Earth History and Biodiversity 3 (2025) 100019

Contents lists available at ScienceDirect

Earth History and Biodiversity

journal homepage: www.sciencedirect.com/journal/earth-history-and-biodiversity/

Exploring susceptibility of protected areas to natural hazards in Karakoram-Himalaya[?]

Siddique Ullah Baig[a,b,*,1], Kamran Ali[c]

[a] Centro de Investigação de Geobiociências, Geoengenharias e Geotecnologias (GeoBioTec), NOVA FCT, Campus de Caparica, Universidade Nova de Lisboa, Caparica 2829-516, Portugal
[b] Department of Comuter Sciences, COMSATS University Islamabad (Abbottabad Campus), Abbottabad 22010, Pakistan
[c] Department of Development Sciences, COMSATS University Islamabad (Abbottabad Campus), Abbottabad 22010, Pakistan

ARTICLE INFO

Keywords:
Natural hazards
Susceptibility
National parks
Analytic Hierarchy Process
Karakoram-Himalaya

ABSTRACT

About 27 % territory of northern Pakistan is occupied by protected areas. Five national parks (~ 19,000 km²), created and protected for conservation of mountain ecosystems are under the threat of natural hazards as 81 % park's territories lie on higher elevations above 4000 m above sea level. This study aims to determine whether, and to what extent, natural hazards pose a substantial threat to national park's territory and wildlife habitats in the Karakoram-Himalaya. Analytic Hierarchy Process, a multi-criteria structured technique is employed to quantify susceptibility of territories entailing eight influencing factors based on pair-wise comparisons of relative magnitudes. The result shows that park's territories lie at nival-belt covered by rocks, snow and ice are comparatively safe as compared to the alpine-belt stretched between the tree-line and snow-line and montane-belt between forests and the tree-line. Specifically, Central Karakoram and Qurumber national parks, are most hazardous due to vast areas occupied by bare soil/rocks, steep-slopes, absence of dense forest and presence of avalanche-nourished larger glaciers and their tributaries. The natural hazards are likely to affect about less than 10 % of Khunjerab, Deosai and Shandur national parks as compared to 15 % of Central Karakoram and Qurumber national parks, suggesting that further analysis is fully justified. A correlation coefficient value signifies a positive relationship or similar nature of influencing factors among the parks. Geographic Information System (GIS) based quantitative technique provided a robust procedure for attaining a deep insight into susceptibility of parks to natural hazards at different elevational ranges.

1. Introduction

About 27 % territory of mountainous Gilgit-Baltistan (GB, ~72000 Km^2), formerly known as northern Pakistan, encompassing significant portions of three mountain ranges (Hindu-Kush, Karakoram and Himalaya), is occupied by Protected Areas (PAs). The idea of PAs in Karakoram-Himalayan portion of northern Pakistan and to set aside land for conservation emerged in the 1960s on the recommendations of World Wide Fund for Nature (WWF) and became a reality in the 1970s. PAs around the world play vital role in maintaining natural and traditional cultural ecosystems (Dudley and Stolton, 2008). National Parks (NPs) - an IUCN Category II type of PAs lie within the Karakoram and Himalayan portion of northern Pakistan, were mainly designated for conservation of wildlife but they are increasingly being recognized as potential tools for their role in aiding Disaster Risk Reduction (DRR).

Seven high-altitude NPs (~ 20,000 km^2) created and protected by the government of Pakistan are hosting ridges, steeps and sloping sides of GB and Chitral, conclusively conserving one or several mountain ecosystems. It is assumed that due to topographical nature, major portions of these parks lie on higher elevations between 4000 m above sea level (m) and 6000 m are under the threat of natural hazards. Although, the elevated territories of NPs help in retaining and protecting abiotic components e.g. glaciers, glacier lakes, alpine grass along with their respective ecosystems but in certain circumstances, causes sudden rock-

* Corresponding author at: Centro de Investigação de Geobiociências, Geoengenharias e Geotecnologias (GeoBioTec), NOVA FCT, Campus de Caparica, Universidade Nova de Lisboa, Caparica 2829-516, Portugal.
E-mail addresses: siddiquebaig@gmail.com, sbbaig@cuiatd.edu.pk (S.U. Baig).
[1] http://orcid.org/0000-0002-9136-3741

https://doi.org/10.1016/j.hisbio.2025.100019
Received 22 April 2024; Received in revised form 18 November 2024; Accepted 7 January 2025
Available online 7 January 2025

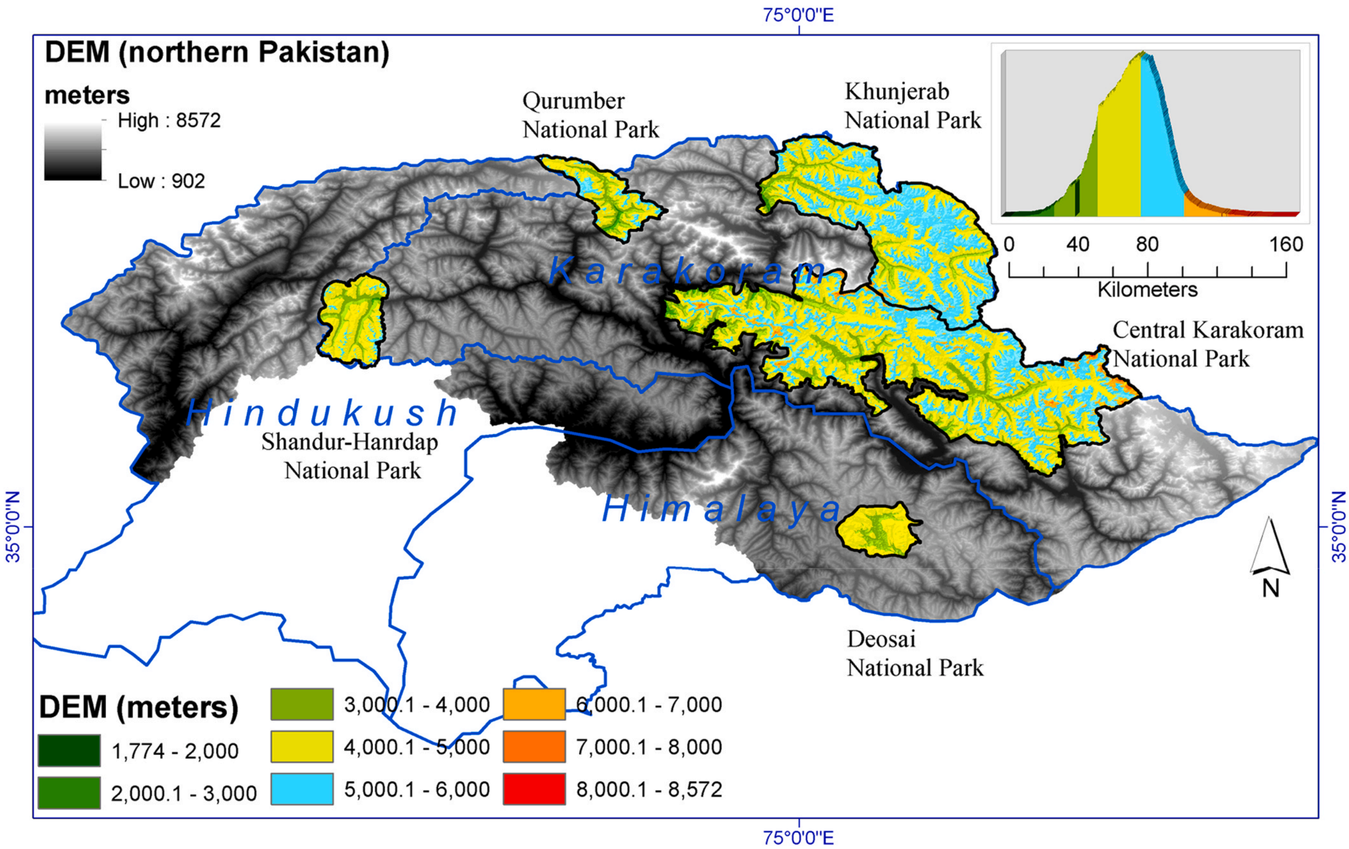

Fig. 1. Territorial boundaries of five national parks lie within the elevation range (in meters) in the Karakoram and Himalayan portion of northern Pakistan.

fall, snow and debris flow from ice-covered mountain peaks and glaciers. Although, ecosystems of park's territories at different levels are adapted to withstand few of the extreme weather events (IPCC, 2014) but territories lie in the middle or lower elevations are under the threat of an extensive diversity of typological disasters (e.g. floods, landslides, mudflows, and avalanches). Moreover, these territories are at environmental risk due to adverse impacts posed by high crustal attenuation (Rafiq and Blaschke, 2012), geomorphological processes (Iturrizaga, 2008), 7253 glaciers (Craig, 2016), 3300 glacier lakes (Baig et al., 2020) and rock-topples from the high-pitched mountains (63 % of total land) and movement of talus cones.

So far, little effort is made to investigate the relationship between these parks and DRR, together. However, many studies have focused on landscape or basin-level hazard assessments (Khan et al., 2020a, 2020b) or comprehensive examination of individual hazards (Rahim et al., 2018; Ali et al., 2015; Calligaris et al., 2017; Khan et al., 2016; Rehman et al., 2014). Multi-hazard risk assessment of Qurumbar valley (Shah et al., 2019) is one of the examples of valley-level assessments. But five NPs of this region encompasses major portions of several districts or valleys, are prone to potentially diverse nature of adverse impacts. Their ability to cope with the adverse impacts are different due to vast area, multiple ecological zones (Baig et al., 2022). For example, the unique geomorphological characteristics of Baltoro, Biafo and Hisper glaciers and high pitched mountain peaks (e.g. K2, Ghashabrum, etc.) lie in the Central Karakoram National Park (CKNP) along the Shigar valley in the Karakoram pose extensive variety of geological hazards (e.g. avalanches, GLOFs and landslides). Historically, hydro-metrological hazards emerged from ~1300 glaciers (Baig et al., 2018) has been affecting topographic settings of Hunza River Basin hosting Khunjerab National Park (KNP). Specifically, Khurdupin glacier-induced GLOF in the KNP poses a greater threat for pastures, ultimately effecting food requirements of big mammals. Giant peaks along with 608 glaciers in the CKNP (Senese et al., 2018) allow big mammals to escape to high altitude areas away from valleys causing reduction in illegal hunting. Ishkomen valley (Ghizer district) hosting Qurumber National Park (QNP) is extremely predisposed to flash and river floods due to presence of 65 glaciers and 17 glacier lakes at its higher elevations. Therefore, for a better hazard preparedness strategy, it is imperative to scale the contributing topographic, environmental and geological factors of NPs which have collectively increased their susceptibility to natural hazards.

In the early 20th century, information extraction from multispectral images obtained via remote sensing sensors and GIS has taken a center stage for understanding disaster-risk scenarios. Both technologies help in identifying areas at different levels of risks within each component of disaster management life cycle (e.g. preparedness, mitigation, response, recovery, etc.). Moreover, these technologies are widely being used for hazard assessments (Richardson, 2019). Mostly, the spatio-temporal interaction between the territories-at-risk and the potential hazards in a specific timeframe are depicted by overlapping of geographic maps with the territories-at-hazard maps. Changes in geography due to spatio-temporal changes in the hierarchy of streams is studied by GIS and Strahler's stream order (Valjarević, 2024). HAZUS, SELENA and CAPRA are few examples of GIS-based hazard and risk modelling methods. These methodologies focus on estimation of probabilistic nature of physical, economic and social impacts from different hazards (e.g. earthquakes, hurricanes, extreme rainfall, and volcanic hazards, flooding, windstorms, landslides and tsunamis) (Van Westen, 2013). However, direct application of these methods for mountain territories is not possible due to limited functionalities with respect to gravity-focused existing conditions like avalanche-related landslides, glacier-induced glacier lake outburst flooding (GLOFs), pushing down sediments, rocks and glacial ice from higher to lower elevations. Therefore, we developed and employed a quantitative approach similar to (Huq, 2020).

Table 1
List of national parks covering portions of mountain range boundaries along with covered area (in square kilometers) and year of the establishment.

National Park	Mountain range	Area (Km^2)	Established (year)
Central Karakoram National Park (CKNP)	Karakoram	10,604	1993
Khunjerab National Park (KNP)	Karakoram	5803	1975
Shandur-Hundrap National Park (SNP)	Karakoram	1298	2012
Qurumber National Park (QNP)	Karakoram	1080	2011
Deosai Plains National Park (DNP)	Himalaya	866	1993

Out of the seven types of terminologies concerning disaster, risk and vulnerability, this study focuses on "exposure" defined as "the degree to which the elements-at-risk are exposed to a particular hazard" (UN-ISDR, 2004). Our quantitative approach takes existing exposure conditions in terms of engineering and focuses on the estimation of direct physical damages (e.g. flooded territories, glacier lake outbursts, rock or debris-falls) resulting directly from the hazardous phenomena. In this study, natural processes or origins as causes or contributing factors are taken as an input to our quantitative method to evaluate susceptibility of NPs to natural hazards. Existing exposure conditions are based three subsets like seismo-tectonic settings, earth surface and composition, and physical geography of NPs.

2. Study area

This study was undertaken on the landscapes of northern Pakistan which lie exclusively within the Upper Indus Basin, encompassing significant portions of the Hindu Kush-Himalaya (HKH) region (Fig. 1). Indus river is an integral part of four NPs lie in the Karakoram, originated from Askai Chin of China, passing through Ladakh (India) and GB (Pakistan). . GB is bounded by Xinjiang in the north and Chitral district in the west along with Afghanistan. Administratively, these parks fall within the GB, bordering with Afghanistan, China, and Indian Kashmir. The study area (landscape) begins in the Ghizer district (Karakoram) in the west and encompasses the majority of GB (Pakistan) and extends to Ghanche district. Details about covered area and year of the establishment of the NPs are presented in Table 1.

Biogeographically, these NPs fall within the Hindu-Kush, Himalayan, Pamir-Tien-Shan highlands, and Tibetan Plateau (Udvardy, 1975). CKNP, the largest NP occupies 10,604 km^2, KNP ~ 5800 km^2 and Shandur National Park (SNP) 1298 km^2. QNP and Deosai National Park (DNP) occupies ~ 1080 km^2 and 866 km^2, respectively. A histogram (Fig. 1) representing a ratio between elevation range and area covered by five NPs shows that a large proportion (42 %) lies between 4000 and 5000 m (medium) altitudes followed by 34 % between 5000 and 6000 m (higher altitude). At highest elevation, 5 % area lie between 6000 and 7000 m. The lowest proportion of land (5 %) lie below 3000 m. Snow and glacial melt water in summer is the source of many streams, springs, lakes, wet meadows, marshes, and peat lands which provide an enabling environment for a variety of fauna and flora. However, spatio-temporal changes in the size and number of 3044 glacial lakes has become a matter of concerned due to the climate extremes in the last two decades (ICIMOD, 2011). Moreover, an increasing number of earthquake incidents around the world (U.S. Geological Survey, Earthquake Hazards Program, 2017) and in and around these parks has made investigation fully justified as well. Specifically, the CKNP lie between 76° 46′ 13″ E – 74° 16′ 63″ E and 36° 22′ 8″ N – 35° 15′ 93″ N and elevation range (3000.1 – 8572 m), was established in 1993, and is the largest NP of northern Pakistan. KNP lie between 76° 0′ 28″ E – 74° 47′ 18″ E and 37° 1′ 3″ N – 36° 1′ 48″ N and elevation range (3000 – 8000 m) on either side of the Karakoram Highway (KKH) is the oldest NP established in 1975. DNP (866 Km^2), lie between 75° 38′ 22″ E – 75° 11′ 23″ E and 35° 7′ 40″ N – 34° 50′ 31″ N and elevation range (3000 – 4000 m) in a relatively flat area within the Himalayan portion of northern Pakistan including significant portions of Astore and Skardu districts. QNP established in 2011 lie between 74° 19′ 10″ E – 73° 38′ 16″ E and 36° 54′ 58″ N – 36° 27′ 34″ N. SNP established in 1995 lie between 72° 53′ 3″ E – 72° 30′ 24″ E and 36° 18′ 42″ N – 35° 48′ 44″ N in the Hindu-Kush Mountains of Ghizer district occupies 1298 km^2 and is one of the least studied NPs in Pakistan.

The Karakoram-Himalaya is aridly temperate and mostly snowy from September to April. July and August are two hot months when the minimum temperature rises above freezing zero and permafrost's under harsh climatic conditions. The maximum water temperatures recorded on the surface of QNP in July 2010 ranged from 6° to 15°C.

These national parks by virtue of their altitude, harsh terrain and climate makes one last limit for large mammal species. Large populations of Himalayan Ibex, Markhoor, Urial, Snow leopard, Brown bear, Blue sheep, and Marcopolo sheep are sighted even in the very last limits of their habitats in the parks. These parks are the prime abode of these human shy wildlife species. However, the prime parts have been taken out in some parks from big mammals by the pastoralists', their settlements and economic activities. Still they have vast area available for their food and shelter. The choices of these species are very few selected niches. The species of large mammals are observed and expected in these parks as reported by a number of organizations. Surveys of large mammal species in these parks have been conducted by Forest, Wildlife & Environment Department Government of Gilgit-Baltistan. Few key species, the Himalayan Ibex, Markhoor, and Blue Sheep has been surveyed in the parks located in Hunza for its numbers, simultaneously enumerating it at several vantage sites. The occurrence of Markhoor,

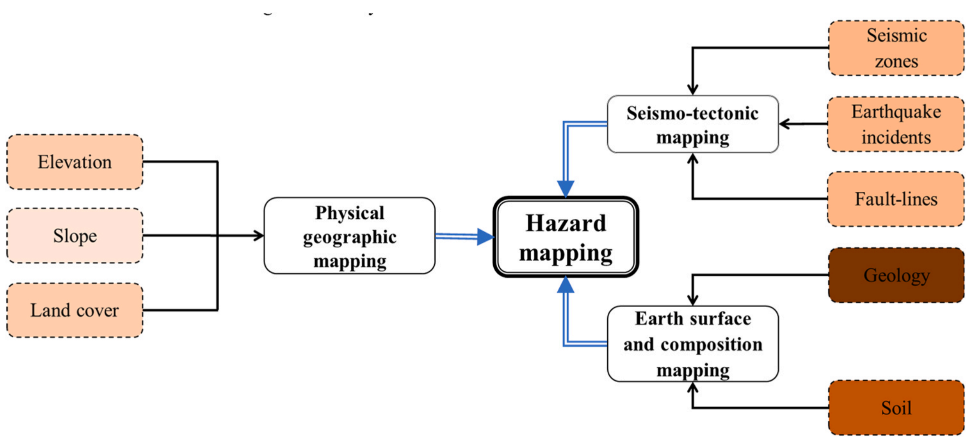

Fig. 2. A multi-criteria susceptibility assessment model representing datasets, mapping of the processes and hazard mapping.

Table 2
Metadata catalogue including names, date and sources (URLs) of datasets pertaining to eight hazard inducing factors used to develop hazard maps.

Indicators	Date / year	Metadata catalogue	URL (Source)
Seismic zone	Dec,1978	A Preliminary geological map of Kohistan and the adjoining areas, N. Pakistan	https://www.worldcat.org/title/preliminary-geological-map-of-kohistan-and-the-adjoining-areas-n-pakistan/oclc/705152056
Fault line	2007–09–25	Fault Lines of Hindu Kush Himalayan (HKH) Region	http://rds.icimod.org/DatasetMasters/Download/3437
Earthquake incidents	2007–09–21	Earthquake Incident Locations of Hindu Kush Himalayan (HKH) Region	http://rds.icimod.org/DatasetMasters/Download/2338
Geology	2007–09–25	This dataset is based on vector layer acquired from USGS.	http://rds.icimod.org/DatasetMasters/Download/2722
Soil	2020–09–08	This dataset is based on vector layer acquired from FAO.	http://rds.icimod.org/DatasetMasters/Download/313
Elevation	2007–09–20	The dataset is derived from USGS, GTOPO30 (global digital elevation model, DEM) with an approximately 1 kilometer spatial resolution.	https://earthexplorer.usgs.gov/
Slope	2012	United States Geological Survey (USGS)	https://earthexplorer.usgs.gov/
Land cover	2011–12–27	Land cover data of Hindu Kush Himalayan region of Pakistan for 2010. This dataset is created using the LandSat 30 m spatial resolution satellite image of 2010.	http://rds.icimod.org/DatasetMasters/Download/28630

Marcopolo Sheep, Himalayan Ibex, Urial, Snow leopard is reported with confirmed sightings. Brown bear are reported as occasional visitors. Mostly, these species are globally endangered and vulnerable according to IUCN red list of species or CITES appendices. They are also listed in the third schedule of protected animals under Wildlife Act, 1975. Tibetan wolf and Golden marmot are commonly seen in these valleys and they are also protected. The earlier surveys conducted to change in the number of species shows that the population of Ibex and other species increased drastically due to community controlled trophy hunting programs.

3. Methodology

Analytic Hierarchy Process (AHP) is a multi-criteria decision analysis method for analyzing complex problems entailing various influencing factors (Saaty, 1977; Saaty, 1990). This method has been employed by many researchers for different purposes like to assess flood hazards (Stefanidis and Stathis, 2013), multi-hazard risk assessment (Aksha et al., 2020) and to water erosion hazard mapping (Neji et al., 2021). In order to implement the model (Fig. 2), the significance of eight environmental contributing factors (Table 3) is employed to produce hazard maps (Fig. 4) through pairwise comparison by evaluating relative importance of one influencing factor over another. Integrated inferences were calculated in the form of an approximation of the potential threat posed by seismo-tectonic dynamics, earth surface and composition and physical geography by using Geographic Information System (GIS) based (AHP) and overlay weight analysis. Finally, we applied correlation coefficients between NPs and two-way ANOVA to evaluate differences between the group averages that are defined by eight hazard factors.

Key environmental indicators (Table 3) are employed based on relative importance of one indicator over another. About 35 % weightage is given to category I (seismotectonics), 40 % to category II (earth surface and composition) and 25 % to category III (physical geography). Overall, highest weightage or influence is given to geological formations of NPs as geological hazards comprised of extreme natural events in the high mountains trigger in the outer shell of the earth, which poses threats to biodiversity and natural resources or habitats. Secondly, mass movement of soil and melt-water from higher to lower elevation is a common phenomenon in the high mountains triggering erosional hazards (e.g. riverbank erosion, rock-falls, debris-falls and landslides, etc.). Therefore, about 15 % weightage is assigned to this factor. The trivial and deep sub-surface structure of the earth's crust (Paul and Hazarika, 2022) is fractured at fault-lines creating seismic waves causing earthquake incidents therefore we assigned 12 % influence to seismic zone, 12 % influence to earthquake incidents and 11 % influence to fault-lines. Topography and land cover plays an important role in controlling adverse impacts of floods in mountains despite the fact that both fulfil the food requirements of wildlife species in the NPs therefore we assigned 10 % influence each to these two factors. Four levels-of-hazards (e.g. minor, insignificant, moderate, and major) are assigned to the reclassified classes for each NP obtained from AHP based weighted overlay method.

4. Datasets

Datasets (Table 2) pertaining to hazard inducing factors are employed to develop six maps (Fig. 3). Two maps representing physical geography comprised of elevation ranges (Fig. 3a), slope ranges (Fig. 3b) of NPs, are developed by using a world-wide compiled, arranged and filtered ASTER Global Digital Elevation Model (GDEM2) (Fujisada et al., 2012) obtained from the United States Geological Survey (USGS). The produced elevation map (Fig. 3a) comprised of six elevation ranges (e.g. 1774 – 3794 m, 3794 – 4474 m, 4474 – 5070 m, 5070 – 5765 m and 5765 – 8572 m) while the slope map (Fig. 3b) comprises of five classes (e.g. 0°– 14°, 14°– 26°, 26°– 37°, 37°– 48° and 48°– 88°). A land cover map (Fig. 3c) is developed by using a dataset obtained from Regional Database System of ICIMOD - a one-stop data portal for the Hindu-Kush Himalaya (https://rds.icimod.org/). This map represents land cover classes such as agriculture (crop), agriculture (fallow), alpine grasses, bare-soil / rocks, dense coniferous forest, dense mixed forest, grasses / shrubs, peat-land, snow/glaciers, sparse coniferous forest, sparse mixed forest and water-bodies. Two combined maps (Fig. 3d and e) representing elements related to ecosystem of NPs (e.g. geology and soil) were developed by overlaying vector layers of two datasets obtained from Regional Database System of ICIMOD. Seismotectonic factors representing seismic zones, fault-lines and earthquake incidents inside or in the vicinity of NPs are overlaid on NP boundaries to develop a combined seismotectonic map (Fig. 3f).

5. Hazard mapping

The 'reclassify' tool of ArcGIS Desktop 10.7.1 is applied to obtain 8 hazard susceptibility sub-models by replacing pixel values of raster-based datasets (see Fig. 2) to alternative common measurement scale (1 = No hazard, 2 = Minor, 3 = Insignificant, 4 = Moderate and 5 = Major) based on susceptibility criteria (Table 3). Values for common measurement scale are based on factor-type and level of influence in hazard development. The highest values as influence to hazards were assigned to land cover classes exists on higher elevations like 'Glaciers', 'Grasses/shrubs', 'Alpine grasses', 'Peat-land' while land cover classes lying on lower elevation e.g. 'Agriculture (cropped)' and 'Agriculture (fallow)' were assigned the lowest values. Similarly, higher elevation ranges above 5765 m may host hazardous or unstable landforms

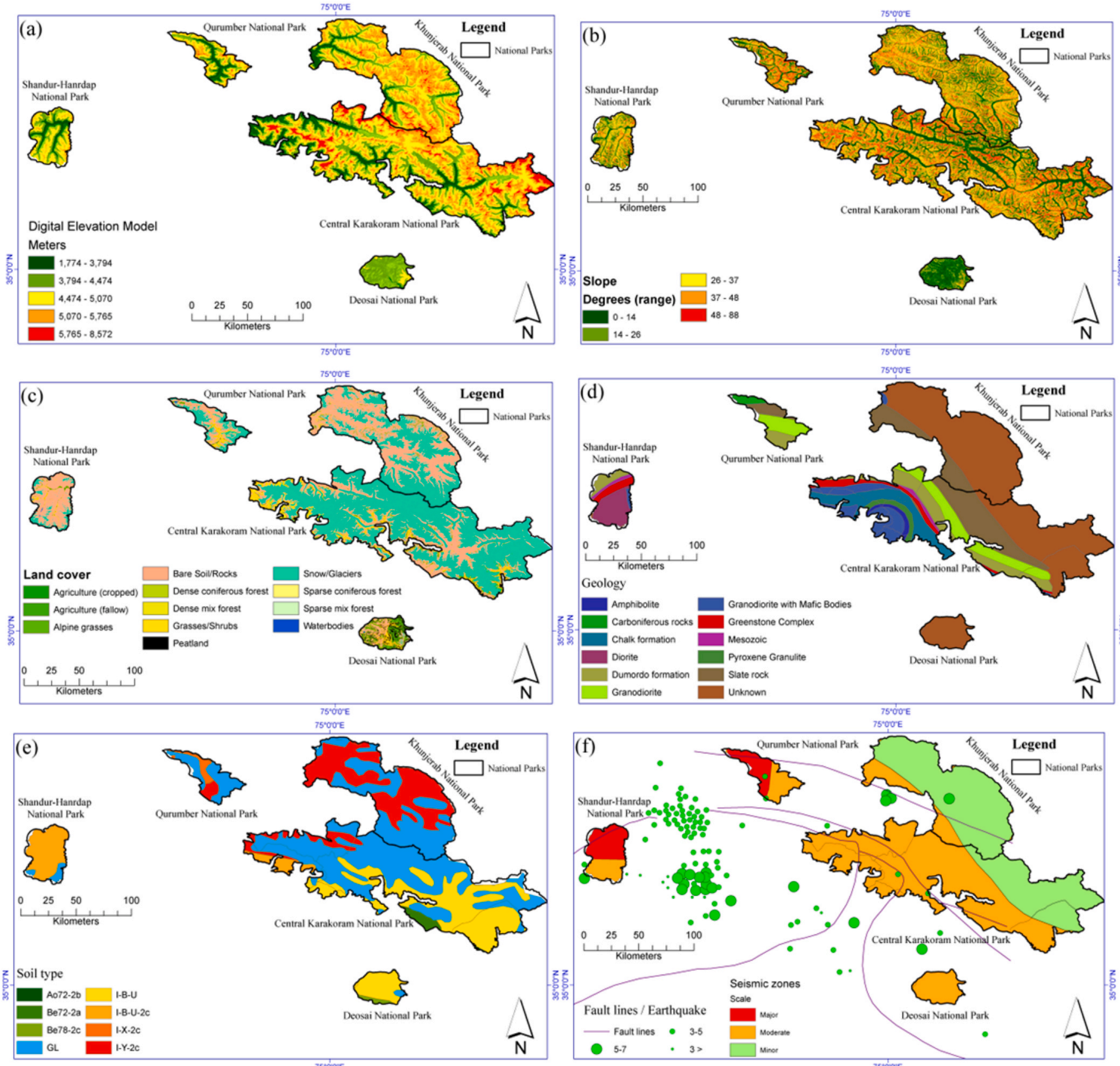

Fig. 3. Mapping of input data (a) digital elevation model, (b) slope gradient, (c) land cover classes, (d) geological formation classes, (e) soil-type classes and (f) seismic zones, earthquake incidents, and fault-lines, employed to susceptibility model.

Table 3
The criteria used for hazard susceptibility modelling based on influencing factors (Seismotectonics, ecosystem, erosion / floods), their weightage (in %) and hazard susceptibility score between (1 = No hazard, 2 = Minor, 3 = Insignificant, 4 = Moderate.

Indicators	Factors	weight	Minor	Insignificant	Moderate	Major
Seismic zone	Seismic zone	12 %	Zone 1	Zone 2	Zone 3	Zone 4
Fault line	Fault line	12 %	No fault-line	No fault-line	Crosscut by one fault-line	Crosscut by two fault-lines
Earthquake incidents						
	Earthquake incidents	11 %	No incidents	No incidents	M < 3	M: 3–5
Earth surface and composition	Geology	25 %	Granodiorite','Diorite','Mesozoic'	Sedimentary rocks	Metamorphic rocks	Boulders
	Soil	15 %	Sand	Silt	Clay	Hard rock
Physical geography	Elevation	10 %	1774–3794 m	3794–4474 m	4474–5070 m	5070–5765 m
	Slope	05 %	$> 0^\circ < 14^\circ$	$> 14^\circ < 26^\circ$	$> 26^\circ < 37^\circ$	$> 37^\circ < 48^\circ$
	Land cover	10 %	Forest	Cultivated		

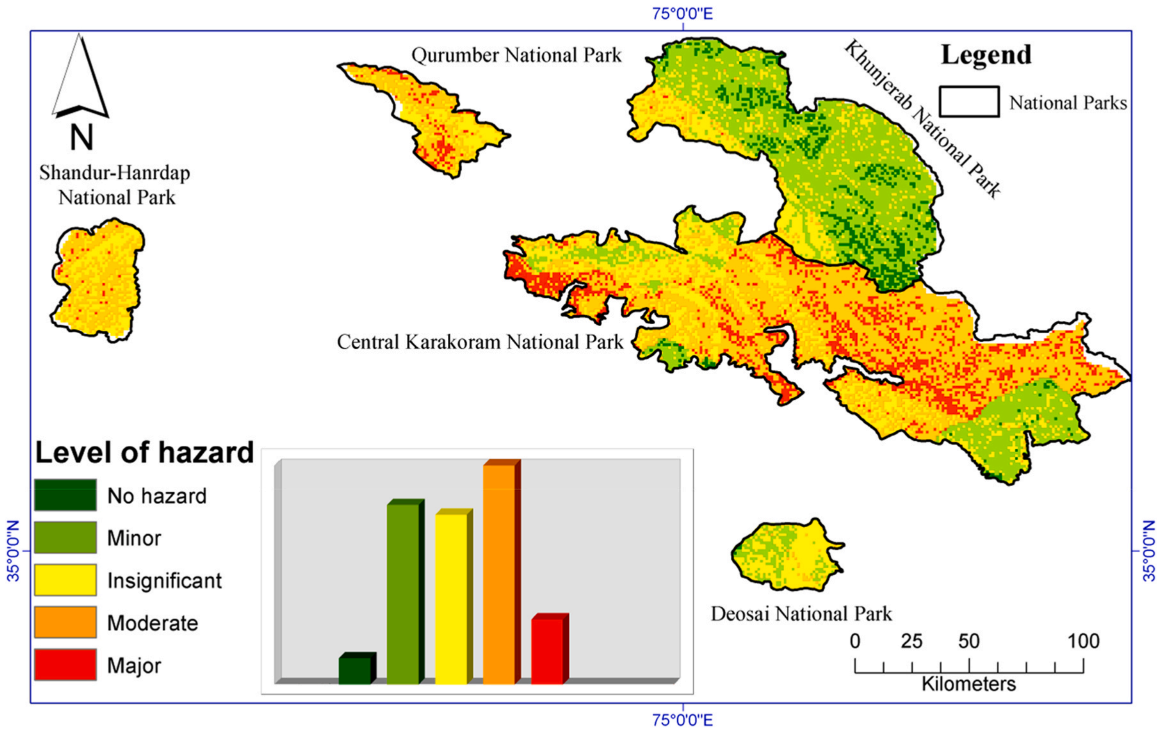

Fig. 4. Map representing the distribution and level of susceptibility (No hazard, Minor, Insignificant, Moderate and Major) of territories of national parks to natural hazards in northern Pakistan.

covered with glaciers / snow therefore were replaced with the highest influencing values (e.g. 4, 5), whereas the lowest elevation ranges are replaced with lowest weightage (1, 2, 3). In mountain environments, (in) stability of a slope create favorable or unfavorable settings for landslides or for other hazards like flooding. We assumed and categories that territories reside on moderate slopes between $> 37^{\circ} < 48^{\circ}$ are stable and on the steepest slopes between $> 48^{\circ} < 88^{\circ}$ within the NPs are unstable which may cause land / mud / rock slide. Similarly, out of the three categories of seismic zones (Fig. 3f), areas lying under the category 'major' have assigned highest weightage due to high degree of potential adverse impacts and lowest to 'low' category. The geological classes of landscape composed of 'Granodiorite', 'Diorite', and 'Mesozoic' are assigned lowest values as they are hardest composition as compared to other classes (e.g. slate rock). Soil class made of 'Glacier' get the highest values.

'Weighted overlay' function of ArcGIS Desktop 10.7.1 allows us to assign influencing weightage to eight hazard susceptibility sub-models obtained from the reclassification process, based on their level of contribution to hazard susceptibility. For example, the processes that shape the land comprised of rocks, soil are more important than the topography associated with the slope, elevation and land cover. Therefore, by using this tool, we assigned highest weightage (40 %) to factors related to the earth surface and structures (e.g. geology and soil) based on their potential influence, 35 % to seismo-tectonics (e.g. seismic zone 12 %, fault-lines 12 % and earthquake incidents 11 %) as twice more important than other factors. About 25 % weightage is assigned to physical geography comprised of land cover along with elevation and slope gradient in NPs. The total influence for all sub-models (raster dataset) equals 100 %.

6. Results and analysis

6.1. Hazard ranking of park's territory

Overall, the area occupied by theseNPs consists of high, steep, snow bound mountains and valleys with extensive slope gradients. Park's territories at lower altitudes are formed through erosion by glacial melt water. Higher areas are stretched between mountains and lows areas often running between mountains or hills. However, the impact of glacial ice on formation of park's territories does not match the geological settings of NPs. Specifically, the magmatic and sedimentary units continue from the KNP into the CKNP of the Karakoram and beyond to DNP of Himalaya. Moreover, the geological boundary of QNP continues up to Pamirs of Afghanistan (Hindu-Kush). The exposed rocks in these NPs are pre-Cambrian to Quaternary. Most of the NPs lie on the Karakoram Batholith (made up of large plutonic units), and is one of the largest bodies of intrusive rock found in the Karakoram (Zanchi and Geatani, 2011).

As shown in map, Fig. 4, the results indicate that small areas scattered in pockets within the NPs in the Karakoram-Himalaya of northern Pakistan are entirely safe while majority of the park's territories are susceptible to natural hazards in one or other way. Relatively, NPs located in the Karakoram portion of northern Pakistan occupy highly hazardous territories along the central region (Baltistan) as compared to the Himalayan portion (Astore) due to high glaciation, slate rock formation, fault-lines and hazardous seismic zones. Especially, due to the absence of dense forest and presence of snow plains (e.g. Hisper) and their tributaries make territory of CKNP unstable. In contrast with Karakoram NPs, Himalayan park, DNP exhibits low level of hazard due to moderate seismic zone, no fault-lines passing through the park, the lowest slope gradient and glaciation and high density of shrub/grass and forest areas being concentrated mainly in the plains at the lower altitudes (roughly 3800–4500 m.). QNP occupies 154 km^2 of extremely hazardous territory posing potential threat to nearby settlements of Qurumber valley like Badswat, Bilhanz, Tashnalot, and Immit. A number of glacier lakes in QNP are beneficial for nurturing and growth of biodiversity and potential tools for their role in aiding disaster risk reduction. However, in extreme weather conditions, steep slopes and hanging glaciers may cause GLOFs similar to earlier massive Badswat GLOF event on July 17–18, 2018.

Within NPs, highly hazardous territories in the KNP are reported to be along the edges in Misgar, Yarish, Sartees and Gircha due to highly

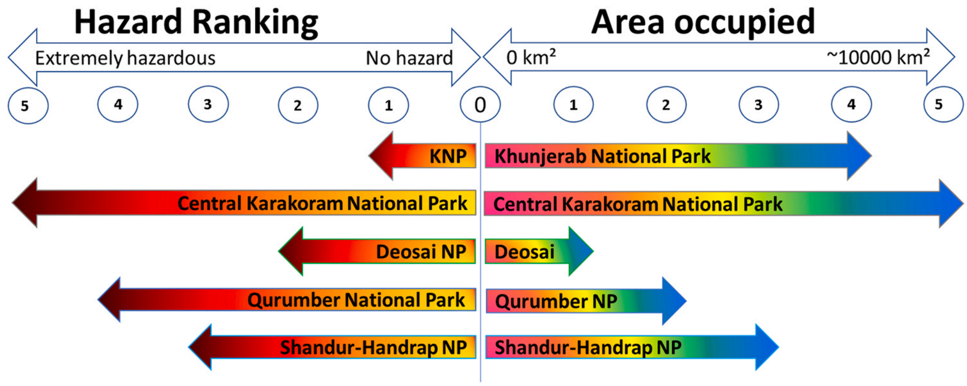

Fig. 5. Distributions of park's territories between 'extremely hazardous' and 'no hazard' and area: hazard raking of territories represent all five categories ('no hazard', 'minor', 'insignificant', 'moderate' and 'major') of susceptibility scale.

glaciated terrains and relatively scattered alpine grasses, rippling and tough topography. However, about 632 km^2 safe territory due to existence of gorges along both sides of the KKH of KNP that allow wildlife to descent to lower altitudes in winters and escape to neighboring gorges in case of chasing by predators or illegal hunters and harsh weather conditions. Comparatively, CKNP is the most hazardous park due to scattered vertical arrangement of ecological zones, vast land, inherent edges along four districts and a variety of soil, geological settings and larger avalanched-nourished glaciers (Biafo, Baltoro, Chogo Lungma, Panmah) and their tributaries.

As shown in Fig. 5, quantitatively, within the range of all five NPs territories, 2.7 % or 524 km^2, ~21 % ~5000 km^2, 38 % or ~7532 km^2, 31 % or ~6100 km^2 and 7 % or ~1386 km^2 lie in the susceptibility zone 'No hazard', 'Minor', 'Insignificant', 'Moderate' and 'Major', respectively. Specifically, the hazard susceptibility map (Fig. 4) and graph (Fig. 5) shows that territories within the 'Moderate' or 'Major' hazard zones are concentrated in the NPs within the Karakoram range as compared to the NPs surrounded by the Himalayan Range of northern Pakistan. Within Karakoram, territories occupied by the Central Karakoram and Qurumber national parks are extremely high and occupy 3516 km^2 and 2807 km^2, respectively. But territories within 'No hazard' zone are also reported in the Karakoram's NP like KNP (632 km^2), CKNP (70 km^2). About 16 km^2 of DNP (which lie in the Himalayan region) is hazard-free.

About 1 % or ~7 km^2 area of SNP lie between Chitral and Ghizer districts is not susceptible to natural hazard, 28 % or 250 km^2 to 'Minor', 67 % or 380 km^2 'Insignificant' and 3.3 % or 29 km^2 'Moderate' level of susceptibility to natural hazards. Moreover, territories of relatively high level of susceptibility to natural hazards are concentrated at the lower elevations of the park. Specifically, about 1897 Km^2 or 17.9 % of total

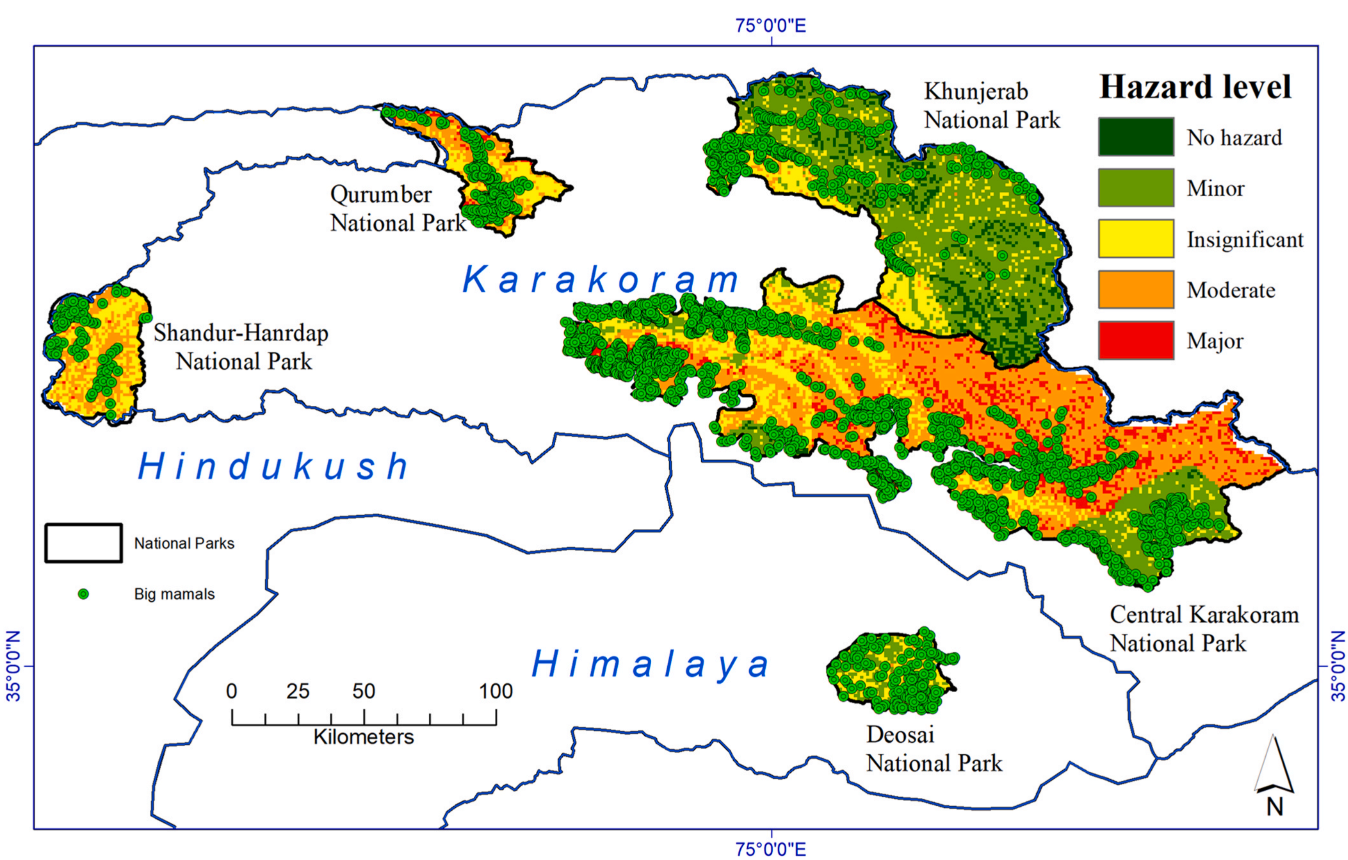

Fig. 6. Distribution of mammals: hazard information is overlaid with wildlife population density based on (Baig et al., 2022).

area of CKNP followed by 1897 Km^2 or 17.9 % of QNP is prone to 'extremely hazardous' due to rippling and tough topography. KNP in the Karakoram Range of northern Pakistan is the safest park followed by Deosai NP (Himalayas) and SNP (Karakoram). Out of the eight hazard indicators, potential adverse impact caused by seismic zone factor is high in the study area followed by geology, soil and fault-lines. Furthermore, although the slope gradient of KNP is high but the average elevation of CKNP is the highest among all NPs. SNP is prone to potential seismic or tectonic impact while the soil composition makes QNP hazard-prone due to presence of a large number of glaciers. Three fault lines pass through CKNP and one through QNP and SNP, making them disaster prone NPs. Highest numbers of earthquake incidents (although low magnitude) were recorded between territorial boundaries of QNP and SNP. Natural settings of land may cause potential adverse impacts in Shigar valley encompassing a significant portion of CKNP.

6.2. *Threat to biodiversity*

High population density of mammals is reported in CKNP despite high level of the susceptibility of this park to natural hazards (more than half or ~ 5000 km^2) of its total area (~10,604 km^2). Distribution of mammals (Fig. 6) in the CKNP is reported in territories prone to low or medium level of susceptibility to natural hazards due to vast area, suitable ecological pockets, low or medium elevation ranges where climatic conditions are far better than higher elevations. CKNP territories surrounded by Baltoro and Biafo glaciers (world's second and third longest glaciers outside the North Pole) and Masherbrum Mountain mostly threaten the northern part (bordering with KNP) of the park. Low or no population of mammals are reported in these hazard-prone areas due to glaciation, landform and sediments, and sparse or no vegetation. However, ravines fed by the melt-water from these glaciers are good suitable territories for mammals which provide food and escape routes. On the contrary, human activities (e.g. tourisms) in KNP (gate-way to China), an important transport route of the KKH passes through the KNP with increased landslide susceptibility may affect the mammals by mass movements prone to geological hazards.

QNP, occupying highly suitable territory hosts wetlands, glacier lakes which provide better habitat environment for Himalayan Ibex and grey wolf but potential GLOFs are likely to destroy water sources, forests and pastures located at lower elevations resulting habitat losses. Relatively highly suitable areas of SNP, concentrated at higher elevations which host Himalayan Lynx are prone to susceptible hotspots. Although, DNP occupies a smaller portion of territory prone to high level of susceptibility to natural hazards but climatic conditions along with tectonics may contribute to direct or indirect habitat losses at medium elevations due to glacier-induced flush-floods.

7. Discussion

In Karakoram-Himalaya, NPs are mainly designated for conservation of wildlife. However, they are increasingly being recognized as potential tools for their role in aiding disaster risk reduction. This study has highlighted the vulnerable and hazard-free territories of NPs despite the fact that natural hazards do not respect NP boundaries. This is the reason why we made district-level hazard, vulnerability and risk maps of GB (Baig et al., 2021) as basis for this study and thus fill in missing data for the hazard assessment of NPs. Moreover, this study represents a significant step in finalizing the NPs database by providing data from district-level hazard and risk assessment of GB, a territory that was not studied in an earlier study (Rafiq and Blaschke, 2012).

In terms of indicators, the high degree of susceptibility is primarily caused by the glaciation, Zone II category of seismicity and passing of two fault-lines that occupy more than ~85 % of all vulnerable territories of the parks. Earthquakes of a lower catastrophic intensity are expected, which can cause a synergistic and rippling effect and may trigger secondary natural disasters, in particular mud or rock-fall or avalanche or mountain collapse. However, results could be different if all values (weightage) assigned to indicators through own decision are changed or taken them out of the literature.

Table 4
Correlation between national parks.

National Park	KNP	CKNP	DNP	QNP	SNP
Khunjerab National Park (KNP)	1				
Central Karakoram National Park (CKNP)	−0.32392	1			
Shandur-Hundrap National Park (SNP)	0.447362	−0.0529	1		
Qurumber National Park (QNP)	−0.46498	0.891505	0.220249	1	
Deosai Plains National Park (DNP)	−0.30721	0.786668	0.421458	0.961484	1

In terms of level of hazard, this study has indicated that surroundings and surface areas of NPs are under the threat not only due to the high glaciation or mountain constraints but fault-lines, seismic zones, terrain and earth surface composition and physical geography as well. Moreover, the susceptibility of NPs to natural hazards is not uniform across the NPs but differs due to the size, spatial location and topography of the parks. Within the range of the most susceptible area, 6.7 % and 52.6 %, lie in seismic zone 'major' and 'moderate', respectively (Fig. 2) indicates that the seismo-tectonic hazard mostly threatens the northern or upper parts of the parks. Level of erosion in the parks depends on types of soil (e.g. minerals, organic matter, living organisms, and water). Glaciers and glacier lakes in the CKNP, QNP and KNP are one of the causes of debris or debris-cones at the base of the terrain slopes. Moreover, rippling and tough topography is likely to trigger landslides and soil erosion and the resulting sedimentation as well.

Particularly, alarming is the susceptibility of the least protection, where the hazards may affect more than 44 % of the territory. DNP and SNP have dense networks of streams and rivers and QNP of glacier lakes in, where the melt-water flows are not contained within the territories of the NPs. Except the KNP, glacier lakes with origins from glacier activities (e.g. melting, eroding the downstream land, filling the depression) in other NPs are easily formed, and it is therefore important to study GLOFs in relation with glacier fluctuations and insist upon the consistent application of mitigating measures (e.g. preparation studies, etc.) as well as effective conservation of the NPs. Similarly, tectonically active high pitched mountain activities (e.g. landslides, rock-fall) happens mostly in remoter parts of bigger NPs (e.g. CKNP and KNP) therefore it is important to study geological hazards in relation with mountain dynamics and terrain characteristics and insist upon the effective conservation of mountain ecology, the landscapes and hence the NPs.

As shown in Table 4, positive or negative correlation coefficients between NPs indicate that there is a linear relationship between them. Specifically, the linear correlation coefficients less than zero, reported between CKNP and KNP (-0.32392), QNP and KNP (-0.46498) and SNP and KNP (-0.30721) are an indication of a negative relationship between KNP and other parks like CKNP, QNP and SNP. This shows that the nature of influencing factors of KNP is different from other parks. However, values greater than zero signify a positive relationship or similar nature of influencing factors between the parks.

As shown in the Table 5, negative correlation coefficient (-0.2) between 'seismic zone' and 'elevation' indicate that there is a non-linear relationship between them. Specifically, the linear correlation coefficients less than zero, reported among all influencing factors except these two is an indication of a positive relationship between them. This shows that except these two, the influencing factors of all parks have an

Table 5
Correlation between national parks.

Indicators	Elevation	Slope	Geology	Soil	Seismic zone	Fault line	Earthquake incidents
Elevation	1						
Slope	0.9	1					
Geology	0.9	1	1				
Soil	1	0.9	0.9	1			
Seismic zone	−0.2	0.1	0.1	0.2	1		
Fault line	0.7	0.9	0.9	0.7	0.5	1	
Earthquake incidents	0.3	0.1	0.1	0.3	0	0	1
Land cover	1	0.9	0.9	1	−0.2	0.7	0.3

Table 6
Analysis of variance: two-factor without replication.

Source of Variation	Sum Square(SS)	Degree of freedom (Df)	Mean Square (MS)	F-value	P-value	F crit	Source of Variation
Level of hazard	0.394499	3	0.1315	2.968689	0.119021	4.757063	0.394499
National parks	9.74E−06	2	4.87E−06	0.00011	0.99989	5.143253	9.74E−06
Error	0.265773	6	0.044296				0.265773
Total	0.660282	11					0.660282

impact on each other. Interestingly, no relationship is found between ‘earthquake incidents’ and ‘seismic zone’ as well as between ‘earthquake incidents’ and ‘fault line’.

We used two-way ANOVA to evaluate differences between the group averages that are defined by eight hazard factors. The P-value in the ANOVA (Table 6) for both level of hazard and NPs shows that they are less than our significance level. These p-values are so low that we used scientific notation to represent them. The interaction effect is not significant because its p-value (0.66) is greater than our significance level which shows that the interaction effect is not significant.

8. Conclusion

Despite hazardous nature, mountains are major providers of ecosystem services to natural environment and biodiversity.This study created a relationship between mountain ecosystems, environment and biodiversity. However, the distribution of biodiversity especially big mammals and hazardous territories of NPs is not uniform but differs and is dependent on the each NP’s natural environment. Territories lie within the same mountain range (e.g. Himalaya) protected through NPs is significantly safe as compared to the park’s territory in Karakoram spread over a number of valleys (Hunza, Skardu, Nagar and Gilgit,). Specifically, the natural hazards are likely to affect less than 10 % of areas in the KNP, DNP and SNP as compared to 15 % of CKNP and QNP, suggesting that further analysis is fully justified. Relatively, NPs (CKNP, KNP, QNK and SNP) located in the Karakoram region of northern Pakistan are highly hazardous territories as compared to DNP, lie in the Himalayan region. This is due to high glaciation, slate rock formation, fault-lines and hazardous seismic zones in the Karakoram region. Considering the overall susceptibility of NPs to natural hazards in the high mountains, the extreme disproportion among KNP, DNP, SNP, CKNP and QNP is whistleblowing for policy makers, legislators and park’s management who are responsible for conservation of parks and their territories.

Employed eight sets of indicators concerning morphology, land cover, topography (elevation), fault-lines, seismic zones, and earthquake incidents, can be extended by including more inputs to improve results. However, land cover classes especially forests and rocky-peaks in the NPs may prevent and mitigate sudden glacier and snow movements by stabilizing soil and standing in the way so as to stop the slippage. Moreover, application of GIS technology to categorize the park’s territories to determine whether, and to what extent, natural occurrences pose a substantial danger to biodiversity and their habitats improved the results although geographic setting is considered to be enough for a first estimation of the overall hazard situation. Geological maps played a vital role in estimation of potential earthquake zones as well.

We opined that efforts are needed to monitor natural degradation processes and causes and to create awareness among permanently residing communities in parks like CKNP and Broghul national park-where identified hazards can anytime become disastrous for these communities and biodiversity. Secondly, it is necessary to strengthen the execution of processes that contribute to the protection of the biodiversity and conditions of NP’s habitats especially in the Shigar and Ishkomen areas as both are hazardous due to high glaciation, terrain sizes and topographic roughness. On the basis of these results, we propose an implementation of the Environmental Protection Act 2018 of Environmental Protection Agency (EPA) of GB in these parks to mitigate from these hazards, and if possible, get them to a higher level of protection.

CRediT authorship contribution statement

Siddique Ullah Baig: Writing – review & editing, Writing – original draft, Project administration, Formal analysis, Conceptualization. **Kamran Ali:** Software, Data curation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This work was financially supported, in part, by the research center GeoBioTec (Project UIDB/04035/2020, https://doi.org/10.54499/UIDB/04035/2020). Moreover, we appreciate COMSATS University Islamabad (Abbottabad Campus) for making authors available for this work. We are delighted to use the datasets shared by the ICIMOD, CITE and the IUCN Red List of Threatened Species.

Data availability

Data will be made available on request.

References

Aksha, S., Resler, L.M., Juran, L., Carstensen, L., 2020. A geospatial analysis of multi-hazard risk in Dharan, Nepal. Geomat. Nat. Hazards Risk 11 (1), 88–111. https://doi.org/10.1080/19475705.2019.1710580.

Ali, Khan, F., Khan, B., Abbas, G., et al., 2015. Hazard vulnerability risk assessment of District Gilgit, Gilgit-Baltistan, Pakistan. Mod. Environ. Sci. Eng. 1 (5), 255–268. Doi: 10.15341/mese(2333-2581)/05.01.2015/007.

Baig, S.U., Khan, H., Din, A., 2018. Spatiotemporal analysis of glacial ice area distribution of Hunza River Basin, Karakoram region of Pakistan. Hydrol. Process. 1–11. https://doi.org/10.1002/hyp.11508.

Baig, S.U., Khan, H., Muneeb, F., et al., 2020. Formation of a hazardous ice-dammed glacier lake: a case study of anomalous behavior of Hassanabad glacier system in the Karakoram. SN Appl. Sci. 2, 1285. https://doi.org/10.1007/s42452-020-2989-4.

Baig, S.U., Malik, A.J., Khan, H., 2022. Wildlife habitat-suitability analysis for high mountain national parks in the Hindu Kush, Karakoram and Himalayan region of northern Pakistan. Model. Earth Syst. Environ. https://doi.org/10.1007/s40808-021-01336-9.

Baig, S.U., Rehman, M.U., Janjua, N.N., 2021. District-level disaster risk and vulnerability in the Northern mountains of Pakistan. Geomat. Nat. Hazards Risk 12 (1), 2002–2022. https://doi.org/10.1080/19475705.2021.1944331.

Calligaris, C., Tariq, S., Khan, H., Poretti, G., 2017. Landslide susceptibility analysis in Arandu Area Shigar Valley, CKNP (Gilgit-Baltistan- Pakistan). In: Mikos, M., Tiwari, B., Yin, Y., Sassa, K. (Eds.), Advancing Culture of Living with Landslides. WLF 2017. Springer, Cham. https://doi.org/10.1007/978-3-319-53498-5_103.

Craig, T. 2016. Pakistan has more glaciers than almost anywhere on Earth. But they are at risk. The Washington Post. ⟨https://www.washingtonpost.com/world/asia_pacific/pakistan-has-more-glaciers-than-almost-anywhere-on-earth-but-they-are-at-risk/2016/08/11/7a6b4cd4-4882-11e6-8dac-0c6e4accc5b1_story.html⟩.

Fujisada, H., Urai, M., Iwasaki, A., 2012. Technical methodology for ASTER global DEM. IEEE Trans. Geosci. Remote Sens. 50 (10), 3725–3736.

Huq, M.E., et al., 2020. Measuring vulnerability to environmental hazards: qualitative to quantitative. In: Fahad, S., et al. (Eds.), Environment, Climate, Plant and Vegetation Growth. Springer, Cham. https://doi.org/10.1007/978-3-030-49732-3_17.

ICIMOD, 2011. Glacial Lakes and Glacial Lake Outburst Floods in Nepal. ICIMOD, Kathmandu.

IPCC. 2014. Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 151.

Iturrizaga, L., 2008. Paraglacial landform assemblages in the Hindukush and Karakoram Mountains. Geomorphology 95 (s 1–2), 27–47. https://doi.org/10.1016/j.geomorph.2006.07.030.

Khan, G., Qureshi, J.A., Khan, A., et al., 2020. a. The role of sense of place, risk perception, and level of disaster preparedness in disaster vulnerable mountainous areas of Gilgit-Baltistan, Pakistan. Environ. Sci. Pollut. Res. 27, 44342–44354. https://doi.org/10.1007/s11356-020-10233-0.

Khan, A.A., Rana, I.A., Nawaz, A., 2020. Gender-based approach for assessing risk perception in a multi-hazard environment: a study of high schools of Gilgit, Pakistan. Int. J. Disaster Risk Reduct. 44, 101427. https://doi.org/10.1016/j.ijdrr.2019.101427.

Khan, K.M., Rashid, S., Yaseen, M., Ikram, M., 2016. Geospatial techniques for allocating vulnerability zoning of geo-hazards along the Karakorum Highway, Gilgit-Baltistan-Pakistan. Am. Geophys. Union 1 (1), 10–15.

Neji, N., Ayed, R.B., Abida, H., 2021. Water erosion hazard mapping using analytic hierarchy process (AHP) and fuzzy logic modeling: a case study of the Chaffar Watershed (Southeastern Tunisia). Arab. J. Geosci. 14 (13). https://doi.org/10.1007/s12517-021-07602-5.

Paul, A., Hazarika, D., 2022. Occurrences of low-stress drop earthquakes in the eastern Ladakh-Karakoram zone of the Trans Himalaya and their tectonic implications. J. Asian Earth Sci.: X 7. https://doi.org/10.1016/j.jaesx.2022.100080.

Rafiq, L., Blaschke, T., 2012. Disaster risk and vulnerability in Pakistan at a district level. Geomat. Nat. Hazards Risk 3 (4), 324–341. https://doi.org/10.1080/19475705.2011.626083.

Rahim, I., Ali, S., M., Aslam, M., 2018. GIS based landslide susceptibility mapping with application of analytical hierarchy process in District Ghizer, Gilgit Baltistan Pakistan. J. Geosci. Environ. Prot. 6 (1), 34–49.

Rehman, G., Ahmad, S., Khan, S.D., 2014. Threat of glacial lake outburst flood to Tehsil Gupis from Khukush Lake, District Ghizer, Gilgit Baltistan, Pakistan. Nat. Hazards 70 (1), 1589–1602.

Richardson, J.A., 2019. High-resolution DEM generation from spaceborne and terrestrial remote sensing data for improved volcano hazard assessment—a case study at Nevado del Ruiz, Colombia. Remote Sens. Environ. 233, 111348. https://doi.org/10.1016/j.rse.2019.111348.

Saaty, T., 1977. A scaling method for priorities in hierarchical structures. Math. Psychol. 15, 234–281.

Saaty, T., 1990. How to make a decision: the analytic hierarchy process. Eur. J. Oper. Res 48, 9–26.

Senese, A., Maragno, D., Fugazza, D., Soncini, A., D'Agata, C., Azzoni, R.S., et al., 2018. Inventory of glaciers and glacial lakes of the Central Karakoram National Park (CKNP – Pakistan). J. Maps 14 (2), 189–198. https://doi.org/10.1080/17445647.2018.1445561.

Dudley, N., Stolton, S. (Eds.), 2008. Defining protected areas: an international conference in Almeria, Spain. IUCN, Gland, Switzerland, p. 220.

Shah, S.K., Khan, G., Ali, S., Qureshi, J.A., Habib, N., Khan, A., 2019. Multi-hazard risk assessment of qurumbar Valley, Ghizer, Gilgit Baltistan, Pakistan. J. Mt. Area Res. 4 (1), 24–31. https://doi.org/10.53874/jmar.v4i0.63.

Stefanidis, S., Stathis, D., 2013. Assessment of flood hazard based on natural and anthropogenic factors using analytic hierarchy process (AHP). Nat. Hazards 68 (2). https://doi.org/10.1007/s11069-013-0639-5.

U.S. Geological Survey, Earthquake Hazards Program, 2017, Advanced National Seismic System (ANSS) Comprehensive Catalog of Earthquake Events and Products: Various, ⟨https://doi.org/10.5066/F7MS3QZH⟩.

Udvardy M.D.V. 1975. A classification of the bio-geographical provinces of the world. IUCN Occasional Paper No. 18 International Union for Conservation of Nature (IUCN) and Natural Resources, Morges, Switzerland.

UN-ISDR, 2004. Living with Risk: A Global Review of Disaster Reduction Initiatives. United Nations Inter-Agency Secretariat of the ISDR (UN-ISDR, Geneva.

Valjarević, A., 2024. GIS-based methods for identifying river networks types and changing river basins. Water Resour. Manag. https://doi.org/10.1007/s11269-024-03916-7.

Van Westen, Cees J., 2013. Remote Sensing and GIS for Natural Hazards Assessment and Disaster Risk Management. Faculty of Geo-Information Science and Earth Observation (ITC), University of Twente, Hengelosestraat.

Zanchi A., Geatani M. 2011. The geology of the Karakoram range, Pakistan: the new 1: 100,000 geological map of Central-Western Karakoram. Italian Journal of Geosciences 130: 161-262. ⟨https://doi.org/10.3301/IJG.2011.09⟩ Ali, Nosheen. 2010. Re-imagining the nature of development: biodiversity conservation and pastoral visions in the Northern Areas, Pakistan. 64.