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Abe Barek landslide and landslide susceptibility assessment in Badakhshan Province, Afghanistan

Abstract Landslide is one of the most widely distributed mass movements in mountainous areas. With its wide spreading, abrupt, and seasonal characteristics, landslide always causes huge risks towards transportation, human settlements, industrial and mining plants, water resources facilities, and hydropower stations. Abe Barek landslide, which happened in the morning of May 2, 2014, in Ago District, Badakhshan Province, Afghanistan, buried 86 houses and took the lives of almost 2700 people. Many factors triggered the occurrence of this disaster. Firstly, the landslide-impacted area has a complex geologic structure that bears concentrated faults with mountain slopes covered by thick loess. Secondly, at the time of landslide, a continuous rainfall had deepened the level of moisture in the loess layer, which made the loess mass heavier and changed the soil body's mechanical properties. Thirdly, a similar landslide once happened on the same slope, which destroyed the land cover and transformed the topology of the slope. In addition, farming and irrigating activities may have also affected the stability of loess mass in this area. Upon an initial examination of landslide distribution in Badakhshan Province by using high-resolution remote sensing images from Google Earth, a total number of 609 landslide sites were identified in this area, and a landslide susceptibility assessment was completed by utilizing weight-of-evidence method. Several suggestions on landslide risk reduction in this remote mountainous area are proposed at the end of this paper.

Keywords Landslide · Afghanistan · Weight-of-evidence approach · Landslide susceptibility assessment

Introduction

Landslide as a natural slope mass movement is very common in mountainous areas. However, massive losses in casualty and property will occur if the landslide mass movement and deposition engages human activities. Mountains occupy 24 % of the global land surface area and are home to 12 % of the world's population. It is widely observed that many a catastrophe have been caused by landslides from time to time. For example, the landslide on April 29, 1903 on the Turtle Mountain, Frank town, Canada killed 70–90 people (Brabb 1991). On October 9, 1963, a large-scale landslide happened at the boundary of Vento and Friuli Venezia Giulia, Italy, where about 260 million cubic meters of rocks fell into the Vajont Dam reservoir, triggering a large flood that killed near 2000 people (Muller 1964). In Pufu town, Luquan County, Yunnan Province of China, a landslide occurred on November 22, 1965, which buried a total of five villages and took the lives of 443 villagers (Zhong 1999). The Panhexiang landslide, which happened on September 23, 1991 in Zhaotong City, Yunnan Province, China, killed 216 people, 252 livestock, and buried 202 houses and 20 ha of croplands (Zhong 1999). Furthermore, landslides induced by earthquakes are more destructive. For instance, a magnitude 7.5 earthquake happened in Maowen County, Sichuan Province, China, in 1933, during which 2428 people were killed by the earthquake-induced landslides, with just one of the landslides near Diexi town killing 577 people (Zhong 1999). The 2008 M_w 7.9 Wenchuan earthquake, which happened in Sichuan Province, China, induced more than 30 thousand landslides, including the Wangjiayan landslide in Beichuan town that buried and killed more than 1000 people.

There have been only a few studies on landslide in Afghanistan due to the region's political and economical uncertainties. Shroder et al. (2011a) investigated 22 mass movements in northeast Afghanistan, including rock falls, rockslides, and debris flows and analyzed the characteristics of each site. Loess landslide was interpreted by Google Earth in this area (Shroder et al. 2011b), where 34 large-scale loess landslides were found, and most of them developed on the north, west, and northwest slopes. Additionally, frequent earthquakes in this region also disturb the slopes' stability, and over-irrigated cropland may lead to loess landslides as well (Shroder et al. 2011a, b).

This research takes the Abe Barek landslide, which happened on May 2, 2014, in Ago District, Badakhshan Province, Afghanistan, as an example. The location, boundary, and hazards of the Abe Barek landslide are extracted by comparing remote sensing images before and after the event. Through real-time reports and images obtained on site, the causes for the occurrence of the landslide are analyzed. By utilizing high-resolution remote sensing images from Google Earth, landslides in Badakhshan Province are interpreted to map their distribution characteristics. Later, a landslide susceptibility assessment in Badakhshan Province is carried out by weight-of-evidence method to support disaster risk reduction and management in the region.

Background of Badakhshan Province

Badakhshan Province is one of the 34 provinces of Afghanistan located in the northeast of Afghanistan. Badakhshan is bordered with Tajikistan in the southeast and with Pakistan in the south (Fig. 1). In the east of the province is a long spur named Wakhan, which borders with China in the easternmost. In history, Badakhshan Province was an important trading center along the Silk Road.

Badakhshan Province covers an area of 44,059 km^2 and consists of 28 districts, 1851 villages with an estimated population of 819,396 people, accounting for 3.5 % of the country's total population. Most of the population in Badakhshan dwells in the eastern and middle part of the province. The Argo District, where the landslide took place, has the largest population across the province, occupying more than 10 % of the provincial population (UNFPA 2003).

Geology

The geologic structure in Badakhshan Province is complicated, and the formation ranges from Archean to Holocene (Fig. 2).

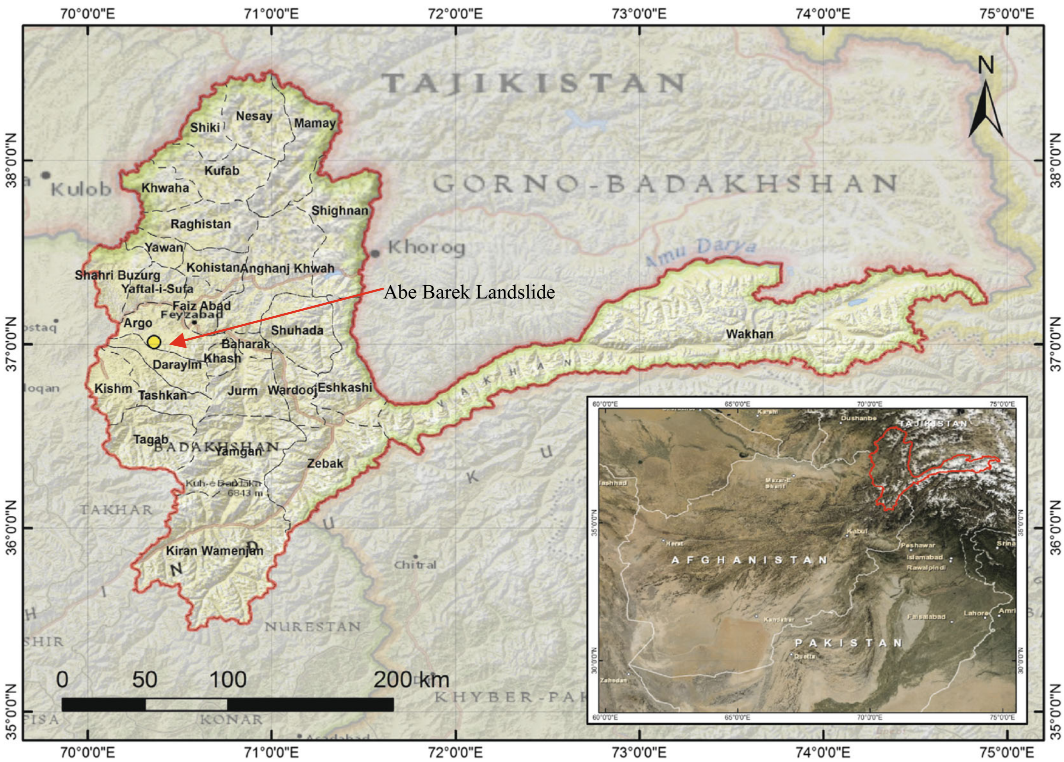


Fig. 1 Location map of Badakhshan Province (source: National Geographic World Map (ESRI 2010))

The oldest rock is gneiss of Archean formation, which consists of Lower Archean formation (Ugn), Middle Archean formation (Vgn), and Upper Archean formation (Wgn). These formations spread across the middle of the province. Proterozoic formation

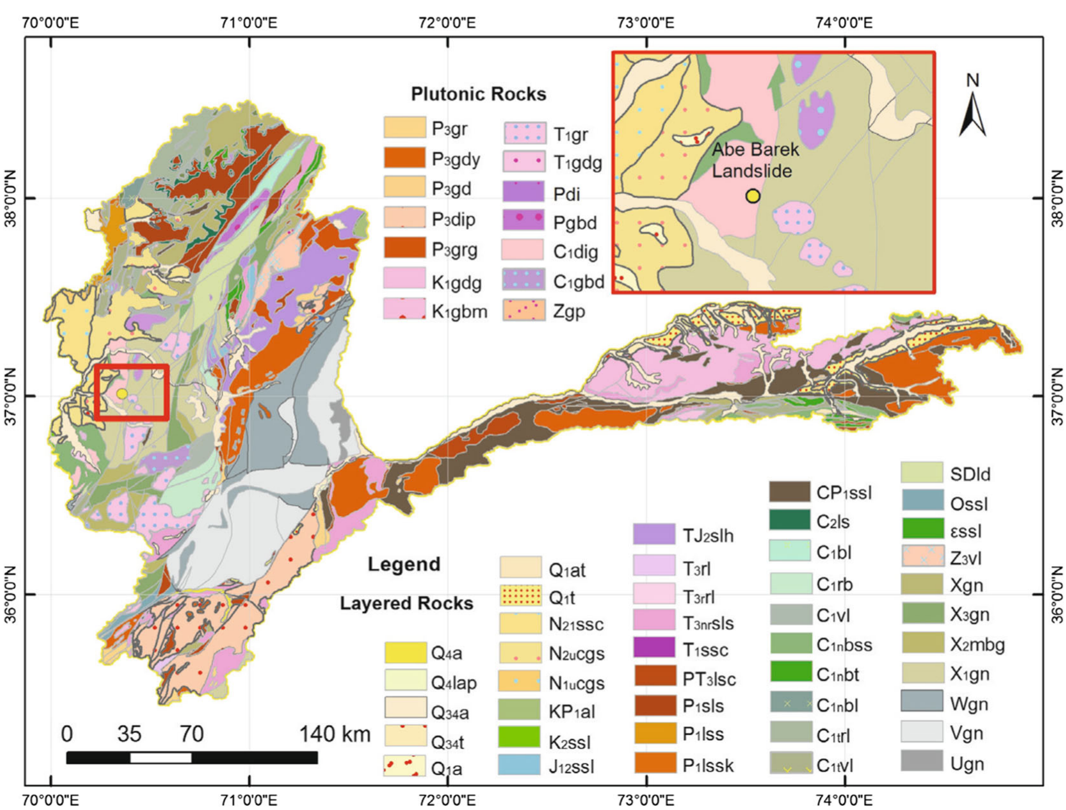


Fig. 2 Geologic map of Badakhshan, Afghanistan (Deobrich and Wahl 2006)

(Xgn) includes gneiss (X_3gn) and lava (Z_3val). Cambrian formation, which consists of mainly sandstone and siltstone with limestone, dolomite, and mafic volcanic rocks is located in the north of the province. Sandstone, siltstone, and chert of Ordovician (Ossl), covering a small area, are located in the south of the province. Devonian formation interfingered with Silurian formation (SDld) and consisting mainly of limestone and dolomite with schist and sandstone is located in the north of the province. Carboniferous formation includes lava (C_{1t}vl), rhyolite lava (C_{1t}rl), basalt tuff (C_{1n}bl), basalt lava (C_{1n}bt), basalt and sandstone (C_{1n}bss), rhyolite tuff (C_1bl), volcanic and sedimentary rocks (C_1rb), and limestone (C_2ls). Sandstone and siltstone formation (CP_1ssl) of Early Permian and Carboniferous are located in the northeast and west of this area. Limestone and sandstone of early Permian formation (P_1lssk, P_1lss, P_1sls) and limestone and chert of late Triassic and Permian (PT_3lsc) are located in the southeastern and northern areas. Triassic formation, which includes sandstone and conglomerate (T_1ssc, T_{3nr}sls), rhyolite (T_{3r}rl, T_3rl), as well as siltstone and shale of Middle Jurassic and late Triassic (TJ_2slh), is located in the southeastern and middle areas. Jurassic formation consists of sandstone and siltstone (J_{12}ssl), and Tertiary formation consists of conglomerate and sandstone (N_{1u}cgs, N_{21}ssc, N_{2u}cgs). Quaternary stratum, which includes till (Q_1t, Q_{34}t), andesite tuff (Q_1at), conglomerate and sandstone (Q_1a, Q_{34}a, Q_4a), and eolian deposits (Q_4lap), is located across the river valleys in the western and eastern areas.

Topography

Badakhshan Province is located in the mountainous area of Hindu-Kush and Pamir. The elevation ranges from 570 to 7492 m, generally with a higher east and lower west. The elevation of most Wakhan District, Zebak District, and Kiran Wamenjan District is higher than 4000 m. The Noshq Mountain with a peak of 7492 m located at the border of Wakhan District with Pakistan is the highest mountain of Afghanistan. The elevation in the north and northeast of the province ranges from 2000 to 5000 m, while the eastern and middle areas are much lower, mostly below 2000 m.

The distribution of slope gradient in the province is calculated, showing that areas with a slope lower than 10° account for 13.66 % of the province's total area, which are generally distributed in the river valleys. Slopes between 20° and 40° cover approximately 78 % of the area, which is the area where landslides could possibly happen. In particular, areas with a slope of 20°~30° have the largest percentage, which occupies 30.22 % of the province's land. Areas with a slope of more than 40° account for 8.12 %.

Climate

The average annual precipitation in Afghanistan is about 240 mm. However, when compared to other provinces, Badakhshan Province enjoys a much more abundant precipitation with an annual precipitation reaching 600 mm. The precipitation concentrates in the south and north of the province, and in some areas, it could reach 1000 mm annually. The precipitation decreases eastward gradually. In the high mountain area of Wakhan District, the annual precipitation could be lower than 200 mm. In the Abe Barek landslide area, the annual precipitation is between 400 and 500 mm. Most of the rainfalls are seasonally disproportionate, occurring mainly between February and May. Badakhshan has six types of climate. The climatic regions from east to west are glacier, cold semi-desert (more than 6 months of freeze), cold semi-desert (less than 6 months of freeze), xerotic-cold dry season marked, xerotic-temperate cold, and xerotic-temperate character, as shown in Fig. 3.

Land cover and land use

The study area has very low vegetation coverage and simplex land use types. The land use types include irrigated cropland, rainfed cropland, mosaic croplands, mosaic vegetation, grassland, sparse vegetation, bare area, water bodies, and permanent snow and ice, as shown in Fig. 4. Grassland is the main land use type with a percentage of 46.30 %. The grassland includes temperate grassland, savannas and montane grassland. The bare land is the second largest land use type. The percentages of bare land and permanent snow and ice are 35.10 and 15.25 %, respectively. These three land use types account for 96.65 % of the province's land, while the rest such as farmland, forest, and water bodies only occupy 3.35 % of the land.

The east and southeast of Badakhshan Province has a higher elevation where the main land use types in the area are grassland, bare land, and permanent snow and ice. Settlements and croplands are distributed in small areas along the river valleys and gullies at a lower elevation. In the north and northeast of the province, where the elevation is relatively high, permanent snow and ice areas, bare land, and grasslands are more commonly distributed. The west and middle of the province, where the elevation is low and mountain slopes are less steep, encompasses a larger population and cropland, which has brought about more active anthropogenic disturbance in this area.

Abe Barek landslide: characteristics and causes

Main characteristics of the landslide

On 2 May 2014, a loess landslide occurred in Argo District of Badakhshan Province, Afghanistan, after prolonged heavy rainfalls. The landslide is located in the west of Abe Barek village, on the opposite side of a river (Fig. 5). The elevation of the landslide's main scarp is 2700 m, while the elevation of the hill foot is 300 m, giving a relative elevation of 2400 m that indicates a long-distance landslide mass movement. According to local villagers, there were two consecutive collapses that happened in 2 h. At 11 o'clock in the morning, the first collapse happened. The landslide mass initially moved along the slope to the hill foot, then went on moving towards northeast and crossed the river, and later buried some houses of Abe Barek village. Soon, some villagers came to rescue the buried villagers, when the second collapse happened, 1 h after the first. The latter landslide buried the rescuing villagers and more houses. The death tolls may have reached 2700 (the number varied according different sources, e.g., UN mission in Afghanistan reported 350 deaths (OCHA 2014), while the Governor of Badakhshan said 2100 deaths (Azam Ahmed 2014). From WorldView-2 images with 0.5-m spatial resolution, 86 houses were buried by the landslide (UNOSAT 2014). A large loess dam of 550 m long along the river was formed after the landslide. The thickness of the dam ranged from 10 to 30 m with the thickest part possibly reaching 60 m. A landslide lake came into formation in the upstream of the dam. This landslide was the most severe natural hazard event following two destructive earthquakes in 1998 in this area (one earthquake of M_w 5.9 happened on 4

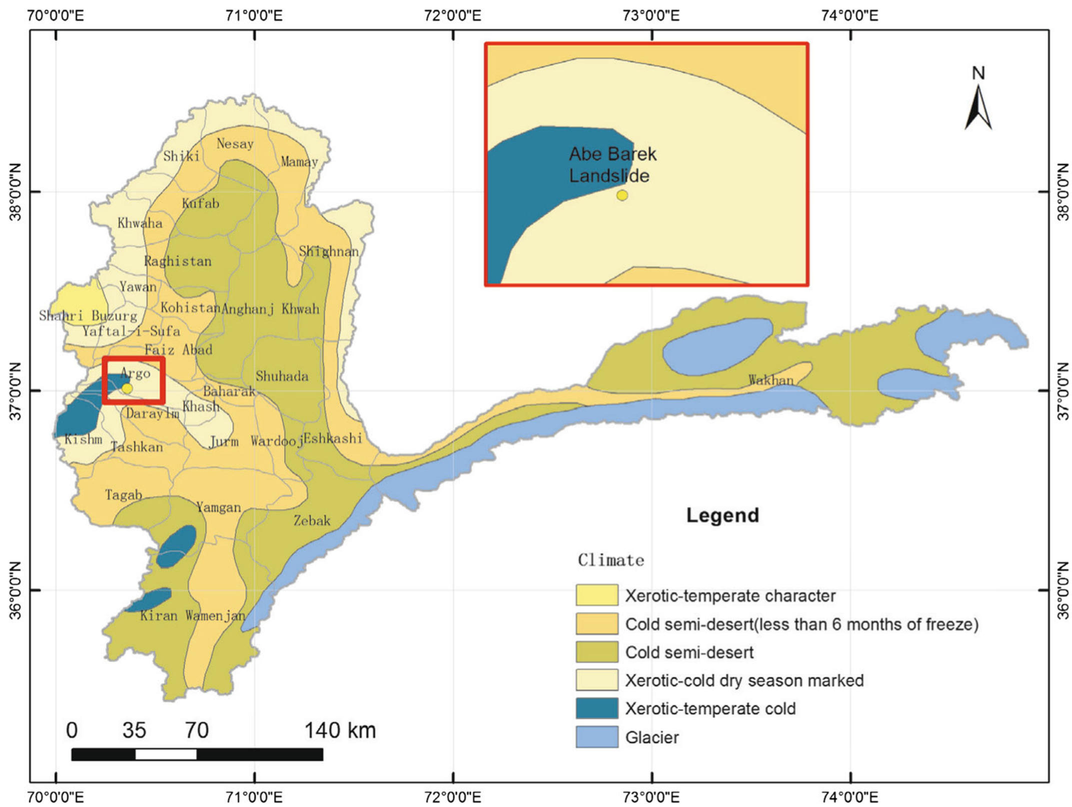


Fig. 3 Climate zone of Badakhshan Province, Afghanistan (Geodesy and Cartography Head Offices 1985)

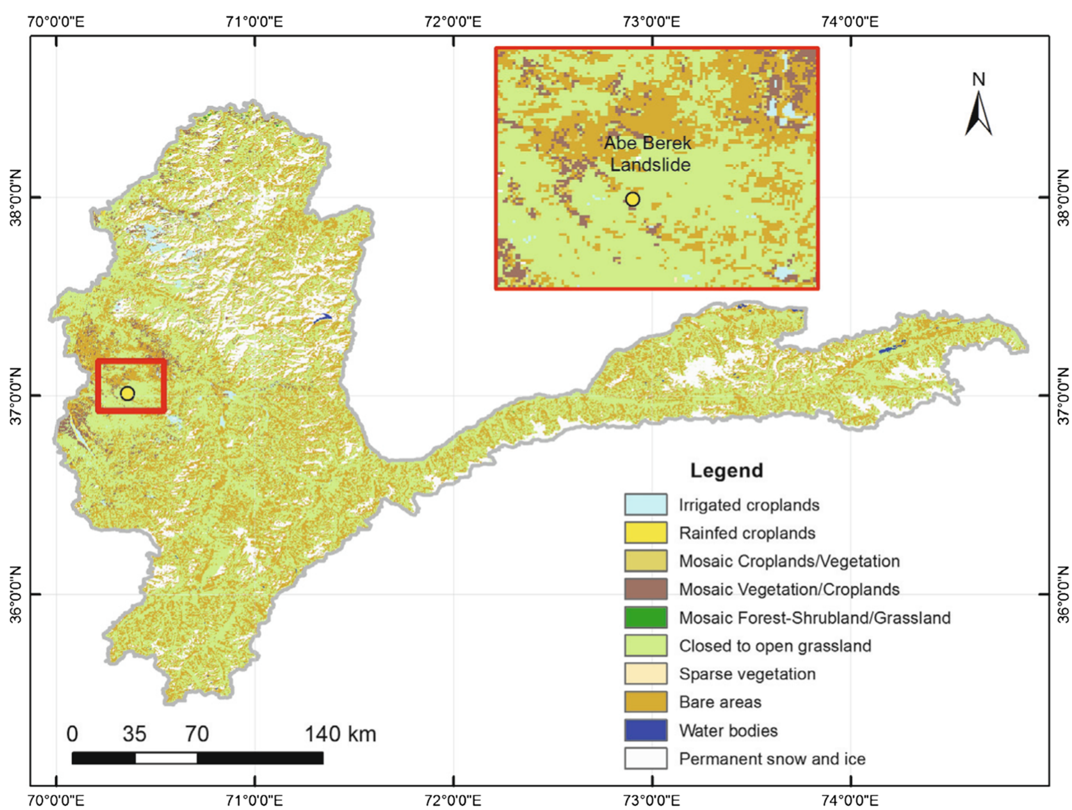


Fig. 4 Land use map of Badakhshan Province, Afghanistan (Bicheron et al. 2008)

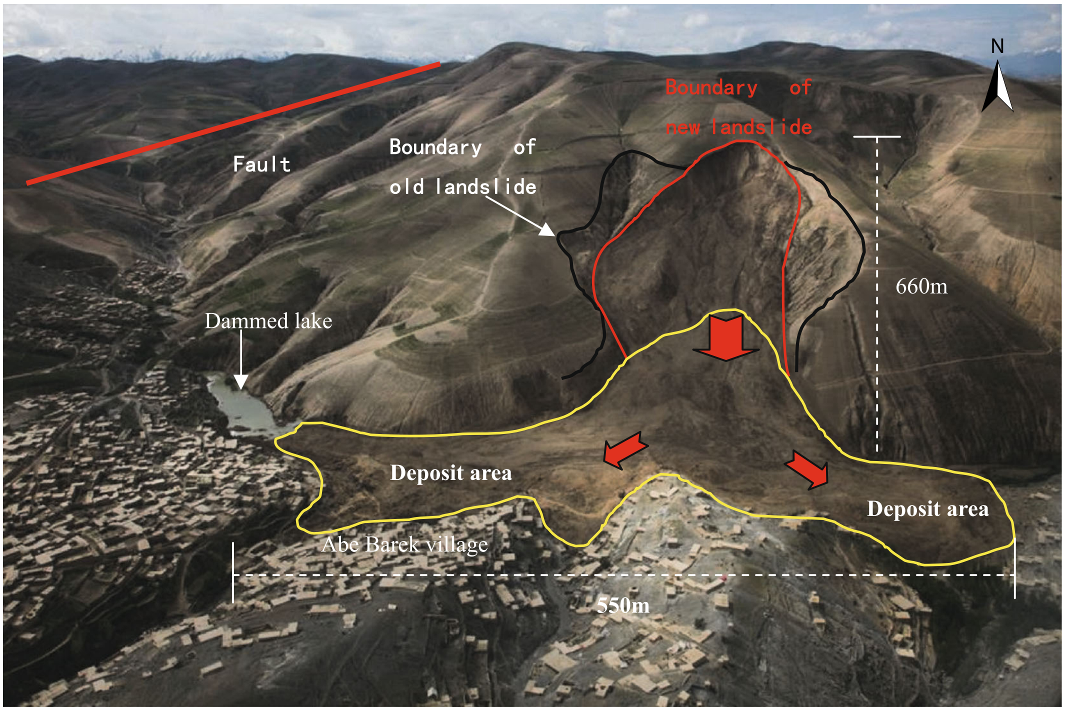


Fig. 5 Photo of Abe Barek landslide (photo: Fardin Waezi/UNAMA (UN 2014))

February, killed near 2323 people, and the other one of M_w 6.9 happened on 30 May, which caused a casualty of at least 4000 deaths in total) (USGS 2012).

Causative analysis

In the Abe Barek landslide, thick loess layer provided the source material, while intense seismicity altered the structure and physical property of the loess. Mountainous topography offered the potential energy for the landslide, while the river eroded the slope's foot forming a free face. Farming and irrigation changed the land cover and moisture of loess. These factors contributed to the basic condition for the cause of the landslide. Concentrated and continuous rainfalls during the monsoon changed the moisture of loess gradually and eventually, induced the mudslide. A detailed analysis is provided below.

Geologic and seismic reasons

The stratum structure of the area where the landslide developed is complicated with concentrated faults. The landslide occurred in the vicinity of a fault, which is about 1 km in the southeast. The stratum in this area could be generally divided into two layers. The lower layer is a bed rock, which is of early carboniferous diorite and granite formation with a small amount of granophyre and plagiogranite rock. The upper layer is loess, which consists of wind-blown dust from the northern desert, and has been deposited over the preexisting topography of the bed rock. The landslide took place in this loess layer.

Loess has characteristics of good water permeability and collapsibility. During the rainy season, it is very easy for the water to permeate into the loess. With increased moisture, the loess becomes heavier, and the shear strength of the loess decreases and the instability of the material increases. At the same time, loess usually has a loose structure, and it becomes more compact under the pressure of water, during which deformation at the back part of the landslide occurs.

Northeast of Afghanistan is an exceptionally high seismic region (Wheeler and Rukstales 2007). Historically, 21 epicenters of earthquakes with magnitudes ≥7 earthquake have been located in or near this area. There was no earthquake when the Abe Barek landslide happened. Therefore, the earthquake cannot serve as a direct factor for this event. However, frequent earthquakes in the past have certainly changed the soil's structure and thus reduced the soil's structural strength and stability.

Topographic reasons

The landslide source area has a maximum slope degree of 34° and a minimum of 10°, with an average slope degree of 30°.

A profile of the slope where the Abe Barek landslide occurred shows that the slope is composed of a convex slope, a straight slope and a concave slope (Fig. 6). The profile is divided into six sections. On the upper part of this slope, ① is a concave slope with a length of 250 m. The elevation of this section is above 2030 m. It might have been a convex slope before, since a historical landslide occurred on this slope where landslide mass moved away and thereafter, formed a concave slope. The lower section of the slope, ② has a length of 150 m and is a straight slope. The elevation of this section ranges from 1980 to 2030 m. The adjoining section ③ with a length of 180 m, similar to section ②, is also a straight slope. This section of slope is the source area of the new landslide. Section ④ is a convex slope, which was formed by the old landslide. Given the upper section slope turned steeper after an old landslide's mass moved down, it formed a free face for section ③ and contributed a topographic factor for the new landslide to occur. At the same time, in this concave slope (section ④), it is

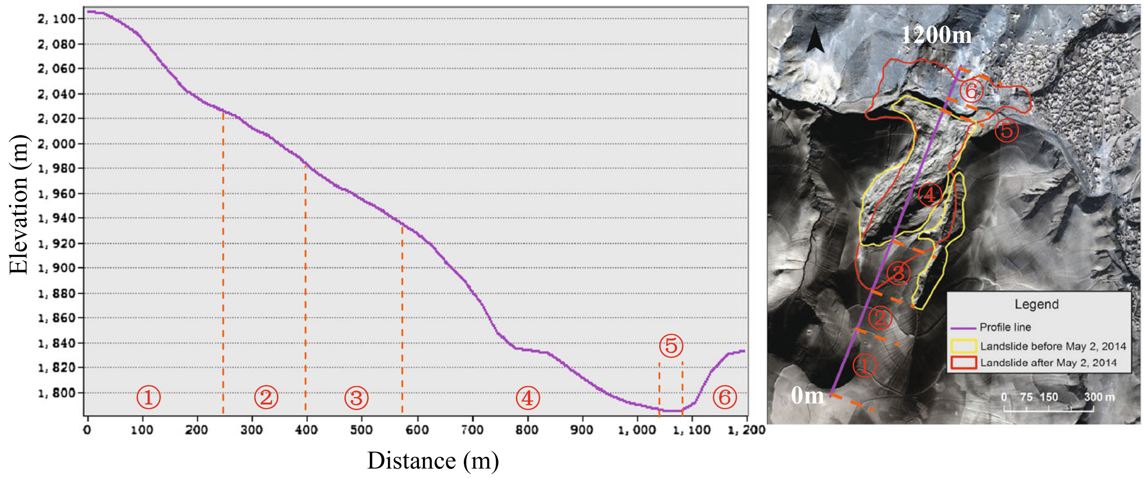


Fig. 6 Topographic profile of Abe Barek landslide (before May 2, 2014)

very easy for the rainfall to accumulate, which greatly increased the moisture of loess in this area and reduced soil body's shear strength. Consequently, the mass in this slope became more prone to instability.

Precipitation reasons

Slope stability is affected by permeation of rainfall through the joints and fissures, where some of these fissures are even filled with water. This permeated rainfall water will increase the weight on the slope and cause a development of pore pressures, softening the slope, and reducing its stability. Furthermore, additional permeation of the rainfall water to the confining bed will create an uplift force that further reduces the stability of the slope (Wang and Zhang 2005).

There are no precipitation records in Abe Barek village. Precipitation data in Faizabad, which is 20 km away from the landslide, is analyzed in this study (Fig. 7). Faizabad has a humid subtropical climate. Precipitation mostly falls between February and May. Each of these months enjoys a precipitation of more than 80 mm. The total precipitation of these 4 months takes up about 72 % of the precipitation for the whole year. From June to September is the dry season, with a monthly precipitation lower than 10 mm. From October to January, the precipitation increases to 20~40 mm per month. It is reasonable to infer that the concentrated rainfalls between February and May have increased the moisture of loess and served as a triggering condition for landslide.

Daily precipitation data from 1 January to 1 May in Faizabad before the landslide occurred is obtained from AccuWeather Company (2014) for statistical analysis (Fig. 8). From January to April, there were rainfalls in each month. January had the highest precipitation of 238 mm. In April, there were also continued rainfalls with a precipitation of 53 mm. The daily precipitations of 3 days before the landslide occurred were 1, 2, and 8 mm. It is believed that these rainfalls increased the moisture of loess in this area. The moisture of soil has a deterministic impact on the occurrence of landslide. When soil moisture exceeds the threshold that soil mass can tolerate, a landslide will occur (Bettis et al. 1986).

Historical landslides

From historical remote sensing images, an old landslide in this slope could be interpreted (Fig. 9). The old landslide destroyed the land cover of this area, making it easier for the rainfall to infiltrate, and hence, influenced the stability of the slope. As mentioned above, the old landslide also deformed the microtopography of this area by forming a steeper slope. On the main scarp of the old landslide, years of rainfalls have eroded slope soil mass and formed a number of gullies that continuously carried away the

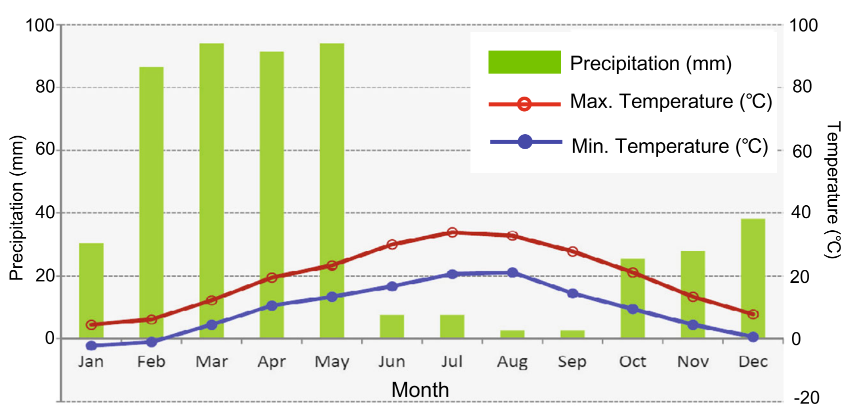


Fig. 7 Monthly rainfall of Faizabad (Afghan Meteorological Authority 2012)

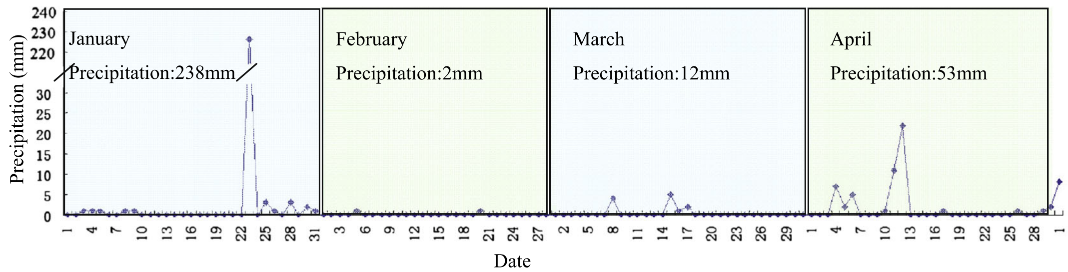


Fig. 8 Daily precipitation in Faizadbad, 2014 (source: AccuWeather Company 2014)

slope masses. Therefore, the slope in this area grew much steeper, and the mass on the old landslide scarp became more prone to collapse.

The landslide occurred in a predominately farming region, where irrigation activities may have deepened the soil moisture and potentially increased the chance of slope instability as well.

Landslide investigation in Badakhshan Province

Landslide interpretation approaches

Topography

On a zonal scale, as a kind of mass movement on the slope, the occurrence of landslide depends on the slope gradient. On the scale of a single landslide, after the landslide happens, it will form a special microtopography. A well-developed landslide usually includes landslide body, landslide boundary, crown, slump blocks, landslide axis, transverse ridges, fissures, main scarp, posterior depression, surface of rupture, sliding zone, landslide bed, shear opening, original surface, etc. (Wu et al. 1993). However, not all landslides have these parts clearly and fully presented. In the remote sensing imagery, only the parts on the ground could be recognized, such as landslide body, landslide scarp, and landslide boundary (Wang 2007). For a mudslide (Fig. 10a, b), the landslide scarp, boundary, and surface of rupture could be easily extracted since the earth is very easily transported via a gully by water. For a rockslide, the landslide mass is deposited at the foot of hill and is adequately recognizable as well (Fig. 10c, d).

Hue and brightness

Landslide destroys and alters the land use and land cover substantially, which reflects as differences in hue on remote sensing images. In Fig. 10a, the land cover is shrub and grass in this area, which shows dark green and brown in real color imagery. After the landslide happened, the landslide impacted area shows in light yellow since the shrub and grass were destroyed and changed into bare land. In Fig. 10b, the land cover is cropland, which shows brown color, while in the landslide area the image shows light yellow.

Same as the change of hue caused by land cover, the brightness also shows many differences due to the change of albedo. Generally speaking, the albedo of landslide is higher than non-landslide areas. Given a different composition of landslide body, the brightness varies. For instance, loess landslide has a low albedo as shown in Fig. 10a, b, while in Fig. 10c, d, rockslide site is brighter than nearby areas because the bed rocks become more visible.

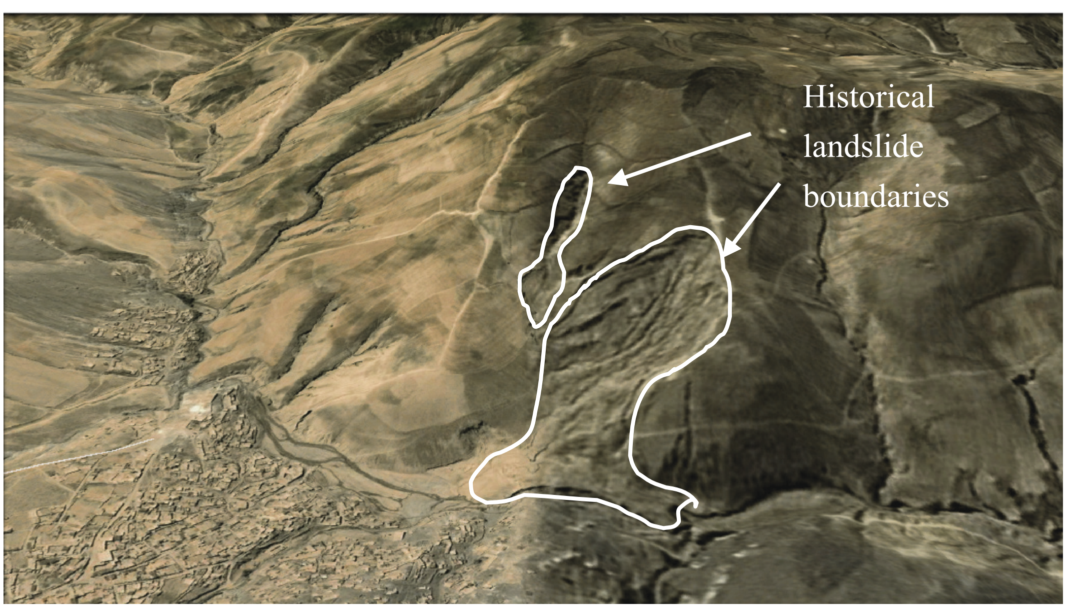
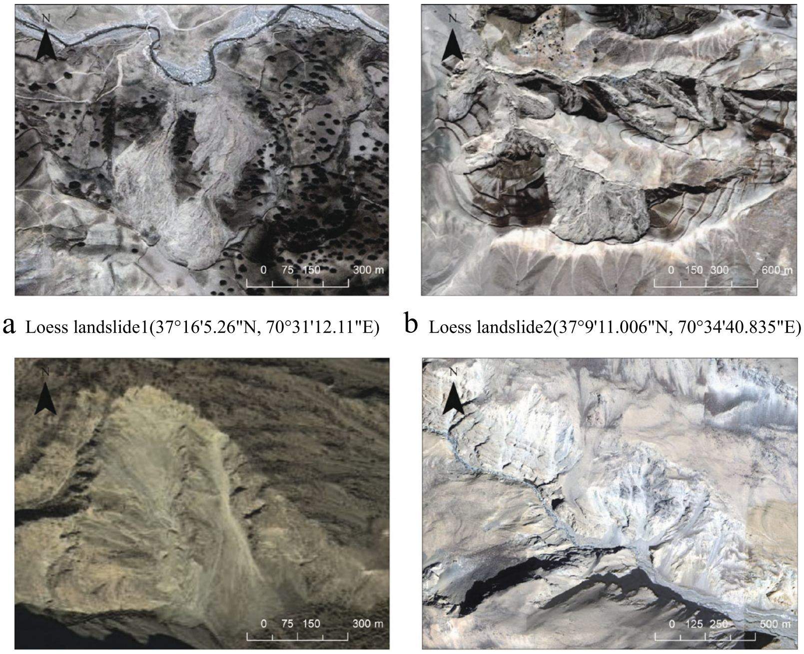


Fig. 9 Historical landslide (image: 10 July 2014, Google Earth)



a Loess landslide1(37°16'5.26"N, 70°31'12.11"E) b Loess landslide2(37°9'11.006"N, 70°34'40.835"E)

c Rock landslide 1(37°37'30.468"N,70°22'45.177"E) d Rock Landslide 2(36°22'21.887"N, 71°13'26.536"E)

Fig. 10 Typical mudslides (**a**, **b**) and rockslides (**e**, **d**) shown in the remote sensing imagery

Texture
For a mudslide, on the scarp and surface of rupture area, when the landslide mass moves down, it also destroys the land cover. Without the protection of vegetation, the soil is prone to rainfall induced erosion. Many gullies are therefore formed along the slope, which appear as parallel texture on the imagery (Fig. 10a). Sometimes, the deposition area of landslide also shows certain texture, especially for a rockslide.

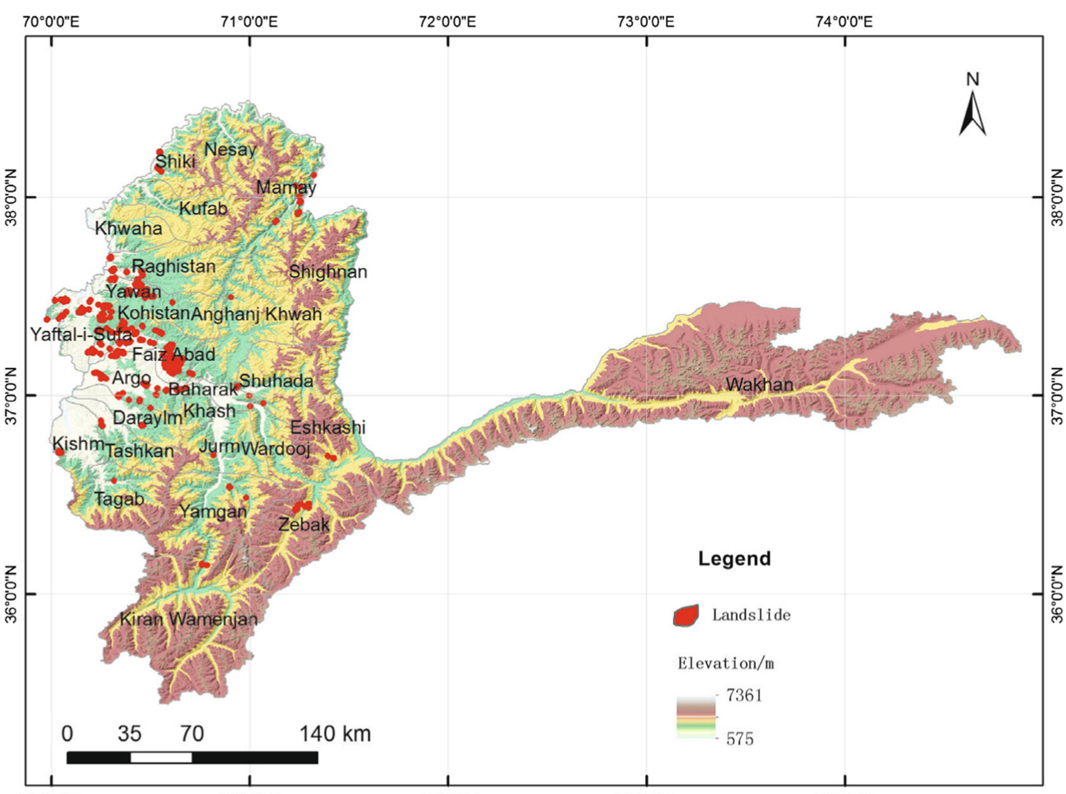


Fig 11 Landslides distribution map for Badakhshan Province, Afghanistan

Table 1 Causative factors, data sources, and classifications

Causative factor		Source	Resolution/ scale	Description	Classification
Topography	Elevation	SRTM DEM	90 m	Jarvis et al. 2008	Eight classes: 0~1000, 1000~2000, 2000~3000, 3000~4000, 4000~5000, 5000~6000, 6000~7000, and ≥7000 m
	Slope gradient	SRTM DEM	90 m	Calculate from SRTM DEM	Eight classes: 0°~10°, 10°~20°, 20°~30°, 30°~40°, 40°~50°, 50°~60°, 60°~70°, and ≥70°
	Curvature	SRTM DEM	90 m	Calculate from SRTM DEM	Five classes: −26~−1, −1~−0.1, −0.1~0.1, 0.1~1, and 1~14
	Slope aspect	SRTM DEM	90 m	Calculate from SRTM DEM	Eight categories: north, northeast, east, southeast, south, southwest, west, and northwest
	Gully density	SRTM DEM	90 m	Calculate from SRTM DEM	Ten categories by natural break method
Geology	Rock type	Geologic and Mineral Resource Map of Afghanistan	1:850,000	–	Four categories: very hard, hard, soft, and very soft
	Distance to faults	Geologic and Mineral Resource Map of Afghanistan	1:850,000	Using the fault layer to calculate the distance to faults	Ten classes by natural break method
Human activities	Land use	Globcover	90 m	This land use data is interpreted from the MERIS imageries with 300 m resolution (Bicheron et al. 2008). In this study, the data is interpolated into 90 m resolution.	Eight categories: irrigated croplands, rainfed croplands, mosaic croplands/vegetation, mosaic forest-shrub lands, close to open grassland, sparse vegetation, bare areas, water bodies, and permanent snow and ice
Precipitation	Annual precipitation	National Atlas of the Democratic Republic of Afghanistan	1:9,000,000	Geodesy and Cartography Head Offices 1985	Eight classes: 0~100, 100~200, 200~300, 300~400, 400~600, 600~800, 800~1000, and ≥1000 mm

When the landslide body moves to the foot of hill and breaks into rocks, in the deposit area of landslide will form regular texture as shown in the imagery.

Landslide distribution

Based on the landslide interpretation approaches aforementioned and analysis of high-resolution remote sensing images from Google Earth, a landslide investigation is carried out for Badakhshan Province, Afghanistan. A total of 609 landslides are interpreted covering an area of 1377.95 ha (Fig. 11). Four districts as Faizabad, Yafta-i-Sufa, Yawan, Argo, and Sharhir Buzurg are deemed the most active areas for landslides. Around 500 landslides are located in these districts, accounting for 82.10 % of the total landslides, and cover an area of 1024.24 ha which occupy 74.33 % of the total landslide area.

Landslide susceptibility assessment

Landslide susceptibility assessment is one of the important components of regional landslide control and risk reduction. Based on the analysis of the characteristics of landslides, the assessment discusses the influences of causative and triggering factors of landslides. Generally, causative factors include geologic factors (rock type, lithology, distance to faults), topographic factors (slope, elevation, relative elevation, aspect, curvature, gully density), and human activities (land use, distance to roads). Typical triggering factors are precipitation, earthquake, and volcanic activity. By using these factors, an assessment model is built to calculate the susceptibility of the study area, measuring the probable degree of landslide occurrence. At present, landslide susceptibility assessment methods include heuristic method, deterministic method, and statistical method.

In this study, the weight-of-evidence (WoE) approach, derived from the software ArcSDM (Sawatzky et al. 2009), is employed to build the assessing model. The general steps to this method are:

a. Factor selection and reclassification: Based on previous studies of landslides and the characteristics of landslides in the study area, choose assessment factors and reclassify them.
b. Samples collection: Choose certain sampling sites for susceptibility modeling and validation in the landslide areas.
c. Weights of factors calculation: Use Calculate Weight command in ArcSDM to calculate the weight of each factor correlated to landslide.
d. Modeling and assessing: Based on the weight derived from the step c, use Calculate Response command to obtain the susceptibility value of landslide.
e. Validation: Grade the susceptibility map from step d, and compare modeling and validation point sites from the landslide area to verify the model.

Assessing factors selection

In this study, susceptibility assessment factors are divided into four classes (Table 1): topography, geology, human activities, and precipitation. The topographical factors are calculated from SRTM DEM. Geologic factors include lithology and distance to faults, which are obtained from the Geologic and Mineral Resource Map of Afghanistan (Deobrich and Wahl 2006). Land use is taken as the human activity factor, which is extracted from the GlobCover data (Bicheron et al. 2008). This data is interpolated from 300 m resolution to 90 m in accordance with other factors. The annual precipitation is taken as the precipitation factor (Geodesy and Cartography Head Offices 1985).

Landslide sampling

Point data as training data is required for the WoE model by ArcSDM. In this research, the pixel of each assessing factor is 90 m. Accordingly, the training data is selected at the interval of 90 m from the landslide scarp area. Using the Training Sites Reduction Command, 80 % of these points were randomly selected as modeling sites. The others were used to verify the model. The sites for modeling and validation in one landslide are shown in Fig. 12.

Landslide susceptibility modeling

Weights for each section of the factors are calculated by utilizing ArcSDM extension. ArcSDM, which calculates the parameters automatically and includes positive and negative weight (W^+ and W^-), contrast and their standard deviations, as well as the studentized contrast for each class in the specified class field. Table 2 shows the positive weight (W^+) in this research. It shows the influences of various classes of each factor on the past landslides. A larger W^+ value means a higher positive correlation. The classes show different relationship with landslide in different study areas. However, in this study area, land use, slope gradient, and elevation factors showed the highest positive correlation to landslide occurrence.

At last, weighted overlap-adding method, which combines the evidence weighted by their associated generalization in the weights-of-evidence table, is applied to assess the probability of landslide in the whole area by the command of Calculate Response. As a result, a landslide susceptibility map (Fig. 13) is prepared and classified into four classes of very high susceptibility, high susceptibility, medium susceptibility, and low susceptibility. Most areas of very high and high landslide susceptibility are located in the east and middle of the Badakhshan Province and concentrated in the slopes near river valleys. Districts that have the highest percentage of very high susceptibility and high susceptibility areas are Faizabad, Shahri Buzurg, and Yaftal-i-Sufa. The percentages are 39.93, 36.61, and 36.36 %, respectively. Argo, Kishm, and Yawa districts come next, and the percentages are 28.82, 28.21, and 25.91 %, respectively (Fig. 14).

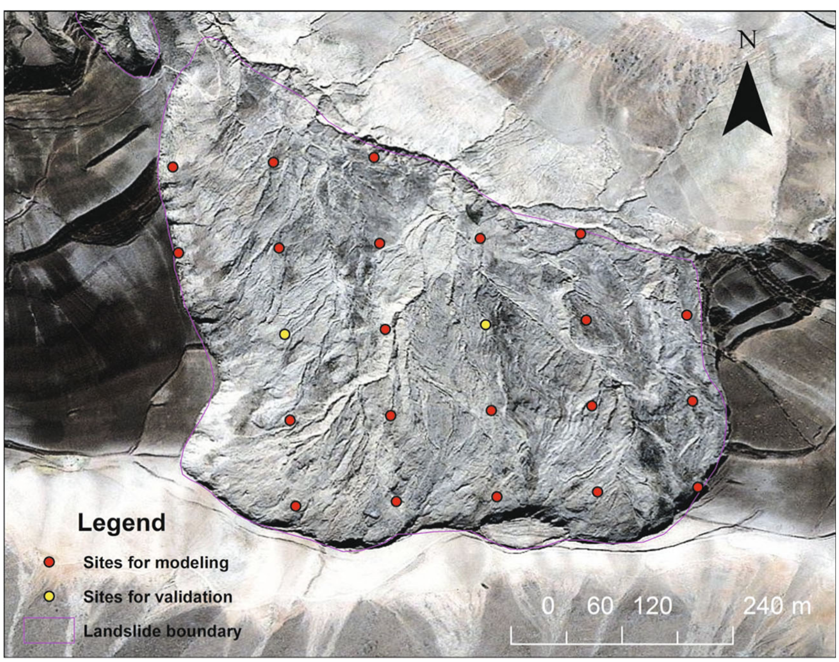


Fig. 12 Sites selected for modeling and validation of WoE model

Table 2 Factors with positive weight

Causative factors	Classification	W^+
Elevation	1000~2000 m	2.0231
	2000~3000 m	0.1821
Slope gradient	20°~30°	0.2452
	30°~40°	0.1591
	≥70°	4.5579
Curvature	−26~−1	0.3672
	0.1~1	0.2219
Slope aspect	North	0.3173
	Northeast	0.0035
	East	0.0035
	Southeast	0.0035
	Northwest	0.6552
Gully density	0.47~0.51 km/km^2	0.5445
	0.57~0.68 km/km^2	1.0470
	0.68~0.83	0.3972
Rock type	Hard rock	0.3355
Distance to faults	0~1 km	0.2868
	1~2 km	0.2390
Land use	Rainfed croplands	1.3907
	Mosaic croplands/vegetation	1.1261
	Sparse vegetation	0.1081
	Bare areas	3.6728
Annual precipitation	300~400 mm	0.7909
	400~600 mm	0.3330

Conclusion and discussion

Compared to other natural disasters such as floods and flash floods in Badakhshan Province, Afghanistan, landslides have a lower influence in terms of frequency, affected area, and scale. To some degree, landslide has been by and large neglected in this area. However, once a landslide occurs, it will bring about large casualties and economic losses. In addition to the suddenness of landslide, the low frequency of occurrence also gives rise to the ignorance and unpreparedness towards the disaster among the locals. When a landslide happens, people do not have adequate know-how to respond to the disaster. Incorrect escape and rescue activities could cause more casualties. In the case of the Abe Barek landslide, if some monitoring of the landslide during the rainy season was in place, an early warning might have helped avoid this disaster. Further, if some initial inspection of the slope's stability was conducted after the first collapse before the villagers went out to rescue, less people would be killed by the second collapse.

Based on the Abe Barek landslide, a series of discussions have been conducted about landslide risk control and reduction in the remote areas of Afghanistan, and some conclusions are presented here:

Landslide investigation

Due to unstable political and economical conditions, there has been little research on landslide in this area. Under the current situation, it is also very difficult to conduct field investigation on landslides in this area. Therefore, a more available and highly efficient approach is the use of remote sensing technology. By utilizing high-resolution remote sensing imageries, a landslide's type, location, scale, and boundary could be carefully extracted. Some possible field work such as locations of landslides and hazards induced by landslides could then be carried out to verify the landslide data interpreted by the remote sensing imageries. More detailed characteristics about landslides could be acquired and measured such as landslide volume, lithology, and movement features. Thus, a regional landslide database could be established for appropriate landslide prevention and management.

Landslide risk assessment

By using a landslide database, landslide features and activities could be better analyzed. Based on physical factors (such as geologic and topographic conditions, human activities), triggering factors (precipitation, historical earthquakes, etc.), as well as economic factors (population, economic development, etc.),

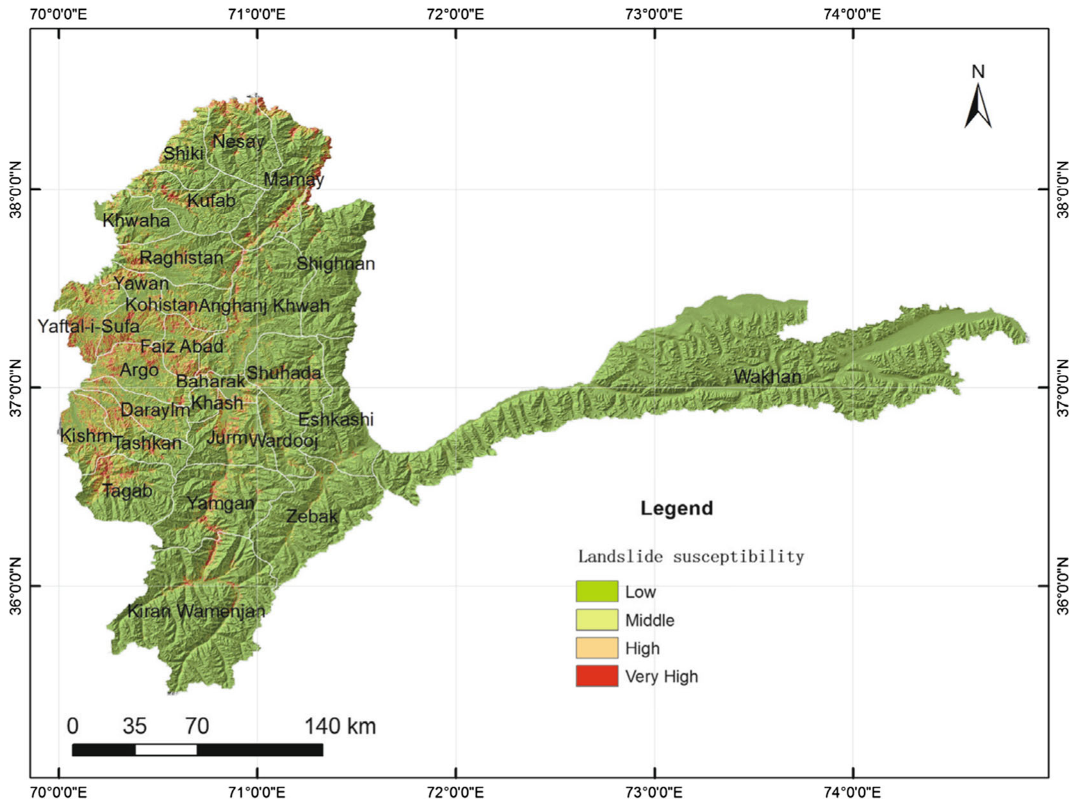


Fig. 13 Landslide susceptibility map of Badakhshan Province, Afghanistan

susceptibility, vulnerability, and risks of the disaster could be assessed to map the distribution of high-risk landslides. The assessment results could provide a reference for concerned government agencies to determine landslide management and mitigation efforts, set the required budget and facilitate proper allocation of funds.

Landslide monitoring and early warning

Landslide monitoring and early warning is urgently needed for this area. Some approaches include technology-based monitoring and community-based observation and prevention.

For large-scale and high-risk potential hazards, the monitoring and warning should depend on professional technological instruments to monitor landslide body displacement, soil moisture, cracks, underground water pressure, precipitation, and other parameters. When the values of such parameters exceed the thresholds, the equipment can release a warning. Nonetheless, for this kind of monitoring, a huge investment is needed to purchase, install, configure, as well as maintain the equipment.

For disaster management in remote and undeveloped areas, a community-based observation and prevention method is much simpler and more practicable. This method is to select a group of villagers and familiarize them with basic knowledge of landslides and their characteristics prior to the occurrence. Then, the trainees or village observers are asked to continually observe and record the conditions of potential landslides such as cracks and displacement. In particular, during heavy rainfalls, the village observers should pay more attention to landslide monitoring. Once there are any indications of instability, they should immediately inform the other villagers and help evacuate them to safety.

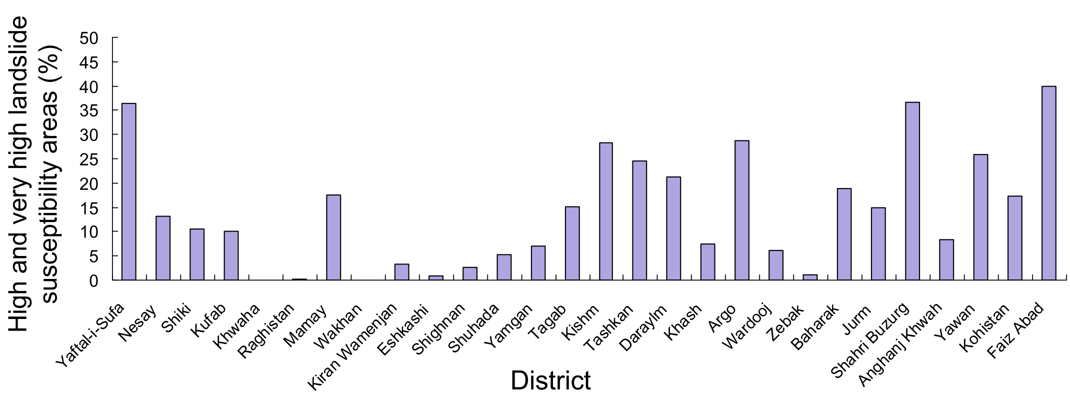


Fig. 14 Percentage of high and very high susceptibility areas in Badakhshan Province

This community-based observation and prevention method is comparatively low-cost and has been widely employed in the mountainous areas of China, where it has been proven to be very effective in terms of mountain hazard prevention and management.

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