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Vulnerability of glacier change in the Tianshan Mountains region of China

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Abstract: The glacier is a crucial freshwater resource in arid and semiarid regions, and the vulnerability of the glacier change is intimately linked to regional ecological services and socio-economic sustainability. Taking the Tianshan Mountains region in China as an example, a basic framework for studying the vulnerability of glacier change was constructed so as to address factors such as physical geography, population status, socio-economic level, agricultural development, and social services. The framework was based on key dimensions, that is, exposure, sensitivity, and adaptability, and this constituted a targeted evaluation index system. We examined the spatial structure and spatial autocorrelation of the glacier change vulnerability using ArcGIS and GeoDa software. The influence and interaction of natural, social, economic, population and other factors on glacier change adaptability was examined using the GeoDetector model. The results suggested the following: (1) The vulnerability level decreased from the western region to the eastern region with significant differences between the two regions. The eastern region had the lowest vulnerability, followed by the central region, and then western region which had the highest vulnerability. (2) Significant positive and negative correlations were found between exposure, sensitivity, and adaptability, indicating that the areas with high exposure and high sensitivity to glacier change tended to have a low adaptive capacity, which led to high vulnerability, and vice versa. (3) The spatial heterogeneity regarding the ability to cope with glacier change reflected the combined effects of the natural, social, economic, and demographic factors. Among them, factors such as the production value of secondary and tertiary industries, the urban population, urban fixed-asset investment, and the number of employees played major roles regarding the spatial heterogeneity of glacier change.

Keywords: glacier change; vulnerability; adaptability; GeoDetector model; Tianshan Mountains, China

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1 Introduction

The glacier is known as a huge natural "solid reservoir", and serves the dual function of water resource provision and regulation of runoff as is the case in Xinjiang Uygur Autonomous Region, China. On the one hand, the glacial meltwater represents a substantial proportion of surface runoff, while on the other hand, glaciers play the role of "peak cutting and valley filling" of river runoff at the intra- and inter-annual scales. While providing abundant freshwater resources, glaciers are also prone to disasters such as glacier floods and glacial lake outbursts, which threaten socio-economic development and the safety of people's lives and properties in the downstream areas (Li *et al*., 2011). Worldwide, glaciers are generally in retreat as a result of global warming. Glacier change and its consequences have attracted considerable interest from the scientific community and the public at large. How to deal with the adverse impacts (ecology, nature, and socio-economy) caused by glacier changes has become a strategic problem, and for which solutions are urgently sought. Glacier wastage and the vulnerability of glaciers are the fundamentals in the quest to formulate countermeasures (Yang *et al*., 2013).

The concept of "vulnerability" was proposed by the French researchers Albinet and Margat in the 1970s with the concept being applied to assessment of groundwater systems (Albinet and Margat, 1970). Subsequently, against a background of the continuous expansion of research on the concept of vulnerability with the integration of multiple disciplines, the connotation of vulnerability developed in the direction of one- to multi-dimensional, and from simple to complex. The vulnerability of glacier change is derived from the vulnerability of cryosphere change. International research on the vulnerability of glacier change is still in its infancy. Since 2007, researchers in China have studied the vulnerability of glacier change, but the research is still at the exploratory stage. At present, research on glacier vulnerability addresses mainly the vulnerability of the glacier itself to climate change and the vulnerability of glacier change; that is, the sensitivity of various systems to the negative impact of glacier change, which encompasses the tenets of exposure, sensitivity, and adaptability (Yang *et al*., 2013). Research concerning the vulnerability of the system to cryosphere change focuses mainly on the following four aspects: (1) Studies that address systematically the impact and vulnerability of cryosphere change identify key issues and define the research directions. Based on the interactions between the cryosphere and the other compartments, some studies have addressed the influence of cryosphere change on the regional socio-economy (Ding and Xiao, 2013; Wang *et al*., 2018). (2) In the construction and measurement of the cryosphere change vulnerability assessment system, various groups have selected assessment factors according to the characteristics of the research area and calculated the vulnerability index by using relevant weighting methods. Delphi, fuzzy mode cross-iteration and principal component analysis have typically been used (Deng, 2012; Yang, 2015; Yang *et al*., 2015). (3) Studies on the vulnerability of different systems to cryosphere change including the human-environmental system, the socio-economic system, and the water resource system, have been undertaken. For example, there are reports on the impact of glacier change on the regional water cycle and human society (He *et al*., 2012; Yao *et al*., 2013). (4) Research on the combination of vulnerability and the adaptation of cryosphere changes has been conducted. Vulnerability research is the link between impact and adaptation, with “impact-vulnerability-adaptation” being the main theme. Assessment of the vulnerability of water resources systems under the influence of glacier change in the Himalayas of northern India and in the Mandala and Yarkant River basins, has enabled the corresponding adaptation plans to be formulated and implemented (Pan, 2011; Bhadwal *et al*., 2013; Grossi *et al*., 2013; Thorsteinsson *et al*., 2013). In general, it can be seen that many studies address the vulnerability of the cryosphere as a whole, whilst few studies are concerned with the vulnerability of glacier change, which is the single critical factor within the cryosphere.

The Tianshan Mountains, which are deep in the Eurasian continent, are one of the main distribution areas for modern glaciers in China. The rich glacier resources provide ample water resources for socio-economic development, natural resource utilization and development of the typical oasis-type agriculture in Xinjiang (Deng and Chen, 2018). Driven by global warming, the glaciers of the Tianshan Mountains are generally in a state of mass loss, especially so given the accelerated melting since the 1980s (Tian *et al*., 2016). It is projected that before 2090, 80% of the glaciers in the northern piedmont of the Tianshan Mountains and 88.6% of the glaciers in the Ili River basin will disappear completely, which will lead to a sharp decrease in the glacial meltwater runoff, greatly weakening the regulation of river runoff and indirectly affecting sustainable use of regional water resources (Li, 2019). Clearly, there is an urgent need to accelerate research on the vulnerability of glacier change in the Tianshan Mountains in the context of regional water resources, the ecological environment, and socio-economic development. However, current research on glaciers in the Tianshan Mountains has tended to focus on the glacier area (Zhao *et al*., 2014; Xing *et al*., 2017), the glacier volume (Wang *et al*., 2012; Li *et al*., 2018), the glacier runoff (Sun *et al*., 2012; Liu and Li, 2016; Jia *et al*., 2019), the glacier mass balance (Wang *et al*., 2014; Xu *et al*., 2017) and the impact of glacier ablation on water resources (Cheng *et al*., 2016; Zhang *et al*., 2017), thus it is imperative to commence vulnerability research.

In this study, taking the Tianshan Mountains as an example, the vulnerability of glacier change from the standpoints of exposure, sensitivity and adaptability is examined, and the relationship between the dimensions of glacier change vulnerability and the impact on glacier change adaptability is discussed, in an attempt to improve the understanding of glacier change vulnerability in the Tianshan Mountains. The overall aim of the research is to provide scientific guidance and decision support to help central and local governments better cope with glacier change and its impact.

2 Study area

The Tianshan Mountains in China, also known as the eastern Tianshan Mountains, trend in an east to west direction, commencing in the border between China and Kyrgyzstan in the west, bordering the Tarim Basin in the south, the Junggar Basin in the north, and the Xingxingxia Gobi in the east. The mountains stretch for a length of about 1700 km (Hu, 2004). The Tianshan Mountains consist of three series of mountain ranges, namely, the North Tianshan, the Middle Tianshan and the South Tianshan, which collectively divide Xinjiang into northern and southern parts. With respect to the geomorphology, the Tianshan Mountains, and the Kunlun Mountains-Tarim Basin-Junggar Basin-Altay Mountains jointly form a geomorphic feature consisting of “three mountain ranges with two basins”, and with clear vertical and a ladder-like structure as the main landform. The average elevation of the Tianshan Mountains is more than 4000 m, and Mount Tomur is the highest (7443.8 m a.s.l.). Affected by its unique geographical location, the Tianshan Mountains have a continental climate, with air temperature and precipitation decreasing from northwest to southeast (Zhao, 2014). The precipitation falls mainly in the summer. The annual maximum precipitation is 600–800 mm, the minimum precipitation is about 150 mm with a mean value of 250–300 mm (Li, 2019). Air temperature in the Tianshan Mountains varies significantly, with the annual average temperature being about 5.0℃. The annual average temperature on the southern slopes of the Tianshan Mountains is significantly higher than that on the northern slopes, being 7.5–10.0℃ and 2.5–5.0℃, respectively (Liu and Ding, 1988). According to the Second Chinese Glacier Inventory, there are 7934 glaciers in the Tianshan Mountains with an area of 7179.78 km^2 and a volume of 756.48 km^3 (Liu *et al*., 2015). The Tianshan Mountains are also the sources of many rivers, including the Bortala River, the Ili River and the Jinghe River on the northern slopes, and the Aksu River, the Kaidu River, and the Konqi River on the southern slopes. The glaciers of the Tianshan Mountains belong to the Ili River, the Tarim, the Turpan-Hami and the Junggar inland river systems. Among them, the number of glaciers in the Junggar river system is the largest, while that in the Turpan-Hami river system is the least (Shi, 2005). In terms of administrative divisions, the glaciers of the Tianshan Mountains in Xinjiang can be found in "one city (Urumqi), four areas (Aksu, Tacheng, Hami and Turpan), and five autonomous prefectures (Changji Hui autonomous prefecture, Bayingolin Mongolian autonomous prefecture, Bortala Mongolian autonomous prefecture, Kizilsu Kirgiz autonomous prefecture, and Ili Kazakh autonomous prefecture)", of which the total glacier area of Aksu is the largest (2988.60 km^2), and Turpan is the smallest (16.40 km^2), involving a total of 34 counties and cities.

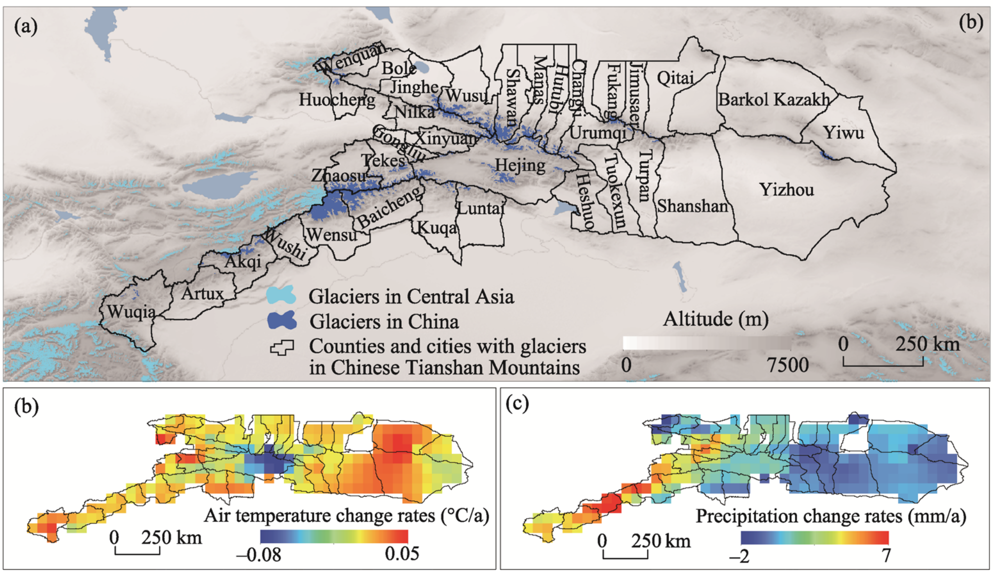

Figure 1 The geographical location of the Tianshan Mountains and distribution of glaciers (a); rates of change of the air temperature (b) and precipitation (c) during the period 1961–2010

3 Data and methods

3.1 Data

The data used in this study include glacier data, the digital elevation model (DEM), meteorological data and socio-economic data. The glacier data are from the first and second glacier inventories of China. The data for the First Chinese Glacier Inventory were generated from the 1:50,000, 1:100,000, and 1:25,000 topographic maps covering 1959 to 1980. Before measurement, the outline of the glacier on the topographic map was calibrated by using aerial photographs. Then the topographic map was revised comprehensively and proofread based on the field survey data. The Second Chinese Glacier Inventory used Landsat TM/ETM+ remote sensing satellite data as the main data source for the description of the glacier boundaries. The current international remote sensing and GIS methods were used together with the self-developed glacier region ridgeline method to extract the dividing ridge of the glacier, and then the final glacier boundary data combined with the revised results were then formed. The absolute error and relative error of the glacier area in the Second Chinese Glacier Inventory were ±1411 km^2 and 3.2%, respectively (Guo *et al*., 2015). The glacier change data used in this paper were based mainly on published results (Xing *et al*., 2017). The Landsat images of the Tianshan Mountains in the Second Chinese Glacier Inventory were acquired in 2006, 2007, 2009 and 2010, of which only 0.6% was mapped in 2006, and most of the glaciers were related mainly to the images of 2007, 2009 and 2010. Considering that the glacier area does not change much on a yearly basis, and for the convenience of statistics and calculation, this study takes 1960 and 2010 as the First and Second Chinese Glacier Inventory years, respectively (Liu *et al*., 2015). The glacier inventory data are from the National Scientific Data Center, which were used mainly to obtain the parameters for the variation of glacier area and volume. The SRTM (Shuttle Radar Topography Mission) DEM (digital elevation model) was used to calculate the altitudinal distribution of glaciers on the Tianshan Mountains with a spatial resolution of 30 m. The SRTM is freely available from the United States Geological Survey (USGS) (http://earthexplorer.usgs.gov/). In addition, we used the monthly surface temperature and precipitation grid dataset (spatial resolution 0.5° × 0.5°) of China to reflect the spatial and temporal variation characteristics of temperature and precipitation in the Tianshan Mountains, which was provided by the National Meteorological Science Data Sharing Service Platform (http://data.cma.cn). It may be noted that the range of the Tianshan Mountains in the literature can vary, and there is also a certain degree of uncertainty, so it is difficult to apportion accurately the number of counties and cities in the Tianshan Mountains region. The distribution of the 34 counties and cities in the Tianshan Mountains region for the purpose of this study was based on the distribution of glaciers in the Second Chinese Glacier Inventory to ensure the expression was rigorous. The socio-economic data for the 34 counties and cities (excluding production and construction companies) with glacier distributions in 2010 come from the China County Statistical Yearbook, the Xinjiang Statistical Yearbook, the Turpan Statistical Yearbook, the Ili Kazak Autonomous Prefecture Statistical Yearbook, the Urumqi Statistical Yearbook, other counties (cities) statistical yearbooks, and statistical bulletins on national economic and social development.

3.2 Methods

3.2.1 Index system construction

Guided by considerations such as objectivity, comparability and operability, this study, from the perspective of the human-land relationships, adopts the target layer-rule layer-index layer method with a decreasing step by step approach for organization of the research framework, and integrates the physical geographical characteristics, the population status, the socio-economic level and other factors into the glacier change vulnerability assessment system to comprehensively estimate the glacier change vulnerability in the Tianshan Mountains. The evaluation index system and the framework are outlined in Table 1 and Figure 2, respectively.

(1) Exposure refers to the adverse degree of external pressure or stress on the system. The exposure of glacier change is the result of the combined effects of the pressure on the glacier caused by physical geographical stress at the location, climate change and the socio-economic capacity, including natural exposure and socio-economic exposure. In this

Table 1 Vulnerability assessment index system of glacier change in the Tianshan Mountains region

Rule layer	Index layer	Comprehensive weight	Index description
Exposure	Relative rate of change of glacier area (%)	0.11	The area change was reflected by the difference in area between two glacial periods (Xing *et al*., 2017)
	Relative rate of change of glacier volume (%)	0.02	The volume change was reflected by the difference in volume between two glacial periods (Zhang *et al*., 2017)
	Elevation of glacier tongue (m)	0.03	Reflects the change of height of the tip of the glacier tongue
	Glacier altitude distribution (m)	0.03	Based on DEM data, the elevation distribution of the glacier is statistically analyzed to reflect the conditions for development
	Urbanization rate (%)	0.04	Reflects the urbanization process affected indirectly by glacier change
	Gross domestic product ($)	0.07	Reflects the overall economic development level of the administrative region
	Population density (person/km^2)	0.06	Reflects the population density under the influence of glacier change
Sensitivity	Rate of change of temperature (°C/10a)	0.03	Reflects the temperature change
	Rate of change of precipitation (mm/10a)	0.05	Reflects the precipitation change
	Total grain output (t)	0.07	Reflects the grain production capacity of the administrative region
	Per capita effective irrigation area (ha)	0.04	Reflects the abundance of regional water resources and their stability in the process of agricultural production
Adaptability	Per capita net income of rural residents (USD)	0.02	Reflects changes in the production level and quality of life of rural residents
	Per capita GDP (USD)	0.09	Reflects regional economic status and people's living standards
	Urban fixed-asset investment completed (USD)	0.08	Reflects the scale, structure, and speed of development of regional capital investment
	Education level (person basis)	0.06	Adopts the number of students in secondary school to reflect the degree of popularity of education and the level of educational facilities
	Medical level (bed)	0.07	Adopts the number of hospital beds to reflect the level of medical infrastructure
	Gross agricultural product (USD)	0.04	Reflects the scale and level of agricultural production
	Added value of secondary industry (USD)	0.10	Reflects the benefits brought by the development of the secondary industry

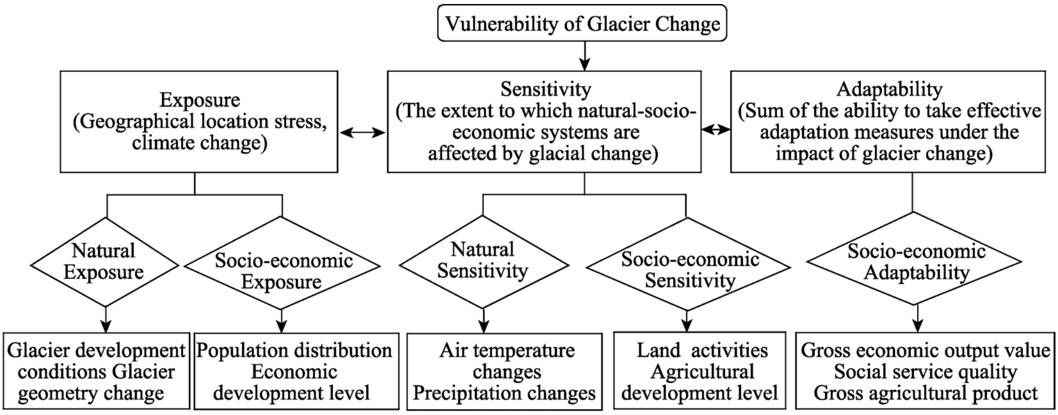

Figure 2 Framework of vulnerability assessment of glacier change in the Tianshan Mountains region

study, the height of the glacier tongue and the altitude reflect the natural conditions of glacier development, and the rate of change of area and volume represents the intensity of exposure of glacier change; thus the joint measure equates to the regional natural exposure. Considering the current situation of economic development, and the differences in the development rate, the process of urbanization, and the uneven distribution of the population, the socio-economic exposure indicators are measured by the regional GDP, the urbanization rate, and the population density.

(2) Sensitivity refers to the degree of response of each element in the system to glacier change. The study links the sensitivity of glacier change to climatic factors and agricultural activities and focuses on the extent to which the utilization of water resources is affected or changed as a result of human-oriented agricultural activities. On the one hand, temperature and precipitation are closely related to glaciers. Temperature determines whether the glaciers melt, while solid precipitation determines the extent of the accumulation of glaciers (Ding *et al*., 2013). The combined action of the two factors determines the formation, development and evolution of glaciers. On the other hand, the replenishment rate of glacier resources to runoff directly affects the utilization of water resources in agricultural activities. Therefore, referring to previous studies, the rate of change of the annual average temperature, the rate of change of the annual average precipitation, the total grain output, and the per capita effective irrigated area of counties and cities in the Tianshan Mountains are used to characterize the sensitivity of glacier changes.

(3) Adaptability refers to the sum of the effective measures taken by human beings under the influence of actual or predicted glacier change. In this study, the adaptability of glacier changes under the dual effects of the social and economic systems are mainly considered. The per capita GDP, the total amount of urban fixed assets investment and the added value of the secondary industry reflect the overall level of regional economic development and whether it has the economic ability to adopt high-level and high-tech adaptive measures. In addition, the level of education and health care indirectly reflects the strength of the regional economy, thus these factors are included in the adaptability evaluation system. The per capita net income of rural residents and the gross agricultural product reflect the level of regional agricultural development. Glacier change will cause variability in the water resources, which is a crucial factor in agricultural development. Therefore, changes in the water resources system play a leading role in agricultural activities.

3.2.2 Vulnerability assessment model

According to the literature, vulnerability is a function of system exposure, sensitivity, and adaptability. However, due to the different measurement units and values for the data of each dimension index, the range standardization method was used to standardize the positive and negative index data in the calculation process to ensure the dimensionless of the data. In this way, comparability between the data was achieved before undertaking vulnerability analysis. Also, the improved entropy method was adopted to determine the index weight (Table 1) (Wang *et al*., 2019). The vulnerability index V is calculated as:

$$V=(E\times S)/A \tag{1}$$

where V is vulnerability, E is exposure, S is sensitivity and A is adaptability. The model reflects the inherent logical relationship between vulnerability and the three dimensions. The higher the system exposure, the stronger the sensitivity, the smaller the adaptability and the greater the system vulnerability and vice versa.

3.2.3 Spatial autocorrelation

(1) Global autocorrelation

To analyze the overall spatial characteristics of the 34 counties and cities in the Tianshan Mountains region, the global autocorrelation model was used to analyze the overall distribution of glacier change vulnerability in the 34 counties and cities to determine whether spatial agglomeration is exhibited in the Tianshan Mountains as a result of glacier change vulnerability. According to relevant vulnerability studies, the commonly used test statistic is the *Moran's I* index (Yang *et al*., 2019):

$$I=\frac{n\sum_{i=1}^{n}\sum_{j=1}^{n}w_{ij}(x_i-\overline{x})(x_j-\overline{x})}{\left(\sum_{i=1}^{n}\sum_{j=1}^{n}w_{ij}\right)\sum_{i=1}^{n}(x_i-\overline{x})^2}\left(i\neq j\right) \tag{2}$$

where x_i and x_j are the vulnerability indexes of glacier change of space objects i and j, respectively; w_{ij} is the spatial weight defined by the adjacent standard, that is, when i and j are adjacent, $w_{ij}=1$, otherwise $w_{ij}=0$; n is the number of spatial objects. The value of Moran's I ranged from –1 to 1, the values being greater than 0 for positive correlation, less than 0 for negative correlation, and equal to 0 for non-correlation.

(2) Bivariate spatial autocorrelation

To describe the spatial distribution characteristics of correlation among multi-variables, the bivariate spatial autocorrelation model proposed by Anselin and Kelejian (1997) was used to test the spatial correlation between exposure and sensitivity, exposure and adaptability, and sensitivity and adaptability.

$$I_{df}^{i}=Z_d^i\sum_{j=1}^{n}w_{ij}Z_f^j \tag{3}$$

$$Z_d^i=\frac{x_d^i-\overline{x_d}}{\sigma_d},Z_f^j=\frac{x_f^j-\overline{x_f}}{\sigma_f} \tag{4}$$

where w_{ij} is the spatial weight, z_d^i is the attribute d value of the space object i, z_f^j is the attribute f value of the space object j, $\overline{x_d}$ and $\overline{x_f}$ are the average values of the attributes d

and f, respectively; σ_d and σ_f are the variances of the attributes d and f, respectively; n is the number of spatial objects; attribute d refers to the exposure or sensitivity index; and attribute f refers to the sensitivity or adaptability index.

3.2.4 GeoDetector model

The GeoDetector model is a statistical method proposed by Wang and Xu (2017) to analyze spatial differentiation and detect the dominant internal factors, which include mainly risk detection, factor detection, interaction detection and ecological detection. These four elements encompass the essential research idea that if the dependent variable plays an important role in the development of the independent variable, the dependent variable and the independent variable in the space with similar characteristics or the distribution of space changes have a certain consistency. The GeoDetector model as used in this study involves mainly factor detection and interaction detection.

(1) Factor detection

Factor detection is a quantitative method to analyze the degree of interpretation of factors that influence the adaptability of glacier change; that is, the importance of each influencing factor in the adaptability is expressed by $P_{D,E}$ as

$$P_{D,E} = 1 - \frac{1}{N\sigma^2}\sum_{j=1}^{F} N_j \sigma_j^2 \tag{5}$$

where $P_{D,E}$ is the degree of factor explanation for the influencing factor D with a value range of 0–1; the more the value of $P_{D,E}$ approaches 1, the greater the influencing factor D has on the adaptability; N is the adaptability of glacier change; σ is the variance of glacier change adaptability; the influencing factors of the study area are divided into F layers, denoted by j = 1, 2, …, F, then N_j and σ_j^2 are the adaptability and variance of glacier changes in the counties and cities of the Tianshan Mountains on layer j, respectively.

(2) Interaction detection

Interaction detection is concerned with identifying whether there is an interaction between the influencing factors, that is, whether influencing factors a and b can enhance or weaken the interpretation of glacier change adaptability when they work together, or whether a certain factor plays an independent role in the adaptability of glacier change, and there is no interaction between the factors. To determine whether there is the interaction between factors, the formulae specified in Table 2 are used (Wang and Xu, 2017).

Table 2 Types of interaction detection

Type		Formula
Enhanced	Ordinary	$P_{D,E}(D_1 \cap D_2) > P_{D,E}(D_1)$ or $P_{D,E}(D_2)$
	Bilinear	$P_{D,E}(D_1 \cap D_2) > P_{D,E}(D_1)$ and $P_{D,E}(D_2)$
	Nonlinear	$P_{D,E}(D_1 \cap D_2) > P_{D,E}(D_1) + P_{D,E}(D_2)$
Weakened	Ordinary	$P_{D,E}(D_1 \cap D_2) < P_{D,E}(D_1) + P_{D,E}(D_2)$
	Bilinear	$P_{D,E}(D_1 \cap D_2) < P_{D,E}(D_1)$ or $P_{D,E}(D_2)$
	Nonlinear	$P_{D,E}(D_1 \cap D_2) < P_{D,E}(D_1)$ and $P_{D,E}(D_2)$
No dependence	Ordinary	$P_{D,E}(D_1 \cap D_2) = P_{D,E}(D_1) + P_{D,E}(D_2)$

4 Results and analysis

4.1 Spatial differentiation characteristics of glacier change vulnerability in the Tianshan Mountains

According to the glacier change vulnerability model, the glacier change vulnerability index for each county and city in the Tianshan Mountains region was calculated, and the natural breakpoint method in ArcGIS software was used to divide the vulnerability, exposure, sensitivity, and adaptability index into five grades (from low to high), thereby obtaining the spatial distribution map of the glacier change vulnerability of each county and city in the region.

4.1.1 The level of vulnerability decreased from west to east, and the difference was significant.

The overall vulnerability of glacier changes in the Tianshan Mountains showed a decreasing trend from west to east, with extreme and high grades in the western regions and slight and light grades in the eastern regions. In counties and cities, extreme and high vulnerability were only found in Akqi and Wuqia in the west, with vulnerability indices of 0.66 and 0.36, respectively; moderate vulnerability was distributed mainly in Artux, Wushi and Wensu in the west and Wenquan in the central region, the vulnerability indices being 0.13, 0.16, 0.19 and 0.13, respectively; light and slight vulnerability levels were distributed mainly in Changji and Hejing in the central region, Shanshan, Qitai and Yiwu in the east, the vulnerability indices being 0.02, 0.04, 0.02, 0.08 and 0.11, respectively. In general, the vulnerability of glacier change in the Tianshan Mountains region occurred mainly at three levels: slight, light, and moderate. The different levels of vulnerability were as follows: slight vulnerability>light vulnerability>moderate vulnerability>high vulnerability, extreme vulnerability, and the corresponding number of counties and cities accounted for 50.00%, 32.35%, 11.77%, 2.94% and 2.94% of the total, respectively (Figure 3a).

4.1.2 High values of exposure were concentrated in the western and central regions and low values of exposure tended to have a scattered distribution.

The vulnerability of glacier changes in the Tianshan Mountains region is mainly a consequence of natural and socio-economic exposures, such as the constraints of natural and social conditions which include a change of glacier area and volume against a background of climate warming, an increase or decrease of the GDP and rapid growth of population. As shown in Figure 3b, the exposures were significantly different in the western, central, and eastern regions. The extreme exposure values were concentrated in Akqi and Wensu in the west and Wusu, Shawan and Changji in the central region, the exposure indices being 0.55, 0.52, 0.50, 0.58 and 0.52, respectively. The high exposure values were located in Manas, Hejing and Kuqa in the central region with exposure indices of 0.44, 0.41 and 0.34, respectively. The moderate and low values for exposure were distributed mainly in Turpan, Shanshan and Yiwu in the east, and in the towns of Xinyuan, Tekes, and Hutubi in the central region, reflecting a scattered distribution. According to the ranking for the exposure values, the results showed that the exposure was generally high, and the number of counties and cities with moderate exposure levels or above accounted for 61.76% of the total number of counties and cities.

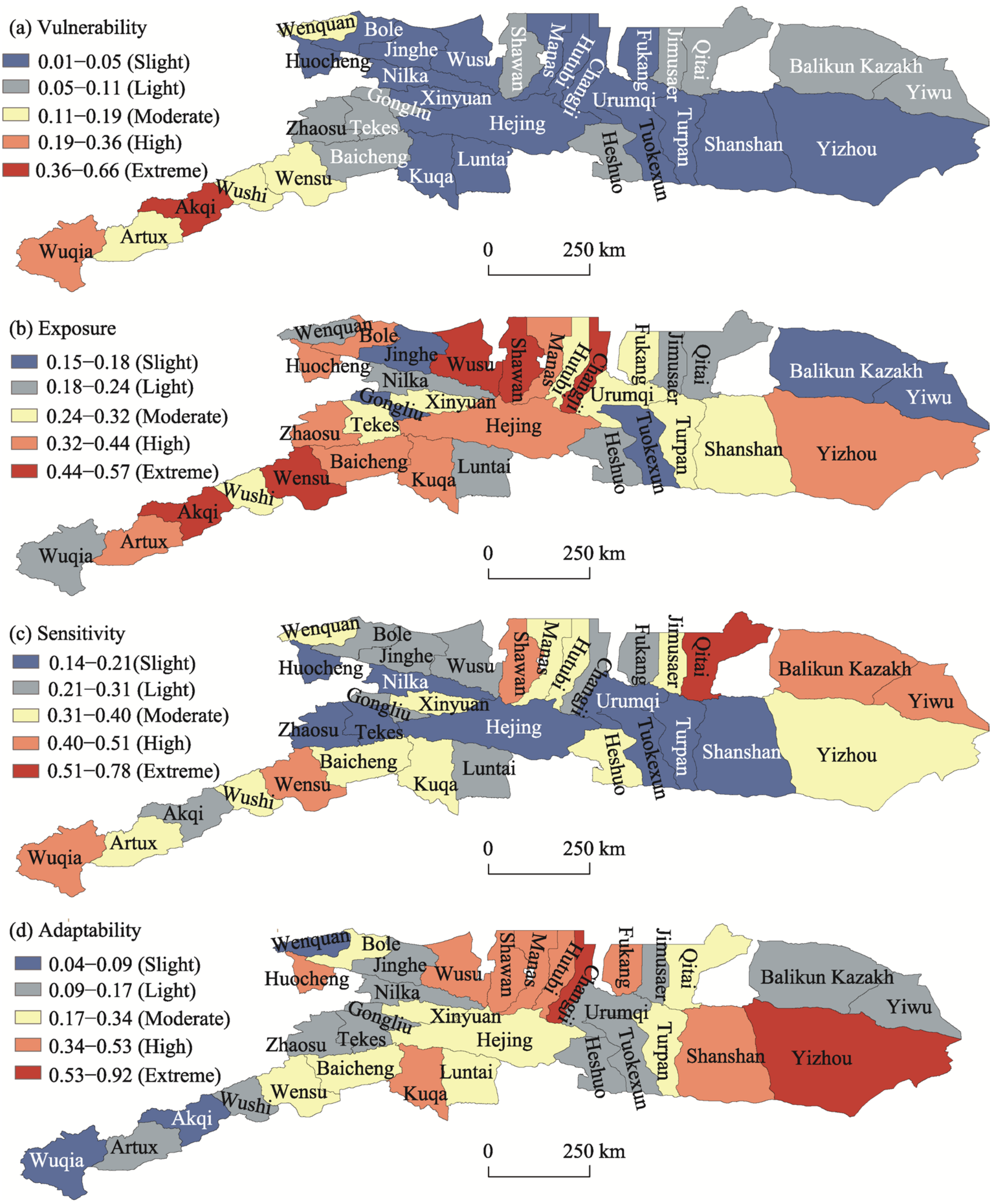

Figure 3 Spatially distributed vulnerability levels of glacier change in the Tianshan Mountains region

4.1.3 The eastern and western regions exhibited high sensitivity while the central region had low sensitivity.

The spatial distribution of the sensitivity of glacier changes in the Tianshan Mountains region presented a pattern that was high in the eastern and western regions and low in the central region (Figure 3c). "East and West" refers to the cluster areas of counties and cities with extreme and high sensitivity. "West" refers to the connecting line between Wuqia-Kuqa in the west, in which the highest sensitivity county was Wensu with a sensitivity index of 0.52. "East" refers to the connecting line between Yiwu-Shawan in the east, in which the highest sensitivity county was Qitai with a sensitivity index of 0.78. The central region was dominated by moderate levels of sensitivity and above, the highest sensitivity county being Wushi, with a sensitivity index of 0.40. In general, the sensitivity of glacier change in the Tianshan Mountains region was mainly moderate, with the number of counties and cities accounting for 32.35% of the total; followed by slight and light sensitivity, accounting for 26.47% and 23.53%, respectively; finally, levels of extreme and high sensitivity, accounted for 17.65% of the counties and cities, these locations being located mainly in areas with a relatively small number and area of glaciers.

4.1.4 The adaptability increased circularly from the western to the central to the eastern regions.

The spatial structure of the adaptability to glacier change in the Tianshan Mountains region was found to be the opposite of that for vulnerability and exhibited an increasing distribution pattern from the western to the central to the eastern regions (Figure 3d). In this pattern, "West" refers to the areas with slight and light adaptability, "Central" refers to areas with a concentration of glaciers and have moderate and extreme adaptability, and "East" refers to areas with sporadic glaciers and have high and extreme adaptability. From the perspective of counties and cities, Akqi and Wuyi in the western region had the lowest adaptability; Changji, Manas and Shawan in the central region had higher adaptability; and Yizhou and Shanshan in the eastern region had the highest adaptability. The order of adaptability for the number of the counties and cities was as follows: light adaptation > moderate adaptation, high adaptation > slight adaptation > extreme adaptation, and the corresponding number of counties and cities were 13, 8, 8, 3 and 2, respectively.

In conclusion, the western region of the Tianshan Mountains had a highly exposed environmental system sensitive to glacier change, and at the same time had the lowest level of adaptability, so the vulnerability of glacier change was high. The central region of the Tianshan Mountains corresponded to a high exposure-low sensitivity environmental system and possessed some adaptability to the impact of glacier change, thus the vulnerability of glacier change was relatively low. The eastern region of the Tianshan Mountains was characterized by a system with low exposure and high sensitivity and had the adaptability to cope with the impact of glacier change, hence the vulnerability of glacier change in the eastern region was the lowest in the whole region.

4.2 Spatial global autocorrelation

The Moran's *I* index, and the scatter plot were selected to study the spatial global autocorrelation of the glacier change vulnerability index for 34 counties and cities in the Tianshan Mountains region. The results indicated that the Moran's *I* index for the glacier change vulnerability in the region was 0.23, a value which passed the significance test at the 0.01 level; the *Z* value was 2.77. It can be seen from Figure 4 that there was a significant positive spatial correlation in the glacier change vulnerability. Most of the vulnerability index values were scattered in the first and third quadrants, while only a few were distributed in the second and fourth quadrants (Figure 4a). In other words, the vulnerability index of glacier change exhibits clustering and interdependence in the region where the high index was adjacent to the high index, and the low index was adjacent to the low index.

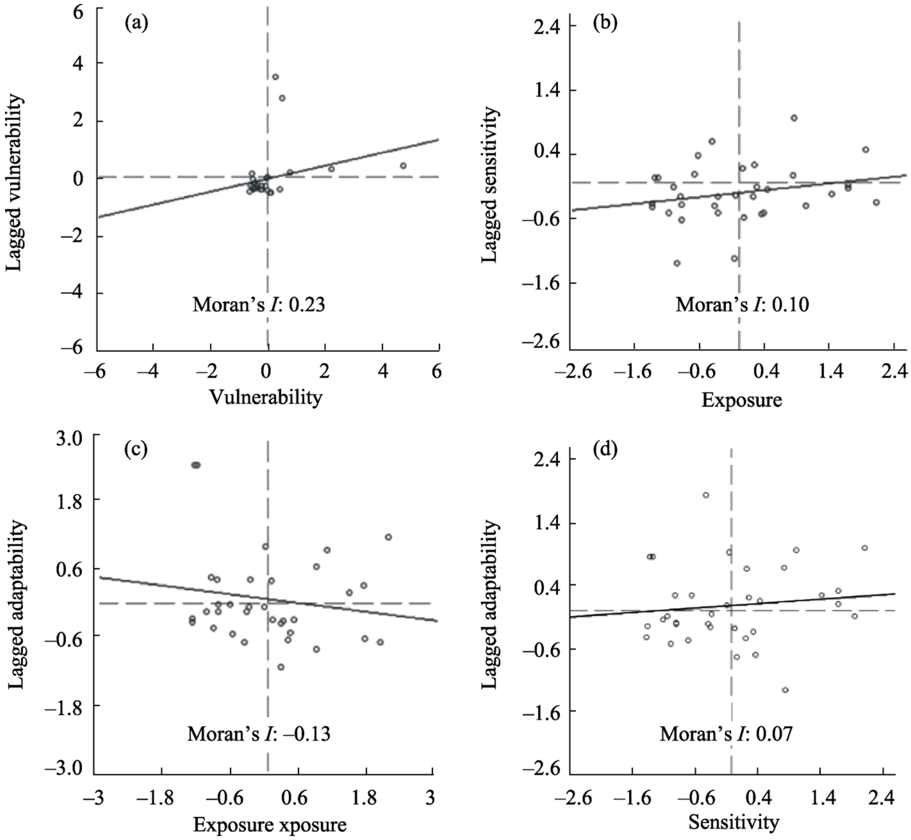

Figure 4 Spatial relationship between the vulnerability of glacier change and the various dimensions in the Tianshan Mountains region

To study whether there was a spatial correlation among the three dimensions (exposure, sensitivity, and adaptability) of vulnerability, bivariate spatial autocorrelation analysis was conducted. Given that the exposure to a large extent depended on the physical and geographical conditions, the study explored the spatial correlation among the exposure, sensitivity, and adaptability in the 34 counties and cities of the region. The results of spatial correlation between exposure and sensitivity are presented in Figure 4b and reveal a Moran's *I* index value of 0.10 and with a significance level of 0.05. This indicates that exposure and sensitivity had a positive correlation in space, and the high (low) exponential distribution area of the system's impact on glacier changes is adjacent to the high (low) exponential distribution area. The results for spatial correlation between exposure and adaptability are shown in Figure 4c, indicating a Moran's *I* index value of –0.13 with a significance level of 0.05. It can be concluded that there was a significant negative spatial correlation between exposure and adaptability, hence the high (low) index distribution area of exposure and low (high) index distribution area of adaptability to glacier changes were clustered adjacent to each other. The spatial correlation results for sensitivity and adaptability are presented in Figure 4d, and reveal a Moran's *I* index of 0.07, a value which is close to zero and indicating a weak positive correlation between sensitivity and adaptability for the space in question. That is, the index distribution area with high (low) sensitivity to glacier changes in the Tianshan Mountains is clustered adjacent to the high (low) index distribution area with high adaptive capacity. The above-mentioned areas with high exposure and high sensitivity to glacier changes in the region tended to have low adaptability, which led to the higher vulnerability of the system, while low exposure and low sensitivity areas had higher adaptability and system vulnerability was relatively low.

5 Factors influencing the adaptability of glacier change

5.1 Variable selection

Using spatial principal component analysis, Yang *et al*. (2013) elaborated on the geographical differences of glacier change vulnerability in China and found that the aspect, the altitude, terrain cover and the rate of change of glacier area were the main factors leading to glacier vulnerability. We attempted to explore the factors affecting the vulnerability of glacier change and its spatial characteristics according to the main factors affecting glacier change, and the related factors in the analysis of the spatial distribution of glacier change vulnerability in the study area, but the exposure largely depended on the physical and geographical conditions. Also, the sensitivity was controlled mainly by the changes of temperature and precipitation, which then indirectly affected the exposure factors. Accordingly, the dimensions of exposure and sensitivity indicated a certain interaction. At the same time, the exposure dimension was relatively stable, and the inter-annual fluctuation of the sensitivity dimension was small, and the two dimensions were less affected by the social economy, thus the sensitivity was not susceptible to great change in the short term. In contrast, adaptability was most susceptible to policy, social, economic, and other factors in a short time. Consequently, the purpose of this study was to explore the differences of natural, social, economic, population and other factors on the adaptability of glacier change in the Tianshan Mountains from the perspective of human-land relationships. The adaptability index was selected as the explained variable, and the topography, the economic development level, the employment level, the social quality of life, the population size and the social services of the counties and cities were taken as the explanatory variables to construct the evaluation system of influencing factors. The explanatory variables were the altitude (X_1), urban fixed-asset investment (X_2), production value of secondary and tertiary industries (X_3), total output value of agriculture, forestry, animal husbandry and fisheries and the services industry (X_4), number of employees at the end of the year (X_5), local financial revenue (X_6), per capita net income of farmers and herdsmen (X_7), urban population (X_8), the volume of postal business (X_9), number of students beyond secondary school (X_{10}), and number of professional health technicians (X_{11}).

5.2 Analysis of the explanatory degree of the influencing factors

Taking the county and city administrative units as the research scale, the GeoDetector software was used to analyze quantitatively the explanatory degree of factors affecting the adaptability of glacier change in the Tianshan Mountains region. In this approach, the relative importance of 11 index factors on the spatial differentiation and level of adaptability were compared. Factor detection revealed that the level and differences of the spatial distribution of the adaptability in the Tianshan Mountains region were affected mainly by socio-economic factors, and natural factors also played a role. The factors were sorted by the size of the $P_{D,E}$ statistic as follows: production value of secondary and tertiary industries (0.86) > urban population (0.79) > urban fixed-asset investment (0.63) > number of employees at the end of the year (0.60) > the volume of postal business (0.57) > number of professional health technicians (0.56) > per capita net income of farmers and herdsmen (0.53) > local financial revenue (0.37) > number of students beyond secondary school (0.36) > altitude (0.20) > total output value of agriculture, forestry, animal husbandry and fisheries and services industry (0.12).

The factor detection results were as follows (Table 3): (1) The production value of secondary and tertiary industries had the highest explanatory degree for adaptability, with the $P_{D,E}$ statistics being as high as 0.86. The $P_{D,E}$ statistics for the urban population, urban fixed-asset investment, and the number of employees at the end of the year were all above 0.6, indicating that these four factors were the core factors affecting the adaptability of the Tianshan Mountains region. The production value of secondary and tertiary industries and urban fixed-asset investment directly affected the improvement of regional adaptability, while the economic strength determined which measures and technical means would be taken regarding the impact of glacier change. The urban population and the number of employees directly affected the scale, speed, and structure of regional economic development. Therefore, the level of urbanization and the regional employment rate exerted an indirect role in improving the adaptability and alleviating regional adaptability differences. (2) The $P_{D,E}$ statistics for volume of postal business, number of professional health technicians, per capita net income of farmers and herdsmen, local financial revenue, and number of students beyond secondary school were all greater than 0.3, implying that these five factors exerted a secondary level effect on the adaptability. With urbanization, the quality of regional social services and whether the equipment was fit-for-purpose or not were important factors in terms of coping with the impact of glacier change. Good quality of social services and well-equipped facilities can help mitigate against negative impacts; otherwise, their roles will be weakened. The level and popularity of education had a significant impact on the implementation of policies and regulations to enhance the adaptability of glacier change in the Tianshan Mountains region. Local residents with a high education level and a wide popularization are commensurate with a high acceptance ability and tolerance, which play a positive role in the process of policy popularization and implementation. Conversely, a low

Table 3 Detection results for factors influencing the adaptability of glacier change in the Tianshan Mountains region

Impact factors	$P_{D,E}$ value	$P_{D,E}$ value sorting	Impact factors	$P_{D,E}$ value	$P_{D,E}$ value sorting
Altitude	0.20	10	Per capita net income of farmers and herdsmen	0.53	7
Urban fixed-asset investment	0.63	3	Urban population	0.79	2
Production value of secondary and tertiary industries	0.86	1	Volume of postal business	0.57	5
Total output value of agriculture, forestry, animal husbandry, fisheries and services industry	0.12	11	Number of students beyond secondary school	0.36	9
Number of year-end employees	0.60	4	Number of professional health technicians	0.56	6
Local financial revenue	0.37	8			

acceptance and difficulty by the residents to understand the relevant policy content may have a negative effect on the implementation of the policy, which is not conducive to improving the regional adaptability. (3) The $P_{D,E}$ statistics of altitude barely exceeded 0.2, which revealed that physical geography was a third level factor adaptability. The physical geographic conditions had a certain influence on the improvement of adaptability, but they did not occupy a dominant position, the socio-economic level playing the leading role. (4) The $P_{D,E}$ statistics of the total output value of agriculture, forestry, animal husbandry and fisheries and services industry were larger than 0.1, which illustrated that the agricultural economy was a fourth level factor concerning adaptability. The development of agriculture, forestry, animal husbandry and fisheries and services industry were not only restricted by natural conditions but also were affected by the level of agricultural technology and mechanical services. Consequently, the agricultural economy played a certain role in the process of socio-economic development and indirectly influenced adaptability.

According to factor detection, the explanatory degree of the factors influencing the adaptability of glacier change in the Tianshan Mountains region had a certain degree of consistency but there were also differences. The consistency indicated that there were only four factors where the explanatory degree for the $P_{D,E}$ statistics were less than 0.3, the explanatory degree of most factors being between 0.5 and 0.8. This indicated that each factor played a certain role in the adjustment process and in improving adaptability. The differences were manifested in the different explanatory degrees for the influencing factors as reflected in the $P_{D,E}$ statistics; the largest and the smallest values were 0.86 and 0.12, respectively, indicating that each factor plays a different role in the process of adjustment and improvement of adaptability. That is, the level of economic development plays a leading role, and physical geography plays a supplementary role.

5.3 Analysis of the interactions of the influencing factors

In studying the detection of interactions, we explored whether the influencing factors had an interactive effect on the spatial differentiation of adaptability and identified whether the interaction between different influencing factors enhanced or weakened the explanatory degree of the dependent variable. The detection results for the interactions of the influencing factors on the spatial differentiation of glacier change adaptability in the Tianshan Mountains region showed that the explanatory degree was significantly enhanced after the interaction of the influencing factors, which was mainly manifested in two combinations of bilinear or nonlinear factor enhancement. The bilinear enhancement between factors was relative. The bilinear enhancement among the factors was more common, indicating that the spatial differentiation in the adaptability of glaciers was not caused by a specific influencing factor, but the result of mutual interactions between the different influencing factors.

The detection results for the interactions presented in Table 4 can be summarized as follows: (1) The interactions among the altitude, urban fixed-asset investment, total output value of agriculture, forestry, animal husbandry, fisheries and services industry, local financial revenue and other factors exhibited nonlinear enhancement. Among them, the explanatory degree of the interaction between altitude and the total output value of agriculture, forestry, animal husbandry, fisheries and services industry increased significantly, with a rate of

Table 4 Detection results for the interactions of influencing factors on the adaptability of glacier change in the Tianshan Mountains region

	X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8	X_9	X_{10}	X_{11}
X_1											
X_2	0.86										
X_3	0.97	0.92									
X_4	0.54	0.76	0.95								
X_5	0.81	0.93	0.95	0.84							
X_6	0.61	0.83	0.87	0.60	0.92						
X_7	0.65	0.84	0.94	0.73	0.85	0.92					
X_8	0.94	0.88	0.95	0.89	0.91	0.88	0.91				
X_9	0.83	0.93	0.95	0.73	0.79	0.86	0.89	0.88			
X_{10}	0.67	0.94	0.97	0.47	0.85	0.89	0.76	0.89	0.87		
X_{11}	0.69	0.77	0.95	0.62	0.93	0.92	0.88	0.91	0.88	0.69	

Note: X_1 – altitude, X_2 – urban fixed-asset investment, X_3 – production value of secondary and tertiary industries, X_4 – total output value of agriculture, forestry, animal husbandry, fisheries and services industry, X_5 – number of year-end employees, X_6 – local financial revenue, X_7 – per capita net income of farmers and herdsmen, X_8 – urban population, X_9 – the volume of postal business, X_{10} – number of students beyond secondary school, and X_{11} – number of professional health technicians.

increase of 65.89%, and the explanatory degree of the interaction between altitude and the number of year-end employees increased by 0.21%, which implied that the explanatory degree became more clear as a result of the interactions of geographical location and social economy, employment level and social services. Therefore, when the results for the Tianshan Mountains region exhibit a response to the impact of glacier changes, natural factors must be taken into consideration when countermeasures are implemented or improved. (2) After the interaction of the total output value of agriculture, forestry, animal husbandry, fisheries and services industry and local financial revenue, the increased rate of the explanatory degree was 23.11%, which indicated that the agricultural economy was a part of the regional economic development, and its influence on adaptability was not clear when acting alone, but fiscal revenue was an indicator of regional fiscal strength to a certain extent, so the explanation of adaptability was enhanced after the interaction of the two factors. (3) The explanatory degree increased by 21.58% after the interaction between the local fiscal revenue and the number of students beyond secondary school, revealing that the explanatory degree was weak when the education level beyond secondary school acted alone, however, with the support of the regional financial strength, the explanatory degree after the interaction between the two factors showed a stronger trend. (4) Besides the above factors, the interaction of the remaining factors presented a bilinear enhancement, which illustrated that the ability of the Tianshan Mountains region to cope with glacier change was multi-factorial. Among them, as a result of the interaction between altitude and the production value of secondary and tertiary industries, the largest explanatory degree was 0.97; this was because the difference in altitudes in the Tianshan Mountains was large, and the development of the secondary and tertiary industries was inevitably affected by altitude. The production value of secondary and tertiary industries had clear interactions with the number of students beyond secondary school, with an explanatory degree of 0.97, demonstrating that the improvement in education levels exerted a promotional effect on the development of secondary and tertiary industries, thus the explanatory degree for the two factors on their adaptability was enhanced. In the light of this finding, clear interaction relationships are existing among the various factors, and the explanatory degree of the interactions was enhanced, the results demonstrating that the ability of the Tianshan Mountains region to respond and cope with glacier change reflects the results of multiple interactions involving natural, social, economic and population factors.

6 Conclusion and discussion

6.1 Conclusion

Using the Tianshan Mountains as an example, a basic framework was constructed to permit the assessment of the vulnerability of glacier change in the region. The study addressed factors such as physical geography, population status, socio-economic level, agricultural development, and social services, and examined the key tenets, namely, exposure, sensitivity, and adaptability. The targeted evaluation index system revealed the spatial characteristics of glacier change vulnerability, and using the GeoDetector model, the influence of natural, social, economic and population factors on the adaptability of glacier change was discussed. The main conclusions are as follows:

(1) The vulnerability level decreased from the western region to the eastern region with significant differences between the two regions. The eastern region of the Tianshan Mountains reflected a system environment with low exposure and high sensitivity and had the adaptability to cope with the impact of glacier change, hence the vulnerability of glacier change was the lowest for the whole region. The central region was a high exposure-low sensitivity system and had certain adaptability to the impact of glacier change, so the vulnerability of glacier change remained relatively low. The western region had a high exposure and high sensitivity to glacier change, and at the same time had the lowest level of adaptability, thus the vulnerability of glacier change was high.

(2) There was a significant positive spatial correlation between the vulnerability of glacier change in the Tianshan Mountains and the significant positive and negative spatial correlation between the exposure, sensitivity, and adaptability in space, indicating that the areas with high exposure and high sensitivity to glacier change tended to have a low adaptive capacity, which consequently led to high vulnerability; in contrast, areas with low exposure and low sensitivity to glacier change tended to have a high adaptive capacity, which led to lower vulnerability.

(3) The spatial heterogeneity regarding the ability to cope with glacier change reflected the combined effects of natural, social, economic, and demographic factors. Among them, factors such as the production value of secondary and tertiary industries, urban population, urban fixed-asset investment, and the number of employees played a leading role, and the explanatory degree was significantly enhanced as a result of the interactions between the influencing factors, which were manifested mainly as bilinear enhancements.

6.2 Discussion

(1) The relationship between the change of glacier area and the vulnerability of glacier

change.

It may have a certain degree of one-sidedness if we hold that the glacier area change has great vulnerability. Clearly, a great change in a glacier area implies that the glacier may be readily disturbed by the external environment as reflected in having a high exposure and high sensitivity. The vulnerability of glacier change may be considered as consisting of three tenets or dimensions, namely, exposure, sensitivity, and adaptability. High exposure would not necessarily mean high vulnerability. For example, data from the First and Second Chinese Glacier Inventory showed that the glacier area of Akqi decreased by 544.48 km^2 with the vulnerability index of glacier change being 0.66; this result indicated that the change of the glacier area was consistent with the vulnerability of glacier change. By contrast, the glacier area of Shawan decreased by 317.32 km^2 with a vulnerability index of 0.07, indicating that the correlation between the change of the glacier area and the vulnerability was extremely poor. In another case, the glacier area of Wuqia decreased by 41.92 km^2 with a vulnerability index of 0.36, again illustrating a relative lack of consistency between the change of the glacier area and vulnerability. Consequently, judging the vulnerability level for glacier change only from the perspective of glacier area has limited value, hence it is necessary to consider dimensions such as sensitivity and adaptability.

(2) The impact of the evaluation index selection on the comprehensive assessment of the vulnerability of glacier change.

Given that many factors affect the vulnerability of glacier change and the interactions are multi-factorial and complex, proper understanding of the exposure, sensitivity, and adaptability, as well as selection of the corresponding index parameters and other parameters, are particularly relevant for progressing research at the large scale. Taking exposure as an example, it is straightforward to obtain the parameters for a natural exposure index and to refer to an alternative index such as the spatial units of a city, state, or county, but the larger the spatial scale is, the clearer any differences will be in the natural exposure levels. In studying the vulnerability of glacier change, it is easier to express the spatial heterogeneity between regions than within regions. Factors such as the socio-economic development level, the population status, and the speed of urbanization of spatial units at different scales are significantly different, so it is difficult to select socio-economic exposure indicators, in which the common index of the spatial unit may be selected to evaluate the degree of vulnerability. In the light of the connotation of the vulnerability of glacier change, the internal structure and stability of the system and the socio-economic development capabilities of human subjects determine whether pressure or coercion is exerted on the system which could break the threshold of the system to support the intended functions. Nevertheless, how to accurately measure the critical threshold of system damage through sensitivity and adaptability indicators is a difficulty in current research on the vulnerability of glacier change.

(3) Vulnerability assessment of future glacier change.

This study takes counties and cities as basic units and focuses on exploring the spatial characteristics regarding the vulnerability of glacier change and examining the factors which influence adaptability, in order to realize comparisons regarding the vulnerability differences of glacier change among spatial units, which have a clear guiding role for implementing efficient adaptive measures. Aside from the assessment of the vulnerability of glacier changes in the past, analysis of the spatio-temporal evolution of the vulnerability of glacier changes in the future is of certain significance for studying the dynamic evolution process of the system vulnerability and its driving mechanisms. However, due to the difficulty in obtaining large-scale glacier data and the presence of certain errors in the data, research on the vulnerability characteristics of glacier change and the factors influencing adaptability based on data from the First and Second Chinese Glacier Inventory remains at an elementary level and lacks the prediction capabilities regarding future changes. Regions with relatively complete glacier data were selected to analyze the evolution characteristics and driving mechanisms regarding the future vulnerability of glacier change and differentiated adaptation strategies have been proposed that will require in-depth research.

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