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Research Article

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Ecological risk assessment of geohazards in Natural World Heritage Sites: an empirical analysis of Bogda, Tianshan

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Abstract: Ecological risk assessment plays an important role in avoiding disasters and reducing losses. Natural world heritage site is the most precious natural assets on earth, yet few studies have assessed ecological risks from the perspective of world heritage conservation and management. A methodology for considering ecological threats and vulnerabilities and focusing on heritage value was introduced and discussed for the Bogda component of the Xinjiang Tianshan Natural World Heritage Site. Three important results are presented. (1) Criteria layers and ecological risk showed obvious spatial heterogeneity. Extremely high-risk and high-risk areas, accounting for 13.60% and 32.56%, respectively, were mainly gathered at Tianchi Lake and Bogda Glacier, whereas the extremely low-risk and low-risk areas, covering 1.33% and 17.51% of the site, were mainly distributed to the north and scattered around in the southwest montane region. (2) The level of risk was positively correlated with the type of risk, and as the level of risk increases, the types of risk increase. Only two risk types were observed in the extremely low-risk areas, whereas six risk types were observed in the high-risk areas and eight risk types were observed in the extremely high-risk areas. (3) From the perspective of risk probability and ecological damage, four risk management categories were proposed, and correlative strategies were proposed to reduce the possibility of ecological risk and to sustain or enhance heritage value.

Keywords: geohazards risk assessment, Natural World Heritage Sites, risk distribution, risk management, Bogda

1 Introduction

Over recent decades, conceptual approaches to risk have undergone considerable paradigm shifts from environmentally deterministic, hazard-centric approaches [1] to political economy and political ecology perspectives [2–4], and finally to holistic concepts that integrate and connect social, economic, political, environmental and governance-related drivers of disaster risk [1, 5–7]. Despite the tendency of ecological risk for complexity and diversification, risk is understood as the probability that ecosystems are affected by adverse impacts resulting from anthropogenic activities and unavoidable natural events and are defined as a product of hazard and vulnerability [8–12]. Ecological risk assessment (ERA) is a powerful technical tool that can be used to assess the potential adverse impacts that may occur or are occurring as a result of exposure to stressors in a given research area [10, 11]. From the concept of risk, the majority of the existing ERA research focuses on two categories: a “potential” for producing a disaster (*i.e.*, hazard) and the susceptibility of exposure to the hazard (*i.e.*, vulnerability) [10]; the hazard is the external source of a disaster, and the vulnerability is the inherent weakness [10]. However, the resources used for ecological risk response recovery actions are usually limited, and a more realistic risk assessment must consider the risk receptors to meet the needs for protection and management of a specific area. Therefore, with the aim of obtaining quantitative results reflecting a wide range of potential impacts, we may consider that risk could be expressed as the convolution of hazard, vulnerability and ecological damage.

Natural World Heritage Sites (NWHSs) are recognized as the most valuable natural assets with Outstanding Universal Value (OUV) that transcend national boundaries

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and are worth conserving for humanity as a whole [13–15]. A natural World Heritage site must meet at least one of four criteria, which, in summary, relate to natural phenomena or aesthetic importance, geology, ecosystems or biodiversity [13]. Geological values include the record of life, significant ongoing geological processes, or significant geomorphic or physiographic features, and ecological and biological values include significant ongoing ecological and biological processes of ecosystems, communities of plants and animals, natural habitats and threatened species [13]. Aesthetic values include superlative natural phenomena or areas of exceptional natural beauty and aesthetic importance. The formation of aesthetic value is widely believed to involve unique geological and geomorphological features, typical of rich ecosystem types or habitats of rare and endangered species [16–19]. In total, 145 NWHSs have been designated as such according to their aesthetic values, and these include ten landscape types, including lakes, waterfalls, coastline, panorama, geology/geomorphology, desert, mountain, forest, meteorology and wildlife [20]. NWHSs display beautiful scenery and realize sustainable development through ecotourism; hence, tourism attributes also were taken into consideration when the aesthetic value of a specific site was evaluated. Tourism resources have been used to measure aesthetic value in the Tomur World Natural Heritage site [16]. Atmospheric phenomena, tourist environment and mountain massif, water body, vegetation, and animals were used to evaluate the aesthetic value of Kanas [21].

However, as one of the most serious problems, geological hazards, such as earthquakes, rockfall and landslides have already caused detrimental effects on NWHSs [22–25], threatened their integrity and compromised values, and pose significant ecological risks. By combining open-source global risk data with risk awareness from the United Nations Educational, Scientific and Cultural Organization periodic reports, Pavlova *et al.* identified 60% of the sites on the World Heritage list as being exposed to at least one geological disaster [22]. To minimize these consequences and achieve sustainability, ecological risk assessment can analyse potential and extreme adverse impacts that can be caused by geohazards, making ERA a powerful technical tool [26–28]. Until now, however, little research has attempted to build ecological risk assessment frameworks oriented to heritage values protection in Natural World Heritage Sites.

Xinjiang Tianshan was added to the World Heritage List in 2013 for its outstanding biodiversity and aesthetic values [29]. Xinjiang Tianshan is a serial heritage site, consisting of four components, namely, Bogda, Kalajun-Kuerdening, Bayinbuluke, and Tomur. As the representative of the north Tianshan Mountains, the Bogda component is facing great challenges in the prevention and control of geohazards. As a result of the complex topography, the action of rainwash, gravitational forces and human impacts, geohazards, mainly rockfall, landslides and debris flows, pose serious disadvantages to the development of heritage sites and safety for tourism [30, 31]. The Bogda component is urgently in need of an ecological risk assessment to protect its OUV from geological hazards that can cause further destruction of the integrity, which would compromise these values. Therefore, establishing a quantitative risk assessment of geohazards is important to achieving sustainable development goals in Bogda.

The Bogda component was selected as the study area for the geohazards ecological risk assessment. A methodology that considers the ecological threats to and vulnerabilities of mountain ecosystems and focuses on the heritage value is introduced and discussed, which will enrich the study method of ecological risk assessment in a specific region. This methodology allows the communication and visualization of risk to relevant decisionmakers and stakeholders, which has practical significance to guide the regional ecosystem protection and promote disaster risk reduction.

2 Materials and Methods

2.1 Study area

Bogda is in Fukang County and Urumqi City, Xinjiang, China (central coordinates: N43°50’00" E88°17’12"), with a total area of 38,739 ha and a buffer zone of 41,547 ha (Figure 1). The topography gradually increases from north to south. The elevation is between 1380 and 5445 m, with the largest relative relief reaching 4065 m [29, 32]. Bogda belongs to the continental temperate climate zone. It is a wet island in the centre of the desert in an arid area. The annual average temperature is 2.5°C. The annual average precipitation is 444 mm, which is concentrated in April to September.

Bogda is in the southern part of the Central Asia Orogenic Belt and is formed by the Bogda syncline of the North Tianshan Mountains fold belt. The main body of the Bogda Mountains is formed by carboniferous, as well as volcanic and volcaniclastic, sedimentary basements, with all flanked by Mesozoic and Cenozoic sediments on the northern and southern sides [33, 34]. Shallow marine carbonates, volcanic clastic rock and terrigenous clastic rock are broadly distributed in the Bogda area, accounting for

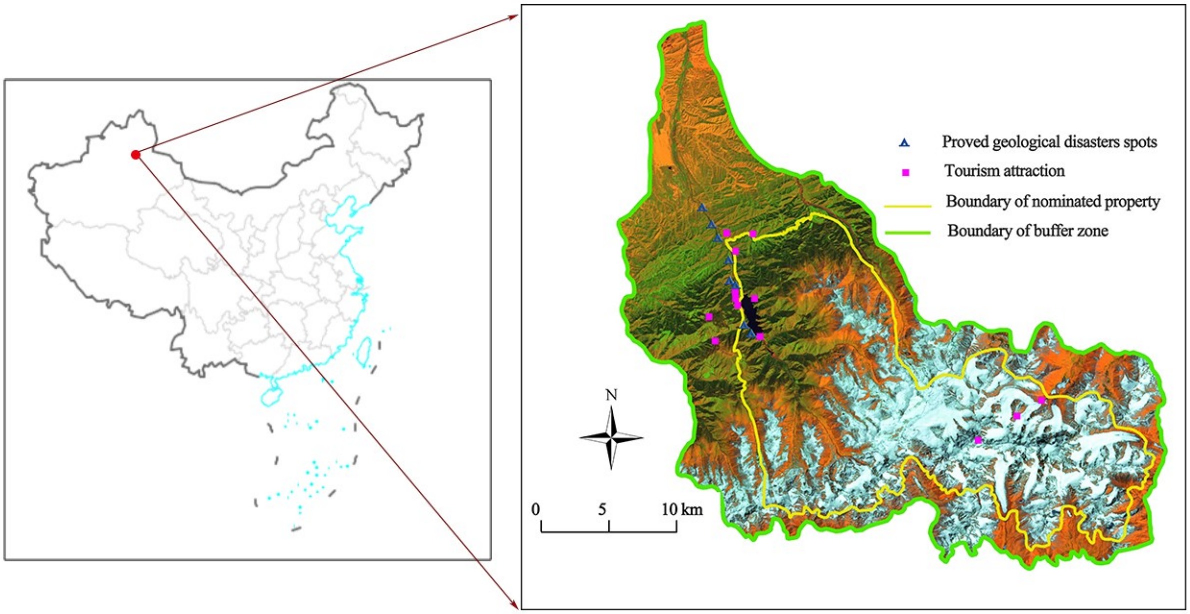

Figure 1: Location of Bogda

60% of the total area [29]. The topography has been uplifted, and large mountain junction zones and ridges have formed. These mountains and ridges are characterized by alpine areas covered with ice and snow and middle mountain zones composed of valleys and glacial relicts. In the plain area in front of the mountain, Quaternary siltstones and gravels have been deposited, and alluvial landforms have developed.

The heritage values of Bogda are summarized as follows [29, 35]: (1) Bogda is the most typical representative of vertical mountain zones in the world's temperate arid zones. (2) Bogda is a typical representative of mountain glacier close to an extremely dry climate in the mid-temperate zones. Its ecology and hydrology are probably the most sensitive indicator of climate change in the world's arid regions. (3) The Bogda component contains the most typical alpine lakes in Xinjiang Tianshan.

2.2 Data Source and Pre-processing

To evaluate the risk of geological hazards in Bogda, a database was established that includes the material declarations for Xinjiang Tianshan NWHS, DEM data, remote sensing data of Landsat-8 OLI, meteorological data, and Earthquake location data. All layers maintained the same geographic extent, coordinate system and cell size (WGS_1984_UTM_45N, 30× 30 m).

The material declaration for Xinjiang Tianshan NWHS contained the Bogda nomination text and spatial information on the river, road, fault, scenic spots, communities and vegetation type of the study area.

DEM data, with a resolution of 30 m, were obtained from the Geographic Data Cloud. Elevation information was included in the DEM data, and slope was extracted from DEM data with ArcGIS 10.5.

Landsat-8 OLI image was downloaded on 2016-07-28 from the USGS (https://glovis.usgs.gov). The satellite data were selected in growing season, as it is the best time to represent land surface vegetation cover. To convert the digital number of the raw images to top-of-atmosphere reflectance and reduce the deviations caused by light and atmosphere, radiometric calibration and atmospheric correction were carried out with ENVI 5.3. Then, the Normalized Difference Vegetation Index (NDVI) was obtained from the processed image as follows:

$$\mathrm{NDVI} = (b_{\mathrm{NIR}} - b_{\mathrm{Red}})/(b_{\mathrm{NIR}} + b_{\mathrm{Red}}) \qquad (1)$$

where b_{NIR} and b_{Red} are the reflectance of the near-infrared and red band of the Landsat 8 OLI image.

The national land use classification system was referenced, and the land type distribution characteristics were considered, with the landscape being categorized into the following types: forest, grassland, bare exposed rock or gravel, glacier and perennial snowfield, water bodies, cropland, and construction land. Landscape pattern indices were calculated with FRAGSTAT 4.2 software.

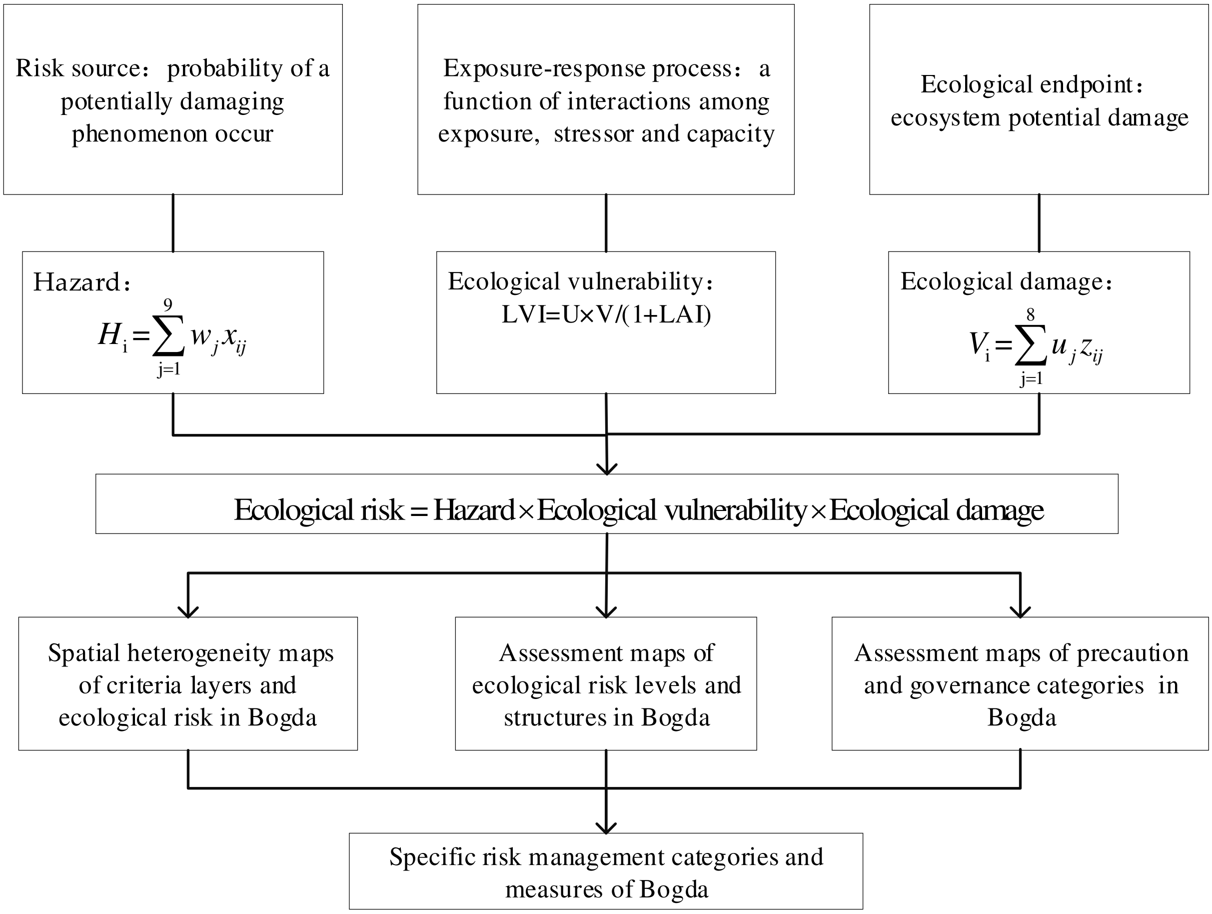

Figure 2: Flow Chart of ERA in Bogda

The annual mean precipitation data from 1985 to 2015 were provided by the Data Centre for Resources and Environmental Sciences, Chinese Academy of Sciences (http://www.resdc.cn). Earthquake location data from 2012 to 2018 were provided by the China Earthquake Networks Centre (http://www.ceic.ac.cn).

2.3 Methodology

2.3.1 Ecological risk assessment model

A three-dimensional framework for ecological risk assessment was constructed (Figure 2) while considering the cause–effect relationship, identified risk source, exposure-response process and ecological endpoint. The hazard focused on disaster-inducing factor, reflecting the threat of geographical and geological conditions and human activities. Vulnerability, a function of interactions among susceptibility factors to exposure, sensitivity to the stressor, and adaptive capacity, was established as a link between risk stressor and risk receptor, and characterized by the landscape pattern [36–38]. From the perspective of protection and management, heritage values can be viewed as the risk receptor, and meanwhile, these values can be used as a tool for weighting the potential damage in NWHS protection [16, 35].

According to the assessment of hazard, vulnerability and heritage values, the risk assessment is calculated based on the following formula:

$$R = H \times V \times E \tag{2}$$

where R, H, V and E represent risk, hazard, vulnerability and heritage value, respectively.

2.3.2 Criteria Layers in ecological risk assessment

(1) Hazards in ecological risk assessment

This study focused on sudden geological disasters, such as rockfall, landslide and debris flow, which were caused

Table 1: Summary of hazard indices processing and weight in Bogda

Project layer	Index layer	Processing	Weight
Geographical environment	Elevation	Extracting from DEM data, and normalized with formula (3).	0.1586
	Slope	Extracting from DEM data, and normalized with formula (3).	0.1609
	Annual mean precipitation	normalized with formula (3).	0.1516
	NDVI	Extracting from Landsat-8 TM data with formula (1), and normalized with formula (4).	0.1182
	Distance to river	A multi-buffer ring of rivers is created, and normalized with formula (4).	0.0304
Geologic structure	Earthquake density	Kernel density of earthquake points is created, and normalization with formula (3).	0.0709
	Distance to fault lines	Euclidean distance of fault lines is created, and normalization with formula (3).	0.0689
Human activity	Distance to Community	Euclidean distance of community is created, and normalization with formula (3).	0.0993
	Distance to road	A multi-buffer ring of roads is created, and normalized with formula (4).	0.1322

by broken rock fragments and loose solid materials. Rockfall is the natural downward motion of blocks involving free falling, rolling, and sliding, and rockfall events are mainly distributed along the S111 road, Feilongjian and Haixi. Landslides occur when the slope undergoes some processes that change its condition from stable to unstable. Rainfall and water erosion made a major impact on the slope instability in Bogda. Debris flows are geological phenomena in which water-laden masses of soil and fragmented rock rush down mountainsides, funnel into stream channels, and form thick, muddy deposits on valley floors. There are 11 active debris flows channels in Bogda, including Laogan valley, Duolong valley, Huaer valley, Wuguan valley, *et al.* According to the Geological Disaster Special Investigation Report in Tianchi and related literatures [30, 31], active tectonics, topography, meteorological, hydrological conditions and damage to the mountain structure for road construction provided suitable endogenic and exogenic conditions for the occurrence of rockfall, landslide and debris flow in Bogda. Therefore, the hazard was assessed according to a combination of the geographical environment, geologic structure and human activity. The geographical environment focused on the stability of disaster-inducing conditions, elevation, slope, annual mean precipitation, NDVI and distance to the river were used to delineate the study area according to the topography, physiognomy, vegetation, meteorology, and hydrology. The increase in the weight by the rainwater, the loss of internal cohesion, and the geometry of the slope (steepness, morphology, height, etc.) lead to destabilization and trigger gravitational mass movement (soil, rock, or debris). As a basic geomorphic indicator, elevation and slope were mostly used to estimate erosion, surface runoff, and landscape [27, 39, 40]. The infiltration of rainwater increased the soil saturation, sharply dropping absorption and causing a substantial decline in shear strength. The loss of stability of the slope material can occur through infiltration and water concentration. Vegetation and water flow were the factors with the greatest effect on soil erosion and slope stability. Vegetation enhances the soil shear strength via a series of mechanical and hydrological effects [27, 39, 41], and NDVI, which indicates the land surface vegetation cover, has been widely used as an influencing factor when quantifying the probability of geodisasters [41–43]. Distance to a river reflects the influence of water flow using simplified representation space from major rivers. Active tectonics play an important role in the occurrence of earthquakes, and the secondary effects of the earthquake will affect specific areas. Therefore, geologic structures were evaluated by earthquake density and the distance to fault lines. Road construction and community development affected the stability of the slopes and the structure of the rock and soil. When the availability of data was considered, the distance to community and the distance to road were selected to describe the effects of human activity.

Before calculation, each index (x_i) was normalized to the same order of magnitude (0-1). For those indices with

Table 2: Selected landscape metrics used in assessing vulnerability

Indicator	Calculation	Landscape ecological significance
Interference degree of landscape (U)	$U = a * FN + b * FI + c * FD$	Interference degree of landscape indicates the degree of loss after the area is disturbed.
Fragmentation (FN)	$FN = MPS \times (N_f - 1)/N_c$	Fragmentation indicates the degree to which a certain landscape is fragmented at a certain period of time, and it can also reflect somewhat the human interference to the landscape. Fragmentation indicators include [0, 1], where 0 indicates the landscape has not been destroyed at all, and 1 implies the landscape has been completely destroyed.
Isolation of landscape (FI)	$FI = \frac{1}{2}\sqrt{\frac{n}{A}} \times \frac{A_i}{A}$	Isolation refers to the separate degree of the different elements or patches in the landscape. It may indicate the impact on landscape structure by human activities to a certain extent. The scatter and instability of the landscape are increased with the increase in isolation.
Reciprocal of fractal dimension (FD)	$FD = \frac{1}{21 \ln(P/4) \log A}$	The fractal dimension of the landscape, which is calculated in terms of the relationship between area and circumference, indicates the complexity of the landscape shape and the spatial stability of the landscape. The more closely the value of the fractal dimension approximates 1, the simpler and more measurable the geometric shape of the patch tends to be. This suggests that the human disturbance is more severe.
Landscape vulnerability (V)	Experts knowledge acquired	Bare-rock areas, glaciers, water bodies, low coverage meadow, medium and high coverage meadow, forest, agricultural areas and construction areas are assigned to 8, 7, 6, 5, 4, 3, 2, and 1, respectively.
Landscape adaptation index (LAI)	$LAI = PRD + SHDI + SHDI$	LAI, which was determined by referencing the research of others, was constituted with the patch richness index, the Shannon diversity index and the Shannon evenness index.
Patch richness index (PRD)	$PRD = m/A$	PRD is the number of patches per unit area; it reflects the dispersion of patches in a landscape type.
Shannon diversity index ($SHDI$)	$SHDI = -\sum_{i=1}^{m}(p_i * \ln p_i)$	Shannon's diversity index is a measure of diversity in landscapes. The index equals 1 when distribution of area among patch types is perfectly even.
Shannon evenness index ($SHEI$)	$SHEI = \frac{\sum_{i=1}^{m}(p_i * \ln p_i)}{-\ln m}$	Shannon's evenness index is expressed such that an even distribution of area among patch types results in maximum evenness.

Explanation: where MPS is got by the average area of all patches divided by the minimum patch area in landscapes; N_f is the total number of patch for certain landscape type; N_c is the ratio of the whole area of landscape to the area of minimum patch; n counts for the element of the landscape type; A_i is the area of i kind of landscapes; A stands for the total area of the case study; P is the patch circumference; m counts for the element of the landscape type; p_i is the proportional coverage of landscape "i".

Table 3: Criterion and weights for assessing heritage values of Bogda component

Criterion	Index	Standard of classification	Weight
Biological and ecological value	Forest	Forests are 1, shrub are 0.6, and others are 0.	0.2688
	Grassland	The high, medium, and low coverage grasslands are 1, 0.8, and 0.6, respectively, and others are 0.	0.0565
	Biodiversity	The area with more abundant vegetation has a higher biodiversity, which will be assigned a higher value by the experts; the value will be assigned from 0-1.	0.1748
Geological value	Lakes	Lakes are 1, and others are 0.	0.1089
	Glaciers	Glaciers are 1, and others are 0.	0.0392
	Geological site	The closer it is to a geological site, the higher value assigned, with the highest value of 1.	0.0909
Aesthetic value	Visibility	Visible areas are 1, and others are 0	0.0707
	Scenery	The scenic spots that are better-known will be assigned higher values by the experts, the value will be assigned from 0-1.	0.1902

positive correlations with ecological hazard, the equation is expressed as follows:

$$X_i = [x_i - \min(x_i)] / [\max(x_i) - \min(x_i)] \tag{3}$$

In contrast, for those indices with negative correlations, the equation is:

$$X_i = [\max(x_i) - x_i] / [\max(x_i) - \min(x_i)] \tag{4}$$

where the value of criterion *j* in any position *i* in the space is X_{ij}, and the weight of criterion *j* is Wj; the hazard for ERA in Bogda is expressed as follows:

$$H_i = \sum_{j=1}^{9} w_j X_{ij} \tag{5}$$

where H_i is the hazard at position *i* in the space. The entropy was used to assess the discrete degree of any individual index.

(2) Ecological vulnerability in risk assessment

Vulnerability reflects the persistent influence of a disturbance on an ecosystem. Landscape patterns, which refer to the arrangement and combination of landscape elements in space, are concrete reflections of a landscape's spatial heterogeneity, as well as a result of various ecological processes [44, 45]. From the perspective of landscape, a vulnerability model was constructed that followed the susceptibility to the exposure sensitivity and stressor adaptive capacity of the framework. Vulnerability of risk can be measured as follows [46–49]:

$$LVI = U \times V / (1 + LAI) \tag{6}$$

where LVI is the landscape vulnerability index, U is the interference degree of landscape types, V is landscape vulnerability, and LAI is landscape adaptation index.

(3) Ecological damage in risk assessment

The core of the NWHS designation is heritage values [13], which are used as a receiver to ecological processes and ecological risk sources and represent the possibility of the negative effects from the disturbance by the risk stressors. Heritage criteria comprising biological and ecological values, geological value and aesthetic value formed the basis of the heritage value of Bogda. Indicators for all criteria were generated in consideration of the characteristics of Bogda, namely, forest, grassland, biodiversity, glacier, lake, geological site, scenery and visibility [29, 35, 50–52]. Expert knowledge was used to explore the weight of each indicator with the AHP process, and a weighted linear combination model was implemented in the GIS environment to combine all layers to generate a heritage value map in Bogda. When the value of index *j* in any position *i* in the space is z_{ij}, and the weight of index *j* is μ_j, then the model for heritage value (V_i) is expressed as follows:

$$V_i = \sum_{j=1}^{8} u_j z_{ij} \tag{7}$$

2.3.3 Risk level and type

The hazard, vulnerability, damage and risk values were calculated using formulas and relevant data. The values were reclassified into five grades (*i.e.*, extremely low, low, medium, high and extremely high) using the natural breaks method to display the level and spatial distribution in criteria and risk.

For further study of risk, the extremely low, low and medium areas of each criteria layers (hazard, vulnerability and damage) were merged into the low-value zone, the extremely high and high areas were merged into the high-value zone. Based on the combination of hazard, vulnerability and damage in different degrees, the risk was categorized into eight types (*i.e.*, Low-Low-Low, Low-Low-High, Low-High-Low, Low-High-High, High-Low-Low, High-Low-High, High-High-Low, High-High-High). “High-High-Low”, as an illustration, is the area with high hazard, high vulnerability and low ecological damage.

2.3.4 Risk management zoning

Risk precaution refers to dividing risk management categories based on ecological risk assessment to provide visual and intuitive support for targeted risk precaution. Ecological damage, as the endpoint in ERA, reflects the state of ecosystem receptors under the interference and stress of geohazards. In addition, heritage values are at the core of NWHS designation, and aesthetic, geological, ecological, and biological characteristics are the criteria for the nomination of an NWHS [13]. Therefore, risk management should include the risk probability and should focus on reducing the risk damage; that is, it should protect the heritage value from geohazards and provide more targeted preventive measures to promote the sustainable development of NWHS. The risk management categories from the perspective of the dominant risk factor and heritage value were useful in an exploration of the study area. Four ecological risk management categories were proposed as follows: protected and recovery zones, natural regulation zones, avoidance and reserve zones and monitoring and early warning zones. Protected and recovery zones were areas with low risk probability and low heritage value. Natural regulation zones were the areas with low risk probability and high heritage value. Avoidance and reserve zones were the areas with high risk probability and low heritage value. Monitoring and early warning zones were the areas with high hazard and/or ecological risk probability and low heritage value.

Table 4: Grades ratio in criteria layers and ecological risk

Grades	Hazard	Vulnerability	Damage	Risk
Extremely high	13.16%	10.48%	2.89%	13.60%
High	28.79%	23.90%	13.38%	32.56%
Medium	25.45%	27.85%	18.39%	34.99%
Low	16.23%	24.96%	40.04%	17.51%
Extremely low	16.37%	12.81%	25.30%	1.33%

3 Results and Discussion

3.1 Spatial Distribution in Criterion Layers

The hazard, vulnerability and damage values were reclassified into five grades of values using the natural breaks method. The area proportion of these five risk categories are shown in Table 4.

From Figure 3, the risk probability reduced gradually from south to north. The hazard was highest in the south-central mountainous area. The region with high and extremely high hazards account for 28.79% and 13.16% of the study area, respectively. These areas were mainly located Bogda Peak, Malu Gully, Dadong Gully and the upper reaches of the Sangong River and Sigong River. High altitude, great gradient and abundant precipitation provided relatively objective disaster-inducing conditions. The areas of extremely low-risk and low-risk probability occupied 16.37% and 16.23% of the study area, respectively, and were mostly located in the north area. The slope of the terrain in the southern area was gentle, which limited the particle motion under gravity action along a certain weak belt or surface, the hazard was reduced, and the geohazard risk probability was low. The central area is the main accumulation region of heritage tourism activities, and road construction was directly related to the risk probability. The stability of loess-covered hillsides was severely damaged by road construction on steep slopes, which led to an increased landslide activity.

Certain spatial correlations existed between the spatial patterns for vulnerability and the status of land use. Areas with extremely high and high vulnerability areas represented 12.81% and 24.96% of the study area, respectively, and mainly were in the alpine area in the southeast and Tianchi Lake in the central area. The regions of extremely low and low vulnerability were mainly in the agricultural areas and construction areas in the northwest and mid mountains at elevations of 1,700-2,800 m, which represented 12.81% and 24.96% of the study area, respectively.

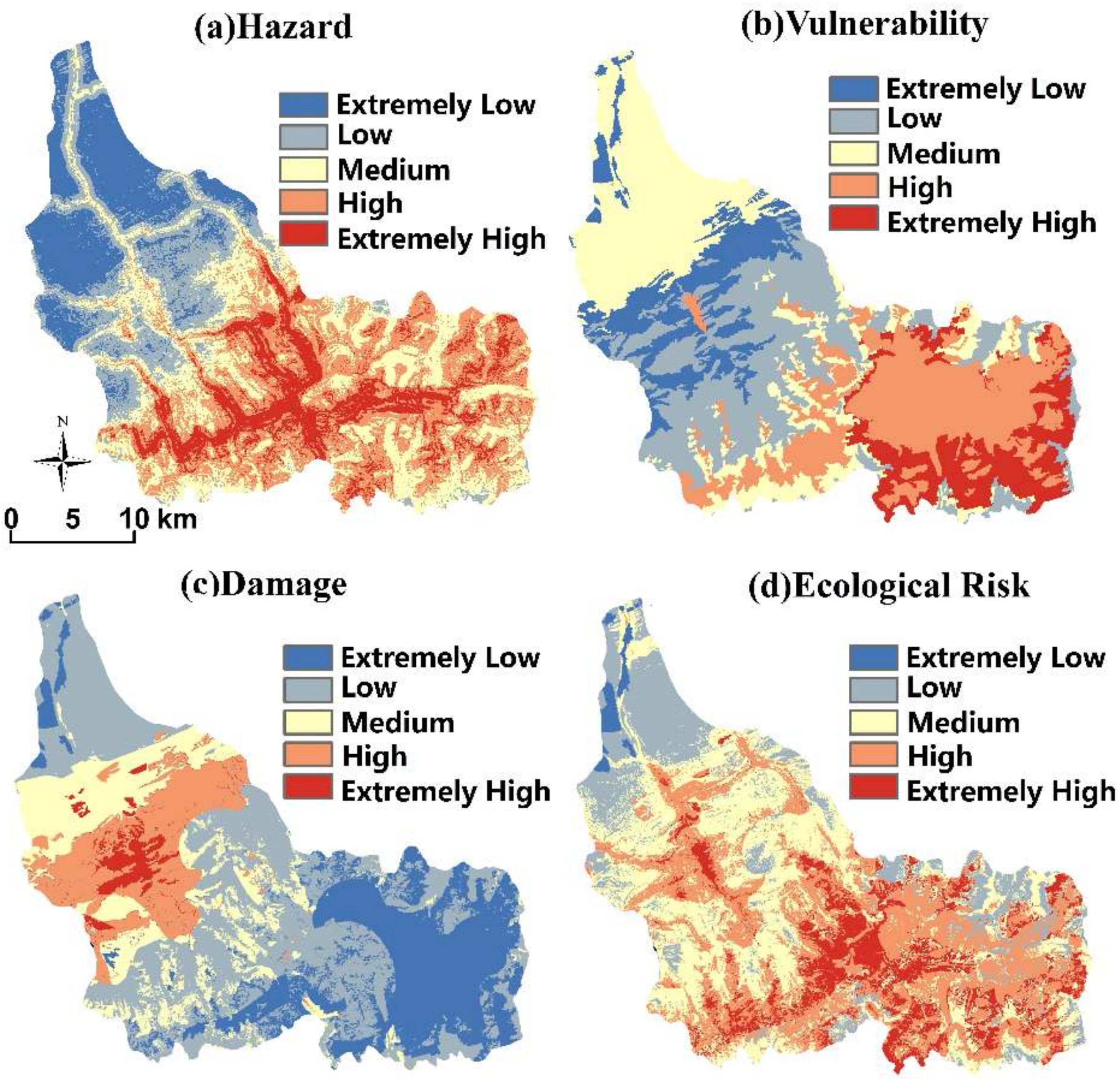

Figure 3: Spatial heterogeneity of criteria layers and ecological risk in Bogda.

The value of ecological damage was highest in the central mountainous area. The region with extremely high and high damage, respectively, account for 2.89% and 13.38% of the study area, and they are mainly concentrated in the tourist area and the middle montane forest belt, which contain abundant biodiversity. Tourism development and biodiversity protection are the most important factors that need to be addressed when geohazards occur. The regions of extremely low and low damage were distributed in the temperate desert in the north and alpine snow zone and alpine cushion vegetation zone in the southeast, which included 25.30% and 40.04% of the study area, respectively.

3.2 Risk distribution and categories

The regions with extremely high and high risk were mainly gathered at Tianchi Lake and Bogda glacier, which accounted for 13.60% and 32.56% of the study area, respectively. The medium-risk areas covered more than 1/3 of the study area and were mainly distributed in the middle of the study area. The extremely low-risk and low-risk areas covered 1.33% and 17.51% of the study area, respectively, and were mainly distributed in the north of the study area and scattered around in the southwest montane region.

When the structural components of the risk at all levels (Figure 4) were compared, the risk types in the extremely low-risk areas are only “Low-Low-Low” and “Low-

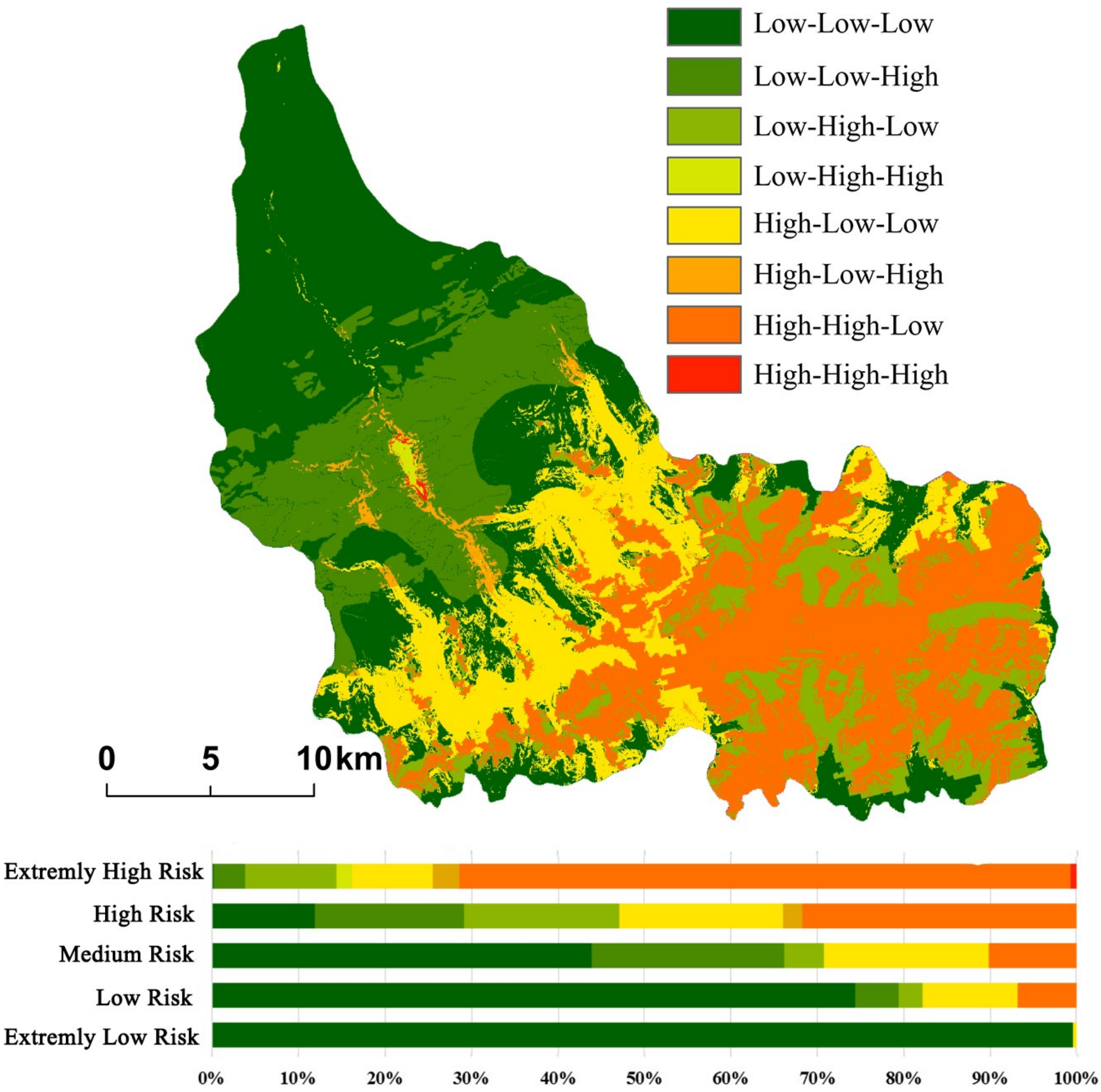

Figure 4: Ecological risk levels and structures in Bogda.

Low-High". "Low-Low-Low", as the main type, accounts for 99.65% of the extremely low-risk areas. Five types of risk occur in the low-risk areas. As the level of risk increases, the types of risk increased. Six risk types were observed in the high-risk areas and medium-risk areas, and the distribution ratio of the various risk structures is relatively uniform. Eight risk types occurred in the extremely high-risk area, and the "High -High-Low" is the main type in the areas for both degrees of risk.

3.3 Risk management categories

Four ecological risk management categories were proposed as follows: protected and recovery zones, natural regulation zones, avoidance and reserve zones and monitoring and early warning zones, each of which account for 44.02%, 13.99%, 40.97% and 1.01% of the study area, respectively.

Protected and recovery zones were distributed in the buffer zone of heritage sites in the north, whereas more were scattered in front of glaciers and bare rocks in the southern region. The ecosystem diversity and resilience of these areas are relatively low, and grazing activities of com-

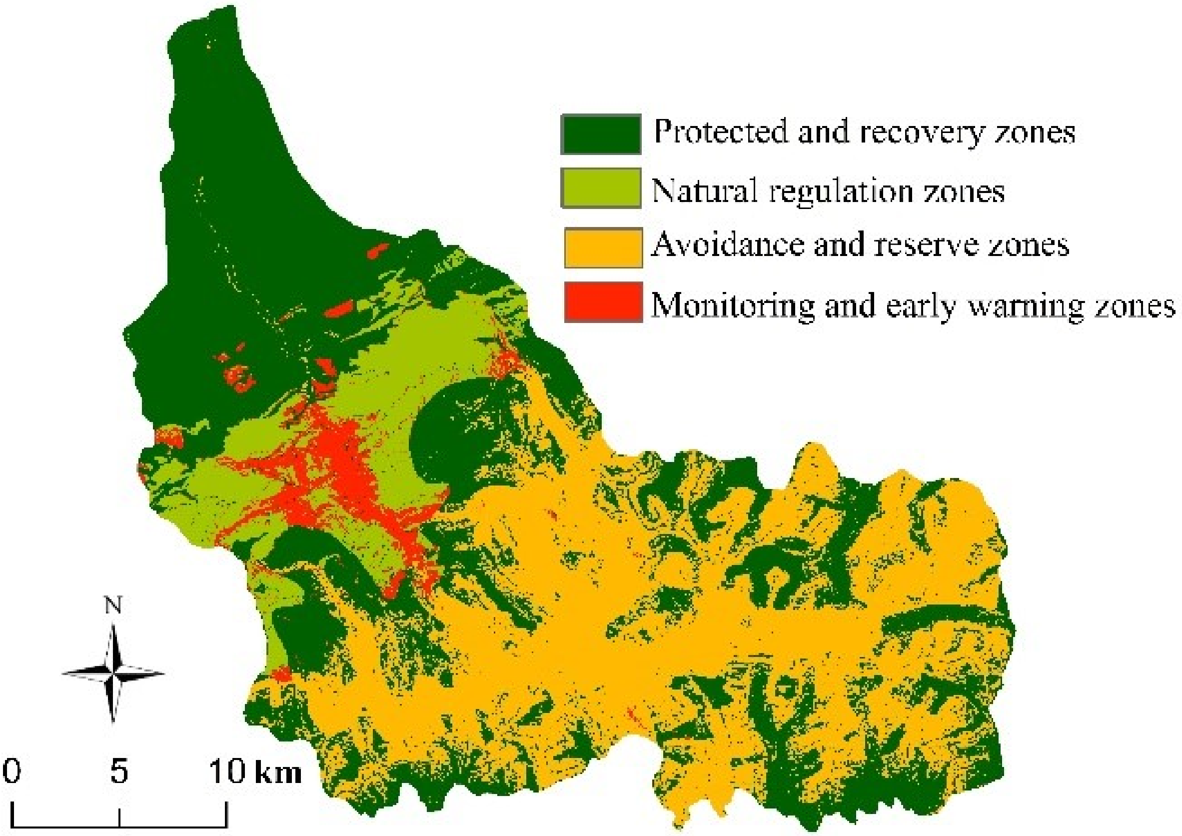

Figure 5: Precaution and governance categories of ecological risk of geohazards in Bogda.

munity residents in the heritage sites are the main factors affecting surface vegetation cover in the region. For protected and recovery zones, risk management should focus on the implementation of the policy of Returning Grazing to Grassland in the region. Under the conditions of reasonable carrying capacity and without affecting ecological protection, appropriate grazing activities should be carried out to ensure the income of community residents and the soil and water conservation in the region.

Natural regulation zones were distributed in the middle of Bogda. Based on the principle of heritage site protection, the areas should be restored by their own resilience. A strict grazing prohibition policy should be implemented to avoid excessive manual intervention affecting the heritage value.

Avoidance and reserve zones were distributed in the southern mountainous and glacier area. For avoidance and reserve zones, the risk receptors exposed to natural disasters and environment stress need to be recognized. Because these areas served as the water source for the rivers and lakes in Bogda, community activities and tourism activities should be avoided in these areas. The number of visitors and the range of activities need to be strictly controlled, and tourists should be prohibited from entering the region where the glaciers are retreating.

Monitoring and early warning zones were concentrated in the main tourist area, including Tianchi Lake, Dahei Gully, Dadong Gully, Xiaodong Gully, etc. Monitoring and early warning zones belong to “hot spots” of risk management, and risk prevention strategies for heritage protection and risk warning should be taken into consideration. Monitoring of geological, hydrological, meteorological and tourism activities should be strengthened, and an investigation of geological hazards should be conducted to recognize the potential disaster spots and endangered range. Engineering measures can be taken to reduce the risk probability of geohazards, thereby protecting the aesthetic value of the heritage site and the safety of visitors.

3.4 Limitations and future research directions

Although the research provided results that give practical guidance for risk management about heritage sites, some problems remain in the actual research that require further perfection and study. For example, (1) assessing disaster risks will become increasingly complex as World Heritage properties experience both the gradual and sometimes catastrophic effects of climate change [10, 53, 54]. Some alterations to natural heritage features cannot be avoided in a changing environment. Therefore, the quantitative threshold indicator for ecological risk assessment in a changing environment remains a challenge, as this relates to the degree of management intervention that is appropriate for a given World Heritage property. (2) Due to the random error [26, 53], the selection of quantification methods and models, incomplete information and data, criteria layers and risk values are inevitably overestimated or underestimated in the ecological risk assessment of geohazards. Future research should focus on sources of ecological risk uncertainty. More attributes of the study area and indicators in risk should be comprehensively considered to ensure that the evaluation results are more reliable, so that decisionmakers can adopt more scientific and effective risk management measures based on the uncertainty degree of the evaluation results.

4 Conclusion

Considering the increasing need for risk evaluations that support informed and balanced decision-making, this estimation of risk is crucial for the effective risk management of natural world heritages in better defining the protection target. A “risk probability-sensitivity-impairment” framework with multiple element indicators and spatialized displays for conducting ecological risk assessments in NWHS was presented, using the Bogda component of the Xinjiang Tianshan Natural World Heritage Site as a case study. From the perspective of risk probability and damage, four risk management categories were proposed, and correlative strategies were offered to reduce the possibility of ecological risk and sustained or enhanced heritage value.

The results were as follows: (1) Criteria Layers and ecological risk showed obvious spatial heterogeneity. The hazard gradually declined from the south to the north, with the high- and extremely high-hazard areas being found mainly at Bogda Peak, Malu Gully, and Dadong Gully in the upper reaches of the Sangong River and Sigong River. Certain spatial correlations were observed between the spatial patterns for vulnerability and the land use status. Areas with extremely high- and high-vulnerability areas are mainly in alpine areas in the southeast and Tianchi Lake in the central. The region with extremely high and high damage were mainly concentrated in the tourist area and the middle montane forest belt, and account for 2.19% and 12.81% of the study area, respectively. High-risk areas were mainly gathered at Tianchi Lake and Bogda glacier, whereas low-risk areas were mainly distributed in north of the study area and scattered around in the southwest montane region. (2) The level of risk is positively correlated with the type of risk, and as the level of risk increases, the type of risk increases. The risk types in extremely low-risk areas are only “Low-Low-Low” and “Low-Low-High”, whereas six risk types exist in high-risk areas and eight risk types exist in extremely high-risk areas. (3) Four ecological risk management categories are proposed. For protected and recovery zones, risk management should focus on the implementation of appropriate grazing activities to ensure the income of community residents and soil and water conservation in the region. Natural regulation zones should be restored by their own resilience, and a strict grazing prohibition policy should be implemented to avoid excessive manual intervention affecting the value of heritage. Community activities and tourism activities should try to avoid avoidance and reserve zones, and the number of visitors and the range of activities need to be strictly restricted. For monitoring and early warning zones, monitoring of geological, hydrological, meteorological and tourism activities should be strengthened to recognize the potential point of disaster and endangered range. Engineering measures should be undertaken if the geohazards threaten the aesthetic value of the heritage site and the safety of visitors.

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