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REVIEW ARTICLE

A review of landslides related to the 2005 Kashmir Earthquake: implication and future challenges

Muhammad Basharat[1] · Muhammad Tayyib Riaz[1,2] · M. Qasim Jan[3] · Chong Xu[4] · Saima Riaz[5]

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Abstract

It has been 15 years since the catastrophic 2005 Kashmir Mw 7.6 earthquake induced thousands of landslides in northern Pakistan and Kashmir. There have been many studies on various aspects of the landslides triggered by the earthquake, such as the mechanisms of individual large landslides, regional seismic landslide inventory mapping, spatial distribution pattern, susceptibility and hazard assessment, and landslide evolution, which provide beneficial scientific results. However, there is currently no summary and generalization of these studies for ready use of the researchers to fully understand the information of the landslide caused by the earthquake. This study comprehensively reviews and summarizes the important results obtained from published data on the landslides. The seismogenic and regional active faults, fragile lithological condition, heavy rainfall, anthropogenic activities, and steep terrain were considered as main controlling factors for the landslide occurrence. Studies on landslide evolution reveal that vegetation on most of the landslides was partially recovered after the earthquake, while slope failures along roads and drainages increased. In the affected area, landslides are still a great threat to communication networks and communities. Despite many past studies, there is still a need or in-depth research using more precise methods to understand the mechanism, hazard, and risk assessment, numerical simulation, landslide risk management and mitigation, and continuous or temporal monitoring of landslides in the affected area. Combined with high-quality data on landslides triggered by other earthquake events in recent years, the study points out the prospects of Kashmir earthquake-induced landslides and summarizes the future challenges of earthquake-triggered landslides research, including accuracy of inventories, the precision of landslide, susceptibility methods, prevention and control of landslide, and landslide hazards and risk assessment. This review can provide a reasonable scientific research and disaster prevention and mitigation strategy and scheme for landslides triggered by a large earthquake in the future.

Keywords Landslide hazard · 2005 Kashmir earthquake · Remote sensing · Himalayas

✉ Muhammad Basharat
basharatgeo@ajku.edu.pk

Extended author information available on the last page of the article

1 Introduction

In mountainous areas, landslides are the most damaging and costly natural hazards, triggered mainly by earthquakes or rainfall. In recent years, researchers have paid much attention to earthquake-triggered landslides because of their strong disaster characteristics and the ability to change the surface of the earth (Keefer 1984, 1994; Owen et al. 2008; Parker et al. 2011; Xu et al. 2014a; Tang et al. 2016; Fan et al. 2019). Many studies have been carried out, such as field investigation (Havenith et al. 2003; Angster et al. 2015; Xu et al. 2015a), information collection (Harp et al. 2011; Xu 2015; Tanyas et al. 2017), mechanism analysis (Michel et al. 2020; Dikshit et al. 2020; Huang et al. 2012; Basharat et al. 2014a; Zhu et al. 2019), numerical simulation (Tang et al. 2009; Dang et al. 2016; Mao et al. 2019), inventorying (Harp et al. 1981, 2011, 2016; Harp and Jibson 1985; Harp and Keefer 1990; Liao and Lee 2000; Xu et al. 2014a, 2015b; Basharat et al. 2016a; Roback et al. 2017), spatial distribution analysis (Sato et al. 2007; Gorum et al. 2013, 2014; Basharat et al. 2014b; Xu et al. 2014b; Shafique 2020), vulnerability, hazard and risk assessment (Guzzetti et al. 1999; Huang et al. 2018; Azarafza et al. 2018; Eker et al. 2014; McCrink 2001; Uchida et al. 2004; Basharat et al. 2016b), and landslide evolution (Saba et al. 2010; Li et al. 2014; Tang et al. 2016; Tian et al. 2020). These studies provide valuable information to understand the mechanism, evolution, and distribution of earthquake-triggered landslides. In recent years, increasing research on landslides triggered by major earthquakes has resulted in a large number of publication, e.g., Northridge, USA, in 1994 (Harp and Jibson 1985; Parise and Jibson 2000), Chi-chi, Taiwan, China, in 1999 (Liao and Lee 2000; Lin et al. 2004), Kashmir in 2005 (Bulmer et al. 2007; Sato et al. 2007; Basharat and Rohn 2015; Basharat et al. 2016a), Wenchuan, China, in 2008 (Dai et al. 2011; Xu et al. 2014a; Li et al. 2014), Yushu, China, in 2010 (Xu et al. 2013; Xu and Xu 2014), Lushan, China, in 2013 (Li et al. 2013; Cui et al. 2014; Xu et al. 2015b; Ma and Xu 2019), Nepal in 2015 (Kargel et al. 2016; Martha et al. 2017; Roback et al. 2017), New Zealand in 2016 (Sotiris et al. 2016; Massey et al. 2018), Hokkaido, Japan, in 2018 (Yamagishi and Yamazaki 2018; Shao et al. 2019a; Wang et al. 2019). The rapid increase in related research causes some difficulties in obtaining quick and accurate information on earthquake-triggered landslides. An example of this is the Mw7.6 earthquake in Kashmir on October 8, 2005, which triggered many landslides and made it an event of great significance for relevant research. In the past 15 years, many contributions have been made on the mapping, spatial distribution analysis, risk assessment, mitigation, and evolution of the earthquake-triggered landslides. It is of great significance to review these results for mastering the comprehensive information of the earthquake-triggered landslides and prospect the future research issues and directions.

A summary of published researches on landslides triggered by individual earthquakes can help in ready understanding of the situation and future research trends. For example, Xu et al. (2010) summarized hundreds of papers related to landslides triggered by the 2008 Wenchuan earthquake in the two years from 2008 to 2009 and divided these studies into several aspects, including field investigations and inventories, mechanism, classification, stability analysis, and numerical simulation of large landslides, spatial distribution patterns, susceptibility assessment, debris flow in the affected area, and rock mechanics tests. Several prospects were proposed, including improving the landslide inventory maps, and establishing a landslide disaster management system; conducting an in-depth analysis of failure, movement, accumulation process and mechanism of typical landslides; exploring the relationship between landslides and the seismogenic fault of the earthquake; and strengthening the research on the formation and hazard mechanism of the landslide disaster chain after the earthquake. These prospects have also been echoed in many studies over the last ten years (Dai et al. 2011; Xu et al. 2014a; Li et al. 2014; Tang et al. 2016; Fan et al. 2018a). On the 10th anniversary of the Wenchuan earthquake, Fan et al. (2018b) also made a similar review, covering mapping and spatial distribution patterns, initiation and failure mechanisms, and landslide dams related to coseismic landslides. The initiation and runout mechanisms of the landslides, changing rainfall thresholds, risk management and mitigation of post-seismic debris flows, multitemporal inventory, and controls on spatiotemporal evolution of post-seismic landslides were also also discussed. Furthermore, weathering-related post-seismic landsliding and landscape evolution related to long-term impacts of large magnitude earthquakes were analyzed. They also made recommendations for future research, such as hazard and risk assessments of the chain of geohazards, quantification of post-earthquake landslide evolution in time, space and in magnitude, developing integrated physically based debris flow simulation models, and improving the understanding of the effect of large magnitude earthquakes on long-term landscape evolution. The two reviews and prospects of the Wenchuan earthquake-triggered landslides are important inspirations for researchers. However, according to the available literature, such work is conducted only in the Wenchuan earthquake.

The Kashmir earthquake (KEQ) of 2005 had devastating consequences for the people living in the mountains of northern Pakistan. Of the more than 87,000 casualties, many thousands were killed by landslides triggered by the earthquake (Peiris et al. 2006; Petley et al. 2006; Mahmood et al. 2015). As such, these earthquake-triggered landslides have attracted much attention, and there have been a plethora of research articles written on them over the past decade. Therefore, this study systematically reviews the KEQ-triggered landslides, the spatial distribution of landslides, landslide susceptibility, individual large landslides, landslide risk management and mitigation and landslide evolution. In addition, it covers future studies prospect in terms of the accuracy of the mapping, the method of susceptibility, hazard and risk assessment.

Landslide hazard assessment involves the landslide monitoring with the aim of early warning of potential landslide, i.e., risk to communities and infrastructure (Chae et al. 2017). Avoidance to landslide risk is not easy, so it is necessary to understand the landslide behavior. The role of landslide early warning and monitoring is important for minimizing and avoiding landslide phenomenon.

Landslide monitoring observes displacements along vulnerable slope sites and estimates the variations in attribute values of causative factors to minimize the landslides associated damage (Chae et al. 2017). Kinematic, climatic, and hydrological monitoring imparts a prominent role in the modification of slope stability models. Studies for landslide monitoring, forecasting and early warning have been extensively carried out in recent years, and the importance of landslide monitoring is emphasized.

2 Kashmir earthquake and impacts

2.1 Kashmir earthquake 2005

On October 8, 2005, most disastrous earthquake having an Mw 7.6 and estimated focal depth of the quake was about 26 km (USGS 2005) struck the northwestern Himalaya (Fig. 1). This most damaging and devastating earthquake in the history of Pakistan caused

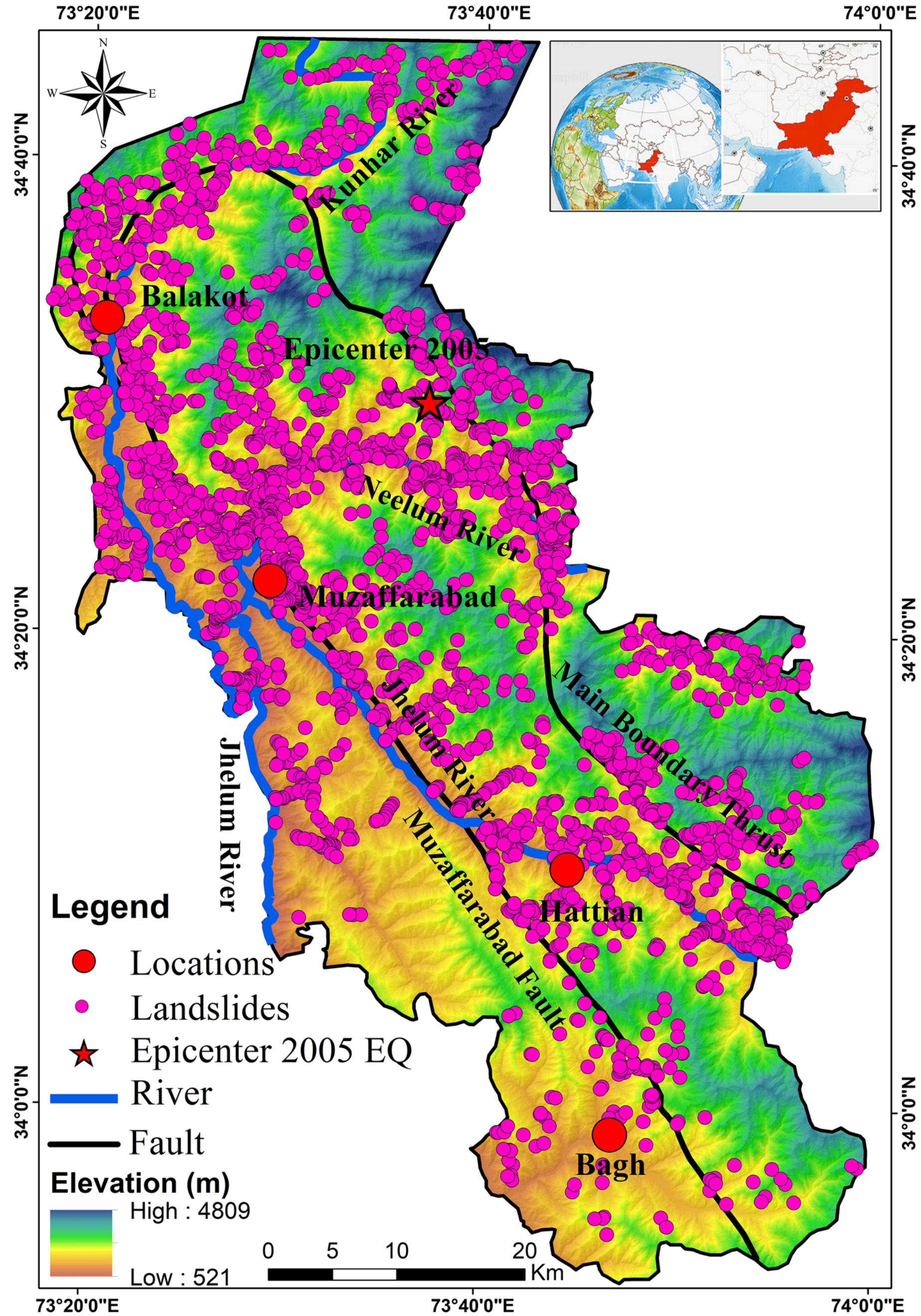

Fig. 1 Location map of the 2005 Kashmir earthquake-affected area and distribution of 2005 Kashmir earthquake-induced landslides; modified after Basharat et al. (2016a)

numerous casualties, destruction of infrastructure, and huge economic loss (Jan et al. 2008). The epicenter of the quake was located 18 km N-NE of Muzaffarabad, the capital of Pakistan Administrated Kashmir. The KEQ-affected areas were among the most vulnerable mountain regions in the Himalaya of Pakistan. According to Peiris et al. (2006) and Petley et al. (2006), the devastating KEQ killed more than 87,000 people, injured over 69,000, and left 2.8 million homeless. The estimated total loss of economy was about 5.2 billion US$, including reconstruction and rehabilitation costs (World Bank and Asian Development Bank 2005). The northwestern part of the Himalaya was predicted to have a lot of potentials for large earthquake events to discharge the accumulated strain (Bilham et al. 2001). The prior great (Mw > 7) earthquake known in and around the 2005 epicentral area was the 1555 Kashmir earthquake having magnitude of about 7.6. The damage from 1555 quake is reported to have been concentrated around Srinagar and its surrounding areas.

The source of the 2005 KEQ has been variously interpreted. According to Baig (2006), reactivated Muzaffarabad fault was the earthquake source, whereas according to MonaLisa et al. (2008, 2009) the earthquake was associated with the NW–SE trending Balakot–Bagh Fault (BBF) of the Indus Kohistan Seismic Zone (IKSZ). From aftershocks locations and Global Positioning System (GPS), it was assumed that the earthquake took place along multiple fault planes (Bendick et al. 2007). In this region, the faults are assumed to accommodate convergence, accumulating at 7 ± mm/yr, suggesting a 680 ± 150 yr recurrence interval for 2005 Kashmir like events. Kaneda et al. (2008) mapped about 70 km long NW–SE trending surface rupture of the KEQ with a vertical separation up to about 7 m based on an ordinary portable GPS receiver. They tentatively estimated the earthquake recurrence interval with a shortening rate of 2–4 mm/yr as 1000–3300 yr. Nakata et al. (1991), based on the interpretation of aerial photographs, had previously mapped this NE dipping active fault, initially called the Tanda Fault (TF). The slip rate varies from 2.5 to 7.0 m along the Muzaffarabad Fault (MF) (Kaneda et al. 2008). Based on GPS measurements, 5–8 mm of shortening is calculated across this region which is significantly less than the convergence velocity of the Indian plate (about 37 mm/yr). On the contrary, according to Reddy and Prajapati (2008), the average velocity of 86 mm/yr along with the Hanging Wall Block (HWB) of Balakot–Bagh fault at Gulmarg in Kashmir is significantly higher, possibly exhibiting post-seismic crustal deformation. Similarly, Jouanne et al. (2011) installed the GPS network across the BBF after the 2005 KEQ to measure post-seismic displacement. From repeated measurements over four years, they observed that along the HWB of BBF, major post-seismic displacements have decreased with time. No study regarding total station and GPS locations as well as geodetic observations for KEQ-triggered landslides has been conducted. A sequence of long and intense aftershocks continued after the main event. Pathier et al. (2006) employed SAR images and found that the 2005 earthquake involved thrust motion along NE dipping fault and found 80-km-long fault trace. They reported that slip occurred mainly in the upper 10 km, between the cities of Muzaffarabad and Balakot.

2.2 Tectonic and geological setting

The KEQ pretentious region is one of the most seismo-tectonically active zones of the world, comprising Himalaya–Karakoram northeastern Hindu Kush mountain ranges, and western Sulaiman–Kirthar region. Seismicity in the Himalayan fold and thrust belt is associated mainly with the regional thrust faults, associated with India-Asia collisional tectonics. These comprise the Main Frontal Thrust (MFT) and Salt Range Thrust (SRT) in the south, the Main Boundary Thrust (MBT), and Main Central Thrust (MCT). Further to the north, the India-Asia collisional zone is marked by the Shyok suture and Indus suture, juxtaposing Kohistan terrain against Karakoram and Himalayan terrains, respectively (Tahirkheli and Jan 1979; Kazmi and Jan 1997a,b; Sayab and Khan 2010). The edge of the outer Himalayas in the south is called Salt Range Thrust (SRT) in Pakistan.

Structurally, the earthquake area is enclosed by the Hazara-Kashmir Syntaxis (HKS), an antiformal structure (hairpin-like structure) that folds the sub and lesser Himalayas. All major thrust faults, including Panjal Thrust (PT) and MBT, are refolded by HKS excluding the MFT. The main tectonic units of HKS are Jhelum Fault (JF), PT, and Muzaffarabad Fault (MF; Wadia 1931; Armbruster et al. 1978; Baig and Lawrence 1987; Baig, 2006).

Sedimentary, metasedimentary, metavolcanics, and metaigneous rock represent the geological units of the KEQ-affected region. The Cambrian to Recent lithostratigraphic rock units of Neelum, Jhelum valleys and Muzaffarabad areas of the HKS are shown in Fig. 2. These include the Tanol and Hazara formations of Precambrian, the Mansehra Granite, and the Muzaffarabad Formation of Cambrian age, the Panjal Formation of Carboniferous-Triassic age, the rock sequence of Paleocene–Eocene age, the Murree Formation of early Miocene age, the Kamlial Formation of late Miocene, and recent alluvium deposits (Calkins et al. 1975; Greco 1989; Hussain et al. 2004).

The Precambrian age of the Tanol Formation comprises garnet–mica schist, chlorite–quartz–mica schist, graphitic schist, chlorite-biotite-quartzofeldspathic schist, metaquartzite, and local marble. This sequence has undergone multiple metamorphism and deformation (Greco 1989; Kazmi and Jan 1997a, b). The Precambrian Hazara Formation comprises shales, slates (cleaved and fractures), and phyllite with minor occurrences of limestone. The Cambrian Muzaffarabad Formation is composed of highly fractured carbonate rocks (dolomites) which are well known for their susceptibility to landslides (Kamp et al. 2008; Chigira et al. 2010). Fault gouge, breccia, fractures, and joints along the MF in Muzaffarabad Formation are present (Basharat et al. 2014a).

The Panjal Formation of Carboniferous-Triassic consists of metavolcanics and metasediments which are fissured, sheared, fractured, and jointed along MBT. These fragile lithologies, steep slopes, and brittle structures control the landslides during an earthquake along the MBT. The sequence of Tertiary age is composed of a wide variety of lithological units, including carbonaceous and calcareous shale, nodular limestone, sandstone, claystone, siltstone, conglomerates, and marl. Most of the landsliding activity occurred in Miocene Murree Formation displaying cyclic deposition of sandstone, siltstone, claystone, and shale. Shallow landslides are associated with the sedimentary sequence of sandstone, siltstone, mudstone, shale, and claystone.

2.3 Impact of earthquake-triggered landslides

Catastrophic earthquakes are responsible for triggering extensive mass movements in mountain terrains (Keefer 1984, 2002; Jadoon et al. 2015), which result in causalities as well as the destruction of infrastructure and property. For instance, the 1920 China earthquake-induced landslides killed about 120,000 people (Wang and Xu 1984). The strong ground shaking during the 2005 KEQ not only caused considerable structural damages in the affected areas, but also triggered thousands of mass movements and produced a large quantity of debris along the MF. These mass movements (Fig. 3) disrupted communication links of the entire affected area, destroyed settlements and infrastructure, and caused great loss of life. The landslide-associated fatalities numbered 26,000, making it probably

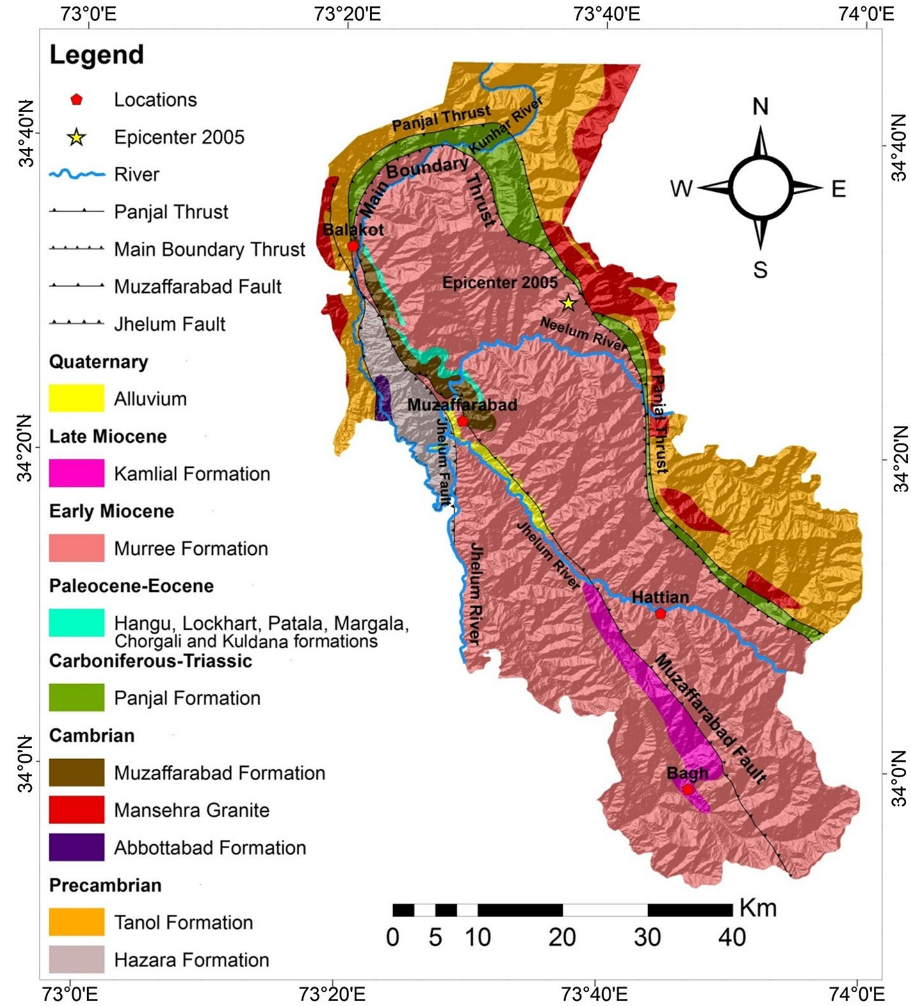

Fig. 2 Simplified geological map, compiled and modified after Wadia (1931), Calkins et al. (1975), Baig and Lawrence (1987), Greco (1989), Hussain et al. (2004) and Kaneda et al. (2008)

the third largest landslide disaster in history (Petley et al. 2006). In the earthquake-affected region (> 7500 km^2), thousands of landslides were triggered (Owen et al. 2008), of which > 2400 were seismically induced landslides (Sato et al. 2007). The Hattian Bala rock avalanche is an example of a massive landslide triggered by the earthquake, with an estimated volume of 9.8×10^7 m^3 (Basharat et al. 2012).

Muzaffarabad city and its surrounding areas were the most affected by the 2005 earthquake. Most of the landslides induced by the earthquake were distributed along the active MF. Communication links were catastrophically affected, and roads were destroyed and remained blocked for many days. Consequently, Balakot, Muzaffarabad (the most affected city), Rawlakot and many other cities, towns, and settlements remained isolated for weeks to months. Initial remote sensing data interpreted by Sato et al. (2007) in the affected area showed that 2,424 landslides were triggered by the earthquake. They observed that the

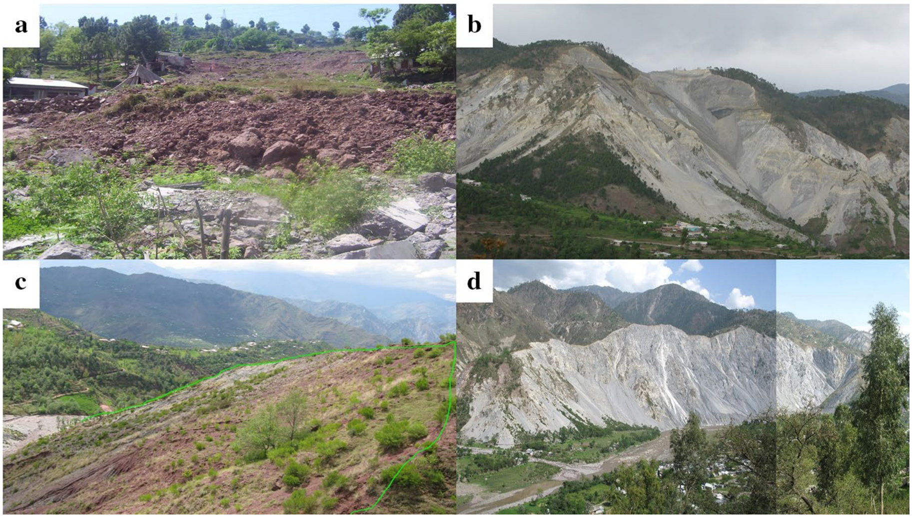

Fig. 3 Field Photographs of earthquake triggered landslides, a Samma Bandi Landslide, b Shahwai Landslide, c Botha Landslide and d Neeli Dandi Rock Fall

landslides were mostly concentrated within the HWB of active MF. Reported causalities since the 2005 KEQ are presented in Table 1 and Fig. 4.

3 Related work

3.1 Distribution and characteristics of landslides

During the period 2005–2021, some 60 articles have been published on earthquake triggered landslides by 42 authors from different countries (Fig. 5). Satellite imageries of various resolutions, sensors, and spatial coverage have been used to generate landslide distribution inventories of the 2005 Kashmir earthquake (Fig. 1; Table 2). In Muzaffarabad and surrounding area of 110 km^2, 100 landslides were identified by Sato et al. (2007) using remote sensing imageries. After that, they reported 2,424 landslides in an area of > 7500 km^2 (Sato et al. 2007). Owen et al. (2008), identified 1,293 landslides in an area of 750 km^2 near Balakot and Muzaffarabad and generated the first field-based 2005 KEQ-affected inventory. ASTER digital image classification and field verification were employed by Kamp et al. (2008) to prepare a landslide inventory (2252 coseismic landslide points) in an area of 2250 km^2. They also prepared the first probability map for the affected area and found that the landslides are concentrated in specific zones associated with causative factors, such as road networks and deforestation. The frequency or concentration of landslides considerably depends on these event-controlling parameters. Champati Ray et al. (2009) found that the causative active fault HWB was responsible for numerous earthquake-triggered landslides in the affected area.

Saba et al. (2010) deliberated spatiotemporal behavior of landslides utilizing satellite imageries of pre- and post-earthquake along MF and detected 158 landslides in an area of 36 km^2. It was observed that the landslides activity reduced within two years after the

Table 1 Reported fatal Landslide since 2005

Location	Description	Event	Fatalities	Source
Hattian	Massive Rock Slide	2005 KEQ	595	Basharat et al. (2012) and Petley et al. (2006)
Phal Jhelum Valley	Burial in Landslide	2005 KEQ	250	Petley et al. (2006)
Chal pani (10 km from Muzaffarabad)	Bus buried by Rock Fall	2005 KEQ	13	Petley et al. (2006)
Chela Bandi, Muzaffarabad	Persons were killed in landsliding	July 23, 2006	13	News report
District Kotli	25 were dead as landslide hit two vehicles	January 6, 2007	25	News report
Kel, Neelum Valley	12 people were killed, by landslides	November 2, 2012	12	News report
Kel, Neelum Valley	A landslide killed three Pakistani soldiers	November 30, 2012	03	News Paper
Doonga Kas (7 km from Muzaffarabad)	Young deputy commissioner of district Neelum, was killed by a landslide	Febrary 28, 2013 and September 25,2016	17	Riaz et al. (2019)
Lahorgali, Muzaffarabad	Jeep was buried beneath the landslide	March 21, 2014	02	News Paper
Kailer Sector in Haveli district on the line of control (LoC)	Mudslide	September 4, 2014	03	News Paper
Sarli Sacha Sharqi village (41 km from Muzaffarabad	Rock fall hit around half dozen houses	March 19, 2016	06	News Paper
District Bagh	Landsliding	March 19, 2016	02	News Paper
Palla Chaudhriyan village, district Haveli	Landsliding	March 19, 2016	02	News Paper
Chaffar village of Poonch district	Landsliding	March 19, 2016	02	News Paper
Neelum Valley	A landslides struck 2 houses	April 4, 2016	08	News Paper
Danna-Sahotar	113 houses destroyed	February 2016		News Paper,

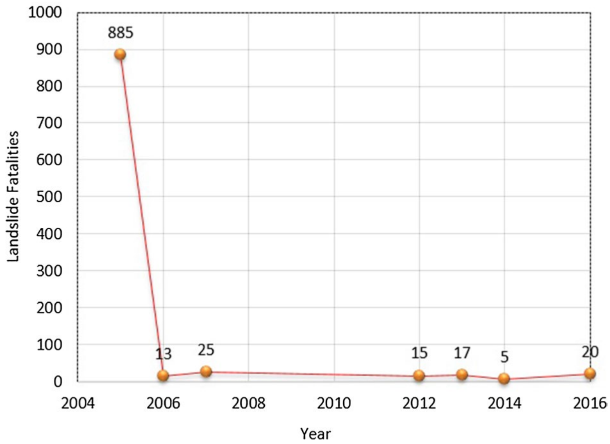

Fig. 4 Reported landslide fatalities from 2005 to 2016

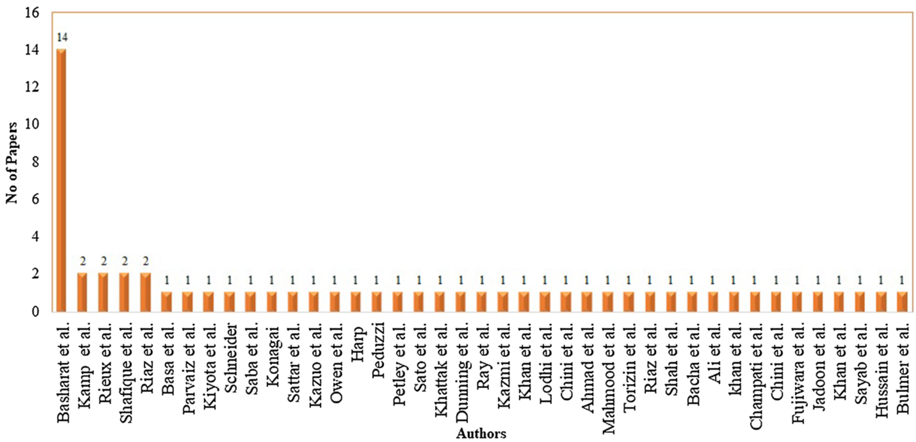

Fig. 5 Authors of earthquake triggered landslide assessment articles for the period 2005–2021

quake. The landslide distribution pattern, statistically analyzed by Basharat et al. (2014a), shows that landslide activity and also landslide concentration were higher along the hanging wall block of MF and in the epicentral area. Field evidence confirmed that the highest slip rate along the fault was the main reason to induce these mass movements. The combined effects of steep slope, reactivation of the MF, slip rate, fragile lithology, and strong ground shaking control the occurrence of these landslides (Petley et al. 2006; Owen et al. 2008; Kaneda et al. 2008; Basharat et al. 2012).

SPOT-5 satellite images after the earthquake have been acquired by Basharat et al. (2014a) to identify landslides (1460 points) covering an area of about 1299 km^2 employing visual image classification. However, they demarcated landslides as points not polygons like Sato et al. (2007) and, hence, the spatial extent of landslides was missed. Furthermore, they have utilized the post-earthquake SPOT images; therefore, the generated inventory also contains the pre-event landslides. Pre- and post-earthquake, high-resolution Quick-Bird satellite imageries were utilized by Chini et al. (2011) to demarcate the coseismic slope failures in some parts of Balakot and Muzaffarabad town, utilizing digital

Table 2 Documented Landslide inventories since 2005

Acquisition date	Method	No. of Landslides	Area	Spatial extent of the area (km^2)	Study
October 2005	SPOT-5 (2.5 m)	2424	Kashmir and Northern Pakistan	2805	Sato et al. (2007)
October 2005	QuickBird (0.6 m)	124	Neelum Valley		Rieux et al. (2007)
October 2007		183	Hattian Bala		Dunning et al. (2007)
27 October 2005	ASTER (15 m) and QuickBird (0.6 m), field investigation	1293	Muzaffarabad and Balakot	> 750	Owen et al. (2008)
27 October 2005	ASTER (15 m)	2252	Kashmir and northern Pakistan	2250	Kamp et al. (2008)
9 October 2005, 27 October 2005	Cartosat-1 (2.5 m), Resourcesat-1 (5.8 m), Landsat-TM (30 ml) and ASTER (15 m)	776	Muzaffarabad and Balakot	545	Ray et al. (2009)
13 August 2004, 12 October 2005, 13 November 2006 and 19 October 2007, 20 September 2008	QuickBird (1 m), IKONOS (1 m), SPOT (2.5 m) and WorldView1 (0.5 m)	158	Muzaffarabad	36	Saba et al. (2010)
25 May 2001	ASTER	369	Muzaffarabad, Balakot, Hattian	2549	Kamp et al (2010)
13 August 2014, 11 August 2004, 19 October 2005	QuickBird (0.6 m)		Muzaffarabad, Balakot	60	Chini et al. (2011)
27 October 2005	ASTER (15 m)				Lodhi (2011)
October 2005	SPOT-5 (2.5 m)	1460	Muzaffarabad	1299	Basharat et al. (2014a, b)
April 2013	Field Investigation	83	Neelum Valley	132	Ahmad (2014)
November 2009	Field Investigation	127	Muzaffarabad	1299	Basharat and Rohn 2015)
October 2005	SPOT-5 (2.5 m)	2930	Kashmir and northern Pakistan	3250	Basharat et al. (2016a, b)
October 2006	Field Investigation	45	Jhelum Valley		Engineering Cell (TRC) ERRA (2007)
August 2015	SPOT-5, Field investigation	459	District Muzaffarabad	1241	Riaz et al. (2018)

Table 2 (continued)

Acquisition date	Method	No. of Landslides	Area	Spatial extent of the area (km^2)	Study
September 2016	Field Investigation	534	District Haveli	540	Basharat et al. (2018)
October 2015	SPOT-5, Field investigations	277	Tehsil Muzaffarabad	600	Basharat et al. (2018)

image classification approach. They demarcated landslides by analyzing the pre- and post-earthquake event images on the criteria of removal of vegetation, based on bright and dull-colored slopes. The proposed mapping approach is quite efficient but acquiring these high-resolution images for a large area (>7500 km^2) is economically not feasible. ASTER image of post-earthquake was utilized by Lodhi (2011) for mapping of coseismic slope failures using NDVI, HIS, and PCA image classification approaches. They verified the derived inventory in field observations as well as IKONOS images.

Das et al. (2007) studied the Kashmir earthquake triggered landslides and founded that landslides extending from Balakot in the NW to Khudpura in the SE through Muzaffarabad and Kuroli displayed slope failures concentrations mostly along the river valley. They also observed that southeast facing slopes were badly affected by slope failures.

In the northern part of Muzaffarabad, coseismic landslides were also mapped by Fujiwara et al. (2006), using IKONOS images of pre- and post-events, and 100 landslides (coseismic) were mapped. Basharat et al. (2014a) performed the spatial distribution analysis of 2005 KEQ-induced landslides and found that the landslide phenomenon decreased with increased proximity to MF and epicenter area. Their statistical analysis showed that the concentration of landslides is mainly influenced by the earthquake source or epicenter distance rather than lithological units and topography. Work regarding total station and GPS observation as well as geodetic measurements for landslide activities in the affected area is lacking; however, limited research has been carried out about landslide monitoring and calculation of landslide parameters.

Basharat and Rohn (2015) mapped 103 landslides from field investigation, to evaluate the association between landslide variables such as travel angle, volume, absolute horizontal distance, fall height, and surface area. The study revealed the differences in mobility and observed run-out distance among different types of slope failures, and some relation in the travel angle and volume of landslide material. Basharat et al. (2018) for the first time mapped the regolith thickness and analyzed its relation with landslide distribution in Muzaffarabad and surrounding areas. They concluded that the regolith thickness plays a significant role in the occurrence of landslides. They mapped 277 landslides using SPOT images and classified these in the field covering an area of about 600 km^2.

3.2 Case studies

Seismically triggered landslides are mostly shallow and responsible for road and infrastructural damages (Basharat et al. 2014b). However, some deep-seated landslides triggered by an earthquake, such as the largest and most destructive Hattian Bala rock avalanche, were just a reactivation of an older feature. Basharat et al. (2012) studied the structural and geological control of this massive landslide and found that slope failure occurred along Danna and Dandbeh syncline (SE plunging), with a 2.3 km horizontal displacement. It killed about 565 people directly and destroyed many small settlements along the valley slope. They calculated the volume of the massive landslide as 9.8×10^7 m^3. Dunning et al. (2007) and Konagai and Sattar (2012), estimated the volume to be around 6.8×10^7 m^3 with length, width, and depth of >1 km, >200 m, and >20 m, respectively. Champati Ray et al. (2009) measured the distance of scarp of the landslide from the rupture of MF as 3.3 km. According to Shafique et al. (2008), the apex of Hattian Bala rock avalanche initiates at the top of the hill that is susceptible to topography-induced amplified seismic shaking. Slope failure may also be the result of amplified induced shaking that eventually leads to failure (Sepulveda et al. 2005; Lee et al. 2010). The satellite data reveal that several assemblages of landslides were present before the earthquake (Dunning et al. 2007; Petley et al. 2006), which were reactivated and spontaneously failed by the strong ground shaking of the 2005 KEQ. Murree Formation comprises interbedded sandstones, siltstones, and shales that were present in the landslide site area (Sato et al. 2007; Basharat et al. 2014b; Kamp et al. 2008). A landslide dammed lake produced by blockage of the drainage of Jhelum valley is a substantial risk of flood in the downstream region (Parvaiz et al. 2011; Sattar et al. 2011). The lake breached out during heavy rainfall in 2010, followed by increased deformation in the debris due to wetting and drying cycles (Kiyota et al. 2011), reducing the flood risk due to lowered water level (Konagai and Sattar 2012). Active landslide in the right bank of the dammed lake can lead to the disastrous condition (Konagai and Sattar 2012; Schneider 2009); therefore, regular monitoring of the lake and adjacent vulnerable steep slopes is suggested to prevent any hazardous condition. Shafique et al. (2016) observed fissuring, lateral spreading, and creeping in the area adjacent to the massive landslide site, which is susceptible to future slope failure. Hence, mitigation measures are suggested to reduce further destruction.

Basharat et al. (2014b) investigated the Neelidandi and Langarpura landslides at the HWB of the MF. They measured the 480 m and 800 m absolute horizontal displacement with estimated volume 3.1 and 5.76 million m^3 of the Neelidandi and Langarpura landslides, respectively. Failure of these landslides occurred due to sheared rocks, coseismic uplift, and ground shaking.

Another massive mass movement near the epicenter, named Panjgran landslide in the Neelum Valley area, blocked the communication system for many days after the earthquake. According to Basharat et al. (2017), the Panjgran landslide was a preexisting slump at the over-steepened slope reactivated during the KEQ. Neelum road remained blocked by a mass movement that traveled 650 m north towards the Neelum River. Failure was initiated by the slumping in weathered and fractured sandstone of the Murree Formation. The total volume of Panjgran mass movement was estimated at approximately 6.75×10^6 m^3.

Riaz et al. (2019) investigated the Donga Kas landslide triggered by the 2005 earthquake using two possible triggering factors such as earthquake and rainfall through laboratory testing. They assessed a critical pore pressure ratio and a critical seismic acceleration for triggering the landslide. Based on the pore pressure control test, they suggested that a pore pressure ratio of 0.371 may have triggered the landslide without an earthquake. A cyclic loading shear test result indicated that the Donga Kas soil is resistant to seismic loading.

The massive Danna-Sahotar landslide initiated during the 2005 earthquake and triggered by heavy rainfall of February 2016 in the south of Muzaffarabad, demolished 113 houses and agricultural land. Khan (2017) investigated the landslide by using geotechnical and geophysical methods. They estimated the depths of the landslide to about 21 m and the calculated volume at about 18.93 million m^3. They observed that landslides had multiple phases of reactivation after the main event. The multiple secondary scarps on the landslide body depict that the landslide has the potential to be reactivated in future.

3.3 Mechanical characteristics of large landslides

Slope stability analysis is the main concern of geotechnical experts to analyze all types of landslides. From an engineering point of view, landslides can be classified as shallow and deep seated, based on the thickness (depth) of sliding material. Water seepage-induced mass movements are more susceptible to form in low-permeability sliding material. In addition to hydrological effect, the mechanical characteristics of the sliding material were also found to be a controlling factors of landslides.

Numerous researchers have been investigating the mechanical characteristics of large landslides after the 2005 Kashmir earthquake (Kiyoto et al. 2011; Sattar and Konagai 2012; Sattar et al. 2011; Riaz et al. 2019). Riaz et al. (2019) conducted ring shear tests using the landslide ring shear simulator to investigate the residual strength along the sliding surface for Donga Kass landslide. In addition, they performed undrained cyclic loading tests to determine the critical pore pressure of a catastrophic landslide. On the basis of ring shear test, it has been concluded that the Donga Kass landslide is resistant to seismic loading. Kiyoto et al. (2011) performed accelerated slaking tests to identify their classes for the Hattian Bala rock avalanche associated with KEQ. Furthermore, advanced direct shear test was also conducted to determine the stress deformation characteristics of the geomaterials which experienced the accelerated slaking process. Based on the rock slaking test, the slaking level of both rocks (sandstone and mudstone) was found to be relatively low. However, advanced direct shear test result confirmed the significant slaking-induced shear deformation. Khan (2017) investigated the catastrophic Danna-Sahotar landslide by using geotechnical assessment. The geotechnical tests of the landslide material reveal that it has sandy soil with organic and porous particles, hence facilitating the water percolation into the strata and increasing the pore water pressure causing weakening of the slope which leads to failure. However, to estimate the effect of hydrological conditions on unstable slope, hydraulic conductivity should also be monitored. In addition, an integrated geophysical and mechanical approach is still required to estimate the hypothetical slip surface and thickness of sliding material.

3.4 Landslide susceptibility mapping

To develop and implement landslide mitigation policies, landslide susceptibility zoning is necessary. Landslide susceptibility map introduces different zones of varying susceptibility, depending upon the local conditions. To minimize the impacts of landslide, these maps play a crucial role in implementing the mitigation strategies. Different topographic, geological, tectonic, precipitation, and anthropogenic factors have been adopted for the preparation of landslide susceptibility maps (Guzzetti et al. 1999; Vanacker et al. 2003; Brenning, 2005; Xu et al. 2012, 2016; Poiraud 2014; Sabokbra et al. 2014; Okalp et al. 2016; Pourghasemi et al. 2018; Reichenbach et al. 2018; Shao et al. 2019b Shano et al. 2020).

Susceptibility mapping starts with the accurate landslide inventories and selection of event controlling parameters that change the slope prone to failure. The later include geomorphic, lithological and topographic attributes, drainage pattern, land-cover changes, and triggering factors, such as intense rainfall, human activities, and earthquakes (Dai et al. 2002). At the regional scale, the uncertainties in input data, especially in landslide causative factors and inventory, may result in over or under probability of the existing hazard (Shafique et al. 2016). Qualitative and quantitative approaches for landslide probability mapping have been used to analyze the seismically triggered landslides after KEQ by different researchers (Kamp et al. 2008, 2010; Sudmeier-Rieux et al. 2007; Basharat et al. 2016b; Torizin et al. 2017; Riaz et al. 2018). These studies generated the landslide probability maps of the 2005 KEQ region.

Kamp et al. (2008) adopted the knowledge-based analytical hierarchy process (AHP) to generate a landslide probability map with 67% prediction accuracy. The weights have been assigned based on expert knowledge in AHP; hence, lithology attains the highest weight considering its major role in landslide distribution. The slope gradient and distance to the tectonic elements have the least impact as compared to lithology. Landslide probability map has been classified into very high, and high (around 1/3 of the area) and moderate to low (2/3 of the area) landslide risk zones. Muzaffarabad Formation of Cambrian age is shown to have very high susceptibility, followed by Miocene age Murree Formation. The fault adjoining areas also revealed high susceptibility to landsliding. Kamp et al. (2010) generated the landslide probability map for the year 2001 and validated with the 2005 earthquake-triggered landslides which demonstrate that about 75% of landslides were present within the very high and high susceptibility zones of 2001 susceptibility map. Sudmeier-Rieux et al. (2007) developed susceptibility maps employing regression modeling, which reveals that less vegetated regions are most prone to landslides activity than forested regions if the fault distance and slope gradient are similar. According to Khan et al. (2013), Khattak et al. (2010) and Saba et al. (2010), most earthquake-induced landslides are stabilized; hence, it is not realistic to use the landslide probability model (coseismic landslides) developed by Kamp et al. (2008) with current situations. So, there is a clear need to generate an updated landslide probability map regarding the current scenario.

Basharat et al. (2016b) developed a landslide susceptibility map utilizing AHP and weighted overlay technique for a part of Balakot with an overall accuracy of 76%. The developed probability map ranked the studied region into very high and high (69%) susceptible zones, revealing that high probability is due to the prevalence of active faults, steep slopes, and fragile geology. However, about one-third of the study area (31%) falls in low and moderate susceptibility classes. Torizin et al. (2017) prepared landslide probability maps for districts Mansehra and Torghar, Khyber Pakhtun Khwa, Pakistan. They used four causative factors, which were distance from fault, geology, landcover, and slope gradient, to produce the landslide susceptibility map.

Riaz et al. (2018) investigated landslide susceptibility using the data-driven weight of evidence (WofE) approach for the district Muzaffarabad. The probability map gives an overall 86.2% accuracy for an area of 1241 km^2. The susceptibility map shows that about 88% area is in low to moderate susceptibility zone while 12% is in the high to very high susceptibility zone.

3.5 Landslide evolution

In mountainous regions, strong earthquakes can prompt widespread mass wasting, fabricating huge amounts of debris material. These deposits and vulnerable slopes are susceptible to be revived or reactivated by intense rainfalls in the succeeding years after the quake tremor (Yunus et al. 2020). Landslide risk evaluation and management involve the accurate prediction of the time when post-event landslide activity will return to the pre-event level.

The 2005 KEQ triggered an exceptional number of landslides, fashioning an amazing natural laboratory to analyze the landslide evolution and their controls on the environment. The post-earthquake mass movement hazard has become a serious concern (Jadoon et al. 2015). Due to large ruptures, surficial material from landslides during earthquake was suspended on the hillslopes, ready to be eroded, get loose, and transported by heavy monsoon rain. Therefore, many researchers observed intense cracking across large areas and predicted long term massive landslides (Petley et al. 2006). However, the area of seismically induced landslides has mostly been stabilized (Khan et al. 2013). Saba et al. (2010) investigated the earthquake-triggered landslide changes activity by analyzing the landslide type changes with time and subsequently monsoon effect on each type and new occurrences (Fig. 6). They concluded that there were many landslides (flow slides and translational slides) before the earthquake. The 2005 earthquake triggered debris avalanches and translational slides. They found that landslide activity was maximum within two years after the earthquake, after which slopes got re-vegetated and most became stable.

Recently Shafique (2020) studied the spatial and temporal evolution of coseismic landslides using SPOT satellite images in KEQ-affected region and found that the coseismic landslides area is decreasing with time. Landslide decline rate is slower as compared to global earthquakes. He also observed that because of heavy monsoon seasons landslide area is continuously reducing with time.

3.6 Landslide risk management and mitigation

Landslide risk management is an essential to mitigating the risk associated with landslides. Fell et al. (2008) suggest this term for the process of landslide risk analysis and decision making (structural and non-structural) for land use planning and urban development. In large landslides, the elements at risk may be damaged in various ways (Glade et al. 2005). The risk mapping and assessment is the end step of a complex method which starts with hazard and susceptibility mapping (Micu 2011). The landslide risk management problem involves risk analysis, risk assessment, landslide risk mapping, landslide vulnerability assessment, understanding to acceptable risk, landslide monitoring, geotechnical methods, and others (Svalova 2018). There are different types of risks to be assessed in landslide risk management, i.e., distributed landslide risk, site-specific landslide risk, and global landslide risk (Dai et al. 2002).

After landslide risk identification, measures (planning control, engineering solution, acceptance, monitoring and warning systems and decision making) may be taken to mitigate landslide risk to the community (Dai et al. 2002). New and emerging technologies, such as remote sensing and GIS, have a vast application in landslide risk identification, assessment and management. Maes et al. (2017) reviewed the practices and challenges of landslide risk reduction strategies from tropics and found that risk management and vulnerability are the

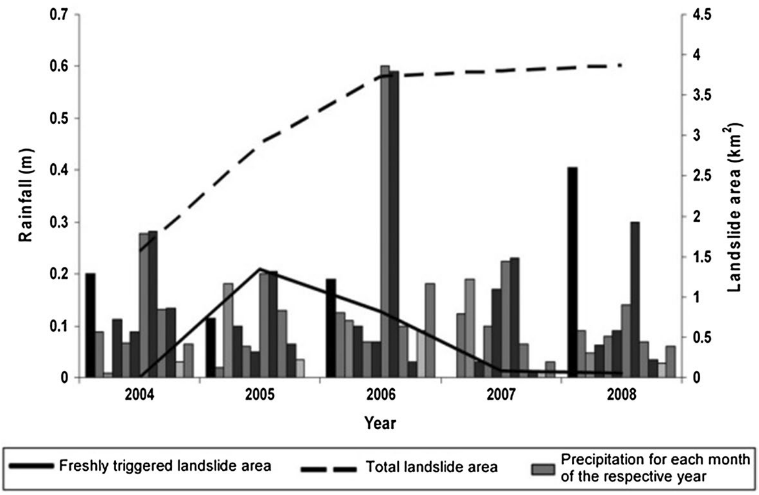

Fig. 6 Spatiotemporal changes in earthquake-triggered landslide area and their relationship with annual precipitation (adopted from Saba et al. 2010)

most recommended risk reduction component while risk assessment is the most implemented component. They also observed that implemented versus recommended risk measures are relative low except for risk assessment. The earthquake-affected region is geologically complex, with precipitous territories. Numerous buildings and roads are constructed in mountainous areas where they may be susceptible to potential slope failures. During rainy seasons, people living in landslide-prone areas are concerned about stability of these slopes. Potential slides on or near slopes are identified by features, such as new cracks, saturated ground, soil creeping away from grounds abnormal seeps, unusual bulges on ground surface, tilting or, broken underground utilities, and other signs of slope movement.

Numerous researchers have suggested risk mitigation measures after the 2005 KEQ. For example, Sattar and Konagai (2012) explained the landslide damming events and their hazard mitigation approaches. They made recommendation for breaching failure of a Hattian Bala landslide dam formed after the earthquake. They suggest the excavation of spillway as an effective mitigation measure. However, the dam failure response time varies from case to case; for example, Tangiashan landslide dammed lake failure occurred less than a month for the response, whereas the Hattian Bala landslide dam breached out after five years due to continuous five days unseasonal rainfall. On the other hand, the Attabad (Hunza Karakoram) landslide dam failure was expected due to overtopping but the dam has survived and continues to pose threat (Sattar and Konagai 2012). The Attabad landslide occurred on January 5, 2010, and the dam is still intact. This suggests that a comprehensive knowledge of the past events will be helpful for correctly analyzing a situation. Shafique et al. (2016) summarized the result from a remote sensing prospective and made useful recommendation for the use of RS in future investigations in landslide-prone areas.

Regarding the non-structural mitigation strategies, researchers have suggested to develop Landslide Early Warning Systems (LEWS) for minimizing the consequences of a landslide disaster (e.g., Shafique et al. 2016; Riaz et al. 2019). LEWS is an effective tool to mitigate the risk posed by rainfall-triggered landslides. Usually, LEWS is a mathematical model that forecasts landslide existence in the inspected areas. Rainfall thresholds have become a well-established and widely adopted approach for rainfall triggered landslide prediction during the last few decades. Rainfall thresholds can be demarcated with comparatively few factors and are very easy to activate, because their application within LEWS is usually based only on the comparison of monitored and/or forecasted rainfall. After the 2005 KEQ, LEWS against landslide disaster was established in the regions of landslide-prone areas. One such system, developed by Japan International Corporation Agency (JICA), comprises of two sets of extensometers and two sets of rain gauges. Despite these good efforts, the temporal change of rainfall thresholds that induced slope failure remains a poorly understood phenomenon. Lack of ground-based rainfall data (rain gauges) badly affects the application and authenticity of LEWS in studied region.

4 Future Challenges

4.1 Accuracy of inventories

Landslide inventory is a detailed dataset that may represent a single, regional, or multiple event. Ignoring the landslide hazard studies not only creates immediate problems concerning geo-environment and socioeconomics of the region, but also has lasting and long term effects. The first step before any hazard mitigation is to know the location (where), cause (why), and conditions (how) of the landslide occurrences. Availability and accuracy of landslide inventory is necessary for any hazard assessment. Different landslide inventories were developed after the 2005 KEQ, using remote sensing and field investigations. Some researchers marked landslides as a point and some as polygons. Minor disparity can be observed in many studies during mapping different types of landslides, due to variation in the spatial extent of area, employing different classification schemes, merging different types in one group, and different landslide inventory sources. Field investigations are necessary for assigning different types of landslides while remote sensing images are effective and crucial for mapping and detecting landslide on a regional scale. For landslide mapping through remote sensing-based data, the spatial resolution of imageries determines the size of recognizable landslides. Kamp et al. (2008), Owen et al. (2008) and Lodhi (2011) have acquired ASTER imageries of the intermediate resolution, which is reasonable for mapping landslides of considerable size at regional-scale studies. Riaz et al. (2018) and Basharat et al. (2016a) used SPOT-5 images of 2.5 m resolution for mapping of landslides which cannot detect landslides of < 5 m spatial extent. Shafique et al. (2011), Saba et al. (2010) and Chini et al. (2011) have effectively utilized high-resolution satellite imageries for landslides identifications (coseismic), but these entail very high costs, long revisit intervals, and their narrow swath size restricts their utilization for the whole region (about 7500 km^2) affected by the KEQ.

Most of the studies depend upon the spectral information of satellite images to identify landslides. Spectral band's details (light color of the weathered landslides) may be confused with agricultural lands, eroded slopes, and logging sites (Sato et al. 2007). The interpretation errors can only be minimized by comparison of remote sensing data with field investigations. Hence, more reliable landslide inventory can be developed by combining the spatial, spectral, and contextual and shape information through visual and object-based classification approach (Martha et al. 2010). A reliable and comprehensive landslide inventory of areas will help to develop the more realistic hazard and probability map that may be adopted by the concerned authorities to minimize the negative consequences of landslides in the future.

Landslide inventories, having temporal components of before and after earthquake events, are very rare. However, after major earthquakes, particularly the 1999 Mw 7.7 Chi-Chi, Mw 7.6 KEQ, and 2008 Mw 7.9 Wenchuan earthquake, some researchers also studied the temporal evolution of landslides (Dadson et al. 2004; Fan et al. 2018a, b; Hovius et al. 2011; Marc et al. 2015; Tang et al. 2016; Yang et al. 2017, 2018; Zhang et al. 2016; Zhang and Zhang 2017). Temporal imageries can address the issues of morphological signatures and erosional patterns of tectonically active ranges. Unfortunately, there is no study concerning multitemporal landslide inventories of 2005 Kashmir earthquake-triggered landslides so far. It is a big challenge and clear need to share the mapping and monitoring data by the research community to enhance further research and meta-analyses. As well, there is a need for generating a digital database of landslide inventories for the region which should include landslide locations, triggering mechanism, date of initiation, landslide types, damage information, etc., for proper management.

4.2 Post-seismic landslides

The recovery rate of vegetation for the KEQ is rather faster than that of the Wenchuan earthquake. In both Kashmir and Chi-Chi earthquakes, the post-seismic landslide rate decays quickly and returns to the pre-earthquake level within a decade (Yunus et al. 2020). Moreover, larger earthquake-triggered landslides expect to remain active for extensive-time period (Fan et al. 2018a). Comparison of size-frequency of earthquake-triggered landslides between KEQ and other recent global earthquakes (Fig. 7) reveals that KEQ triggered fewer landslides than the Wenchuan earthquake (Yunus et al. 2020). These studies suggest the less amount of sediments in Kashmir catchments as compared to Wenchuan and hence shorter recovery spam for the KEQ than other earthquakes. However, these studies were limited to area and time, and there remain some major challenges that must still be overcome. Volume estimation of landslide remains highly ambiguous, as does our capability to investigate the evolution of slope to failure after a major triggering event, sediment transport, and the control of landslides on both tectonic processes and long-term erosion rates. The limited case studies for the KEQ-affected region also revenues that we still scuffle to predict consequences for triggering events in diverse geological environments, such as mountainous landscapes or fragile lithologies. The observational evidence is still a great challenge for landslide evolutional studies adopting vegetation recovery rate for earthquake-triggered landslides. The quantification of vegetation regrowth is still a great challenge in the KEQ-affected region to overcome the decaying trend of post-event landslide phenomena. To estimate the spatiotemporal evolution of post-event landslide activity, the understanding of vegetational regrowth sensitivity is very important.

4.3 Prevention and control of landslide

In hilly regions, any mega projects need geological and geotechnical engineering measures to protect the assets from hazardous landslides. On the basis of slope stability recommendations, mitigation measure are to be adopted. Slope stabilization techniques involved soil

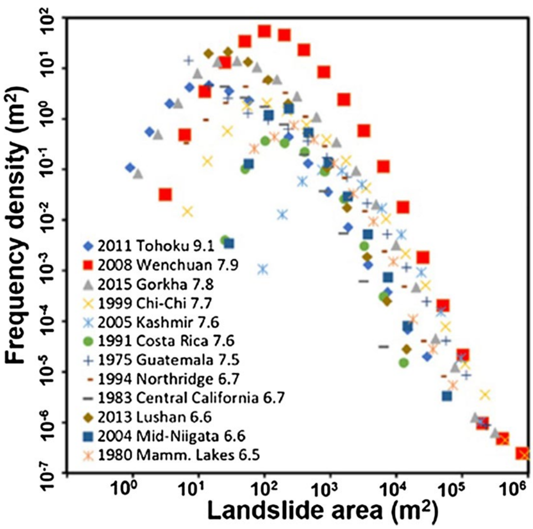

Fig. 7 Comparison of size – frequency distribution plot of Kashmir earthquake and global major earthquakes (adopted from Yunus et al. 2020)

bioengineering techniques, proper surface and subsurface drainage, benching to reduce the height and steepness of slopes, slope anchorage, construction of retaining walls and ground improvement techniques. There are a lot of potential geotechnical fixes, but mostly these are not effective and expensive especially for loose debris in the studied region. Landslide remedial measure selection depends upon economic suitability, engineering practicability, legal/regulatory conventionality, environmental acceptability, and social adequacy. Geotechnical engineers and geologists should map these potential sites and concerned authorities should be more proactive in implementing required precautions for any renovations or construction in hazardous region. The key to landslide disaster prevention and reduction should rely on generating a national level platform for sharing information of landslide mitigation which integrates anticipation, treatment and effective management techniques.

5 Concluding remarks and recommendations

In the 15 years after the 2005 Kashmir Mw7.6 earthquake, many studies have been carried out on the landslides triggered by the earthquake. The multisource and multitemporal remote sensing image-based inventories provide a brief overview of landslide concentration and spatiotemporal distribution in the earthquake-affected region. Regional scale landslide inventories have been developed using ASTER imagery; however, due to moderate resolution of the images (15 m), landslides smaller than a couple of the grids cannot be detected. High and very high-resolution satellite imageries (0.5–2.5 m), such as QuickBird, IKONOS, SPOT-5, and WorldView, are effective for identifying small-scale slope failures; however, purchasing, processing, and evaluating these high and very high-resolution satellite images for large study areas may not be economically attainable. Landslide identification from an immense source of satellite images is a crucial preparatory work for landslide inventories, mapping, and landslide hazard assessment. Establishment of semi-automatic to automatic methods for landslide identification using different machine learning algorithms can be efficiently employed to instantly generate updated landslide inventories of seismic landslides on a local scale. The accuracy of earthquake-induced landslide inventories developed through either visual or digital image classification approaches shall be improved through field verification. Spatial distribution analysis revealed that the coseismic landslides distribution is dynamically associated with the active fault lines, fragile lithological units, land cover and topographic attributes. Different spatiotemporal analysis of satellite imageries and air photography studies of mass movement reveals that the seismically triggered slope failures are mostly stabilized. The spatiotemporal response of slopes can be monitored by comparison of the regional temporal behavior of mass movements utilizing optical or radar-based satellite data of seismically triggered landslides. The effective monitoring of active landslides, such as those of Hattian Bala, Danna-sahotar, Donga Kas, Panjgran, and other adjacent unstable slopes, is strongly suggested to high risk of future disasters. The massive mass movement and unstable slopes are yet a main threat to infrastructure and population. Therefore, to understand the process, behavior, and spatial concentration of the movements, it is necessary to develop a relevant mitigation and management plan.

The following recommendations are suggested to address future challenges, including accuracy of inventories, the precision of landslide, susceptibility methods, and landslide hazards and risk assessment.

1. A reliable systematic digital landslide data base should be developed, separating pre- and post-earthquake events, specifically those triggered by rainfall and earthquake. The suggestions of Harp et al. (2011) dealing with landslide mapping and inventory development should be followed. Landslide inventory of unexplored areas of the earthquake-affected region should also be prepared. Landslide susceptibility and hazard maps require a comprehensive and absolute landslide inventory that can be used by the concerned personals to minimize the negative effects of landslides.
2. Lithology has great control on landslide distribution in the region as observed by many researchers. However, the existing lithology map of the KEQ region is small scale (at formation level) and integration of various lithologies in one formation makes it impossible to analyze the effect of lithological units on landslide intensity. It was recommended to develop a unitwise geological map of the region. There is still a need to generate the lithological map at least the 1:10,000 scale in the earthquake-affected area.
3. To minimize the hazardous effects of active landslides, real-time monitoring is necessary. Indications of major activity or movement can be detected with the help of real-time monitoring of landslides. Large active landslides are a constant threat to the encompassing society. Real-time observations of massive mass movements should help to forecast movement and hence notify the concerned specialists for necessary measures to limit the damages. Early warning systems for the landslides of the earthquake-affected area should be developed. Mobile telephones can be a big help in this regard.
4. The development of landslide density maps to measure the spatial abundance of landslides is recommended. A reliable probabilistic model should be generated to assess the landslide hazard that actually meets the standard definition of hazard. It is also recommended to evaluate the landslide hazard risk to personals and populations using a quantitative landslide risk assessment (QLRA) framework.
5. It is also recommended that landslide inventories should be updated on a regular basis to monitor the unstable slopes of the KEQ-affected region. Generating updated inventories is imperative to comprehend the effect of different triggering parameters for mass movements that ought to be regarded for slope stability measurements. It is suggested to use the regional scale fine resolution satellite imageries and new methods to detect, monitor and evaluate the causes of the active landslides of the earthquake-affected regions. Spatial changes in the extent of landslides can be detected using optical images, however, these images cannot detect vertical changes. Therefore, the InSAR or SAR satellite imageries should be encouraged to be used with the integration of optical imageries to assess the vertical changes in the slopes over a long period of time. The susceptibility map of the earthquake-affected area should be updated with the help of these combined information.
6. The activities to reduce the hazard damages principally rely upon the sound knowledge of elements at risk, vulnerabilities (either social or environmental), intensity, and recurrence interval of event and existing risk in the region (UNISDR 2005). Accessibility of such data and accuracy of the information should help the concerned persons to generate and actualize a landslide management system. In addition, these data can likewise be utilized for land-use planning or any formative or developmental ventures.

7. Resilient coordination between decision-making personnel and researchers should be established. Awareness and preparedness about landslide hazards and risks should be promoted to societies.

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Authors and Affiliations

Muhammad Basharat[1] · Muhammad Tayyib Riaz[1,2] · M. Qasim Jan[3] · Chong Xu[4] · Saima Riaz[5]

1 Institute of Geology, University of Azad Jammu and Kashmir, Muzaffarabad, Pakistan

2 Department of Geology, University of Azad Jammu & Kashmir Neelum Campus, Athmuqam, Azad Kashmir, Pakistan

3 NCE Geology, University of Peshawar, Peshawar, Pakistan

4 Institute of Crustal Dynamics, China Earthquake Administration, Beijing 100085, China

5 Geotechnical Engineer, WSP Sweden, Stockholm-Globen, Sweden