Hazards profile of the Shigar Valley, Central Karakoram, Pakistan: Multicriteria hazard susceptibility assessment

Munazza Afreen[1], Fazlul Haq[2,*], Bryan G. Mark[2]

[1] Government College University Faisalabad, Department of Geography, Pakistan
[2] Ohio State University, Byrd Polar and Climate Research Center, USA
[*] Corresponding author: haq.47@osu.edu

ABSTRACT

The rapid deglaciation in the Upper Indus Basin (UIB) significantly impacts local landscapes, watersheds, and basin-wide hydrology. While creating new opportunities, such as emerging landscapes and hydrological changes, deglaciation simultaneously heightens the risk of glacio-hydrological hazards in adjacent and downstream regions. With limited available land for agriculture and settlements, communities around glaciers expand human activities toward newly formed floodplains and deglaciating valleys, necessitating a comprehensive understanding of associated risks and vulnerabilities. This study employs Geographical Information System (GIS) and Remote Sensing products for a multicriteria hazards susceptibility assessment in the Shigar Valley, located in the downstream of major Himalayan glaciers – the Baltoro (63 km) and Biafo (67 km) glaciers. The research reveals that 28.3% of the valley is highly susceptible to multiple hazards, emphasizing the urgency of informed decision-making in the region. Only 0.03% area lies in the very low susceptible category, 9.7% in the low susceptible, 60.6% in the moderately susceptible, and 1.04% in the very highly susceptible categories. These findings highlight the need for proactive measures, adaptive strategies, and sustainable development in the Shigar Valley to mitigate the escalating risks posed by deglaciation and changing hydrological patterns.

KEYWORDS

glacial hazards; landslides; snow avalanches; floods; multi-hazards; hazard susceptibility

Received: 23 January 2024
Accepted: 6 May 2024
Published online: 22 May 2024

Afreen, M., Haq, F., Mark, B. G. (2024): Hazards profile of the Shigar Valley, Central Karakoram, Pakistan: Multicriteria hazard susceptibility assessment. AUC Geographica 59(1), 77–92
https://doi.org/10.14712/23361980.2024.5

1. Introduction

The Hindukush-Karakoram-Himalayan (HKH) region, one of the most geologically active and environmentally sensitive areas on our planet, has consistently been the focus of various scientific investigations, primarily due to its inherent geological complexity, climatic variability, and susceptibility to natural hazards (Richardson and Reynolds 2000; Wang et al. 2021; Chowdhury et al. 2021; Kropáček et al. 2021). Cryo-hydro-climatic dynamics in the Upper Indus Basin (UIB), have been producing severe consequences in the proximal areas as well as in the Lower Indus Basin throughout history in the form of water shortages and catastrophic flooding (Lutz et al. 2016; Ishaque et al. 2022; Yao and Khan 2022). Following the history's most devastating flooding in 2010 (Khattak et al. 2012), the recent floods of 2022 resulted into the displacement of millions of people when almost two third of the country was under water (Saifi et al. 2022). With only a gap of 2 years, several areas in the HKH region were recently hit by severe flash floods in April 2024, causing widespread damages especially to standing crops, agricultural land, and other property. Besides such large-scale catastrophic flooding, the local communities have been suffering the impacts of these changes in the form of glacial lake outburst floods (GLOFs), water stress associated with fluctuating and uncertain snowmelt, landslides, and river blockages etc. (Iqbal et al. 2014; Gao et al. 2021).

The Shigar Valley in Pakistan is one of the most dynamic areas in the HKH exposed to a complex set of hazards, challenging its inhabitants and the environment. This valley is not only home for the local population but also a region of great cultural, economic, and ecological significance. Yet, it is distressed by multiple natural hazards, including landslides, glacial lake outburst floods (GLOFs), earthquakes, and avalanches, which pose a constant threat to the lives of the local and downstream populations, as well as to the infrastructure, and sustainability of the valley (Sangha et al. 2019; Kumar et al. 2018; Kumari et al. 2016). Located in the Karakoram Range, this valley is a region characterized by diverse topographic, climatic, and geological conditions. Its location near the converging boundaries of the Indian and Eurasian tectonic plates makes it particularly susceptible to seismic events (Mondal et al. 2021). Moreover, the presence of numerous glaciers in the region increases the risk of GLOFs, a hazard that has claimed lives and caused significant damage in the past (Bajracharya et al. 2015; Shrestha et al. 2019). Landslides, often triggered by a combination of factors including precipitation, thawing of permafrost, and seismic activity, further compound the vulnerability of the area being (Adhikari et al. 2019; Bajracharya et al. 2020). In addition, avalanches represent a constant threat to transportation routes and residential areas, especially during the winter months (Bhutiyani et al. 2008).

Understanding and mitigating these hazards are critical for the resilience and long-term survival of the communities residing in the Shigar Valley and the downstream communities. As climate change accelerates, the frequency and magnitude of these hazards are likely to increase, making it imperative to adopt advanced methodologies for assessing vulnerability and risk in this region (Clark-Ginsberg et al. 2021; Jaiswal et al. 2010). This study seeks to address this pressing need by employing advanced Multi-criteria Hazard Assessment (MHA) methods, leveraging the power of Geographic Information Systems (GIS) and Remote Sensing (RS) technologies to provide a comprehensive understanding of the vulnerability of the Shigar Valley to a range of natural hazards.

The existing literature on hazard assessment in the Shigar Valley provides valuable insights but lacks the comprehensive, integrated approach required to address this multifaceted challenge. Past studies have often focused on individual hazards in isolation or have relied on limited data sources and traditional vulnerability assessment methods, which may not capture the complex interplay of factors affecting the region's vulnerability to multiple hazards (Mokarram et al. 2021; Yang et al. 2021). Furthermore, the landscape is continuously evolving, both due to natural processes and human activities, making it essential to have up-to-date, accurate, and dynamic information for effective hazard assessment and risk management (Kaur et al. 2019).

The utility of GIS-based susceptibility maps cascades into illuminating the geographical distribution of multi-hazard risks for the perusal of decision-makers and stakeholders. The techniques range from overlay analysis and weighted overlays to the efficacy of machine learning algorithms (Chen et al. 2018; Li et al. 2020). These utilities manifest their worth in guiding the scale of land-use planning, infrastructure development, disaster management and response, and targeted mitigation measures (Wenwu Chen and Zhang 2021; Piao et al. 2022; Ha-Mim et al. 2022; Kornejady et al. 2019). Multi-hazard analyses entail the integration of various factors and methodologies to assess the susceptibility of an area to multiple hazards simultaneously. These analyses employ advanced techniques such as Geographic Information Systems (GIS) and Remote Sensing (RS) to incorporate diverse parameters such as topography, geology, climate, land use, and infrastructure into the assessment process (van Westen 2000; Abella et al. 2008; Olaya Calderon et al. 2024). By considering multiple hazards in conjunction, these analyses provide a more comprehensive understanding of the overall risk landscape, allowing for better-informed decision-making and proactive risk reduction strategies (Jaiswal et al. 2010; Kaur et al. 2019). Furthermore, multi-hazard analyses enable the identification of synergies and interactions between different hazards, which may exacerbate overall risk levels (Ward et al. 2020; Pham et al. 2021). This holistic approach is particularly crucial in regions like the Shigar Valley, where various hazards coexist and intersect, necessitating a nuanced understanding of their combined impacts on local communities and ecosystems. By conducting multi-hazard analyses, researchers and stakeholders can effectively prioritize resources, implement targeted interventions, and enhance the resilience of vulnerable areas to a wide range of natural hazards. However, it is important to recognize that GIS-based multi-hazard assessments encounter several challenges, including issues of data heterogeneity, uncertainty, and the compelling need for the evolution of advanced modeling methodologies (Ujjwal et al. 2019; Ward et al. 2020; Pham et al. 2021).

The purpose of this study is to utilize advanced multi-criteria decision analysis methods, integrating Geographic Information Systems (GIS) and Remote Sensing (RS) products, to assess the vulnerability of the Shigar Valley, Himalayas, Pakistan, to a spectrum of natural hazards. This research aims to perform a comprehensive analysis of various natural hazards in the Shigar Valley by incorporating multi-criteria, including topography, geology, climate, land use, and infrastructure, in the vulnerability assessment process, enabling a holistic understanding of the region's susceptibility to hazards. The methodology for multi-criteria hazard susceptibility assessment in the Shigar Valley integrates geographical considerations and the unique conditions of the Shigar Valley. The criteria for hazard mapping are formulated with a specific focus on the valley's characteristics, recognizing its importance in the execution of Multi-Criteria Decision Analysis (MCDA). The assessment criteria are established through a comprehensive review of relevant literature and consultations with experts. The literature review aims to gather information applicable to GIS-based MCDA, drawing from primary sources obtained through reputable research databases (Belay et al. 2022). Different MCDA methodologies, including Analytic Hierarchy Process (AHP), Analytic Network Process (ANP), Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), and Weighted Sum Model (WSM), are explored for assessing multi-hazard susceptibility.

This analysis will establish risk zones within the Shigar Valley, which can serve as a foundation for informed decision-making and the development of hazard-specific risk reduction strategies. By achieving these objectives, this study aims to offer a comprehensive and up-to-date understanding of the vulnerabilities that the Shigar Valley faces, enabling local authorities, policymakers, and stakeholders to enhance proactive measures for disaster risk reduction and sustainable development.

2. Study area

The Shigar Valley is located in the central part of the Karakoram Range stretching from 35°29′14″ N to 35°23′54″ N latitude and 75°41′56″ E to and

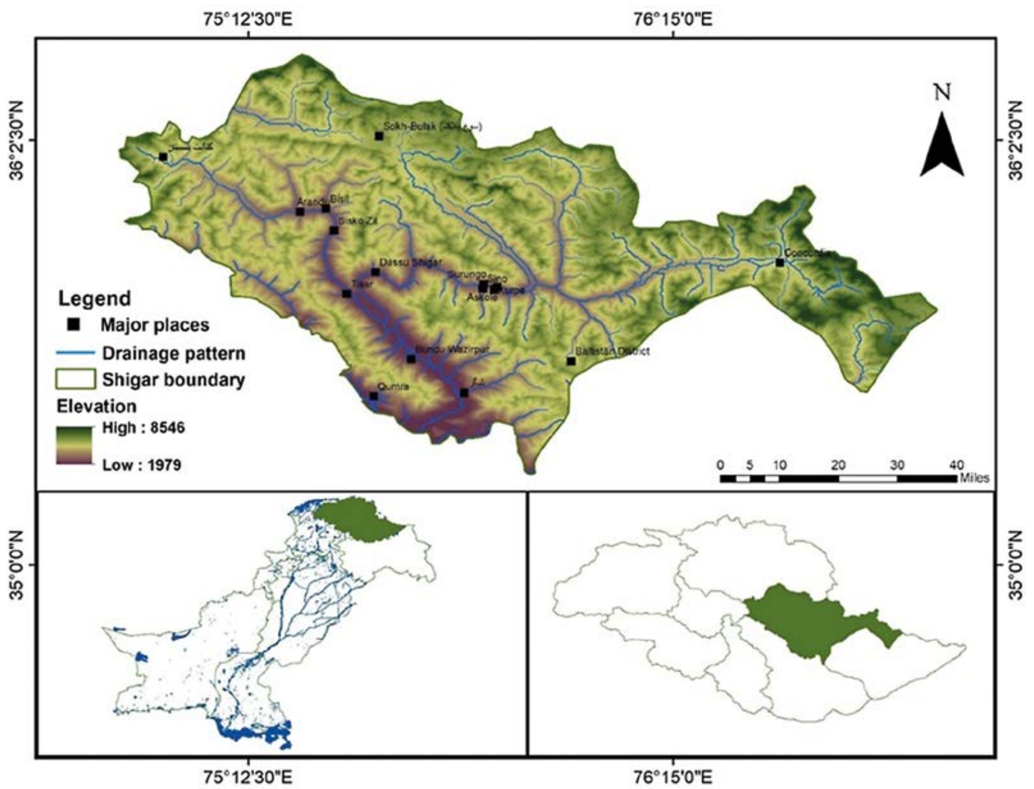

Fig. 1 (a) Location map of the study area. Elevation was calculated in ArcGIS using SRTM data, while the boundary layers were obtained from DivaGIS.com.

75°44′57″ E longitude (Fig. 1a). The Shigar Valley shares a border with China and is characterized by high peaks such as K-2 (8611 meters), Broad Peak (8047 meters), Angel Peak (6858 meters), and Skil Brum (7360 meters) with a population of 75 thousand according to the census of 2017 (Abbas et al. 2017). The valley consists of several small villages situated on alluvial fans, terraces, and gentle slopes along the river and its tributaries at altitudes ranging from 2300 m (Marapi) to 3050 m (Askole) (Schmidt 2008). It is one of the best tourism destinations in the northern areas of Pakistan (Khan et al. 2023).

The Shigar River drains the valley and is supplemented by numerous smaller tributaries flowing from the surrounding mountains, primarily sourced from glaciers. This river takes its origin from the Hispar glacier situated at the base of the Haramosh and Kanjut Sar peaks in the Shigar valley. A vital tributary of the Shigar River originates from the Baltoro Glacier near Masherbrum Peak, flowing westward to join the main channel. This river drains the meltwaters of the significant Baltoro and Biafo glaciers in the Karakoram Range. The catchment area is shaped by glaciers, with a deep upper valley that widens near the mouth. A small river island forms at the junction of the main river and the Baltoro Glacier tributary. The high-altitude, low-rainfall catchment area is sparsely vegetated, and human habitation is limited. The valley is characterized by moraines and glacial deposits resulting from the presence of these glaciers (Seong et al. 2009). Additionally, the Shigar Valley hosts several glacial lakes, often formed by the meltwater originating from the surrounding glaciers (Ali et al. 2023).

Shigar Valley's physiography is distinguished by its numerous landforms (Fig. 1b), which include valleys, mountains, glaciers, and river systems (Ali et al. 2023; Fatima et al. 2022). This area was selected for this study because of geophysical settings making it susceptible to a variety of natural hazards and the fact that it is home to a considerable population. Geologically, the area spans the northern end of the Kohistan-Ladakh Island Arc (KLIA) and the southern edge of the Asian plate. The Main Karakoram Thrust (MKT), situated at the northern suture and passing through the Shigar Valley, acts as a dividing line between the meta-sediments of the Asian plate and the volcano-clastic rocks of the KLIA. Seismic activity not only makes it susceptible to earthquakes but also induced landslides and historically the area has been hit by severe landslide t (Calligaris et al. 2017). Furthermore, the area is highly susceptible to snow avalanches and glacial hazards. Several disastrous events can be noted from history such as the debris flow on Jul 27, 2000, which destroyed 124 houses, and a gigantic glacial flow on Apr 7, 2012 that took the lives of 139 people along with infrastructure and livestock damages (Gilany and Iqbal 2017).

Fig. 1 (b) Pictures captured by the first author during a recent visit to the study area in November 2023. The left image depicts Arando Village in the Shigar Valley, an area prone to recurrent flash floods in recent years. These floods have caused substantial damage, including sedimentation on agricultural land and accelerated erosion. The right image showcases a newly discovered granite complex near Bisil, Shigar, presenting potential economic prospects. However, this area is also susceptible to landslides and avalanches.

2. Methodology

This study recognizes the importance of selecting factors influencing susceptibility to various hazards, including elevation, slope, flow accumulation, rainfall, distance from river, topographic wetness index, land use, lithology, normalized difference vegetation index (NDVI), curvature, distance from fault, stream power index, aspect, distance from road, and drainage density.

2.1 Data collection and preprocessing

Different sources and methods were used to extract and process the data for different factors considered for the multicriteria analysis. Several factors related to the characteristics of physical landscape (Tab. 1) were extracted from digital elevation model (DEM). These factors include elevation, slope, curvature, slope aspect, stream power index, flow accumulation, and drainage density. Curvature is classified into three classes: concave slope (negative value), flat plane (value −0.1 to 1.0), and convex slope (value greater than 0.1) (Gizaw et al. 2023). The stream power index calculates the erosive force of water in rivers or streams which was also extracted from the DEM (Okoli et al. 2023; Olii et al. 2023). Likewise, flow accumulation was extracted from DEM. The topographic wetness index (TWI) quantifies terrain moisture availability. TWI was obtained from DEM (Moharir et al. 2023) using ArcGIS and divided into 5 groups. Drainage density was also extracted from DEM with 250 m intervals (Ozegin et al. 2023; Upwanshi et al. 2023).

Tab. 1 Description of spatial data for different parameters.

Parameter	Source	Description
Elevation	ALOS-PALSAR DEM	12.5 m^2 resolution DEM image
Slope	ALOS-PALSAR DEM	12.5 m^2 resolution DEM image
Distance to fault	ALOS-PALSAR DEM	12.5 m^2 resolution DEM image
Aspect	ALOS-PALSAR DEM	12.5 m^2 resolution DEM image
Flow accumulation	ALOS-PALSAR DEM	12.5 m^2 resolution DEM image
Distance to river	ALOS-PALSAR DEM	12.5 m^2 resolution DEM image
Drainage density	ALOS-PALSAR DEM	12.5 m^2 resolution DEM image
Curvature	ALOS-PALSAR DEM	12.5 m^2 resolution DEM image
LULC	Sentinel-2 image	10 m^2 resolution from USGS
NDVI	Sentinel-2 image	10 m^2 resolution from USGS
Soil type	FAO	Soil shape files
Geology	Geological map	1 : 50,000 from GSP
Lithology	Geological map	1 : 50,000 from GSP
Topographic wetness index	ALOS-PALSAR DEM	12.5 m^2 resolution DEM image
Distance to road	Topgraphical map	1 : 50,000 from GSP
Rainfall	Metrological department	30-years data from PDM

Data for rainfall was collected for local meteorological stations from the Pakistan Meteorological Department (PMD) Lahore head office (Tab. 1). Rainfall was mapped using the Inverse Distance Weightage (IDW) method in ArcGIS (Al-Taani et al. 2023; Li et al. 2023) and classified into three classes. Proximity to rivers provides valuable insights into flood risk (Majeed et al. 2023; Shekar and Mathew 2023). In this study, five classes, with intervals of 250 m extracted from DEM, were generated in ArcGIS (Fig. 2).

Land use and land cover (LULC) and NDVI data were acquired using Sentinel-2 satellite imagery and supervised image classification, six classes – glaciers, water bodies, agricultural land, vegetation cover, and built-up areas – were identified (Belazreg et al. 2023; Bandyopadhyay et al. 2023; Meshram et al. 2023). Lithology layer ws created using the geological survey data in ArcGIS (Farhat et al. 2023; Mushtaq et al. 2023), while soil type layer was generated from the Food and Agriculture Organization (FAO) shape files.

Another crucial geological characteristic in multicriteria hazard assessment, distance from fault, is measured in intervals of 200 meters using the geological survey of Pakistan data, with five classes generated in ArcGIS (Faryabi 2023; Ke et al. 2023; Kumar et al. 2023). Additionally, distance from road was extracted from 1 : 50,000 topographic map.

2.2 Analytical Hierarchy Process (AHP) method

Susceptibility maps based on AHP provide a quantitative representation of areas vulnerable to various threats (Hu et al. 2018). It involves pairwise comparisons of criteria and sub-criteria to determine their relative relevance. A preference scale, inspired by Saaty (2008) and Kursunoglu et al. (2021), is employed to assign weightings reflecting the perceived importance of each factor. The AHP-based susceptibility evaluation relies on the collection and preparation of spatial data, organized within the hierarchical structure of the AHP framework (Bui et al. 2019; Javidan et al. 2021). Pairwise comparison matrices and weightings are utilized to assign priority scores to locations based on their susceptibility to threats. Higher scores indicate greater vulnerability, aiding decision-making by highlighting areas requiring targeted risk reduction actions (Cheng et al. 2020; Lee and Seo 2016; Youssef and Pourghasemi 2021).

The consistency ratio in AHP is a critical metric assessing the dependability of decision-makers' judgments during pairwise comparisons of criteria and alternatives (Scapozza and Bartelt 2003). It is calculated as the Consistency Index (CI) divided by the Random Index (RI) (Scapozza et al. 2019).

The CI measures the degree of consistency in the pairwise comparison assessment. It is determined by comparing the largest eigenvalue (λ_max) of the matrix to its order (n), expressed as:

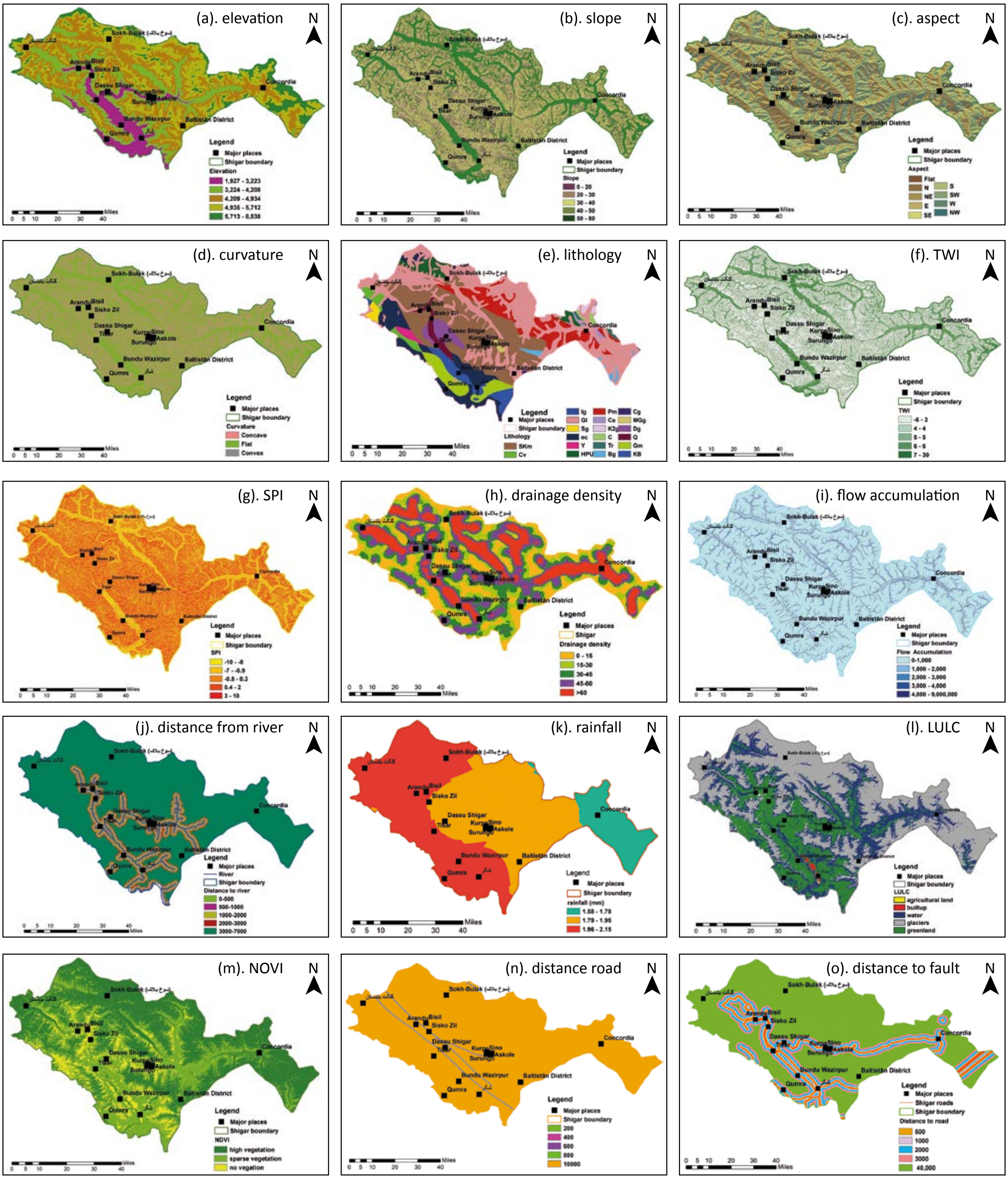

Fig. 2 Layers for multicriteria hazards susceptibility assessment. Detail methods and sources of data have been discussed in the methodology description.

$$\text{Consistency ratio} = \frac{\text{Consistency Index (CI)}}{\text{Random Index (RI)}}$$

The Random Index (RI) serves as a reference value to estimate the consistency level of randomly generated matrices, ensuring the reliability of decision-making judgments. If the calculated CR is close to or less than 0.10, the judgments are considered reasonably consistent and acceptable. However, if the CR exceeds 0.10, it suggests inconsistencies in the pairwise comparisons, requiring further scrutiny or revisions.

The CR is computed to ensure consistent judgments, defining the ratio. If the calculated CR is less than or near 0.10, judgments are deemed reasonably

Tab. 2 Conversion of language preferences into numerical scores.

Scale value	Importance of scale	Example in detail
1	Equally important	Both variables are equally significant
3	Moderately important	One variable is slightly significant
5	Strongly important	One variable is strongly significant
7	Very strongly important	One variable is dominantly significant
9	Absolutely important	One variable is entirely significant
2,4,6,8	Intermediate	Intermediate value

Tab. 3 Random index values to calculate consistency ratio.

N	1	2	3	4	5	6	7	8	9	10	9	10
RI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49	1.45	1.49

consistent and acceptable. A CR exceeding 0.10 indicates inconsistencies, necessitating further inspection or revisions.

Decision-makers use a scale created by Saaty, ranging from 1 to 9. These scale values are logarithmically separated to maintain qualitative comparisons. Tab. 2 illustrates the numerical scale used to convert language preferences into numerical score values (Rehman et al. 2022).

Tab. 3 presents random index values used to calculate the consistency ratio. The CI, expressing the degree of consistency in pairwise comparisons, is determined by comparing λ_max to its order (n). The Random Index (RI) is a reference value assessing the consistency level of randomly generated matrices.

2.3 Multi-hazards weight assignment

Weights assigning is a crucial step in developing the multi-hazards index map to reflect the varying degrees of risk in the research area with high degree of accuracy. In this study, we employed a weighted overlay in ArcGIS, to ensure integration of multiple hazard factors. Given the region's varying susceptibility to different hazards, each hazard category was carefully considered. This integrated approach ensures that the contribution of each hazard factor is adequately considered in the multi-hazards index map. The following weights were assigned to different hazards based on experts' observations drawing from different literature sources (Park et al. 2018; Rehman et al. 2022).

Flood Weight (40%)

The study area, situated in a high-risk zone, experiences frequent flooding events and therefore it was assigned the highest weight (40%) to conduct a final multi-hazards susceptibility map.

Landslide Weight (30%)

A weight of 30% was assigned to landslides due to the region's topographical characteristics aligning with the observed vulnerability of the area to slope failures and associated risks.

Earth Snow Avalanches Weight (25%)

Considering the substantial risk of snow avalanches, particularly at higher steep slopes, a weight of 25% was assigned acknowledging the threats associated with this landscape.

Earthquake Weight (5%)

While earthquakes contribute to the overall hazard profile, the weight assigned to this factor was set at 5%. This decision reflects the seismic activity in the region but acknowledges that other hazards pose comparatively greater risks.

Using weighted overlay analysis, the individual hazard indices were integrated to generate an overall susceptibility index map, depicting the varying degrees of susceptibility across different areas (Rahman et al. 2022). The resulting polygons were then converted into a projected coordinate system to facilitate the calculation of areas corresponding to different susceptibility categories using the field calculator tool in ArcGIS.

3. Result and discussion

Flood hazards, exacerbated by glacial-fed drainage and the formation of glacial lakes in the upper catchment of the Shigar River and its tributaries, pose a significant threat in the study area, making it susceptible to Glacial Lake Outburst Floods (GLOFs) (Campbell 2004; Batool et al. 2016). To comprehensively assess flood susceptibility, detailed mapping was conducted, integrating multiple factors (Afreen et al. 2022) such as elevation, slope, flow accumulation, rainfall, distance to river, drainage density, topographic wetness index, land use, soil type, lithology, NDVI, and curvature.

The resultant flood susceptibility index map provides insights into the vulnerability of the study area, particularly concerning the very high and high categories (Fig. 3a). Notably, the downstream region in the densely populated lowland exhibits a pronounced susceptibility to floods. Conversely, areas characterized by very low flood susceptibility are limited and predominantly situated in high steep slopes. A significant portion of the landscape falls within the moderately to low susceptible categories.

Statistically, the analysis reveals that a total of 59.3 km^2, constituting 1.04% of the total area, falls under the very highly susceptible category in terms of flood hazards. The heightened flood risk in this region is compounded by its dense population and its role as the primary cultivation zone in the valley. Similarly, 1604.9 km^2 or 28.3% of the area is classified as highly susceptible (Tab. 4), primarily concentrated in the floodplains of the main Shigar River and its major tributaries. These zones, observed through inventory

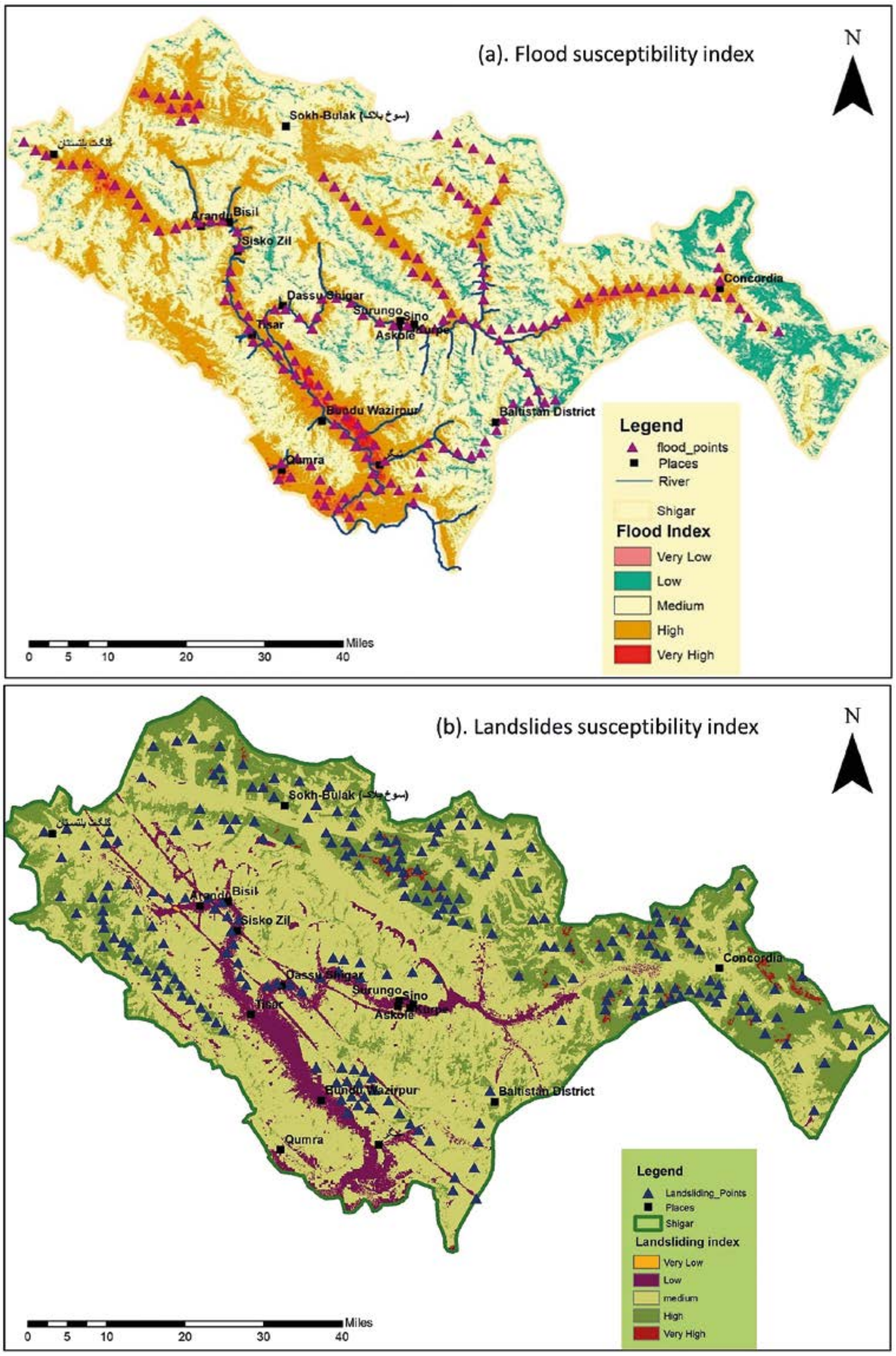

Fig. 3 Flood and landslide susceptibility index maps. The maps were created in ArcGIS using the relevant layers.

points and previous studies, have experienced frequent inundation events (Gilany and Iqbal 2016). In particular, several major villages are located within the high to very high susceptible zones, including Chaqpo, Tissar, Churtron, Haiderabad, Lansa, Marapi, Churka, Alchori, Qulpur, and Kashmal.

Landslides, with the second-highest weight in the hazard susceptibility index, emerge as a frequent and impactful hazard within the study area. A comprehensive approach to landslide hazard mapping involved the consideration of ten key parameters, including lithology, soil type, slope, land use, distance to road, distance to river, distance to fault, elevation, aspect, and precipitation. The intricate interplay of these factors in the region's topography and climatic conditions establishes a substantial susceptibility to landslides, as corroborated by existing literature (Hewitt 1999; Calligaris et al. 2017).

The results of the study elucidate that a significant portion of the study area, 1459 km^2, which makes

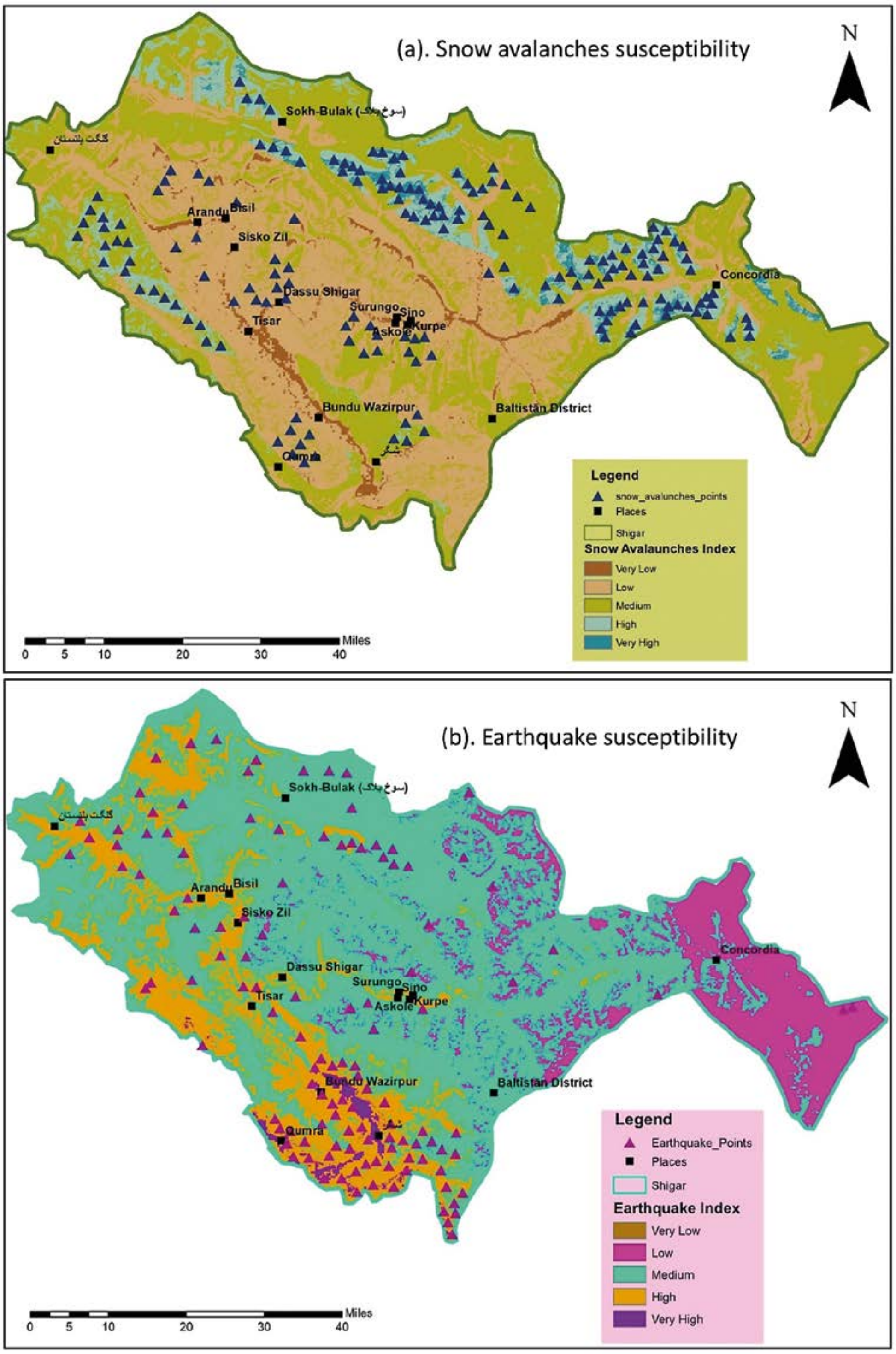

Fig. 4 Earthquake and snow avalanches susceptibility index maps. The maps were created in ArcGIS using the relevant layers.

25.8% of the total land, is characterized by a high susceptibility to landslide hazards (Tab. 4). The resultant landslide susceptibility index map provides a representation of vulnerability distribution across the study area (Fig. 3b). The susceptibility to landslides demonstrates an escalating trend toward higher elevations and steeper slopes, accentuating the topographic influence on landslide occurrence. Within the highly susceptible zones, notable villages such as Hoto, Daso, Demal, Haiderabad, and Arandu are situated, underscoring the threat to populated areas. A substantial yet distinct portion, comprising 64.6% of the total, falls within the moderately susceptible classification. This delineation reflects the nuanced topographic hostility inherent in the region.

Despite the prevalence of moderately susceptible areas, a closer examination reveals that only a select few out of approximately 50 villages are positioned in the high to very high susceptible zones. This underscores the concentrated nature of landslide vulnerability, with specific communities facing heightened risks. Navigating the landscape challenges posed by landslides necessitates a tailored understanding of the localized susceptibility patterns, enabling targeted mitigation efforts and community resilience strategies.

In exploring the hazards prevalent in our study area, snow avalanches emerge as a significant concern (Hewitt 1988; Hewitt et al. 2011; Hasson et al. 2014; Gilany and Iqbal 2017), demanding a detailed evaluation (Shroder et al. 2011). We adopted a thorough approach, considering twelve factors like slope, distance to fault, lithology, and others to create a Snow Avalanche Susceptibility Index (Ali et al. 2023). The susceptibility index, depicted in Tab. 3, assigns different levels ranging from low to very high vulnerability.

Examining the map (Fig. 4a), it's evident that high and very high susceptibility zones cluster in elevated terrains, primarily in the upper northern and northwestern parts of our study area. Zooming in, villages such as Wazir Pur, Churka, Hasnupi, and others fall within these high-risk zones. These findings highlight the localized nature of avalanche susceptibility, emphasizing that certain communities face elevated risks due to where they're situated.

On the flip side, most low-lying regions showcase low susceptibility. This spatial distribution of susceptibility levels points to areas where avalanche risks are comparatively lower, providing valuable insights for targeted safety measures and community planning. Breaking down the stats, areas with very high susceptibility cover 40.7% of the total land, while high susceptibility areas account for 11.8%. On the lower end, low susceptibility areas make up 2.35%. This statistical breakdown gives us a clearer picture of the varying risk levels across the landscape. Our assessment of snow avalanche susceptibility helps uncover the mix of factors influencing risk. Identifying high-risk zones and areas of lower susceptibility is vital for crafting safety measures tailored to specific communities. This down-to-earth understanding is crucial for decision-makers working to safeguard our communities from the challenges posed by alpine hazards.

In our study, our primary aim was to create a comprehensive picture of the risks in the Shigar Valley by looking at multiple hazards simultaneously. We achieved this by assigning weights based on expert opinions from existing literature, ensuring a well-rounded analysis (Zhou et al. 2016; Rehman et al. 2021; 2022). By doing this, we move beyond just individual hazards and gain a holistic understanding of how various threats come together, influencing the overall risk profile of the study area. Our holistic approach allows us to look at the bigger picture, giving us insights into how different hazards interact. This in-depth exploration provides a detailed view of vulnerability, crucial for managing and planning human activities in the region.

Looking at the results, the susceptibility of the study area to combined hazards is quite worrisome. A significant portion of the valley, about 28.3%, falls into the highly susceptible category, and an additional 1.04% is classified as very highly susceptible (Tab. 4). These areas are predominantly along the floodplains of the Shigar River and its tributaries, which are crucial zones for human activities (Fig. 5). Moving beyond the high susceptibility zones, we find that approximately 60% of the total land in the study area is moderately susceptible to multi-hazards. This moderate susceptibility is spread throughout the valley, presenting challenges for a range of activities. It's not just about the extremes; even the moderate risk areas demand attention and planning. In contrast,

Tab. 4 Area susceptible to various hazards and overall multi-hazards susceptibility index.

Susceptibility index →	Low		Very low		Medium		High		Very high	
Hazards ↓	Area (km²)	%age	Area (km²)	%age	Area (km²)	%age	Area (km²)	%age	Area (km²)	%age
Floods	1.73	0.030	550.2	9.70	3436.0	60.7	1604.9	28.3	59.3	1.04
Landsides	1.61	0.020	494.8	8.70	3654.5	64.6	1459.7	25.8	40.3	0.70
Avalanches	135.50	2.300	2410.1	42.65	2304.5	40.7	667.8	11.8	132.8	2.35
Earthquake	0.34	0.005	866.3	15.30	3507.1	61.9	1229.1	21.7	58.7	1.03
Multi-hazard	1.73	0.030	548.6	9.70	3432.0	60.8	1602.1	28.3	59.2	1.04

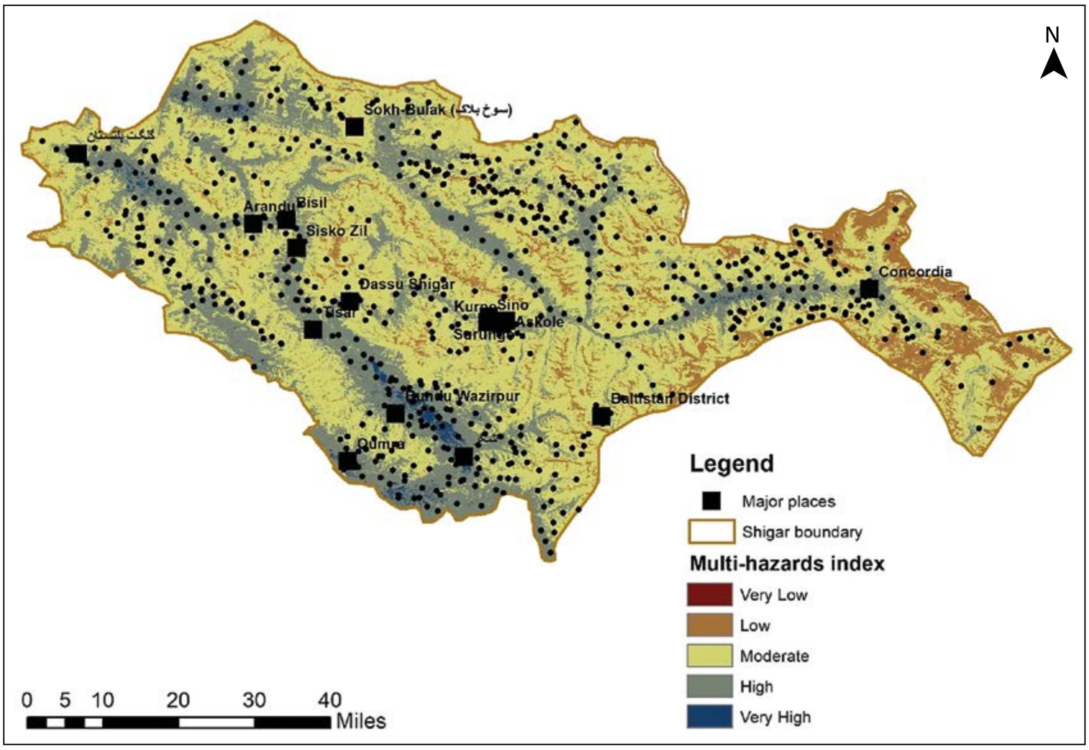

Fig. 5 Multi-hazards susceptibility index of the study area. The map was created using weighted overlay in ArcGIS combining all the hazards susceptibility indices.

the low and very low susceptibility categories cover a relatively small proportion of the total land. Most of these areas are located in uninhabited high mountains and glacial terrain.

Understanding the dynamics of highly susceptible zones along with moderately and less susceptible areas is crucial for adapting resilient strategies. The valley's vulnerability is not just about the extreme risks but also about managing day-to-day activities in areas that might seem less risky but still demand attention. Balancing these aspects is key to ensuring a secure and sustainable future for the Shigar Valley.

4. Conclusion

In undertaking a comprehensive multi-hazard susceptibility assessment for the Shigar Valley, our study has provided invaluable insights into the complex risk landscape of this region. As we conclude, it becomes evident that navigating the hazards in the Shigar Valley requires a nuanced understanding and strategic planning to foster sustainable resilience. Our research delved into individual hazards, uncovering the specific threats posed by floods, landslides, snow avalanches, and earthquakes. By carefully mapping susceptibility indices for each hazard, we laid the groundwork for a detailed exploration of the challenges faced by the Shigar Valley.

Floods emerged as a recurrent and severe hazard, particularly in lowland areas adjacent to the Shigar River and its tributaries. The susceptibility mapping illuminated the vulnerabilities of densely populated regions, emphasizing the need for targeted risk reduction strategies and preparedness measures. Landslides, with their significant weight in the susceptibility index, showcased a substantial portion of the study area as highly susceptible. The distribution of vulnerabilities revealed a correlation with higher elevations and steeper slopes, impacting villages like Hoto, Daso, Demal, Haiderabad, and Arandu. The susceptibility map for snow avalanches unveiled high and very high susceptibility in the elevated regions, affecting villages like Wazir Pur, Churka, Hasnupi, Daso, Dasonid, Doka, Zil, and Surungo. Low susceptibility prevailed in low-lying areas, emphasizing the need for specific mitigation strategies based on local terrain. Given the historical significance of earthquakes in the HKH region, our earthquake susceptibility assessment indicated considerable vulnerability. Highly susceptible zones were concentrated in populated southern and southwestern lowlands, emphasizing the need for resilient infrastructure and emergency preparedness.

Moving beyond individual hazards, we adopted a holistic approach by combining all hazards into a multi-hazard susceptibility index. Assigning weights based on expert opinions enabled us to capture the interconnectedness of these threats. This approach not only identified highly susceptible zones but also highlighted moderate risk areas that demand attention for comprehensive hazard planning. Our integrated analysis painted a concerning picture, with a substantial area classified as highly and very highly susceptible. Balancing the need for development and human activities in these areas requires meticulous planning, emphasizing the importance of community awareness and engagement. As we conclude, it is imperative to consider our findings in guiding sustainable development and resilience strategies in the Shigar Valley. Additionally, our study emphasizes the need for ongoing monitoring and adaptive management to address the dynamic nature of hazards in this region. In navigating the multi-hazard landscape of the Shigar Valley, our research lays the groundwork for informed decision-making, fostering a resilient future for the communities that call this vulnerable yet picturesque landscape home.

References

Abbas, Z., Khan, S., Alam, J. et al. (2017): Medicinal plants used by inhabitants of the Shigar Valley, Baltistan region of Karakorum range-Pakistan. J Ethnobiology Ethnomedicine 13: 53, https://doi.org/10.1186/s13002-017-0172-9.

Abella, E. A. C., Van Westen, C. J. (2008): Qualitative landslide susceptibility assessment by multicriteria analysis: A case study from San Antonio del Sur, Guantánamo, Cuba. Geomorphology 94(3–4), 453–466, https://doi.org/10.1016/j.geomorph.2006.10.038.

Adhikari, R., Gautam, D., Jha, P., Aryal, B., Ghalan, K., Rupakhety, R., Dong, Y., Rodrigues, H., Motra, G. (2019): Bridging multi-hazard vulnerability and sustainability: approaches and applications to Nepali highway bridges. In: Noroozinejad Farsangi, E., Takewaki, I., Yang, T., Astaneh-Asl, A., Gardoni, P. (eds) Resilient Structures and Infrastructure. Springer, Singapore, https://doi.org/10.1007/978-981-13-7446-3_14.

Afreen, M., Haq, F., Mukhtar, Z. (2022): Flood susceptibility analysis of the Panjkora Valley Northern Pakistan, using frequencyratio approach. International Journal of Disaster Resilience in the Built Environment 13(5), 601–614, https://doi.org/10.1108/IJDRBE-09-2020-0104.

Ahmed, T., Rehman, K., Shafique, M., Ali, W. (2023): GIS-based earthquake potential analysis in Northwest Himalayan, Pakistan. Environmental Earth Sciences 82(4), 113, https://doi.org/10.1007/s12665-023-10798-2.

Ali, F., Zhang, J.-H., Alam, M., Sajjad, M., Abbas, S., Hussain, A., Ramzan, M., Hussain, F. (2023): Avalanche Susceptibility mapping of District Shigar, Pakistan using GIS-based MCDA–AHP modeling, 16 January 2023, PREPRINT (Version 1) available at Research Square, https://doi.org/10.21203/rs.3.rs-2237380/v1.

Ali, S., Khan, G., Qureshi, J. A., Hassan, M., Kheirandish, S. (2023): Climatic and topographic controls on glacial changes (1973–2020) in Shigar Basin, Central Karakoram, Northern Pakistan. Environmental Science and Pollution Research 30, 74889–74899, https://doi.org/10.1007/s11356-023-27648-0.

Al-Taani, A., Al-husban, Y., Ayan, A. (2023): Assessment of potential flash flood hazards. Concerning land use /land cover in Aqaba Governorate, Jordan, using a multi-criteria technique. The Egyptian Journal of Remote Sensing and Space Science 26(1), 17–24, https://doi.org/10.1016/j.ejrs.2022.12.007.

Andrabi, T., Daniels, B., Das, J. (2023): Human capital accumulation and disasters: Evidence from the Pakistan earthquake of 2005. Journal of Human Resources 58(4), 1057–1096, https://doi.org/10.3368/jhr.59.2.0520-10887R1.

Aslam, B., Zafar, A., Qureshi, U. A., Khalil, U. (2021): Seismic investigation of the northern part of Pakistan using the statistical and neural network algorithms. Environmental Earth Sciences 80, 1–18, https://doi.org/10.1007/s12665-020-09348-x.

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

Bajracharya, R. M., Shrestha, H. L., Shakya, R., Sitaula, B. K. (2015): Agro-forestry systems as a means to achieve carbon co-benefits in Nepal. Journal of Forest and Livelihood 13(1), 59–68, https://doi.org/10.3126/jfl.v13i1.15366.

Bajracharya, S. R., Maharjan, S., Shrestha, F., Sherpa, T., Wagle, N., Shrestha, A. (2020): Inventory of glacial lakes and identification of potentially dangerous glacial lakes in the Koshi, Gandaki, and Karnali River Basins of Nepal, the Tibet Autonomous Region of China and India. International Centre for Integrated Mountain Development, United Nations Development Programme, Kathmandu, Nepal, https://doi.org/10.53055/ICIMOD.773.

Bandyopadhyay, J., Rahaman, S. H., Karan, C. (2023): Agricultural potential zone mapping with surface water resource management using geo-spatial tools for Jhargram district, West Bengal, India. Knowledge-Based Engineering and Sciences 4(1), 1–18.

Batool, S., Khan, T., Karim, R., Zafar, M., Ahmed, S. (2016): Climate Change and Agricultural Transformation in Shigar Valley, Gilgit-Baltistan, Pakistan: A Commune-Scientific Perception. International Journal of Environment, Agriculture and Biotechnology 1(4), 902–906, https://doi.org/10.22161/ijeab/1.4.39.

Belay, S., Goedert, J., Woldesenbet, A., Rokooei, S. (2022): AHP based multi criteria decision analysis of success factors to enhance decision making in infrastructure construction projects. Cogent Engineering 9(1): 2043996, https://doi.org/10.1080/23311916.2022.2043996.

Belazreg, N. E. H., Hasbaia, M., Şen, Z., Ferhati, A. (2023): Flood risk mapping using multi-criteria analysis (MCA) through AHP method case of El-Ham wadi watershed of Hodna basin (Algeria): Natural hazards 120, 1023–1039, https://doi.org/10.1007/s11069-023-06239-9.

Bhutiyani, M., Kale, V. S., Pawar, N. (2008): Changing streamflow patterns in the rivers of northwestern Himalaya: implications of global warming in the 20th century. Current Science, 618–626.

Bui, D. T., Ngo, P.-T. T., Pham, T. D., Jaafari, A., Minh, N. Q., Hoa, P. V., Samui, P. (2019): A novel hybrid approach based on a swarm intelligence optimized extreme learning machine for flash flood susceptibility mapping.

Catena 179, 184–196, https://doi.org/10.1016/j.catena.2019.04.009.
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.
Campbell, J.G. (2004): Inventory of Glaciers and Glacial Lakes and the Identification of Potential Glacial Lake Outburst Floods (GLOFs) Affected by Global Warming in the Mountains of India, Pakistan and China/Tibet Autonomous Region. International Centre for Integrated Mountain Development (ICIMOD) G. P. O. Box 3226, Kathmandu, Nepal.
Chen, W., Zhang, S. (2021): GIS-based comparative study of Bayes network, Hoeffding tree and logistic model tree for landslide susceptibility modeling. Catena 203: 105344, https://doi.org/10.1016/j.catena.2021.105344.
Chen, W., Shahabi, H., Zhang, S., Khosravi, K., Shirzadi, A., Chapi, K., Pham, B. T., Zhang, T., Zhang, L., Chai, H. (2018): Landslide susceptibility modeling based on GIS and novel bagging-based kernel logistic regression. Applied Sciences 8(12): 2540, https://doi.org/10.3390/app8122540.
Cheng, X., Cheng, Y., Zhang, N., Zhao, S., Cui, H., Zhou, H. (2020): Purification of flavonoids from Carex meyeriana Kunth based on AHP and RSM: Composition analysis, antioxidant, and antimicrobial activity. Industrial Crops and Products 15: 112900, https://doi.org/10.1016/j.indcrop.2020.112900.
Chowdhury A., Kroczek T., Kumar De S., Vilímek V., Chand Sharma M., Debnath M. (2021): Glacial Lake Evolution (1962–2018) and Outburst Susceptibility of Gurudongmar Lake Complex in the Tista basin, Sikkim Himalaya (India): Water 13(24): 3565, https://doi.org/10.3390/w13243565.
Clark-Ginsberg, A., Easton-Calabria, L. C., Patel, S. S., Balagna, J., Payne, L. A. (2021): When disaster management agencies create disaster risk: a case study of the US's Federal Emergency Management Agency. Disaster Prevention and Management: An International Journal 30(4/5), 447–461, https://doi.org/10.1108/DPM-03-2021-0067.
Farhat, B., Souissi, D., Mahfoudhi, R., Chrigui, R., Sebei, A., Ben Mammou, A. (2023): GIS-based multi-criteria decision-making techniques and analytical hierarchical process for delineation of groundwater potential. Environmental Monitoring and Assessment 195(2): 285, https://doi.org/10.1007/s10661-022-10845-8.
Faryabi, M. (2023): A fuzzy logic approach for land subsidence susceptibility mapping: the use of hydrogeological data. Environmental Earth Sciences 82(9): 209, https://doi.org/10.1007/s12665-023-10909-z.
Fatima, S. U., Khan, M. A., Shaukat, S. S., Alamgir, A., Siddiqui, F., and Sulman, N. (2022): Geo-Spatial Assessment of Water Quality in Shigar Valley, Gilgit Baltistan, Pakistan. Health 14(5), 535–552, https://doi.org/10.4236/health.2022.145040.
Gao, Y., Liu, S., Qi, M., Xie, F., Wu, K., Zhu, Y. (2021) Glacier-Related Hazards Along the International Karakoram Highway: Status and Future Perspectives. Frontiers in Earth Science 9:611501, https://doi.org/10.3389/feart.2021.611501.
Gilany S.N., Iqbal, J. (2016): Geospatial analysis of glacial hazard prone areas of Shigar and Shayok basins. International Journal of Innovation and Applied Studies 14(3), 623–644.
Gilany, S. N., Iqbal, J. (2017): Glacial avalanche hazard's comparative geospatial analysis in Shigar and Shyok basins. In 2017 Fifth International Conference on Aerospace Science and Engineering (ICASE), Islamabad, Pakistan, 1–7, https://doi.org/10.1109/ICASE.2017.8374279.
Gizaw, E. A., Bawoke, G. T., Alemu, M. M., Anteneh, Z. L. (2023): Spatial analysis of groundwater potential using remote sensing and GIS-based multi-criteria decision analysis method in Fetam-Yisir catchment, Blue Nile Basin, Ethiopia. Applied Geomatics 15, 659–681, https://doi.org/10.1007/s12518-023-00518-7.
Ha-Mim, N. M., Rahman, M. A., Hossain, M. Z., Fariha, J. N., Rahaman, K. R. (2022): Employing multi-criteria decision analysis and geospatial techniques to assess flood risks: A study of Barguna district in Bangladesh. International Journal of Disaster Risk Reduction 77: 103081, https://doi.org/10.1016/j.ijdrr.2022.103081.
Hasson, S., Lucarini, V., Khan, M. R., Petitta, M., Bolch, T., and Gioli, G. (2014): Early 21st century snow cover state over the western river basins of the Indus River system. Hydrology and Earth System Sciences 18(10), 4077–4100, https://doi.org/10.5194/hess-18-4077-2014.
Hewitt, K. (1998): Catastrophic landslides and their effects on the Upper Indus streams, Karakoram Himalaya, northern Pakistan. Geomorphology 26(1–3), 47–80, https://doi.org/10.1016/S0169-555X(98)00051-8.
Hewitt, K. (1999): Quaternary Moraines vs Catastrophic Rock Avalanches in the Karakoram Himalaya, Northern Pakistan. Quaternary Research 51(3), 220–237, https://doi.org/10.1006/qres.1999.2033.
Hewitt, K., Gosse, J., Clague, J. J. (2011): Rock avalanches and the pace of late Quaternary development of river valleys in the Karakoram Himalaya. GSA Bulletin 123(9–10), 1836–1850, https://doi.org/10.1130/B30341.1.
Hu, J., Chen, J., Chen, Z., Cao, J., Wang, Q., Zhao, L., Zhang, H., Xu, B., Chen, G. (2018): Risk assessment of seismic hazards in hydraulic fracturing areas based on fuzzy comprehensive evaluation and AHP method (FAHP): A case analysis of Shangluo area in Yibin City, Sichuan Province, China. Journal of Petroleum Science and Engineering 170, 797–812, https://doi.org/10.1016/j.petrol.2018.06.066.
Iqbal, J. M., Shah, H. F., Chaudhry, A. H., Baig, N. M. (2014): Impacts of Attabad Lake (Pakistan) and its future outlook. European Scientific Journal 10(8), 107–120.
Ishaque, W., Tanvir, R., Mukhtar, M. (2022): Climate Change and Water Crises in Pakistan: Implications on Water Quality and Health Risks. Journal of Environment and Public Health 22: 5484561, https://doi.org/10.1155/2022/5484561.
Jaiswal, K., Wald, D., Porter, K. (2010): A global building inventory for earthquake loss estimation and risk management. Earthquake Spectra 26(3), 731–748, https://doi.org/10.1193/1.3450316.
Jaiswal, P., van Westen, C. J. (2010): Use of remote sensing data for landslide susceptibility mapping

in central Nepal. Proceedings of the International Conference on Geoinformatics for Disaster Management 4–6.

Javidan, N., Kavian, A., Pourghasemi, H. R., Conoscenti, C., Jafarian, Z., Rodrigo-Comino, J. (2021): Evaluation of multi-hazard map produced using MaxEnt machine learning technique. Scientific reports 11(1): 6496, https://doi.org/10.1038/s41598-021-85862-7.

Kaur, H., Gupta, S., Parkash, S., Thapa, R., Gupta, A., Khanal, G. C. (2019): Evaluation of landslide susceptibility in a hill city of Sikkim Himalaya with the perspective of hybrid modelling techniques. Annals of GIS 25(2), 113–132, https://doi.org/10.1080/19475683.2019.1575906.

Kaur, P., and Singh, B. (2019): Multi-hazard vulnerability assessment of Indian Himalayan region using geospatial technique. Natural Hazards 98(1), 435–456.

Ke, C., He, S., Qin, Y. (2023): Comparison of natural breaks method and frequency ratio dividing attribute intervals for landslide susceptibility mapping. Bulletin of Engineering geology and the Environment 82: 384, https://doi.org/10.1007/s10064-023-03392-0.

Khan, A., Farah, H., Khan, S., Azmat, M. (2023): Comparative assessment of spatiotemporal variability in cryosphere and hydro-climatic regime of the Hunza, Astore and Shigar Basins (Hindukush-Karakoram–Himalaya Region) in Pakistan. Arabian Journal of Geosciences 16(5), 350–365, https://doi.org/10.1007/s12517-023-11440-y.

Khattak, I., Rahman, F., Haq, F. (2012): The Flood Event of July 2010: Socioeconomic Disruptions in Lower Dir District. The Journal of Humanities and Social Sciences 20(2), 57–76.

Khurshid, A., Yielding, G., Ahmad, S., Davison, I., Jackson, J. A., King, G. C. P., Zuo, L. B. (1984): The seismicity of northernmost Pakistan. Tectonophysics 109(3–4), 209–226, https://doi.org/10.1016/0040-1951(84)90141-0.

Kornejady, A., Pourghasemi, H. R., Afzali, S. F. (2019): Presentation of RFFR New Ensemble Model for Landslide Susceptibility Assessment in Iran. In: Pradhan, S., Vishal, V., Singh, T. (eds) Landslides: Theory, Practice and Modelling. Advances in Natural and Technological Hazards Research 50. Springer, Cham, https://doi.org/10.1007/978-3-319-77377-3_7.

Kropáček J., Vilímek V., Mehrishi P. (2021): A preliminary assessment of Chamoli ice and rock fall in Indian Himalayas by remote sensing. Landslides 18, 3489–3497, https://doi.org/10.1007/s10346-021-01742-1.

Kumar, A., Gupta, A. K., Bhambri, R., Verma, A., Tiwari, S. K., Asthana, A. (2018): Assessment and review of hydrometeorological aspects for cloudburst and flash flood events in the third pole region (Indian Himalaya): Polar Science 18, 5–20, https://doi.org/10.1016/j.polar.2018.08.004.

Kumar, M., Singh, P., Singh, P. (2023): Machine learning and GIS-RS-based algorithms for mapping the groundwater potentiality in the Bundelkhand region, India. Ecological Informatics 74: 101980, https://doi.org/10.1016/j.ecoinf.2023.101980 .

Kumari, N., Chowdary, V., Waghaye, A., Tiwari, K. (2016): Assessment of surface Runoff and Sediment Yield using WEPP model. Nature Environment and Pollution Technology 15(2), 491.

Kursunoglu, S., Kursunoglu, N., Hussaini, S., Kaya, M. (2021): Selection of an appropriate acid type for the recovery of zinc from a flotation tailing by the analytic hierarchy process. Journal of Cleaner Production 283: 124659, https://doi.org/10.1016/j.jclepro.2020.124659.

Lee, S., Seo, K. K. (2016): A hybrid multi-criteria decision-making model for a cloud service selection problem using BSC, fuzzy Delphi method and fuzzy AHP. Wireless Personal Communications 86, 57–75, https://doi.org/10.1007/s11277-015-2976-z.

Li, R., Huang, S., Dou, H. (2023): Dynamic Risk Assessment of Landslide Hazard for Large-Scale Photovoltaic Power Plants under Extreme Rainfall Conditions. Water 15(15): 2832, https://doi.org/10.3390/w15152832.

Li, X., Sovilla, B., Jiang, C., Gaume, J. (2020): The mechanical origin of snow avalanche dynamics and flow regime transitions. The Cryosphere 14(10), 3381–3398, https://doi.org/10.5194/tc-14-3381-2020.

Lutz, A.F., Immerzeel, W., Kraaijenbrink, P., Shrestha, A.B., Bierkens, M.F. (2016): Climate change impacts on the upper Indus hydrology: sources, shifts and extremes. PloS ONE 11(11): e0165630, https://doi.org/10.1371/journal.pone.0165630.

Majeed, M., Lu, L., Anwar, M. M., Tariq, A., Qin, S., El-Hefnawy, M. E., El-Sharnouby, M., Li, Q., Alasmari, A. (2023): Prediction of flash flood susceptibility using integrating analytic hierarchy process (AHP) and frequency ratio (FR) algorithms. Frontiers in Environmental Science 10: 1037547, https://doi.org/10.3389/fenvs.2022.1037547.

Meshram, S., Tirivarombo, S., Meshram, C., Alvandi, E. (2023): Prioritization of soil erosion-prone sub-watersheds using fuzzy-based multi-criteria decision-making methods in Narmada basin watershed, India. International Journal of Environmental Science and Technology 20(2), 1741–1752, https://doi.org/10.1007/s13762-022-04044-8.

Moharir, K. N., Pande, C. B., Gautam, V. K., Singh, S. K., Rane, N. L. (2023): Integration of hydrogeological data, GIS and AHP techniques applied to delineate groundwater potential zones in sandstone, limestone and shales rocks of the Damoh district, (MP) central India. Environmental Research 228: 115832, https://doi.org/10.1016/j.envres.2023.115832.

Mokarram, M., Negahban, S., Abdeldjalil, B. (2021): GIS-based fuzzy-analytic network process (FAHP), fuzzy-analytic hierarchy process (FANP) methods and feature selection algorithm (FSA) to determine earthquake-prone areas in Kermanshah Province. Environmental Earth Sciences 80: 633, https://doi.org/10.1007/s12665-021-09934-7.

Mondal, M., Haldar, S., Biswas, A., Mandal, S., Bhattacharya, S., Paul, S. (2021): Modeling cyclone-induced multi-hazard risk assessment using analytical hierarchical processing and GIS for coastal West Bengal, India. Regional Studies in Marine Science 44: 101779, https://doi.org/10.1016/j.rsma.2021.101779.

Mushtaq, F., Farooq, M., Tirkey, A. S., Sheikh, B. A. (2023): Analytic Hierarchy Process (AHP) Based Soil Erosion Susceptibility Mapping in Northwestern Himalayas: A Case Study of Central Kashmir Province. Conservation 3(1), 32–52, https://doi.org/10.3390/conservation3010003.

Okoli, J., Nahazanan, H., Nahas, F., Kalantar, B., Shafri, H. Z. M., Khuzaimah, Z. (2023): High-Resolution Lidar-Derived

DEM for Landslide Susceptibility Assessment Using AHP and Fuzzy Logic in Serdang, Malaysia. Geosciences 13(2): 34, https://doi.org/10.3390/geosciences13020034.
Olaya Calderon, L. J., Cocuccioni, S., Romagnoli, F., Atun, F., Pittore, M., Schneiderbauer, S., van Westen, C., Sliuzas, R., Armas, I., Mocanu, R., and Kundak, S. (2024): Analysing historical disasters to support multi-hazard risk assessment: enhancing forensic analysis through Impact Chains, EGU General Assembly 2024, Vienna, Austria, 14–19 Apr 2024, EGU24-10177, https://doi.org/10.5194/egusphere-egu24-10177.
Olii, M. R., Olii, A., Pakaya, R., Olii, M. Y. U. P. (2023): GIS-based analytic hierarchy process (AHP) for soil erosion-prone areas mapping in the Bone Watershed, Gorontalo, Indonesia. Environmental Earth Sciences 82(9), 1–14, https://doi.org/10.1007/s12665-023-10913-3.
OpenAI. (2023): ChatGPT: Language Models for Drafting Assistance. OpenAI, Available at: https://chat.openai.com/.
Ozegin, K., Ilugbo, S., Ogunseye, T. (2023): Groundwater exploration in a landscape with heterogeneous geology: an application of geospatial and analytical hierarchical process (AHP) techniques in the Edo north region, in Nigeria. Groundwater for Sustainable Development 20: 100871, https://doi.org/10.1016/j.gsd.2022.100871.
Park, S., Son, S., Han, J., Lee, S., Kim, J. (2018): Groundwater vulnerability assessment using an integrated DRASTIC model using frequency ratio and analytic hierarchy process in GIS. In Proceedings of the EGU General Assembly Conference Abstracts, Vienna, Austria, 4–13 April 2018.
Pham, Q. B., Achour, Y., Ali, S. A., Parvin, F., Vojtek, M., Vojteková, J., Al-Ansari, N., Achu, A., Costache, R., Khedher, K. M. (2021): A comparison among fuzzy multi-criteria decision making, bivariate, multivariate and machine learning models in landslide susceptibility mapping. Geomatics, Natural Hazards and Risk 12(1), 1741–1777, https://doi.org/10.1080/19475705.2021.1944330.
Pham, B. T., Bui, D. T., Prakash, I., Indrajit, I., and Revhaug, I. (2021): GIS-based multi-hazard susceptibility assessment in Central Vietnam. Natural Hazards 105(3), 3113–3140.
Piao, Y., Lee, D., Park, S., Kim, H. G., Jin, Y. (2022): Multi-hazard mapping of droughts and forest fires using a multi-layer hazards approach with machine learning algorithms. Geomatics, Natural Hazards and Risk 13(1), 2649–2673, https://doi.org/10.1080/19475705.2022.2128440.
Rehman, A., Song, J., Haq, F., Ahamad, M. I., Sajid, M., Zahid, Z. (2021): Geo-physical hazards microzonation and suitable site selection through multicriteria analysis using geographical information system. Applied Geography 135: 102550, https://doi.org/10.1016/j.apgeog.2021.102550.
Rehman, A., Song, J., Haq, F., Mahmood, S., Ahamad, M. I., Basharat, M., Mehmood, M. S. (2022): Multi-hazard susceptibility assessment using the analytical hierarchy process and frequency ratio techniques in the Northwest Himalayas, Pakistan. Remote Sensing 14(3), 554, https://doi.org/10.3390/rs14030554.
Richardson, S. D., Reynolds, J. M. (2000): An overview of glacial hazards in the Himalayas. Quaternary International 65, 31–47, https://doi.org/10.1016/S1040-6182(99)00035-X.
Saaty, T. L. (2008): Decision making with the analytic hierarchy process. International Journal of Services Sciences 1(1), 83–98, https://doi.org/10.1504/IJSSCI.2008.017590.
Saifi, S., Turner B., John, T. (2022): Over 900 killed by Pakistan monsoon rains and floods, including 326 children. CNN, August 24, 2022.
Sangha, K. K., Evans, J., Edwards, A., Russell-Smith, J. (2019): Measuring environmental losses from natural disasters: A case study of costing bushfires in the Northern Territory. Australian Journal of Emergency Management 34(4), 31–39.
Scapozza, C., Bartelt, P. (2003): Triaxial tests on snow at low strain rate. Part II. Constitutive behaviour. Journal of Glaciology 49(164), 91–101, https://doi.org/10.3189/172756503781830890.
Scapozza, C., Ambrosi, C., Cannata, M., Strozzi, T. (2019): Glacial lake outburst flood hazard assessment by satellite Earth observation in the Himalayas (Chomolhari area, Bhutan). Geographica Helvetica 74(1), 125–139, https://doi.org/10.5194/gh-74-125-2019.
Schmidt, M. (2008): Land use, land administration and land rights in Shigar, Baltistan. In Modern Ladakh, 241–266. Brill, https://doi.org/10.1163/ej.9789004167131.i-313.90.
Seong, Y. B., Bishop, M. P., Bush, A., Clendon, P., Copland, L., Finkel, R. C., Shroder, J. F. (2009): Landforms and landscape evolution in the Skardu, Shigar and Braldu valleys, central Karakoram. Geomorphology 103(2), 251–267, https://doi.org/10.1016/j.geomorph.2008.04.026.
Shekar, P. R., Mathew, A. (2023): Assessing groundwater potential zones and artificial recharge sites in the monsoon-fed Murredu river basin, India: An integrated approach using GIS, AHP, and Fuzzy-AHP. Groundwater for Sustainable Development 23: 100994, https://doi.org/10.1016/j.gsd.2023.100994.
Shrestha, H. L., Poudel, N. S., Bajracharya, R. M., Sitaula, B. K. (2019): Mapping and Modelling of Land Use Change in Nepal. Journal of Forest and Livelihood 18 (1), 39–53, https://doi.org/10.3126/jfl.v18i1.59621.
Shroder, Jr., Owen, J. F., Seong, L. A., Bishop, Y. B., Bush, M. P., Caffee, A., Kamp, U. (2011): The role of mass movements on landscape evolution in the Central Karakoram: Discussion and speculation. Quaternary International 236(1–2), 34–47, https://doi.org/10.1016/j.quaint.2010.05.024.
Ujjwal, K., Garg, S., Hilton, J., Aryal, J., Forbes-Smith, N. (2019): Cloud Computing in natural hazard modeling systems: Current research trends and future directions. International Journal of Disaster Risk Reduction 38: 101188, https://doi.org/10.1016/j.ijdrr.2019.101188.
Upwanshi, M., Damry, K., Pathak, D., Tikle, S., Das, S. (2023): Delineation of potential groundwater recharge zones using remote sensing, GIS, and AHP approaches. Urban Climate 48: 101415, https://doi.org/10.1016/j.uclim.2023.101415.
Usman, M. (2016): A study on the enhancing earthquake frequency in northern Pakistan: is the climate change responsible? Natural Hazards 82, 921–931, https://doi.org/10.1007/s11069-016-2226-z.

Van Westen, C. J. (2000): The modelling of landslide hazards using GIS. Surveys in geophysics 21(2), 241–255, https://doi.org/10.1023/A:1006794127521.

Wang, S. W., Munkhnasan, L., Lee, W.-K. (2021): Land use and land cover change detection and prediction in Bhutan's high altitude city of Thimphu, using cellular automata and Markov chain. Environmental Challenges 2: 100017, https://doi.org/10.1016/j.envc.2020.100017.

Ward, P. J., Blauhut, V., Bloemendaal, N., Daniell, J. E., de Ruiter, M. C., Duncan, M. J., Emberson, R., Jenkins, S. F., Kirschbaum, D., Kunz, M. (2020): Natural hazard risk assessments at the global scale. Natural Hazards and Earth System Sciences 20(4), 1069–1096, https://doi.org/10.5194/nhess-20-1069-2020.

Ward, P. J., Jongman, B.,Weiland, F. S., Bouwman, A., van Beek, R., Bierkens, M. F., … and Winsemius, H. C. (2020): Strong influence of El Niño Southern Oscillation on flood risk around the world. Proceedings of the National Academy of Sciences, 117(37), 22952–22958.

Yang, L., Luo, W., Zhao, P., Zhang, Y., Kang, S., Giesy, J. P., Zhang, F. (2021): Microplastics in the Koshi River, a remote alpine river crossing the Himalayas from China to Nepal. Environmental Pollution 290: 118121, https://doi.org/10.1016/j.envpol.2021.118121.

Yao, Y., Khan, A. Z. (2022): Predicting Pakistan's next flood. Science 378 (6619), https://doi.org/10.1126/science.ade7824.

Youssef, A. M., Pourghasemi, H. R. (2021): Landslide susceptibility mapping using machine learning algorithms and comparison of their performance at Abha Basin, Asir Region, Saudi Arabia. Geoscience Frontiers 12(2), 639-655, https://doi.org/10.1016/j.gsf.2020.05.010.

Zhou, S., Chen, G., Fang, L., Nie, Y. (2016): GIS-based integration of subjective and objective weighting methods for regional landslides susceptibility mapping. Sustainability 8(4): 334, https://doi.org/10.3390/su8040334.