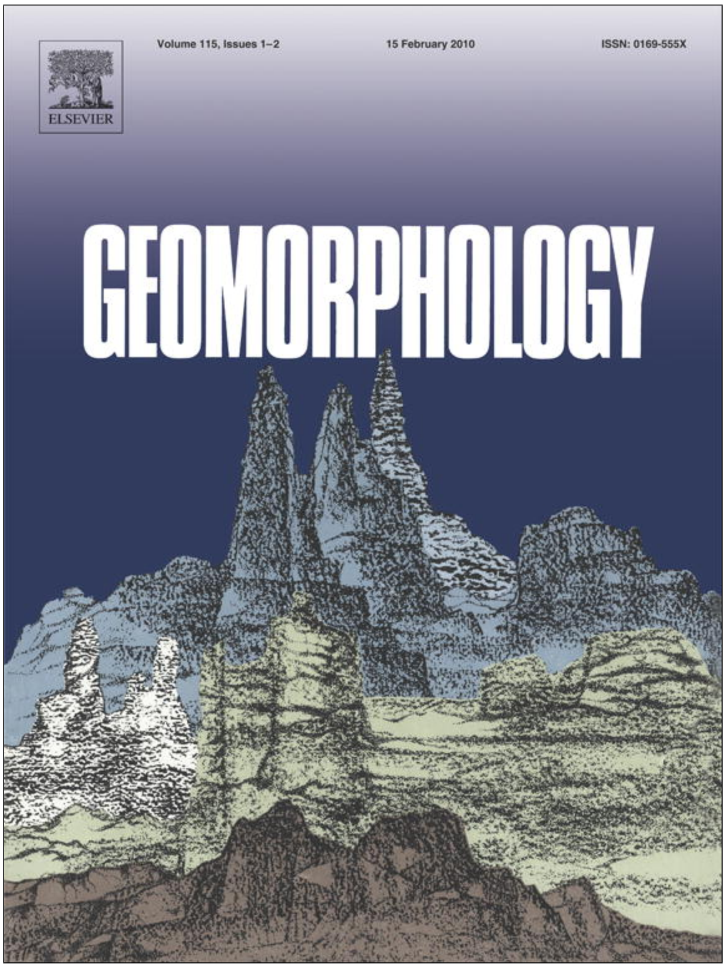
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# Evolution of earthquake-triggered landslides in the Kashmir Himalaya, northern Pakistan

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ABSTRACT

The influence of the 08 October 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 locations 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 locations showed no or very little change, 11% of the locations showed a partial vegetation recovery on the slopes, while 9% showed an increase in the landslide area. All those locations that showed an increase in 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.



## 1. Introduction

Landslides constitute one of the most common natural hazards in many mountain regions of the world and pose a great threat to both human lives and property. This is particularly the case for high mountains such as the Himalaya (Gupta and Joshi, 1990; Owen et al., 1995; Anbalagan and Singh, 1996; Nath, 2004). 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 (Keefer, 1984; Dai et al., 2002; Crosta, 2004). This was well illustrated on 08 October 2005, when an earthquake measuring *M*7.6 struck Azad Jammu and Kashmir (AJK) and the North West Frontier Province (NWFP) in northern Pakistan affecting an area of >30,000 km$^2$ and triggering thousands of landslides that resulted in ~25,500 fatalities (Peiris et al., 2006; ERRA, 2006, 2007; USGS, 2006; Dunning et al., 2007; Sato et al., 2007; Kamp et al., 2008, in press; Owen et al., 2008). This included the Hattian Bala landslide that destroyed three villages and killed ~1000 people (Harp and Crone, 2006; Dunning et al., 2007; Owen et al., 2008). Snowmelt and rainfall during the subsequent spring and monsoon seasons threatened to exasperate the hazard by eroding landslide scars and remobilizing landslide slopes and debris to cause the landslides to continue to evolve (Owen et al., 2008).

For earthquake-triggered landslides, however, most of the studies have been concerned with the identification, description, and documentation of coseismic landslides, particularly those caused by catastrophic earthquakes (Keefer, 1984; Harp and Jibson, 1996; Jibson et al., 2004a, b), but relationships between coseismic and post-seismic landsliding activity are 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. 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. We therefore studied the evolution of earthquake-triggered landslides at 68 locations in earthquake-affected areas of AJK and the NWFP in the western Himalaya of northern Pakistan.

## 2. Study area

The study area located in AJK and the NWFP covers an area of >750 km$^2$, which is centered on the epicenter of the 08 October 2005 Kashmir earthquake (Figs. 1 and 2). Three rivers drain the study area; the Kunhar (forming the Kaghan Valley), and the Neelam and Jhelum Rivers. The Pir Panjal Range bounds the study area to the ESE, crossing the Jhelum Valley. To the north, the topography is characterized by high

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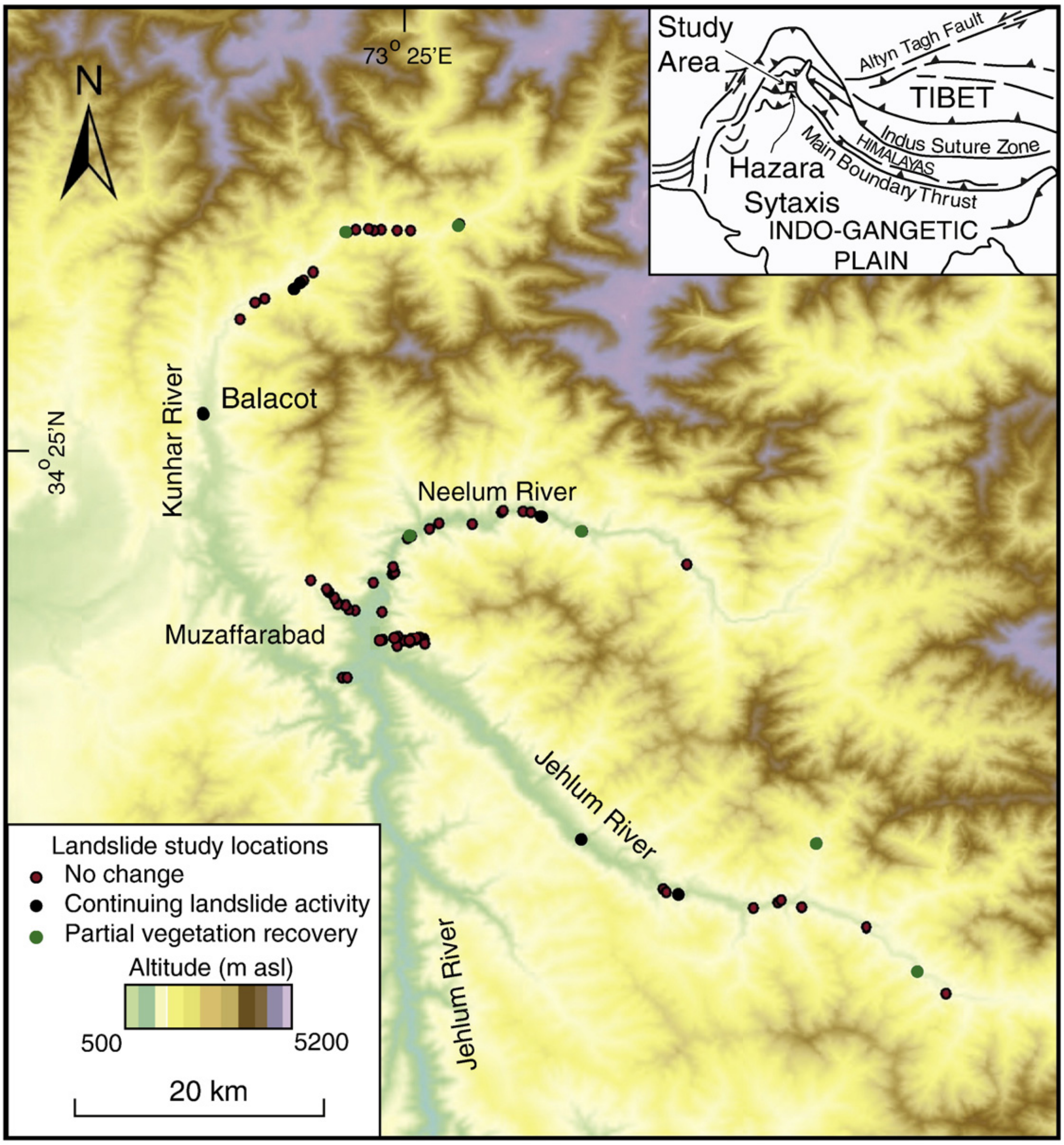


**Fig. 1.** Study area and locations of study sites.

mountains forming the watershed between the Neelam and Kunhar Rivers and by the mountains of the tribal area of 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 the 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 °C and 3.2 °C, and 37.6 °C and 22.1 °C, respectively (WMO, 2007, 2008). 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 landsliding, 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 significantly increasing the height of the groundwater table.

In November 2005, 4 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 bedrock, regolith, and soil. Furthermore, >50% of all landsliding sites were associated with road construction and human activity. In addition, Owen et al. (2008) reported extensive fissuring in many of the valley slopes, particularly in the Precambrian dolomites and siliciclastic rocks of the Muzaffarabad Formation, and also noted that many of the slopes in the footwall rocks and on midslopes, where gradients were <20°, showed very little evidence of landsliding or fissuring. Similarly, Sato et al. (2007) reported earthquake-related liquefaction and fissuring in the Neelum Valley, and Jayangondaperumal et al. (2008) noted similar features around the city of Jammu in Indian-controlled Kashmir, ~240 km SE of the earthquake's epicenter.

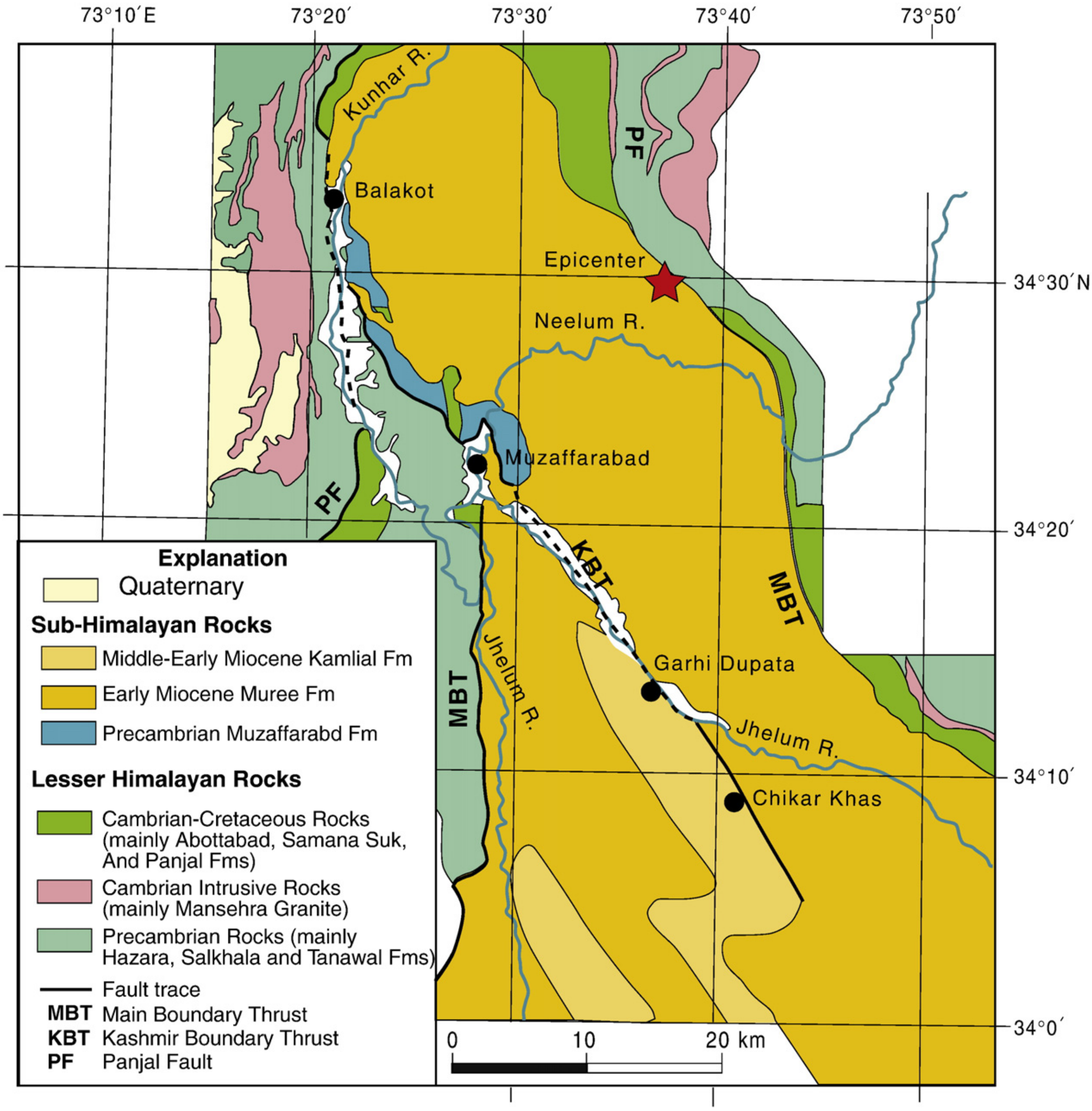


**Fig. 2.** Geological map of the study area (simplified after Kaneda et al., 2008).

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°) 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 et al. (2007) and Kamp et al. (2008) showed that: (i) 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 (ii) rocks NW of Balakot had the highest landslide density (~3.3 landslides/km$^2$).

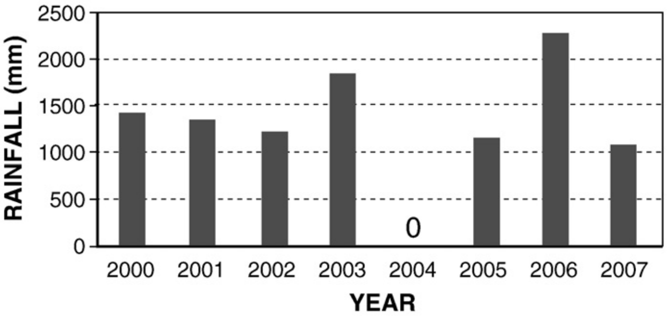


**Fig. 3.** Annual rainfall distribution from 2000 to 2007 at Balakot (N. 34°33′, E. 73°21′; WMO, 2008). 0 — missing data.

Using a series of different satellite images, Dunning et al. (2007) identified 85 pre-earthquake, 73 coseismic and 21 post-seismic landslides in the Hattian Bala catchment. Dunning et al. (2007) 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.

Kamp et al. (2008) undertook a land-cover classification using ASTER satellite imagery from October 2005 and mapped 2252 landslides. They noted that 2.4% of the entire study area was covered by

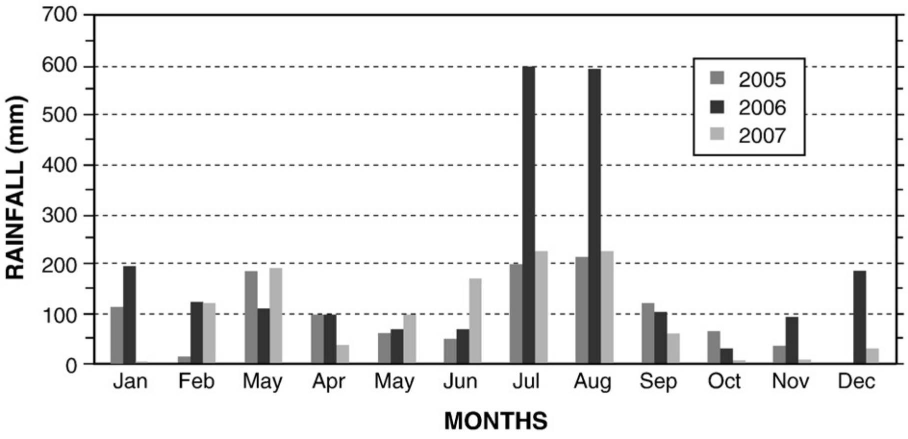


**Fig. 4.** Monthly precipitation from January 2005 to December 2007 at Balakot (N. 34°33′, E. 73°21′: WMO, 2008).

landslides in October 2005, 3 weeks after the earthquake. Analysis by Kamp et al. (2008) also showed that the bedrock lithology was the most important landslide-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 to 35° 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.'s (2008) study also supported the earlier studies of Kumar et al. (2006), Sudmeier-Rieux (2007a, b) and Owen et al. (2008), which showed that many landslides occurred along faults, rivers and roads cuts.

Kamp et al. (in press) undertook pre-earthquake landslide mapping using 2001 ASTER data and compared the results with 2005 ASTER data by Kamp et al. (2008). The study by Kamp et al. (in press) 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. (in press) assumed that the new landslides were triggered by the 2005 earthquake and its aftershocks and noted that many of the coseismic/post-seismic landsliding in 2005 occurred in areas that had been defined as potentially dangerous on the 2001 landslide susceptibility map.

## 3. 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. This included photographing and describing all the active slope failures and fissuring at the 174 locations. 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 snowmelt and monsoon 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 four 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 $\pm$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 change in surface area is calculated by on-screen digitization of field photographs. Varnes' (1978) classification was used to describe landslide types.

## 4. 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 (Dunning et al., 2007; Sato et al., 2007; Kamp et al., 2008, in press; Owen et al., 2008). Our study revealed that, between 2005 and 2007, ~80% of the sites either showed no or very little change in slope conditions after the earthquake (supplementary data Table 1; 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 also revealed that only 9% of the sites showed an increase in the surface area of landsliding (Fig. 3). These data showed that all the reactivated landsliding occurred either along rivers or roads or both. No correlation between post-earthquake landslide activity and rainfall is evident, and all secondary failures were concentrated along roads and/or rivers (supplementary data Table 1). Similarly, all those sites showed an increase in the surface area after the 2006 snow melt season, which continued to be modified by landsliding after the 2006 and 2007 monsoon seasons.

## 5. 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; Harp and Jibson, 1995, 1996; Jibson et al., 1998; Cascini et al., 2005). In the case of the 2005 Kashmir earthquake, the total number of reported coseismic landslides (Sato et al., 2007; Kamp et al., 2008; Owen et al., 2008) was 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, which may increase the number of landslides in the coming years.

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 of 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 6-year mean being 319 mm for July and 304 mm for August. Surprisingly, post-summer monsoon (2006) repeat photography does not show any


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

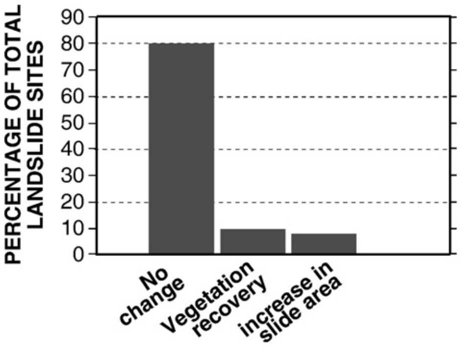


**Fig. 6.** Post-earthquake landslide activity at the study sites.

significant new landsliding on slopes that 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, more extensive landslide activity in the area would have been more if conditions were wetter at the time of the earthquake. 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 Kamp et al. (2008, 2009) and Owen et al. (2008) 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 these secondary failures.

## 6. Conclusions

The Kashmir earthquake generated extensive landsliding and fissuring throughout the study area. Within the 2 years after the earthquake, 80% 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 2006. 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.

The recurrence of an earthquake of the same magnitude in the region is not very 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.

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## Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.geomorph.2009.09.035.

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**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 Muzaffarabad–Chakothi road in Jhelum Valley. Secondary landsliding occurred along the fissures produced by seismic shaking. (C) Rapid growth of vegetation on almost vertical slope along the Kunhar River in Kaghan valley. More than 70% of the slope is re-covered by vegetation by 2007. (D) and (E) Shallow rockfalls in Kaghan and Neelam valleys, respectively. No significant changes occurred after the earthquake. J = June; A = August.

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