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Landslide Susceptibility Analysis in Arandu Area Shigar Valley, CKNP (Gilgit-Baltistan-Pakistan)

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Abstract

The Pakistani Gilgit-Baltistan are recognised as being one of the most beautiful and interesting places in the world due to the presence of the longest glaciers and the highest reliefs. This area remained remote and inaccessible before 1965, after which began the construction of the first roads (Karakoram Highway—KKH). In 1992, the Pakistani Government delegated the responsibility for initiating a preliminary survey to outline the borders of the Central Karakoram National Park (CKNP) which allowed a preliminary outline of the borders (about 3000 km^2) where the major mountain massifs (as Mt. K2), watersheds, and glaciers were included. Since then, several proposals followed. With the aim of preserving this natural beauty for future generations as well as providing the CKNP of a Management Plan, a 5-year multidisciplinary project called SEED (Social, Economic, Environmental Development) started. One of the project's objectives was the analysis of the landslide geohazards aiming at the implementation of a landslide inventory and the realization of a susceptibility map. The Arandu village and its surroundings, which is part of Shigar valley, where the Chogolungma glacier is, was chosen as pilot area. During the summer survey had in 2012, part of the landslide-prone areas, previously identified through DEM analysis (derived from ASTER and Remote Sensing (RS) images) and GIS techniques were identified validating the obtained maps. The Analytical Hierarchy Process (AHP) was used to extract the factor weights in a pairwise comparison matrix. Frequency ratio (FR) method was adopted to drive each class weight. The Weighted linear combination was used in the end to determine the landslide susceptibility index value (LSI).

Keywords

Landslides • Geographical information system (GIS) • Susceptibility • ASTER images • Pakistan

Introduction

Gilgit-Baltistan, formerly known as the Northern Areas of Pakistan, is the northernmost administrative Pakistani territory (Fig. 1). The Central Karakorum National Park (CKNP) was created here (www.cknp.org); it is the highest park in the world in terms of elevation (m a.s.l.). Pakistan, especially the Northern Areas, are among the most fascinating places in the world, world-renowned for sky-high mountains, lush green valleys, mighty rivers, beautiful lakes, and diverse wildlife. Precisely for this reason, the CKNP area must be preserved in order to maintain its beauty, as well as its

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delicate ecosystem and cultural values for the benefit of present and future generations.

Scientists consider this area particularly fragile due to the presence of significant tectonic structures on which the Himalayas and Karakoram ranges were set. Crushing arcs and plates determine the presence of a pronounced seismicity, considered to be one of the most important triggering factors in the occurrence of landslides as was the case in the 2005 earthquake in Muzaffarabad (Basharat et al. 2014; Kamp et al. 2008), and the last dramatic event in Nepal on 25th April 2015. In order to strike a balance between an environment, which is both beautiful and hostile, it is necessary to learn to cohabitate with extremely dangerous phenomena and to identify the safest areas for human activities. In addition to the historical knowledge of the older generation, these areas can also be approached using innovative techniques and tools in order to indicate the most suitable areas to invest and build. Within the framework of sustainability, the 5-year multidisciplinary SEED project (Social, Economic Environmental Development in the CKNP Region) was initiated. It was developed in cooperation with the Italian Ev-K2-CNR Committee under the leadership of the Pakistani Government with the purpose of launching integrated social, economic and environmental development, including the realisation of the Management Plan of the Central Karakorum National Park (Mari et al. 2014). The project operated in compliance with the priorities defined in the Implementation Plan for Agenda 21, developed at the World Summit of Sustainable Development in 2002 to achieve the reduction of poverty and support the sustainable development of mountain ecosystems. SEED (http://www.cknp.org/cms/nature-research/project/seed/) is made up of several different projects, each focused on a different theme. One of the latter concern the issue of geohazard and more precisely landslide susceptibility. In the framework of sustainable development, as suggested by Guzzetti et al. (2012), the first thing to do is to have the knowledge of the environment and this pass through the implementation of a cadastre of landslides. This is a precious instrument providing the stakeholders an important updatable tool for territorial planning, as required also by the national park management plan, where a zoning system for ecosystem conservation and tourism promotion is recommended.

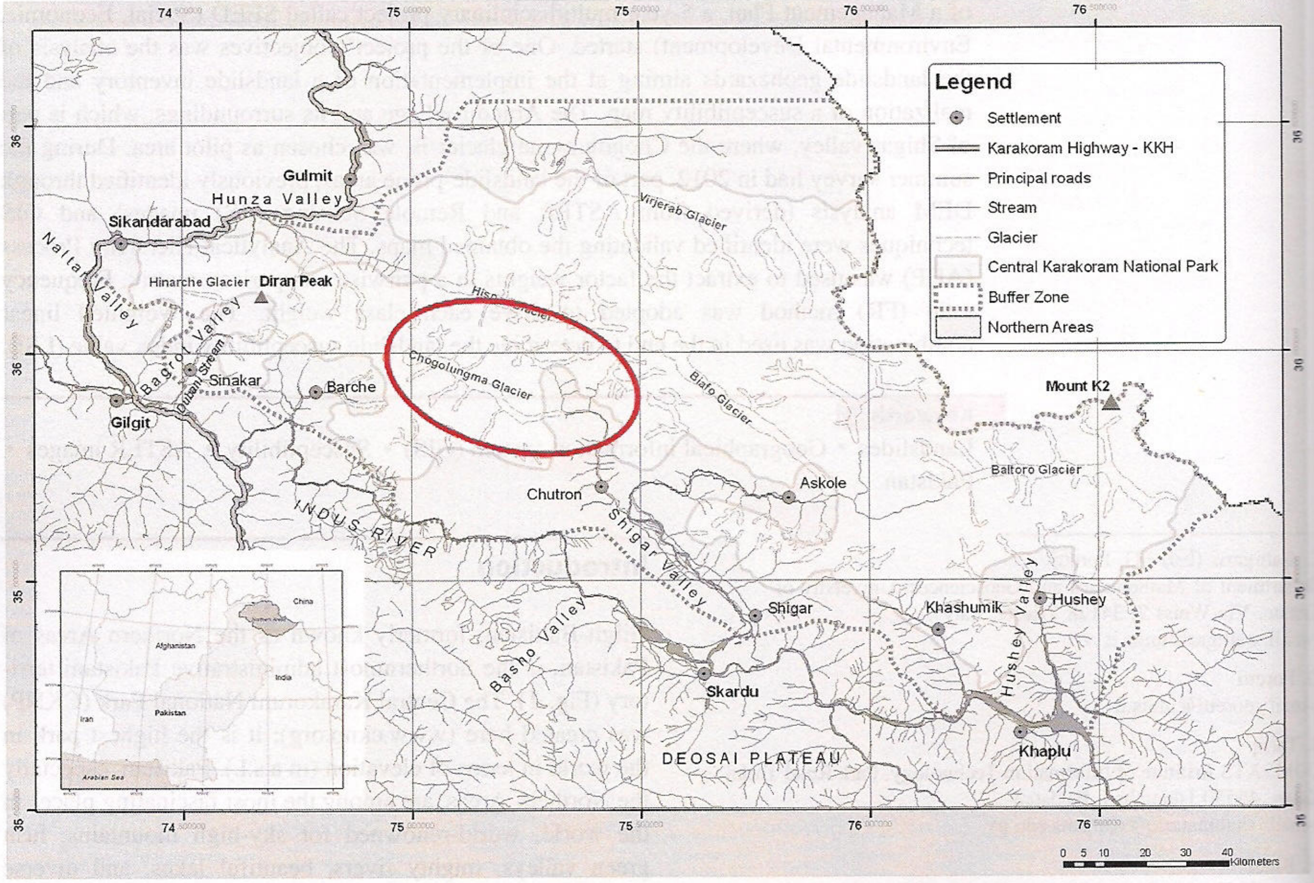

Fig. 1 Study area overview. CKNP is located in the extreme NE part of Pakistan at the border with China and India; in the *red ellipse*, the pilot area

However, the study area is particularly wide and remote and basic data are not always available, representative, reliable and easily accessible. For this reason, the Geographic Information System (GIS) used applying the Analytical Hierarchy Process (AHP), the Frequency Ratio (FR) and the Weighted Linear Combination (WLC) allowed to analyse the territory taking into account several different controlling parameters already established by the literature as suitable for landslide susceptibility mapping (Ayalew et al. 2004; Dahal et al. 2007; Fell et al. 2008; Guzzetti et al. 2012; Saaty 1980; Sarkar and Kanungo 2004; Van Westen et al. 2008).

The aim of the present research is in fact to draw a susceptibility map for the slope instability issue foreseen in the SEED project, taking advantages of GIS and remote sensing tools (Dhakal et al. 2000; Gardner and Saczuk 2004; Guzzetti et al. 2012; Milevski et al. 2009; Ahmed and Rogers 2014; Ahmed et al. 2014). In addition, the research aims updating the implemented landslide inventory created within the framework of SEED by the Operative Unit of the Trieste University.

The landslide susceptibility map, realised for the CKNP was field validated in the Chogo Lungma glacial test site area, located within the park (Fig. 1). Through the analysis of Digital Elevation Model, different slope morphologies were pointed out and the main landslides were identified and classified according to WP/WLI (1994).

Methodological Approach

The Method

Seen that the aim of the present research is to draw a susceptibility map for the slope instability issue, a multivariate approach was applied (Kamp et al. 2008; Ruff and Czurda 2008).

Several are the researchers who focused on the same topic as, just to name a few, Yalcin et al. (2011), Park et al. (2013), and the last in order of appearance, Kanwal et al. (2016). They used different approaches but considered similar event controlling parameters as geology, tectonic structures (thrusts and faults), plan curvatures, slope angles, aspect, drainage network, glaciated areas and land cover (Bajracharya and Bajracharya 2008; Dahal et al. 2007; Othman et al. 2012; Ruff and Czurda 2008).

For the present research, the landslide inventory map, prepared for the Bagrot valley area (Calligaris et al. 2013) was used as a reference map and was updated with the data collected in the Chogolungma glacial area during the field survey held in June 2012. Prior to go to the field, a Landslide Susceptibility Map (LSM) was created which allowed to define the landslide-prone areas independently from spatial and temporal controls (Chacon et al. 2006; Spiker and Gori 2000). To prepare the LSM, the geological and lithological conditions were previously analysed, and later the main geomorphologic parameters (slope angle, aspect and plan curvatures) computed. Furthermore, the LSM was obtained combining the different parameters in accordance with their relative influence to the landslide occurrence following the Analytical Hierarchy Process (AHP). The latter rates not only the parameters, but also the classes in which each parameter is classified (Ayalew et al. 2004; Intarawichian and Dasanada 2010; Komac 2006; Moradi et al. 2012; Phukon et al. 2012; Saaty 1980). The parameters, arranged in hierarchical order of priority in rows and columns, generated a pair-wise comparison matrix. Frequency ratio (FR) method was adopted to drive each class weight (Table 1).

The parameters were later combined through the Weighted Linear Combination (WLC) where secondary-level weights are opinion-based scores (Ayalew et al. 2004). The result is the Landslide Potential Index map (LPI) calculated using the following formula:

$$\mathrm{LPI} = \sum (\mathrm{Ri} \times \mathrm{Wij}) \tag{1}$$

where $i = 1 - 9$, Ri is the rank for parameter i, and Wij is the weight for class j of i factor.

The resulting map is due to the overlapping weighted raster datasets and represents the distribution of the LPI index values classified into 6 classes of potential landslide susceptibility (Fig. 3) (Davis 1986; Sarkar and Kanungo 2004).

The Parameters

As previously described, several are the parameters usable in order to define a landslide susceptibility map. For the work done and here presented, the chosen parameters are: geology, tectonic structures (thrusts and faults), plan curvature, slope angle, aspect, drainage network, glaciated areas and land cover.

The geolithology of the investigated area and the lineaments as fractures, discontinuities and shear zones were derived from the Geological Map of Hunza to Baltistan (Karakoram—Koisthan—Ladakh—Himalaya North Pakistan) implemented by Le Fort and Arnaud in 2002 at 1:150,000 scale (Le Fort and Arnaud 2002; Pêcher and Le Fort 1999). For the research, the Authors digitized the map improving it after the field survey adding elements at 1:5.000 scale.

The topographical base used derives from the high-spatial-resolution multispectral images (ASTER images —30 m grid cell size). The stereo images from NASA

Table 1 Frequency ratio (FR) computed for each single class

	Class	FR		Class	FR
Geology	cgM	0.00	Distance to river	0–50 m	0.54
	csiZ	1.15		50–100 m	0.63
	Ey	1.14		100–250 m	0.84
	gB	0.27		>250 m	0.99
	gcsiMB	1.17	Distance to faults	0–5 km	0.39
	L	2.63		5–10 km	0.99
	Mcsi	1.12		>10 km	1.07
	mKK	0.16	Curvature	Hollow	1.25
	mT	1.00		Nose	0.81
	sKK	0.62		Planar	0.94
Slope angle	0–5°	0.29	Slope aspect	Flat	0.00
	5–10°	0.54		N	1.03
	10–20°	0.96		NE	0.70
	20–30°	0.94		E	0.86
	30–40°	0.98		SE	1.56
	40–50°	1.11		S	1.28
	50–60°	0.95		SW	0.97
	>60°	0.60		W	0.51
				NW	0.70
Land cover	Bare rock and/or coarse fragments				0.72
	Bare soil and scattered vegetation				2.31
	Closed forest				0.44
	Cultivated areas				0.73
	Open forest				1.02
	Pastures and/or Meadows <3750 mt				0.42
	Pastures and/or Meadows >3750 mt				0.43
	Snow				0.38
	Sparse vegetation				1.75
	Glaciers				0.00

For the geology, hereafter are explained the acronyms used. *cgM* miar conglomerate; *csiZ* zil felsic gneiss; *Ey* old screes and eluvial deposits; *gB* Baltoro granite; *gcsiMB* Mangol Bulk or Basha dome; *L* Landslide; *Mcsi* magmatic gneiss; *mkk* marble; *mT* Tagafari limestone; *sKK* unidifferentiated metasediments

collected by spacecraft in-track stereo way have been used to produce single-scene (60 × 60 km) Digital Elevation Models (DEMs) at a resolution of 30 m, having vertical accuracies (RMSE) generally between 10 and 25 m.

DEM-derived products (Ansari et al. 2012; Ahmed and Rogers 2014; Ahmed et al. 2014), as suggested by Gullà et al. (2008) and by Kamp et al. (2003) were used to investigate topographic surface at a regional scale. In these barren territories were data are not always available, detailed enough or of good quality these data are incredibly useful (Ahmed and Rogers 2014). Abrams (2000) and Tarolli et al. (2009) highlight the use of ASTER data for geological features extraction for the landslide hazard assessment as other Authors already did (Calligaris et al. 2013; Fourniadis et al. 2007; Chang and Tsai 1991; Ohlmacher 2007). ASTER DEM applied in the evaluation of landslide susceptibility map is discussed in Chau et al. (2004), Choi et al. (2012), Gokceoglu (2012), Song et al. (2012) and Toutin (2008). Moreover, the DEM extracted from ASTER is used in the Artificial Neural Network (ANN) approach for landslide susceptibility mapping, for the generation of geomorphological parameters (Choi et al. 2012; Nefeslioglu et al. 2008; Kawabata and Bandibas 2009). The interaction of land cover and landslides is analysed by Peduzzi (2010) on an area of North Pakistan using ASTER DEM for the extraction of landslides susceptibility maps.

All the data were elaborated in a GIS environment (ArcGIS 10.4 developed by ESRI) using as reference

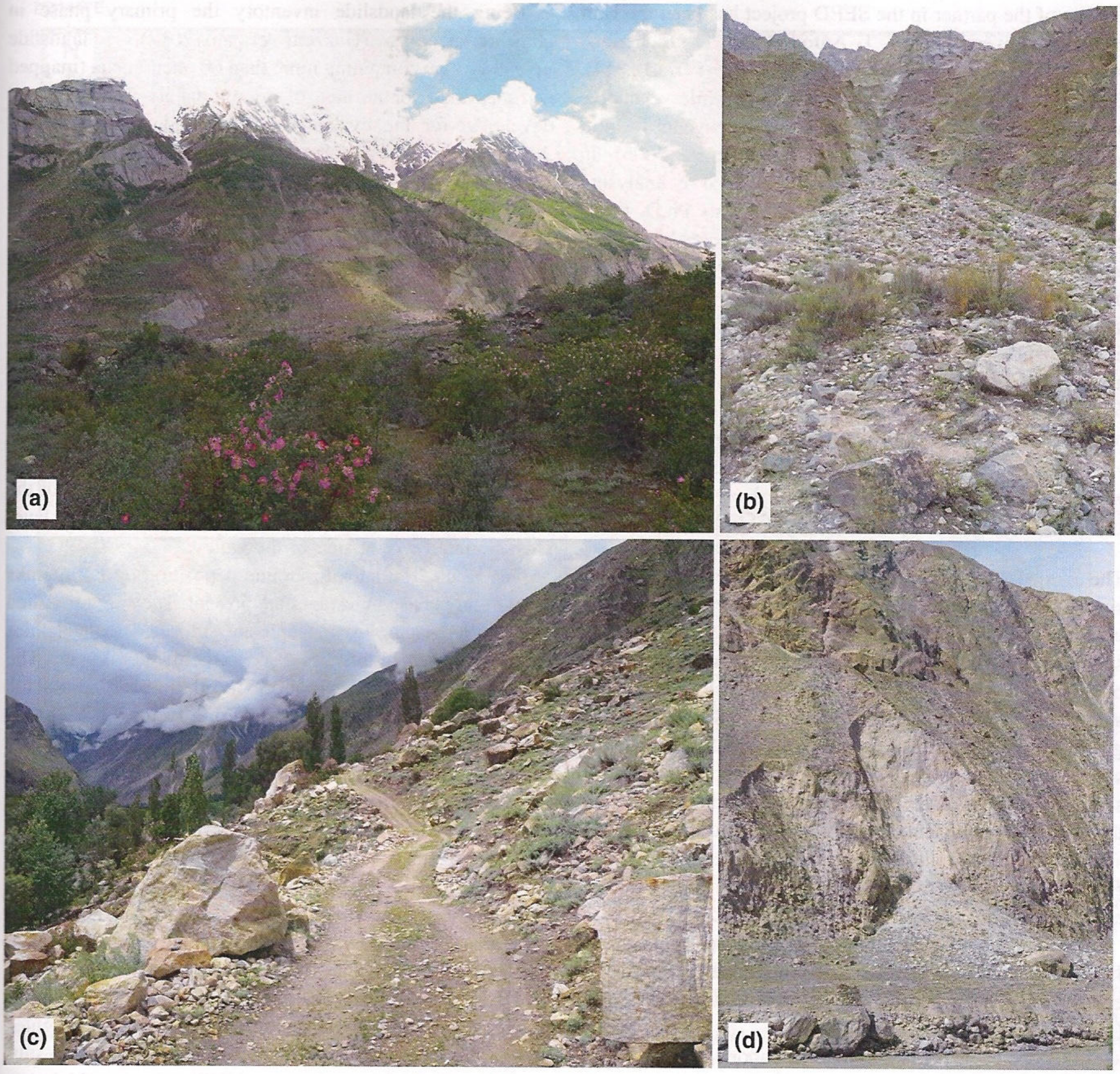

Fig. 2 Examples of landslides identified in the Chogolungma valley during the field survey (2012). **a** Traslational landslide; **b** Debris flow fan; **c** Rockfalls; **d** Shallow landslide

system, the datum WGS 1984, UTM Zone 43 N and a cell size of 30 m (Fig. 2).

The slope angle values (0°–75°) were subdivided into eight different classes (Ruff and Czurda 2008). Nine classes characterize the aspect value, which is used as an indicator for valley asymmetries. Surface curvatures are useful to describe the physical characteristics of a drainage area defining the geomorphic development of landslide terrains (Ohlmacher 2007; Tarolli et al. 2012). According to the morphology of the investigated area, three different types of curvature were recognized: hollows, noses and planar regions (Calligaris et al. 2013).

The importance of the fault/lineament parameter was simulated drawing three buffer zones: 0–5, 5–10, >10 km according to their influence on the geotechnical characteristics.

Distance to streams was also evaluated. An approach similar to the one used for the lineaments was adopted. The buffer was chosen in accordance with the erodibility of each specific lithological unit.

One of the partner in the SEED project has been the Unit of Padua University (Prof. T. Anfodillo and Dr. E. Ferrari) who focused its work on the land cover issue (Ferrari 2014). Barren slopes are more prone to landslide while vegetative areas tend to reduce the action of climatic agents by preventing the erosion and the slides (Saha et al. 2005). In mountain regions, land use data were obtained by analysing remote sensing datasets. Ferrari (2014) in his Ph.D. thesis classified the area on the base of the spectral response variations. Satellite analysis was compared with field observations for selected detailed studied areas in order to validate the work done. Following the procedure, nine land cover classes were identified: sparse vegetation, cultivated areas, snow, bare soil and scattered, open forest, closed forest, pastures and/or meadows >3750 mt, pastures and/or meadows <3750 mt, and bare rock and/or coarse fragments.

Results, Discussion and Conclusions

The applied AHP method to the case study corresponds to a simple pair-wise comparison in which two parameters may be considered at a time and this obviously corresponds to a simplification of the weighting process making it widely opinion-based dependent even if, the FR analysis decreased a lot the subjectivity. At the same time, the method can guarantee the obtainment of preliminary results also in areas where few data are available and where accessibility is scarce. The scale of the presented work is data dependent: the available geological map (1:150,000) and the DEM cell size (30 m) do not allow to obtain a detailed analysis, but guarantee a wide overview at regional scale. Several event-controlling parameters were considered.

The aspect was evaluated and ranked according to the frequency ratio: south- and east-facing slopes were considered to be more susceptible to landslides ($1.28 < FR < 1.58$).

The slope angle is one of the most important predisposing factors: landslides mainly occur in slope angles between 20 and 40° according to Ruff and Czurda (2008), but in the study area, rock falls occur at higher angles (30–50° with $0.98 < FR < 1.11$).

Regarding the land cover, the landscape is dominated by forest and shrub land/grassland. Agricultural land is restricted to the river terraces and the alluvial fans along the floodplains and the terraced steeper slopes. The urban areas are settled along the rivers. Snow/ice is present on some of the higher ridges to the north. Furthermore, the results of the land cover classification defined 42% forest, 42% uncultivable land mainly for grazing, 13% cultivated land, and 3% urbanized area.

Being the landslide inventory the primary phase in landslide-mapping (Guzzetti et al. 2012), a landslide inventory map containing more than 60 phenomena (mapped and classified for an area of approximately 220 km^2) was developed for the evaluation of landslide affected areas. A field survey was performed allowing the validation of the work done using the Spot-5 imagery.

In the followed analysis, 12.6% of the entire study area is covered by landslides. Their majority occurred in shrub land/grassland (70%) and on agricultural land (20%). Only 2% occurred in forested areas.

Debris falls, debris flows, and rock falls are equally distributed on both sides of the valley where it is possible to identify coalescing debris fans. Upstream steep cliffs, heavily subjected to physical weathering with a decrease in the geotechnical characteristics and an accelerated weakening of the rocks, gives rise to daily rock falls and occasionally to debris flows. Due to the structural settings of the area, translational landslides slipping on the strata layer characterize the right side of the valley.

The result of a lateral moraine deposition on both banks shows that persistent terraces are present. They are interested heavily by glacial erosion and are subjected to landslides forming, in some places, a continuous debris fan. The heights of the terraces may reach 100 m. In addition, the toe erosion is the main landslide triggering factor.

All the Chogo Lungma valley pilot area is interested by active rock falls, only some small portions of the surveyed territory may be considered as not subjected to these phenomena. The areas subjected to rock falls have a maximum length of 2.5 km with an elevation difference of 1600 m in some places. One of the smallest phenomena has a scree extension of about 50 m. Most of the debris flows are active. In this region, rest point areas, shelters, and villages rise on the debris flow stabilized fans where the gentle slope defines quite wide plane areas.

To obtain the landslide susceptibility map (Fig. 3), as previously defined, parameters were ranked and weighted and each weight was combined using the WLC. The results were later divided into six susceptibility classes which correspond to six landslide susceptibility classes.

With respect to the previous study realized in similar remote areas (Calligaris et al. 2013), the land cover (including glacier covers extension) parameter was analysed and the Frequency Ratio method was adopted. This is an improvement of knowledge in places where some fundamental information is still missing. These analyses give the possibility to the stakeholders to take decisions on future territorial planning over always less opinion-based updatable maps, strengthening the decision support system and the institutional mechanism for a better management of these remote but very attractive areas.

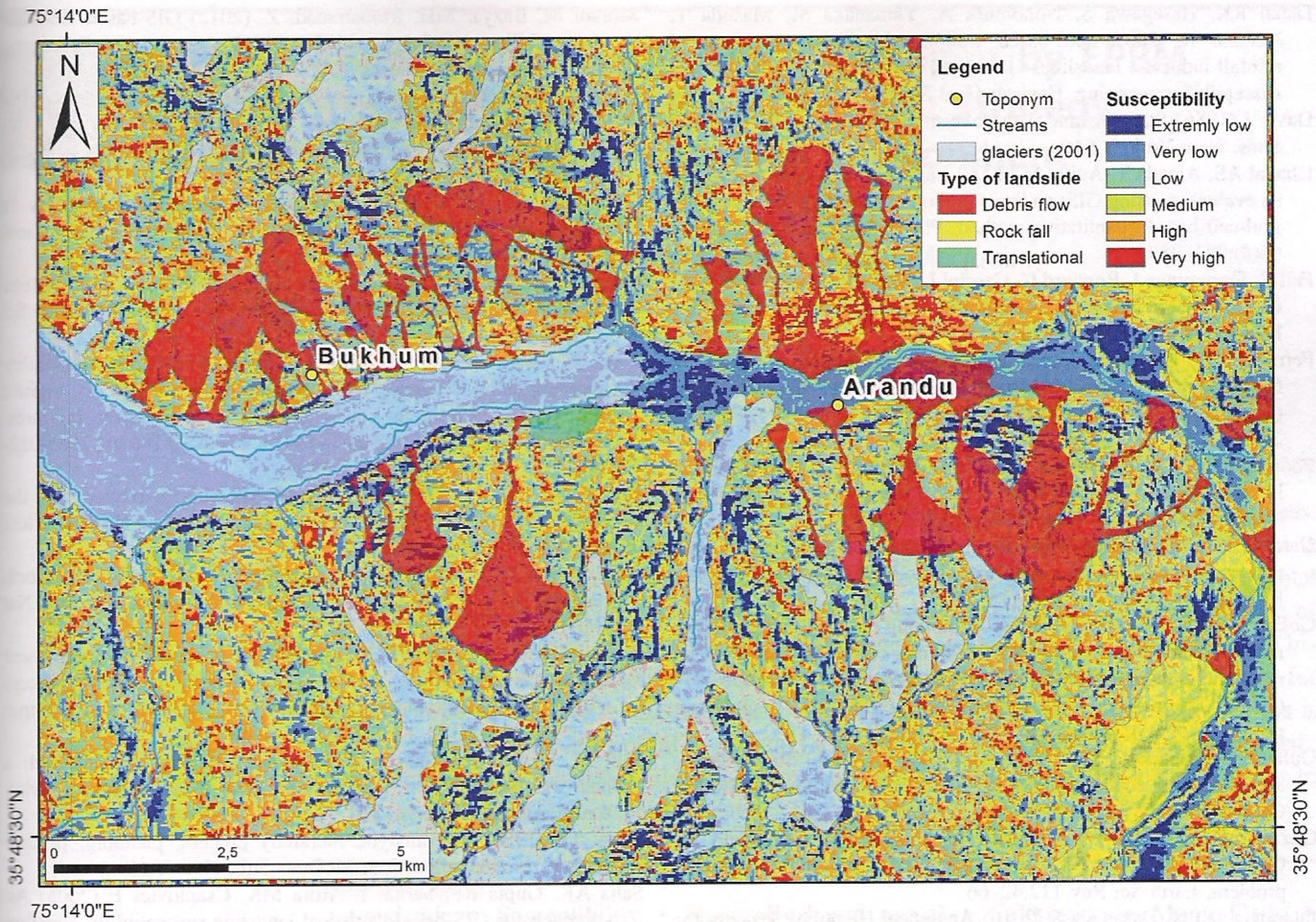

Fig. 3 Landslide susceptibility map (LSM) computed for the Chogolungma glacial valley

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