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Documenting five years of landsliding after the 2005 Kashmir earthquake, using repeat photography

Shah F. Khan [a], Ulrich Kamp [b,*], Lewis A. Owen [c]

[a] National Centre of Excellence in Geology, University of Peshawar, Peshawar, Pakistan
[b] Department of Geography, The University of Montana, Missoula, MT 59812, USA
[c] Department of Geology, University of Cincinnati, Cincinnati, OH 45221, USA

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ABSTRACT

The 8 October 2005 Kashmir earthquake triggered thousands of landslides at different scales through the Hazara–Kashmir region of northern Pakistan. A landslide inventory was prepared within a few months after the earthquake, which included detailed photographs and studies of landslides at 164 locations. Photographs were retaken in 2006 at all the 2005 locations and at selected 68 landslide locations in 2007. In 2010, 123 of the 2005 landslide locations in the inventory were reexamined and photographed again. Existing literature predicted that extensive landsliding, particularly under wet conditions, was likely to occur in the region in the years immediately following the earthquake. Surprisingly, the repeat studies revealed that the total landslide area increased only slightly over the five-year period of study, even given a particularly heavy monsoon rainfall season in 2006, with 46% of the locations showing little or no increase and 10% showing a noticeable increase in landsliding; in 44% of the locations vegetation growth was significant or complete within the exposed landslide slip area. Many of the new or reactivated failures occurred along roads and rivers, particularly along steeper slopes. We conclude that the landscape returned to equilibrium within only a few years after the earthquake. Nevertheless, a potential for future slope instability and landsliding in the region still exists. Hence continuation of landslide monitoring and risk assessment is still important for hazard mitigation in this region.

1. Introduction

On 8 October 2005 at 8:50 a.m. local time (03:50 UTC), northern Pakistan experienced one of the most destructive earthquakes in its history. The M_w 7.6 (with intensities of up to X–XI) earthquake had its epicenter located at 34.493° N./73.629° E., 20 km NE of Muzaffarabad in Azad Kashmir, with a focal depth of ~26 km (USGS, 2012; Fig. 1). An area of about 30,000 km^2, mainly between the cities of Balakot and Bagh, in the district of Khyber-Pakhtunkhwa [KPK] and Azad Kashmir (formerly North West Frontier Province) was affected resulting in >73,000 fatalities, >130,000 injuries, and >611,000 homes destroyed or partially damaged resulting in >3 million homeless people (ERRA, 2010a,b). The cities of Balakot and Muzaffarabad experienced major destruction with 90% and 80% of the buildings destroyed, respectively; and some city areas were totally destroyed (ERRA, 2006). Both cities reported some of the highest fatality rates in Kashmir. The high number of fatalities and casualties was mainly the result of building collapse (ERRA, 2010a,b).

Earthquake-triggered landsliding represents a dangerous natural hazard that causes significant damage to property and infrastructure, injury, and loss of life. Earthquake-triggered landslides may also dam drainages to form lakes that constitute a secondary hazard because of their potential to burst and create catastrophic floods. The 8 October 2005 earthquake triggered thousands of landslides throughout the affected region, and some of them were directly responsible for human casualties. The Hattian Bala landslide was the most disastrous, destroying three villages and killing ~1000 people (Harp and Crone, 2006; Dunning et al., 2007; Owen et al., 2008). In the Jhelum valley, landslides killed ~250 people in Pahl and 30 people in Bandhi Tanholia; 98 houses were buried under a landslide in Jabla (Petley et al., 2006). The earthquake not only reactivated existing landslides but also triggered new landslides, particularly in areas close to the earthquake fault.

To assess the causal factors, we have implemented a long-term study of past, present, and future landsliding in Azad Kashmir (Kamp et al., 2008, 2010; Owen et al., 2008; Khattak et al., 2010). Here, we present the results from the fourth field campaign undertaken in 2010 and from the overall analysis of landsliding between 2005 and 2010, building on our work presented in Khattak et al. (2010). Our main conclusion is that the hazard posed by future landsliding has generally been overestimated in recent literature. In essence, the landscape returned to its geomorphic equilibrium within a few years after the earthquake, possibly because most of the landslides

* Corresponding author. Tel.: +1 406 243 6469; fax: +1 406 243 4840.
E-mail address: ulrich.kamp@umontana.edu (U. Kamp).

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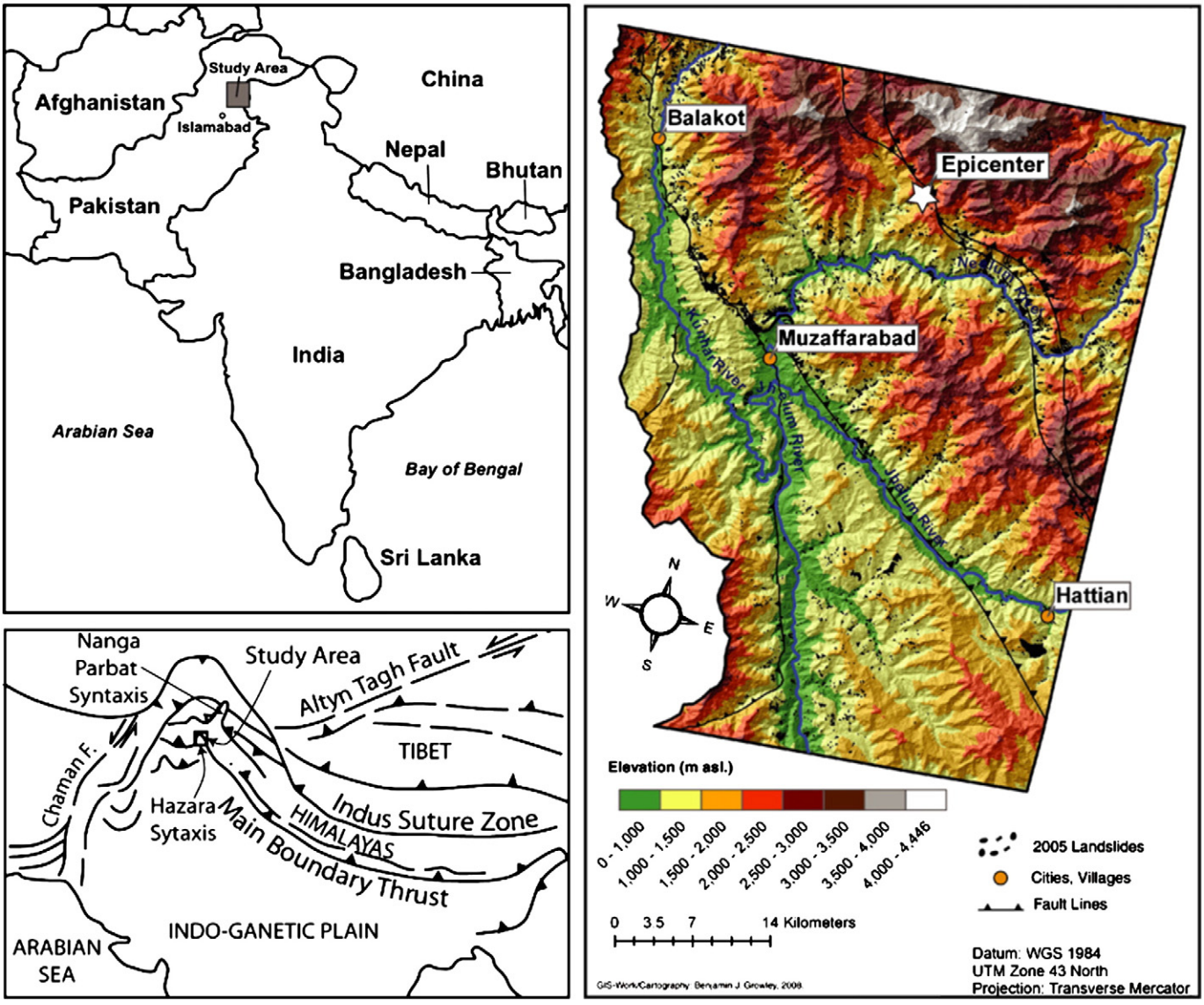

Fig. 1. The study area (2550 km^2) in Kashmir, northern Pakistan. The epicenter lies ~10 km NE of Muzaffarabad, the district capital of the state of Azad Jammu and Kashmir in northern Pakistan. The right map displays parts of the Kashmir Boundary Thrust (KBT) between Balakot and Hattian (adapted from Kamp et al., 2008).

were a shallow type and because of rapid growth of vegetation that helped stabilize the slopes.

2. Background

Landslides can have a direct or indirect impact on human lives and properties; hence, the literature on seismic landslides is extensive (e.g., Keefer, 1984, 1994, 1998; Owen et al., 1995; Harp and Jibson, 1996; Ravindran and Philip, 1999; Rodriguez et al., 1999; Luzi et al., 2000; Barnard et al., 2001; Antonini et al., 2002; Wang et al., 2003; Evans and Bent, 2004; Chen et al., 2006; Rathje et al., 2006; Hasegawa et al., 2009; Willige, 2010). Two kinds of seismically-induced ground failure exist: those such as liquefaction, consolidation subsidence, and some lateral spreading that are characteristic responses to earthquakes and those that include slumping, rock falls, and debris flows that might have occurred under nonseismic conditions but were exacerbated or enlarged by the tremors. In mountainous regions, earthquake-triggered landslides often occur in specific geologic–geomorphologic–anthropologic settings (Owen et al., 2008). Knowledge about such settings specific to individual regions and occurring landslide frequencies is crucial for reconstruction and rehabilitation.

The 8 October 2005 Kashmir earthquake initiated numerous investigations on landslide assessment and related hazard management (e.g., Harp and Crone, 2006; Petley et al., 2006; Vinod Kumar et al., 2006; Bulmer et al., 2007; Sato et al., 2007; Kamp et al., 2008, 2010; Owen et al., 2008; Champati Ray et al., 2009; Khattak et al., 2010; Peduzzi, 2010; Saba et al., 2010; Konagai and Sattar, 2012). Dunning et al. (2007) mapped 85 pre-earthquake, 73 co-seismic, and 21 post-seismic landslides from repeated satellite imagery in the Hattian Bala area where a landslide dammed the main valley and created two lakes. Sato et al. (2007) mapped 2424 landslides in the earthquake-affected region using SPOT 5 satellite images and showed that most of the landslides occurred on the hanging wall of the Kashmir Boundary Thrust (KBT). Sato et al. (2007) further noted that the majority (79%) of the landslides were <1 ha (<10^4 m^2) in size and that they were mostly rock falls and rockslides. This view was supported by Owen et al. (2008) who showed that 90% of the identified 1293 landslides in 164 locations in their study area were rock falls and debris falls with sizes ranging from single boulders to thousands of square meters; some of the landslides were very deep (tens of meters), whereas most were only shallow (a few meters). Owen et al. (2008) identified six specific geomorphic–geologic–anthropogenic landslide