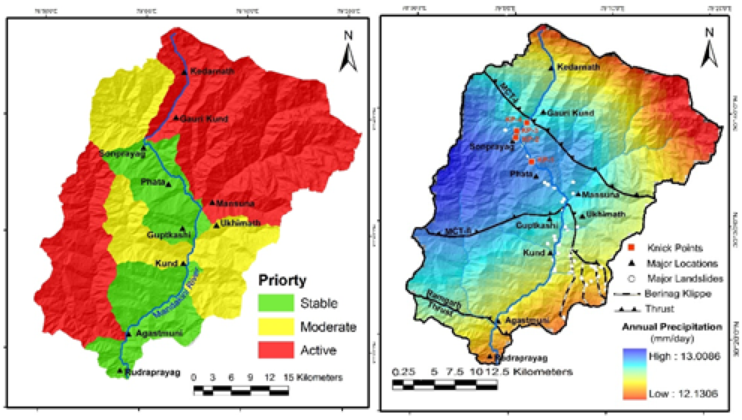

Figure 4: (a) Watershed prioritization map for Mandakini watershed and (b) shows annual precipitation map with landslide events.

shows that rainfall is mainly constricted south of MCT. As one move further south of MCT, precipitation decreases, indicating that MCT acts as orographic barrier. The analysis indicates that rainfall for last 16 years is not equally distributed both in duration and intensity. This attributes that though mean annual precipitation has decreased for last sixteen years, one day extreme rainfall events have increased in western Himalayan region leading to various water hazards with standard deviation of 272.859 mm and annual average for 16 years 677.279 mm. One day increase in extreme rainfall has also proportionately increased the rate of natural hazards. The extreme events in this area are mostly restricted to lesser Himalaya south of MCT zone which is an area receiving high rainfall as noticed in Figure 3. The analysis shows that the frequency of extreme events for year 1951 to 2000 is much lesser than that of year 2001 to 2014 (Figure 2). One such mega event of extreme precipitation led to Kedarnath disaster of June 2013 in the Mandakini Valley. The area received more than 400 mm rainfall in just 12 hours in two days as result of cloudburst at Chorabari glacier. This cloudburst triggered massive landslide resulting into loss of lives and economy. Precipitation coupled with tectonic activity and the anthropogenic activities has caused mega disasters in the past and as well as in the present. It is therefore suggested that the database on precipitation pattern, tectonic activity and extreme events should be maintained to study the relationship between the precipitation and events/disasters. This will also act as a forewarning for probable events/disasters in this area.

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