Evolution of earthquake-triggered landslides in the Kashmir Himalaya, NW Pakistan

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ABSTRAC T

The influence of the October 08, 2005 Kashmir earthquake and subsequent snow melt and monsoon rainfall on slope stability was evaluated using repeat photography in the Kashmir Himalaya of northern Pakistan. Sixty eight landslide-affected sites were selected and photographed in November 2005, May/June 2006, June 2007, and August 2007 to evaluate all potential geomorphic changes. Eighty percent of the sites showed no or very little change, 11% of the sites showed a partial vegetation recovery on the slopes, while 9% showed an increase in the landslide area. All those sites that showed an increase in the landsliding were located along rivers and/or roads. The small change in landslide extent is remarkable given that the region experienced one of the heaviest monsoon seasons in the last decade and is counter to earlier predictions of accelerated slope erosion by landsliding in the immediate years following the earthquake. Extensive fissures and ground cracks at many localities, however, still present a potential of future landsliding under wetter conditions.

Keywords: Kashmir; earthquake; landsliding; Himalaya; photography

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1. Introduction

The October 08, 2005 Kashmir earthquake, measuring M7.6, was the most devastating natural disaster ever to have struck northern Pakistan and affected an area of > 30,000 km^2 (USGS, 2006). More than 100,000 people were killed and over 3 million people were left homeless in Azad Jammu and Kashmir (AJK) and the North West Frontier Province (NWFP) (ERRA, 2006; Peiris et al., 2006). Most of the damage occurred as a result of ground shaking, and in some areas the structural destruction was 100%. The most affected areas were the cities of Balakot, Battagram and Garhi Habibullah in the NWFP and Muzaffarabad, Garhi Dopatta, Bagh and Rawalakot in the AJK. Two major, densely populated towns, Muzaffarabad and Balakot, experienced the greatest damage. In Muzaffarabad, ~90% of housing structures were completely destroyed (ERRA, 2007). The main reason for this heavy damage was the location of the epicenter close to Muzaffarabad. Similarly, in Balakot, which was located on the hanging wall of the earthquake fault, structures were almost completely flattened. The extent of damage was so great that the city was relocated. The new city is now under construction ~20 km south of its previous location (ERRA, 2006).

The earthquake also triggered ground subsidence and triggered thousands of landslides (Sato et al., 2007; Dunning et al., 2007; Owen et al., 2008; Kamp et al., 2008, 2009), causing ~ 25,500 fatalities (Dunning et al., 2007), and destroying infrastructure such as buildings, roads, bridges, and communication links (Kamp et al., in prep.). In addition, the earthquake triggered the Hattian Bala sturzstrom (long runout landslide), which is the largest landslide in the study area. The sturzstrom occurred within a cluster of pre-existing landslides and created a scar >1 km long, >200 m wide and 60-80 m deep; and produced a 130 m thick debris pile that blocked the Karli and Tang streams (Owen et al., 2008). The landslide destroyed three villages and killed ~1,000 people (Harp and Crone, 2006; Dunning et al., 2007; Owen et al., 2008). Recurrence of an earthquake of the same magnitude in the region is less likely in the near future (Bendick et al., 2007; Kondo et al., 2008; MonaLisa et al., 2008), but ongoing landsliding, which was initiated by the earthquake, still poses a serious threat to life and property.

Sato et al. (2007) counted 2,424 earthquake-triggered landslides using SPOT 5 satellite images. They noted that the most of the landslides are concentrated on the northeast side (hanging wall) of the earthquake fault. They also noted that ~79% of the total landslides were small (<0.5 ha in area) shallow rock falls and slides, and only ~9% of landslides were >1 ha in area and mostly comprised of shallow disrupted rockslides. Dunning et al. (2007) identified 85 pre-earthquake, 73 co-seismic and 21 post-seismic landslides in the Hattian Bala catchment using a series of different satellite images. They noted that most of the landslides that postdate the earthquake-triggered landslides are located around the margins of the two lakes (Karli and Tang) formed by the damming of the drainage. In addition, Owen et al. (2008) mapped 1293 landslides at 174 locations and classified them into six geomorphic-geological-anthropogenic settings. These included: (a) highly fractured carbonate rocks comprising the lowest beds in the hanging wall of the likely earthquake fault; (b) Tertiary siliciclastic rocks along antecedent drainages that traverse the Hazara-Kashmir Syntaxis; (c) steep (>50^{o}) slopes composed of Precambrian and Lower Paleozoic rocks; (d) steep (>50^{o}) slopes of fluvially undercut Quaternary valley fills; (e) ridges and spur crests; and (f) failures associated with road cuts. Owen et al. (2008) also concluded that >50% landslides are associated with road construction and human terracing. Kamp et al. (2008) produced a landslide susceptibility map based on ASTER satellite imagery from October 27, 2005 and concluded that bedrock lithology and slope gradient were the most important factors affecting the distribution of the landslides. Moreover, Kamp et al. (2008) noted that >60% of the landslides were concentrated in the early Miocene Murree Formation, which comprised weakly cemented mudstone, siltstone and sandstone. Similarly, Kamp et al. (2008) noted that most of the landslides occurred on slopes of 25-35^{o}, and agricultural land, shrubland and grassland were highly susceptible to landsliding while forest cover seemed to effectively protect slopes from landsliding. Kamp et al.'s (2008) study also supported the earlier studies of Kumar (2006), Sudmeier-Rieux (2007a, b) and Owen et al. (2008), which show that many landslides occurred along faults, rivers and roads cuts.

Landslides are one of the most common natural hazards in many mountain regions of the world and pose a threat to both human lives and property. There are several natural and human-made factors that can trigger a landslide, but in general earthquakes and rainfall are considered as two major mechanisms that trigger landslides (Keefer, 1984; Dai et al., 2002; Crosta, 2004). For earthquake-triggered landslides, most of the studies have been concerned with the identification, description and documentation of co-seismic landslides, particularly those caused by catastrophic earthquakes (Keefer, 1984; Harp et al., 1991; Jibson et al., 1994; Harp and Jibson, 1996), but relationships between co-seismic and post-seismic landsliding activity is still poorly understood for most mountain regions. A large earthquake may initiate disturbance in the substrate creating fissures, increasing porosity and dilating joints, and hence can affect the stability of slopes for a long period after the earthquake. Therefore, to predict the landslide behavior for a region that has experienced a large earthquake, it is necessary to track the response of slopes to landsliding for a significant period after the earthquake. Today, landslide monitoring and mitigation strategies include susceptibility/hazard/risk mapping and repeat photography.

The 2005 Kashmir earthquake provided a unique opportunity to study earthquake-triggered landslides and the subsequent influence of snowmelt and monsoon rainfall on the affected slopes. To study the evolution of earthquake-triggered landslides, we developed a landslide inventory that included 174 landslide locations, which were photographed and described soon after the earthquake by Owen et al. (2008). Sixty eight of these locations were re-photographed in May/June 2006, June 2007 and August 2007 to evaluate changes after two spring snow melts and two summer monsoon seasons (Fig. 1 and Data supplement item).

2. Study area

The study area is located in Azad and Jammu Kashmir (AJK) and the North West Frontier Province (NWFP) in the western Himalaya, south of the Indus River in North Pakistan, and covers an area of > 750 km^2, that is centered on the epicenter of the October 8, 2005 Kashmir earthquake (Fig.1). Three rivers drain the study area; the Kunhar (forming the Kaghan Valley), the Neelam and Jehlum rivers. The Pir Panjal Range bounds the study area to the east-southeast, crossing the Jhelum Valley. To the north, the topography is characterized by high mountains forming the watershed between the Neelam and the Kunhar rivers and by the mountains of the tribal area of the Indus-Kohistan on the northern flank of the Kaghan Valley. To the west, the area is bounded by the northward-trending Gali Hills from the towns of Murree and Abbottabad. Geologically, the region is marked by the Hazara-Kashmir Syntaxis (HKS), which is bounded by Main Boundary Thrust (MBT) that thrusts Precambrian metasedimentary rocks over Tertiary sedimentary rocks of the Murree Formation (Calkins et al., 1975; Hussain and Khan, 1996; Hussain et al., 2004; Fig. 2). The earthquake occurred on the western limb of the HKS and the NW-SE trending Kashmir Boundary Thrust (KBT), which was reactivated during the Kashmir earthquake (Baig, 2006; Yeats et al., 2006).

The study area has a monsoonal climate with very wet summers (Figs. 3 and 4). In Muzaffarabad (at ~700 m asl), mean maximum and minimum temperatures in January and June are 15.9 ^{o}C and 3.2 ^{o}C, and 37.6 ^{o}C and 22.1 ^{o}C, respectively (WMO, 2007). Muzaffarabad receives >1500 mm precipitation on average during the year, of which one-third falls as rain during the monsoon season from late June until the end of August (District Census Report, 1998; Figs. 3 and 4). This often results in severe flooding and landslides, notably debris flows. During the winter, precipitation falls as snow at elevations above 1500 m asl. Little precipitation occurs in spring, but snowmelt provides abundant surface waters to slopes, which results in erosion and/or infiltration into slopes increasing the height of the groundwater table.

3. Co-seismic and post-seismic landsliding

In November 2005, four weeks after the 2005 Kashmir earthquake, Owen et al. (2008) studied 1293 landslides at 174 locations in the study area and produced a detailed landslide inventory. Owen et al. (2008) grouped landslides into six different geomorphic-geological-anthropogenic settings and noted that >90% of landslides were small (<1000 m^2 in area) shallow rock and debris falls and mostly involved the top few meters of weathered bed rock, regolith and soil. Similarly, Owen et al. (2008) also noted that >50% of all landsliding sites were associated with road construction and human activity. Owen et al. (2008) also reported extensive fissuring in many of the valley slopes, particularly in the Precambrian dolomites and siliclastic rocks of the Muzaffarabad Formation, and also noted that many of the slopes in the footwall rocks and on midslopes, where gradients were <20^{o}, showed very little evidence of landsliding or fissuring. Similarly, Sato et al. (2007) also reported earthquake related liquefaction and fissuring in the Neelum Valley. Jayangondaperumal et al. (2008) noted similar features around the city of Jammu in Indian-controlled Kashmir, ~ 240 km southeast of the earthquake's epicenter.

Sato et al. (2007) mapped 2424 landslides using black-and-white 2.5 m resolution SPOT-5 satellite imagery, and noted that >1900 (~80%) of the landslides were small (<0.5 ha in area), whereas 207 (~10%) of the landslides were large (>1 ha) and occurred on steeper (>30^{o}) slopes. Sato et al. (2007) also noted that most of the landslides occurred on the hanging wall of the earthquake fault and >700 (<30%) of the landslides occurred within 1 km from the earthquake fault. Analysis by Sato at al. (2007) and Kamp et al. (2008) showed that: (a) most of the landslides were concentrated in the Miocene mudstone, siltstone and sandstone (50% in Sato et al.'s (2007) study and >60% in Kamp et al.'s (2008) study); and (b) rocks northwest of Balakot had the highest landslide density (3.2 and 3.3 landslides/km^2, respectively).

Kamp et al. (2008) undertook a land-cover classification using ASTER satellite imagery from October 2005 and mapped 2,252 landslides. They noted that 2.4% of the entire study area was covered by landslides in October 2005, three weeks after the earthquake. Analysis by Kamp et al. (2008) also showed that the bedrock lithology was the most important landsliding-controlling parameter and most of the landslides occurred in highly fractured shale, slate, clastic sediments, limestone and dolomite, mainly of the Murree and Salkhala formations. Kamp et al. (2008) noted that most of the landsliding occurred on slopes ranging from 25-35^{o}, and that one third of the landslides occurred along rivers and one fifth occurred along roads. In conclusion, Kamp et al. (2008) showed that areas around many settlements such as Muzaffarabad and Balakot are still “highly” to “very highly” susceptible to future landsliding.

Kamp et al. (2009) undertook pre-earthquake landslide mapping using 2001 ASTER data and compared the results with 2005 ASTER data by Kamp et al. (2008). This study by Kamp et al. (2009) showed that the number of landslides increased from 369 in 2001 (covering an area of 8.2 km^2) to 2252 in October 2005 (covering an area of 61.1 km^2). Kamp et al. (2009) assumed that the new landslides were triggered by the 2005 earthquake and its aftershocks and noted that many of the co-/post-seismic landsliding in 2005 occurred in areas that had been defined as potentially dangerous on the 2001 landslide susceptibility map.

4. Methodology

Four weeks after the 2005 Kashmir earthquake, Owen et al. (2008) visited the area and examined ~1293 landslides at 174 locations in Kaghan Valley in NWFP and the Neelam and Jhelum valleys in AJK. Owen et al. (2008) photographed and described all the active slope failures at these locations and noted extensive fissuring in many of the valley slopes and warned of future landsliding hazard, especially after the spring snow melt and summer monsoon seasons.

Our study builds on field photographs taken in November 2005 by Owen et al. (2008). Sixty eight of Owen et al.’s (2008) sites were selected and re-visited and re-photographed in May/June 2006, June 2007 and August 2007, to assess slope conditions at each location after the snow melt and monsoon rain-fall seasons (Figs. 1 and 5). This allowed us to make an assessment of the short-term changes that occurred after the October 2005 earthquake. A data set of 4 photographs per site was therefore produced to compare landslide changes after the earthquake (Data supplement item). Photographs were adjusted to the same scale within an accuracy of ±5% using Corel Draw graphic software version 12.

For the sites that showed minor changes (< 5% area change) between 2005 and 2007, visual estimates were made to calculate percent changes in landslide surface area. For those locations, which showed significant landslide activity (> 5% area change), the percent changes in surface area were calculated by on-screen digitization of field photographs. Varnes' (1978) classification was used to describe landslide types.

5. Results

Previous studies showed that the Kashmir earthquake triggered not only thousands of landslides but also produced extensive fissures and cracks, making the slopes unstable (Sato et al., 2007; Dunning et al., 2007; Owen et al., 2008; Kamp et al., 2008, 2009). Our study revealed that ~80% of the sites either showed no or very little change in slope conditions after the earthquake (Table 1[1] and Fig. 6). Vegetation growth is clearly very rapid in this monsoon climate but only 11% of sites showed notable vegetation recovery on the slopes. Our results show that only 9% of the sites showed an increase in the surface area of landsliding between 2005 and 2007 (Fig. 3). These data show that all the reactivated landsliding occurred either along rivers or roads or both. There is no apparent correlation between post-earthquake landslide activity and rainfall and all

[1] Supplementary Data: Table 1.

secondary failures are concentrated along roads and/or rivers (Table 1). Similarly, all those sites that showed an increase in the surface area after 2006 snow melt season, that continued to be modified by landsliding after 2006 and 2007 monsoon seasons.

6. Discussion

Factors that contribute to slope failure during an earthquake are generally complex and difficult to assess with confidence but in general a critical magnitude and peak ground acceleration has to be reached for triggering landslides during an earthquake (Keefer, 1984; Wieczorek, 1996; Cascini et al., 2005; Harp and Jibson, 1995, 1996; Jibson et al., 1998). In the case of the 2005 Kashmir earthquake, the total number of reported co-seismic landslides (Sato et al., 2007; Kamp et al., 2008; Owen et al., 2008) were significantly lower than the number of landslides expected to be generated by an earthquake of similar magnitude (Keefer, 1984), although this might be because not all the earthquake-triggered landslides were recorded, particularly the smaller landslides. Furthermore, Owen et al. (2008) highlighted that the earthquake-generated extensive fissures and cracks throughout the region had the potential to cause more landsliding.

The available rainfall data from the Pakistan meteorological rain-gauge station at Balakot show that 2005 was the driest year and only received a total 1166 mm rainfall compared to 2284 mm in 2006 and 1212 mm in 2007 (Fig. 4). Rainfall during July (597 mm) and August 2006 (596 mm), however, was the heaviest since 2000 with the six year mean being 319 mm for July and 304 mm for August. Surprisingly, post-summer monsoon (2006) repeat photography does not show any significant new landsliding on slopes which were severely disturbed by earthquake shaking (Fig. 5). We assumed that the ground conditions were very dry and that the amount of rainfall was not sufficient enough to initiate any new or secondary landslides. Similarly, if conditions were wetter at the time of the earthquake, there would have been much more extensive landslide activity in the area. The study area was already experiencing drought conditions before the earthquake, which may have been significant in minimizing the influence of pore water pressures on landsliding. In the field, many local inhabitants noted that water levels continuously dropped in dug-wells, and natural springs began to dry up over the past few years. It is likely that rainfall amounts in the study area were not sufficient to exceed the threshold for landslide initiation.

Our study shows that most of the secondary landsliding occurred on slopes along roads and/or rivers (Table 1), which supports the observations of Owen et al. (2008) and Kamp et al. (2008, 2009) that more than half of the earthquake-triggered landslides are located along rivers and roads. Undercutting of slopes by river erosion and human activities such as road construction, deforestation, terracing and agricultural activities are probably the main reasons for theses secondary failures.

7. Conclusions

The Kashmir earthquake generated extensive landsliding and fissuring throughout the study area. Eighty percent of the sites examined in our study showed very little or no change, 11% of sites showed a partial vegetation recovery on slopes, while 9% showed an increase in the landslide areas. All those sites that showed an increase in landsliding were located along rivers and/or roads. This lack of significant change might be attributed to drought conditions in the area before the earthquake and insufficient rainfall after the earthquake, despite the heaviest rains since 2000 occurring in 2007. However, despite the few slope changes at the study sites, the extensive fissuring still poses a potential hazard in the region as the slopes are still susceptible to future landsliding under wetter conditions. Many settlements and major towns like Muzaffarabad and Balakot, Garhi Dopatta are still at risk to future landsliding, and future urban planning must account for this long-term potential threat.

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Figure Captions

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Fig. 1. Study area and locations of study sites.

Fig.2. Geological map of the study area (simplified after Kaneda et al., 2007).

Fig. 3. Annual rainfall distribution from 2000 to 2007 at Balakot (N 34^{o}33`, E 73$^{o}$21`). o - missing data.

Fig. 4. Monthly precipitation from January 2005 to December 2007 at Balakot (N 34^{o}33`, E 73$^{o}$21`).

Fig. 5. Examples of repeat photography at five different sites. (A) Landsliding along Kunhar River in Kaghan Valley. Initial earthquake-shaking produced very few shallow slope failures but produced extensive fissures and cracks, which resulted in extensive secondary landsliding. (B) Landsliding along main Muzaffarabd-Chakohti road in Jhelum Valley. Secondary landsliding occurred along the fissures produced by seismic shaking. (C) Rapid growth of vegetation on almost vertical slop along Kunhar River in Kaghan Valley. More than 70% slope is re-covered by vegetation by 2007. (D) & (E) Shallow rockfalls in Kaghan and Neelam valleys, respectively. No significant changes occurred after the earthquake. J - June; A - August.

Fig. 6. Post-earthquake landslide activity at study sites.

Landslide data supplement

Landslides inventory is built on field photos taken in November 2005 by Owen et al., (2008). Sixty-eight of Owen et al.'s (2008) sites were selected and re-visited and re-photographed in May/June 2006, June 2007 and August 2007, respectively. A data-set of 4 photographs for each site was developed to compare landslide changes after the earthquake. Photographs were adjusted to same scale within an accuracy of ±5% using graphic software (Corel Draw). For those sites, which show minor changes (<5%), visual estimates were made to calculate percent changes in landslide area. While for those locations which show significant landslide activity between 2005 and 2007, percent changes in area were calculated by on-screen digitization of field photos. Varnes (1978) classification was used to describe landslide types.

Data supplement item 1: Table 1. Landslide inventory and changes between November 2005 and August 2007.

Date supplement item 2: Photographs of landslides showing changes from November 2005 and August 2007.

Figure 1
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Figure 1.

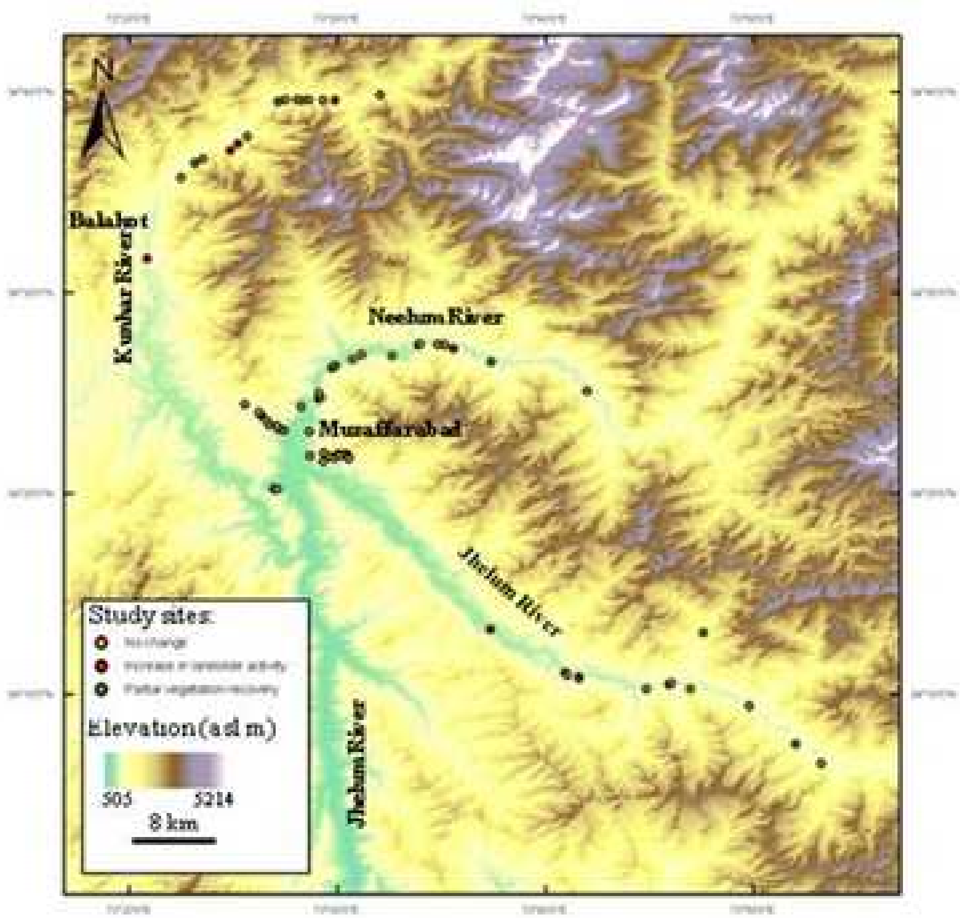
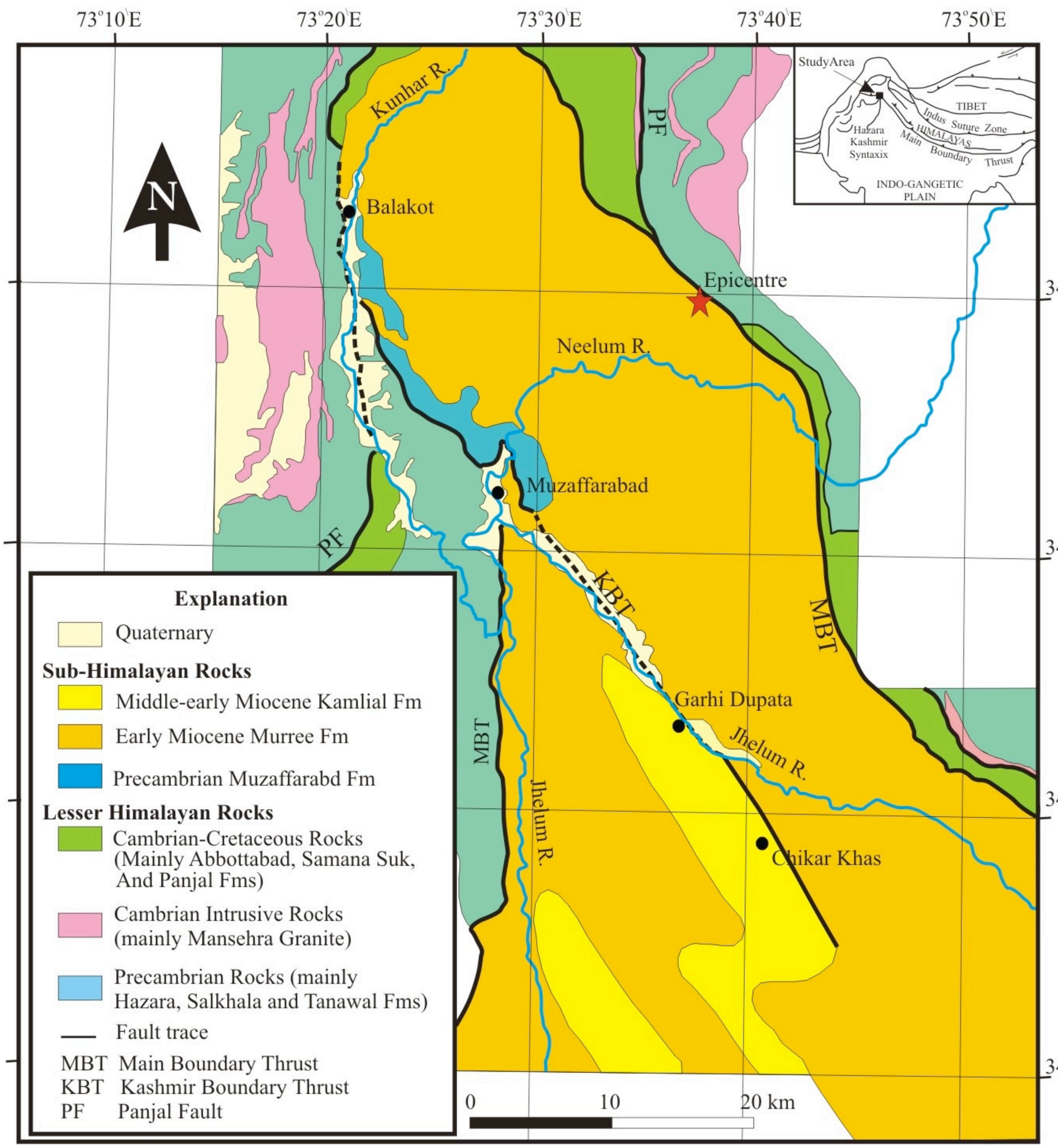


Figure 2

Figure 2.



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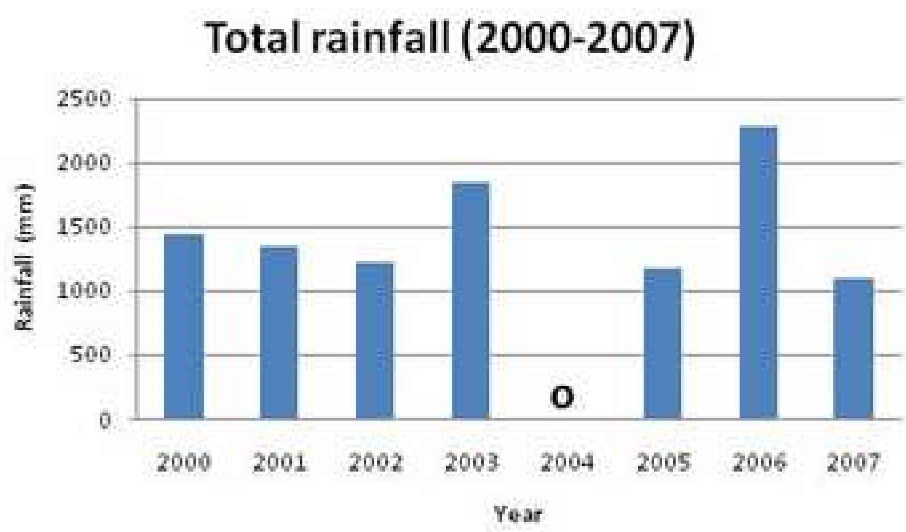

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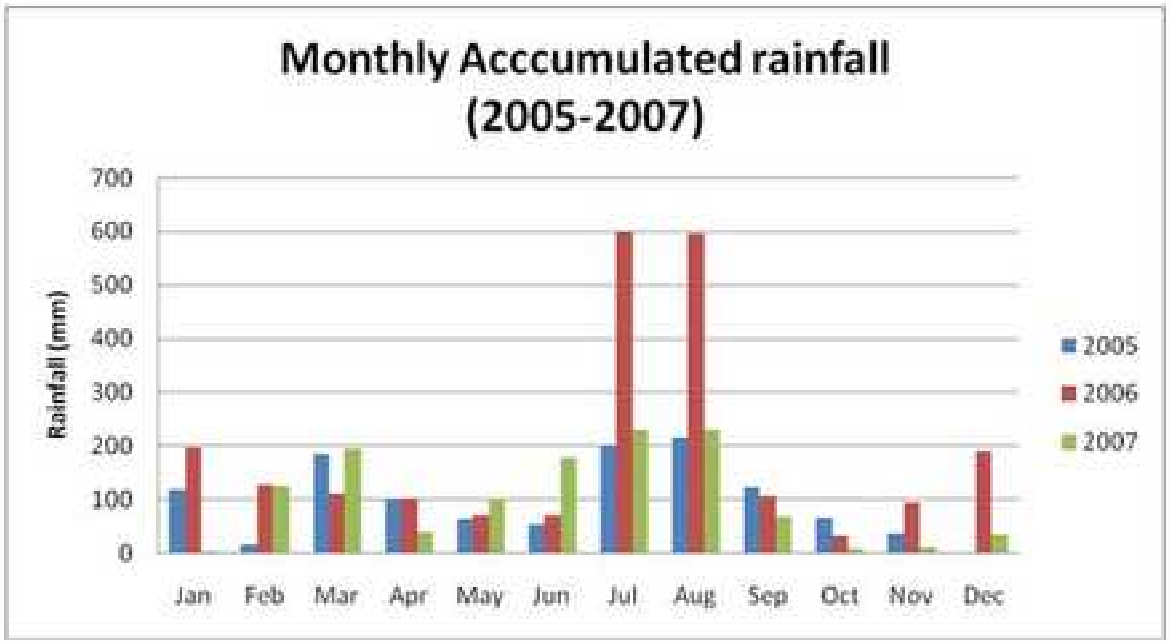

Figure 5

A. Site # 23 B. Site # 95 C. Site # 26 D. Site # 27 E. Site # 23

Figure 6
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Figure 4.