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Glacier wastage and its vulnerability in the Qilian Mountains

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Abstract: Glaciers are a reliable freshwater resource in arid regions of West China and the vulnerability of its changes is closely related to regional ecosystem services and economic sustainable development. Here, we took the Qilian Mountains as an example and analyzed the spatiotemporal characteristics of glacier changes from 1998 to 2018, based on remote sensing images and the Second Chinese Glacier Inventory. We estimated the basic organizational framework and evaluation index system of glacier change vulnerability from exposure, sensitivity and adaptability, which covered the factors of physical geography, population status and socio-economic level. We analyzed the spatial and temporal evolutions of glacier change vulnerability by using the vulnerability evaluation model. Our results suggested that: (1) Glacier area and volume decreased by 71.12±98.98 km^2 and 5.59±4.41 km^3, respectively, over the recent two decades, which mainly occurred at the altitude below 4800 m, with an area shrinking rate of 2.5%. In addition, glaciers in the northern aspect (northwest, north and northeast) had the largest area reduction. Different counties exhibited remarkable discrepancies in glacier area reduction, Tianjuan and Minle presented the maximum and minimum decrease, respectively. (2) Glacier change vulnerability level showed a decreasing trend in space from the central to the northwestern and southeastern regions with remarkable differences. Vulnerability level had increased significantly over time and was mainly concentrated in moderate, high and extreme levels with typical characteristics of phases and regional complexity. Our study can not only help to understand and master the impacts of recent glacier changes on natural and social aspects but also be conducive to evaluate the influences of glacier retreat on socio-economic developments in the future, thus providing references for formulating relevant countermeasures to achieve regional sustainable development.

Keywords: glacier change vulnerability; vulnerability level; spatiotemporal change; Qilian Mountains

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1 Introduction

Known as a huge natural "solid reservoir", glaciers have a double function of water resources and runoff regulation in arid areas of northwestern China (Sorg *et al*., 2012; Deng *et al*., 2019). On the one hand, glacial meltwater occupies an important proportion of surface runoff, such as it accounts for more than one-third of river runoff in the Shule River Basin (Immerzeel *et al*., 2010). On the other hand, glaciers play the role of "peak cutting and valley filling" on river runoff at intra- and inter-annual scales (Pritchard, 2017). Continuous glacier shrinkage has increased the instability of runoff in glacierized watersheds under the background of climate warming (Thayyen and Gergan, 2010; Huss *et al*., 2014; Farinotti *et al*., 2015), which in turn influences the ecological environment and sustainable development of the social economy (Immerzeel *et al*., 2010; Kraaijenbrink *et al*., 2017). How to deal with a series of impacts caused by glacier changes has become a strategic problem, which should be solved urgently. Glacier wastage and its vulnerability are the fundamentals to formulate countermeasures.

As a multi-functional concept, vulnerability indicates the extent to which humans and environmental systems may suffer damage due to external disturbance or coercion, which was originally used in natural disasters, and then widely used in the domains of climate change, ecological assessment, sustainable livelihoods and poverty (Li *et al*., 2005; Yu *et al*., 2011; Sahoo *et al*., 2016; Chen *et al*., 2018; Zhao *et al*., 2018; Wang *et al*., 2019; Détrée *et al*., 2020). Its connotation also changed correspondingly due to different research purposes. Especially since the 1990s, the vulnerability had become hot and cutting-edge research on global change and regional sustainable development (Su *et al*., 2010; Nguyen *et al*., 2016), which had gradually attracted the attention of the International Geosphere-Biosphere Program and the International Human Dimensions Programme on Global Environmental Change. For instance, the concept of vulnerability to climate change was put forward in the Fifth Assessment Report of IPCC (Intergovernmental Panel on Climate Change) (IPCC, 2014). Glacier change vulnerability is derived from the vulnerability to climate change and is generally understood as the sensitivity of various systems to the negative impact of glacier changes, including exposure, sensitivity and adaptability (Ding and Xiao, 2013; Yang *et al*., 2015). Now the international research on glacier change vulnerability had converted from conceptual and theoretical qualitative analysis to quantitative research, and its research contents mostly focused on: (1) the construction and measurement of glacier change vulnerability assessment system, different scholars scientifically and objectively select assessment factors based upon the characteristics of the study site, and use relevant models to calculate the vulnerability index (Immerzeel *et al*., 2020; Mustafa, 2020); (2) studies on the vulnerability of different systems to glacier changes, including human-environmental systems, socio-economic systems, water resources systems, and the impact of glacier changes on the regional water cycle and human society (Anderson and Radić, 2020). The commonly used vulnerability assessment methods of glacier change included vulnerability function model evaluation, a comprehensive index and fuzzy matter-element evaluation (Yang *et al*., 2015; Mustafa, 2020). However, factors such as fuzzy positioning of research purposes, poor spatial and temporal integrity of data, diversity of evaluation index systems, and differences in evaluation models were the main obstacles for vulnerability assessment (Tian and Chang, 2012). On the evaluation of regional glacier change vulnerability, the uncertainties of system elements and scales affect the objectivity and accuracy of the evaluated results, meanwhile, there was a contradiction between precision and breadth in the selection of indicators (He *et al.*, 2012), so it is difficult for us to study the vulnerability of glacier change in a long sequence and small scale. For one thing, regional sustainable development mainly focused on national, provincial or municipal scales. As the most direct management unit of ecology and social economy, counties had received little attention on the study of glacier change vulnerability. For another, regional sustainable development constantly involves data of each county, which were not always easy to obtain, so long-term study on glacier change vulnerability was relatively weak. It is therefore very urgent to implement the vulnerability of regional glacier change with long time series and small scale.

The Qilian Mountains host the main glacierized area in West China, abundant glacial water resources provide a strong guarantee for agricultural irrigation, industrial hydropower, residents and wetland eco-environmental protection in Qinghai and Gansu provinces (Sun *et al.*, 2018). Driven by global warming, glaciers had shrunk on a large scale in the Qilian Mountains, especially since the 1990s, which has contributed to the arrival of glacier runoff "peak water" (Gao *et al.*, 2011), which greatly weakens the regulation capacity of glaciers on runoff and indirectly affects the sustainable utilization of water resources (Zhang *et al.*, 2019). Strengthening the study of glacier changes and their vulnerability had important practical significance for regional water resources, ecological environment, and socio-economic development. Previous studies mainly focused on the changes and impacts of single glaciers, watershed glaciers (Liu *et al.*, 2018; Xu *et al.*, 2019) or regional glaciers (Sun *et al.*, 2018; Wang *et al.*, 2020), the vulnerability of glacier changes in the entire Qilian Mountains was currently missing. Thus, based on multi-source remotely sensed imageries, the Second Chinese Glacier Inventory, meteorological data and socio-economic data, this study systematically reveals the characteristics of glacier changes in the whole Qilian Mountains during the past 20 years and analyzes the vulnerability of glacier changes from the perspective of exposure, sensitivity and adaptability, to improve the insight and understanding of glacier change vulnerability in the Qilian Mountains and provide scientific guidance and decision-making support for responding to glacier changes and its effects.

2 Study site

The Qilian Mountains are located in the interior of the Eurasian continent (36°30′–39°30′N, 93°30′–103°00′E), extending from Wushaoling in the east to Dangjin Mountain in the west, connecting Qaidam Basin in the south and Hexi Corridor in the north (Chen *et al.*, 2015), with a total length and width of 800 km and 300 km (Sun *et al.*, 2020), respectively (Figure 1a). The Qilian Mountains are situated at the intersection of the three major climate regions of the monsoon, non-monsoon and Qinghai-Tibet Plateau (Dong *et al.*, 2014). Precipitation presented a decreasing trend from east to west with an average annual precipitation of 30–600 mm (Sun *et al.*, 2020). The mountainous area has complex natural conditions and big differences in hydrothermal conditions and belongs to a typical continental climate with an annual mean air temperature of 5 °C (Zhang *et al.*, 2012).

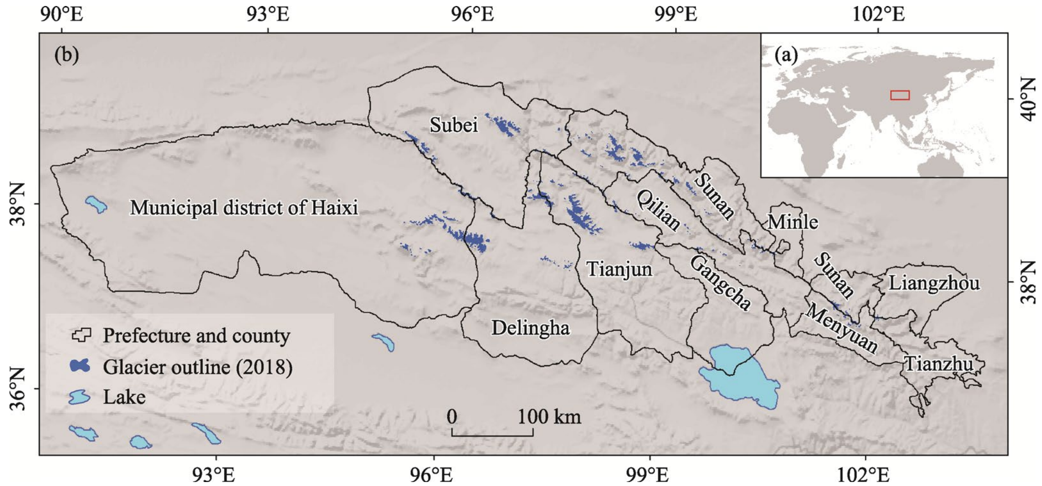

Figure 1 Location of the Qilian Mountains (a) and the 11 counties with glaciers distribution (b)

The towering terrain makes the glaciers widely distributed on the mountain above 4000 m a.s.l., which have become the main supply of river runoff, including the Hexi inner river system, Qaidam river system and the Yellow River Basin water system (Wang *et al.*, 2010). According to the Second Chinese Glacier Inventory, there were 2683 glaciers with an area and a volume of 1597.81±70.30 km^2 and 84.48±3.13 km^3, respectively (Liu *et al.*, 2015). The Qilian Mountains span Qinghai and Gansu provinces, involving 37 counties, glaciers situated in two autonomous prefectures (Haixi and Haibei) of Qinghai Province and three cities (Wuwei, Jiuquan and Zhangye) of Gansu Province, involving 11 counties (Figure 1b). Tianjun County contained the largest glacier area (431.09 km^2) and coverage rate (1.83%); glaciers in Delingha, Yugur Autonomous County of Sunan, Mongolian Autonomous County of Subei and municipal district of Haixi came the second, with a total area of 337.90 km^2, 265.18 km^2, 261.04 km^2 and 218.31 km^2, respectively, and the corresponding coverage rate was 1.29%, 1.36%, 1.01% and 0.24%, which was quite different. The total glacier area in Qilian County and Menyuan Hui Autonomous County was significantly different, being 53.05 km^2 and 19.33 km^2, respectively, but the coverage rates were relatively close (0.40% and 0.35%, respectively). The total glacier area and coverage rate in Liangzhou District, Minle County, Tianzhu Tibetan Autonomous County and Gangcha County were less than 5 km^2 and 0.20%, respectively.

3 Data and methodology

3.1 Input data

The original data used for glacier change vulnerability evaluation included Landsat images, digital elevation model (DEM), the Second Chinese Glacier Inventory, meteorological data and socio-economic data (Table 1).

We selected 16 Landsat 8 Operational Land Imager (OLI) images from 2016 to 2019 (3 Landsat 8 in 2016, 5 Landsat 8 in 2017, 7 Landsat 8 in 2018 and 1 Landsat 8 in 2019), 6 Landsat 5 Thematic Mapper (TM) and 8 Landsat 7 (Enhanced Thematic Mapper) ETM+ images from 1997 to 2001 (2 Landsat 5 in 1997, 4 Landsat 5 in 1998, 5 Landsat 7 in 1999,

Table 1 Data types and sources

Type	Time (year)	Resolution	Sources
Landsat images	1997–2001, 2016–2019	30 m	United States Geological Survey (https://glovis.usgs.gov/)
Glacier inventory	2005–2009	–	National Cryosphere Desert Data Center (http://www.ncdc.ac.cn/portal/)
DEM	2000	30 m×30 m	United States Geological Survey (https://glovis.usgs.gov/)
Meteorological data	1998–2018	0.5°×0.5°	National Meteorological Science Data Center (http://data.cma.cn/site/index.html)
Socio-economic data	2006 2018	—	Statistical Yearbook

2 Landsat 1 in 2000 and 1 Landsat 1 in 2001), with a spatial resolution of 30 m and cloud <5%, to reflect glacier distribution in 2018 and 1998, respectively. Note that the image acquisition dates were concentrated at the end of the ablation season to reduce the influence of snow cover. The paths and rows ranged from 132 to 137 and 033 to 034, respectively. The Landsat images were available from the United States Geological Survey (https://earthexplorer.usgs.gov/) and preprocessed with system radiation correction, geometric correction of ground control points and terrain correction. In addition, glacier distribution of 2006 was derived from the Second Chinese Glacier Inventory, which was available from the National Cryosphere Desert Data Center (http://www.ncdc.ac.cn/portal/), the methods used in the glacier inventory had been published by Guo *et al*. (2015). GNSS (Global Navigation Satellite System) surveys and high-resolution remote sensing images suggested that the inventory had high positioning accuracy and glacier area accuracy.

The Shuttle Radar Topography Mission (SRTM) DEM was used for glacier elevation determination, which was derived from C-band radar interferometry with a 30-m spatial resolution. The DEM was obtained from the United States Geological Survey (https:// earthexplorer. usgs.gov/) with the coordinate system of the World Geodetic System 1984 (WGS84). The relative and absolute vertical accuracy is 6 m and 16 m, respectively (Rabus *et al*., 2003). Air temperature and precipitation data used in this study for the period 1998–2018 were calculated from the 0.5°×0.5° monthly air temperature and precipitation gridded datasets, which were provided by the National Meteorological Science Data Center (http://data.cma. cn/site/index.html).

The 2006 and 2018 socio-economic data of the 11 counties with glacier distribution were collected from China County Statistical Yearbook (https://www.epsnet.com.cn/index.html), Gansu Development Yearbook, Gansu Rural Yearbook (http://tjj.gansu.gov.cn/), Qinghai Statistical Yearbook (http://tjj.qinghai.gov.cn/), as well as county or autonomous prefecture statistical yearbook, national economic and social development statistical bulletin (https://navi.cnki.net/KNavi/Yearbook.html).

3.2 Methodology

3.2.1 Glacier boundary delineation and uncertainty assessments

The uncertainty in glacier area includes systematical error and accidental error (Bolch *et al*., 2010). The errors caused by snow cover, mountain shadow, side debris and human misunderstanding can be regarded as the systematic error, which can be reduced by selecting high-quality remote sensing images, cooperating with multi-scene remote sensing images and improving glacier interpretation experience, but cannot be accurately estimated. Here the delineation of glacier boundary was implemented by manual visual interpretation with the help of Google Earth high-resolution image correction to reduce the systematic error. Remote sensing image resolution, spectral characteristics, debris, snow on the posterior wall of glaciers and differences in human understanding can be regarded as accidental error. Here we mainly considered the error related to image resolution since different factors can result in various errors in bare rock areas at the edge and inside of glaciers (Liu *et al.*, 2015). Thus, the uncertainty in glacier area (ε) caused by the image resolution can be determined by calculating the total number of pixels (N) at the edge of a glacier:

$$\varepsilon = N \times r^2 / 2 \tag{1}$$

where r denotes the spatial resolution of Landsat images (30 m) (Liu *et al.*, 2015; Sun *et al.*, 2018). The final calculated uncertainty in glacier area was ±71.53 km^2, ±70.30 km^2 and ±68.42 km^2 in 1998, 2006 and 2018, respectively. The uncertainty in glacier area change (ε_c) can be calculated based on the law of error propagation (Zemp *et al.*, 2013):

$$\varepsilon_c = \sqrt{\varepsilon_{t1}^2 + \varepsilon_{t2}^2} \tag{2}$$

where ε_{t1} and ε_{t2} represent two acquisition dates (t_1 and t_1) of glacier areas. The calculated value was ±100.29 km^2, ±98.98 km^2 and ±98.10 km^2, during the periods 1998–2006, 1998–2018 and 2006–2018, respectively.

3.2.2 Glacier volume estimation and uncertainty assessments

Ground-penetrating radar (GPR) is a well-established tool to evaluate individual glacier volume, but it is impossible for region-wide glacier volume estimates. The statistical volume-area scaling is one of the easiest and simplest approaches, which has been widely used for volume estimates of region-wide glaciers (Guo *et al.*, 2015; Gao *et al.*, 2018). Here we used this method to determine the glacier volume of the whole Qilian Mountains:

$$V_g = cA_g^{\lambda} \tag{3}$$

where V_g and A_g indicate glacier volume and area, respectively; c and λ indicate the scaling factors and are variables in different studies. Here we used c=0.0365 and λ=1.375 (Radić and Hock, 2010), c = 0.0433 and λ =1.29 (Grinsted, 2013), to estimate glacier volume, respectively.

The final calculated volume was the average value of the two scaling factors. Those scaling factors had also been used in the Second Chinese Glacier Inventory (Liu *et al.*, 2015). The uncertainty of volume (ε_V) estimates was determined based upon the error of glacier area:

$$\varepsilon_V = c\varepsilon^{\lambda} \tag{4}$$

The uncertainty in glacier volume was estimated to be about 3.18 km^3, 3.13 km^3 and 3.05 km^3 in 1998, 2006 and 2018, respectively. The uncertainty in glacier volume change was also calculated based on the law of error propagation (Zemp *et al.*, 2013).

3.3 Establishment of glacier change vulnerability assessment system

Under the guidance of the principles of objectivity, scientificity, comparability and operability, we considered the perspective of the man-land relationship as its starting-point and took counties as evaluation units, adopted the method of the gradual decline of the target layer, criterion layer and index layer, and integrated the natural geographical characteristics, population status, and social and economic level into the assessment system to comprehensively evaluate glacier change vulnerability in the Qilian Mountains (Figure 2 and Table 2).

Exposure indicates the adverse degree of external pressure or coercion on the system. The exposure degree of glacier change is the result of the combined effects of the stress on physiographical position, pressure on glaciers due to climate change and socio-economic affordability. Here we used the changes in glacier area and volume to characterize the nature exposure intensity of glacier changes. We adopted the altitude of glacier terminus and peak, and the mean glacier elevations to reflect the natural conditions of glacier development. Considering economic development status, the difference in the development rate, the process of urbanization, and the uneven population distribution of each county in the Qilian Mountains, the socio-economic exposure indicators are regional GDP, urbanization rate, population density, the added value of primary industry and crop planting area (Table 2).

Sensitivity refers to the response degree of each element in the socio-economic system to glacier changes. Glacier changing sensitivity is associated with climatic factors and agricultural activities, with a focus on the extent to which water resource utilization is affected or changed in human-oriented agricultural activities. On the one hand, air temperature is the basic condition for the formation and development of glaciers, solid precipitation is the mass prerequisite for the development of glaciers, both of which have a decisive foundation in the development, size and evolution of mountain glaciers. On the other hand, continuous glacier shrinkage will result in changes in hydrological processes and seasonal distribution of water

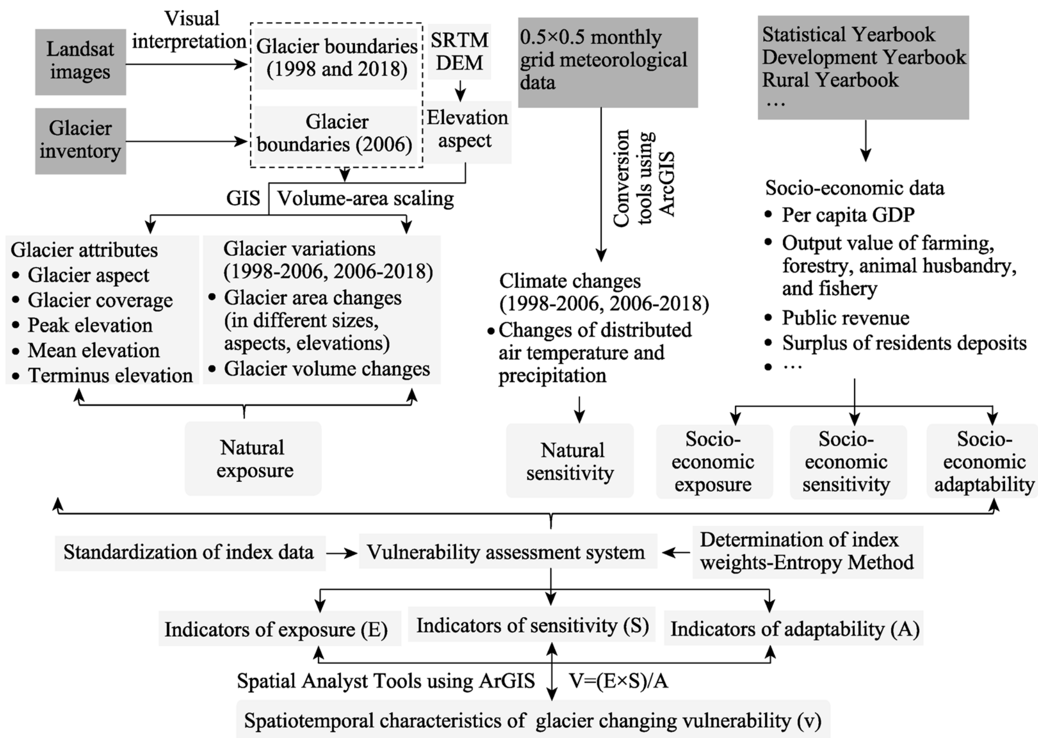

Figure 2 Vulnerability assessment structure of glacier change in the Qilian Mountains

Table 2 An index system for glacier change vulnerability assessment in the Qilian Mountains

Objective layer	Component	Indictor	Weight
Glacier change vulnerability	Exposure	Glacier area coverage (%)	0.09
		Glacier area change rate (%)	0.03
		Glacier volume change rate (%)	0.03
		Absolute variation of glacier area (km^2)	0.11
		Absolute variation of glacier volume (km^3)	0.13
		Average altitude of glacier tongue (m)	0.05
		Average altitude of glacier peak (m)	0.05
		Average altitude of glacier (m)	0.05
		Population density (person/km^2)	0.06
		Urbanization rate (%)	0.03
		Sown area (km^2)	0.10
		Primary industry added value (yuan)	0.12
		Gross domestic product (yuan)	0.15
	Sensitivity	Annual temperature change rate (%)	0.16
		Annual precipitation change rate (%)	0.26
		Total grain output (t)	0.11
		Effective irrigation area (km^2)	0.11
		Agricultural added value (yuan)	0.09
		Secondary industry added value (yuan)	0.17
		Tertiary industry added value (yuan)	0.09
	Adaptability	Per capita GDP (yuan)	0.04
		Output value of farming, forestry, animal husbandry, and fishery (yuan)	0.09
		Public revenue (yuan)	0.09
		Surplus of resident deposits (yuan)	0.15
		Urban disposable income (yuan)	0.03
		Per capita of rural net income (yuan)	0.02
		Total water supply (km^3)	0.14
		Number of students in ordinary secondary schools (person)	0.13
		Number of beds in hospital (bed)	0.12
		Total retail sales of consumer goods (yuan)	0.14
		Fixed asset investments (yuan)	0.06

resources, and then profoundly affect the sustainable development of the economy, society and population. Based on this, we characterized glacier changing sensitivity with air temperature and precipitation change rate, total grain output, effective irrigation area, the secondary and tertiary industrial increments (Table 2).

Adaptability means the total amount of effective and adaptive measures taken by human subjects under the influence of actual or predicted glacier changes. This study mainly considers the adaptability of glacier changes under the dual effects of social and economic systems. Per capita GDP, urban fixed-asset investment, total retail sales of social consumer goods and disposable income of urban residents reflect the overall economic development of the region and the economic strength of adjusting human society to adapt to glacier changes, to reduce potential losses or take effective measures in time to make the impact of glacier change develop in a good direction. Besides, the level of education and medical care is also the manifestation of economic development, which is attributed to the decisive role of socio-economic strength in adapting to glacier changes. The total amount of water supply reflects the capacity of living, production and ecological water use in the economic and social system. Glacier changes affected water resources, which indirectly influenced the total amount of domestic life, industrial production and ecological water consumption. The net income per capita of rural residents and the total output value of agriculture, forestry, animal husbandry and fishery reflect the level of regional agricultural development (Table 2). Glacier shrinkage will cause changes in water resources, which is the decisive factor for agricultural development, thus the change of water resources system plays a leading role in agricultural activities. In this context, the stronger the social and economic strength is, the stronger the degree of exposure, sensitivity and adaptability of glacier change is.

3.4 Evaluation model

(1) Standardization of index data

Since the differences in measurement units and each index data, we use the range standardization method to standardize the positive and negative index data to realize the dimensionless data and achieve comparability between the data (Ma *et al.*, 2015). Standardization of positive and negative indicators can be described as follows:

$$Y_{it} = \frac{X_{it} - X_{\min}}{X_{\max} - X_{\min}} \tag{5}$$

$$Y_{it} = \frac{X_{\max} - X_{it}}{X_{\max} - X_{\min}} \tag{6}$$

where Y_{it} is the index value after standardization with a range between 0 and 1. Here we replaced the value of 0 after standardization by one-tenth of the minimum value after dividing 0 in the index value to ensure that each index value is greater than 0. X_{it} is the original index value of area i and item t; $X_{\max}$ and $X_{\min}$ are the maximum and minimum values of the original index of item t, respectively.

(2) Determination of index weights–Entropy Method

The determination of indicator weight is a key link for vulnerability evaluation. Indicator weight is to clarify the importance of an indicator to the entire index system. We used the Entropy Method to determine the weight of the glacier change vulnerability evaluation index system to reduce the influence of human factors. The Entropy Method calculates the entropy weight of evaluation indicators based on the distribution or dispersion of evaluation indicators and uses information entropy (Constantin *et al.*, 2011). The weight was determined as follows:

the weight P_{it} of index item t in the year i:

$$P_{it} = \frac{Y_{it}}{\sum_{i=1}^{m} Y_{it}} \tag{7}$$

entropy e_t of index item t:

$$e_t = -k\sum_{i=1}^{m} P_{it}\ln(P_{it}) \tag{8}$$

otherness coefficient H_t of index item t:

$$H_t = 1 - e_t \tag{9}$$

the weight W_t of index item t:

$$W_t = \frac{H_t}{\sum_{i=1}^{m} H_t} \tag{10}$$

(3) Vulnerability evaluation model

Vulnerability is a function of system exposure, sensitivity and adaptability according to previous relevant studies and can be expressed as (Yang *et al*., 2015):

$$V = (E\times S) / A \tag{11}$$

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

(4) Rating system of vulnerability

We need to divide the vulnerability indexes into several levels to evaluate different vulnerabilities. The natural breakpoint method is based on the inherent natural grouping in the data, and the data is divided into discontinuous gaps, and similar values are grouped to maximize the difference of data at all levels. Here we used ArcGIS 10.2 software to classify the vulnerability index of each county: slight vulnerability ($0.07<V\leqslant 0.17$), light vulnerability ($0.17<V\leqslant 0.43$), moderate vulnerability ($0.43<V\leqslant 1.08$), high vulnerability ($1.08<V\leqslant 1.92$) and extreme vulnerability ($1.92<V\leqslant 3.04$).

4 Results

4.1 Glaciers variations

4.1.1 Spatiotemporal variations of glacier area

(1) Overall changes

Glaciers in the Qilian Mountains had shown pronounced shrinkage with a reduced value of 71.12±98.98 km^2 during the period 1998–2018. Specifically, glacier area reduced from 1626.01±71.53 km^2 in 1998 to 1597.60±70.30 km^2 in 2006 with an annual shrinkage rate of 1.75%. The shrinkage of glaciers mainly occurred in the period 2006–2018 with a relative reduction of 42.75±98.10 km^2, which was slightly higher than the former period, indicating a trend of accelerated reduction.

(2) Variation in different sizes, altitudes and aspects

We looked into the behaviors of glacier variation by analyzing statistically the relations between topographic parameters (size, altitude, aspect) and glaciers using the extracted glacier polygon data from 1998–2018. Figure 3 shows the relationship between glacier area and glacier change, according to the glacier size class (<0.1 km^2, 0.1–0.5 km^2, 0.5–1 km^2, 1–2 km^2, 2–5 km^2, 5–10 km^2, 10–15 km^2, 15–20 km^2, >20 km^2). Small glaciers with areas less than 1 km^2 occupied 34.0% of the total glacier area, and only one glacier (Laohugou Glacier No. 12) was larger than 20 km^2. Different sizes of glacier areas presented a shrinking trend over the whole investigated period except for area <0.1 km^2. In the whole period, the strongest shrinkage in the areal extent of those glaciers studied was in 5–10 km^2 (13.44%), followed by 10–15 km^2 (8.83%) and 1–2 km^2 (7.45%). In contrast, small decreases in glacier area were found in 0.1–0.5 km^2, 0.5–1 km^2, 2–5 km^2, 15–20 km^2 and >20 km^2, corresponding shrinking rate was 1.72%, 0.63%, 1.42%, 2.49% and 1.06%, respectively (Figure 3).

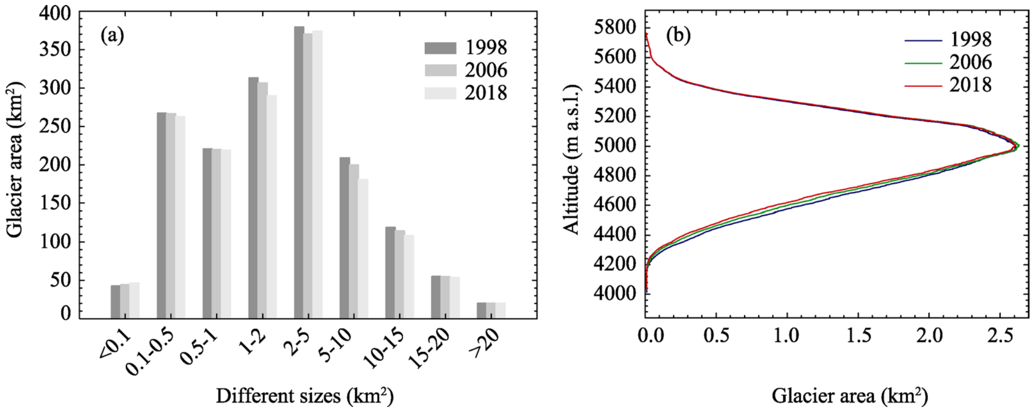

Figure 3 Changes in glacier area by glacier size (a) and altitude (b) in the Qilian Mountains during 1998–2018

Glacier area elevation distribution derived from the three investigated years remained similar, the area appeared to be normally distributed and most developed in the elevations between 4800 and 5200 m, with a combined area of 926.06±68.42 km^2 in 2018, which accounted for 58.4% of the total glaciers (Figure 3b). Comparison among the three years suggested that area reduction took place at the lower-elevation regions below 4800 m, and the shrinking rate was 2.1% and 2.5% during 1998–2006 and 2006–2018, in particular in the elevations ranging from 4400 m to 4600 m. The abovementioned changing patterns may be attributed to glacier terminus retreat, indicating that climate status in different elevations influenced the behavior of glacier variations, and glacier ablation in the lower elevations was promoted by higher temperature and lower solid precipitation (Figure 3b).

Further examination of the relationship of glacier areas and aspects throughout the period indicated that the majority of the glaciers were oriented northward, followed by north, northwest and northeast, with an area of 434.49±19.12 km^2, 316.78±13.94 km^2 and 295.25±12.99 km^2, accounting for 27.49%, 20.31% and 18.99% of the total glacier area, respectively. Meantime, all aspects demonstrated a recession, the largest area variation emerged in the northward aspects (northwest, north, and northeast), nevertheless, shrinking by 50.08±2.20 km^2 or 4.5% of the total glacier area. There were roughly the same glacier areas on the east and west aspects, whereas the reduced area and rate of the former (8.00±0.42 km^2, 5.6%) were higher than the latter (3.85±0.20 km^2, 2.6%). We found that although the glacier area in the southeast aspect was less than 100 km^2, its glacier area manifested a remarkable recession. Compared with other aspects, glaciers in the south and southwest aspects presented relatively smaller shrinkage with values of 1.76±4.15 km^2 and 1.36±4.85 km^2, respectively (Figure 4).

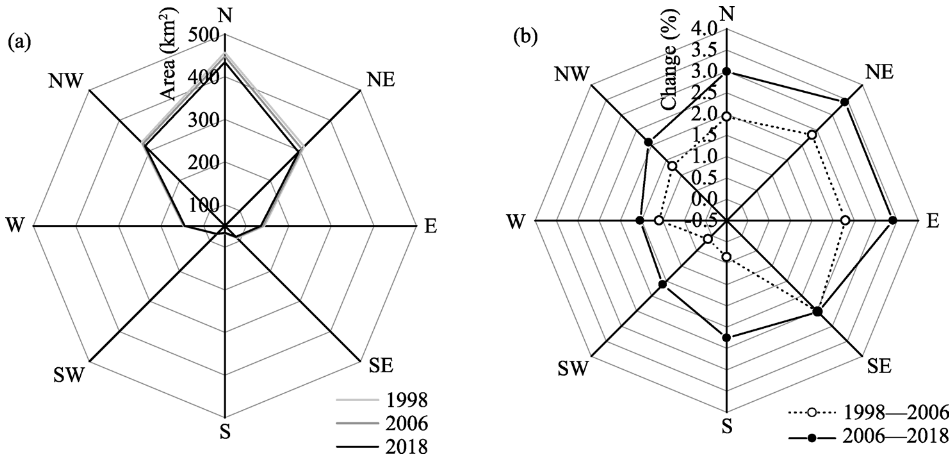

Figure 4 Distribution of glacier area (a) and their changes (b) according to aspect in the Qilian Mountains during 1998–2018

(3) Changes in different counties

The spatially distributed glaciers of each county or autonomous prefecture presented a distinguishing difference (Figure 5). The glaciers in the study region were mostly concentrated in Haixi of Qinghai Province, with an area of 965.40±29.16 km^2, accounting for 62.1% of the total area. In light of the proportion of glacier area in Haixi Prefecture, the area in Tianjun was the greatest, followed by Delingha and municipal district of Haixi, accounting for 43.4%, 34.4% and 22.2% of the Haixi area, respectively. The mean glacier area of all counties in Qinghai Province was approximately 172.70±8.03 km^2, whereas in Haibei, only 23.59±1.22 km^2. Therefore, the glacier area in Haibei was the lowest compared with Haixi, especially Gangcha with an area of only 1.11±0.06 km^2, while Qilian and Menyuan were slightly higher with values of 50.81±2.63 km^2 and 18.86±0.98 km^2, respectively.

The total glacier area in Gansu Province was about half of that of Qinghai Province, which was overwhelmingly centered in Zhangye and Jiuquan, where the glacier size was relatively large, the corresponding area occupied 50.2% and 48.4% of the total glacier, respectively. Wuwei had the least glacier area with a total value of 6.77±0.30 km^2. We examined the features of glacier distribution in each county of Gansu Province, which clearly indicated that the glacier area of Subei and Sunan was 25 times the total glacier area of Liangzhou, Tianzhu and Minle, revealing that glacier area distribution of Gansu Province was significantly different.

The glacier area shrinking rate in 11 counties of the Qilian Mountains was prominently different in the study period. The higher speed recession in the glacier area existed in Tianjun with a reduced area of 19.27±26.67 km^2, followed by Sunan and Delingha, with a reduced area of 17.40±16.31 km^2 and 11.21±20.99 km^2, respectively. Subei and municipal district of Haixi, where the total glacier area both greater than 200 km^2, had a slightly decreased area of 8.95±16.16 km^2 and 6.26±13.57 km^2, respectively. The minimized recession of glacier area by 0.26±0.27 km^2 in Liangzhou, 0.18±0.25 km^2 in Tianzhu, 0.12±0.07 km^2 in Gangcha, and 0.11±0.21 km^2 in Minle, was probably owing to those regions possessing the smallest glacier area. The recent glacier recession (2006–2018) occurred at a higher rate than that of 1998–2006, except for Qilian, Gangcha and Menyuan (Figure 5).

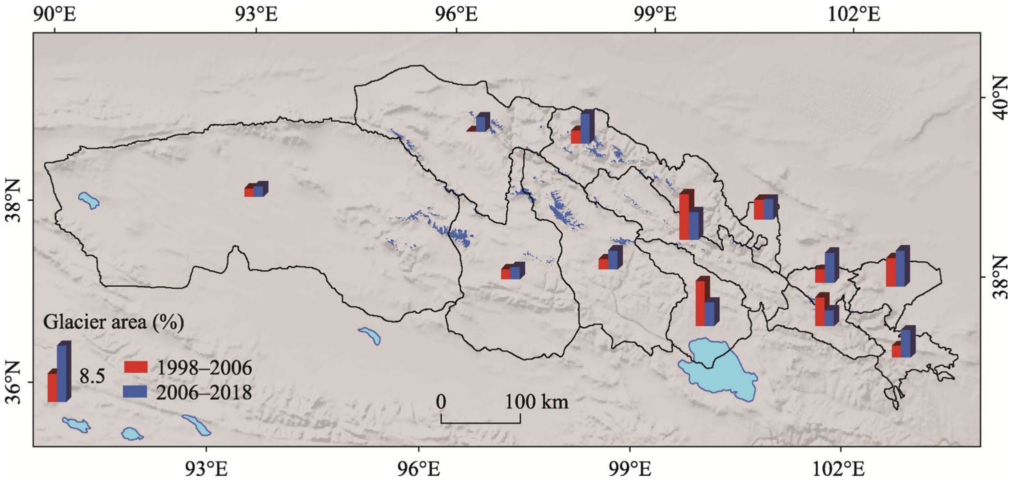

Figure 5 Glacier area reduction in different counties in the Qilian Mountains during 1998–2018

4.1.2 Glacier volume

Glacier volume in the Qilian Mountains decreased from 86.29±3.18 km^3 in 1998 to 80.70±3.05 km^3 in 2018 with a reduced value of 5.59±4.41 km^3. Especially for 2006–2018, glaciers exhibited the greatest volume loss and the corresponding decrease was 3.78±4.37 km^3. On balance, we found an apparent wastage in glacier volume for the full investigated period.

Among the 11 counties, total glacier volume loss varied from 0.01±0.002 km^3 (Gangcha, Tianzhu and Minle) to 1.37±0.73 km^3 (Sunan), with the value of 1.00±0.60 km^3 for the municipal district of Haixi, 1.36±0.66 km^3 for Delingha, 1.14±1.19 km^3 for Tianjun, 0.42±0.15 km^3 for Qilian, 0.04±0.05 km^3 for Menyuan, 0.02±0.01 km^3 for Liangzhou, and 0.59±0.72 km^3 for Subei. The decreasing rate ranged from 4.3% to 53.5% among the 11 counties over the whole period. The higher rate occurred in the regions where relatively smaller glacier areas were covered, such as Tianzhu and Minle.

The greatest volume loss occurred in Sunan, Delingha and Tianjun for the whole period, with the reduced value of 1.37±0.73 km^3, 1.36±0.66 km^3 and 1.14±1.19 km^3 each, and the corresponding relatively changing rate was 12.2%, 4.9% and 5.7%, respectively. While the smaller loss of glacier volume appeared in Gangcha, Liangzhou, Tianzhu and Minle, the diminished value was almost close to 0 km^3. The average decreased value in glacier volume of the 11 counties varied from 0.17±0.41 km^3 during 1998–2006 to 0.40±0.39 km^3 during 2006–2018. In respect to the 11 counties in recent years of 2006–2018, Delingha, Tianjun and Sunan presented higher values (0.95±0.66 km^3, 0.96±0.84 km^3 and 0.99±0.52 km^3, respectively) compared with the average volume loss. These counties are characterized by larger glacier area coverage.

4.2 Spatial pattern of vulnerability

4.2.1 Spatial characteristics of exposure

Here we divided the value of exposure into five levels: slight (0–0.1], light (0.1–0.2], moderate (0.2–0.3], high (0.3–0.4] and extreme (>0.4), and high values indicate greater exposure (Figures 6b and 7b). In 2006, moderate exposure levels had the largest number of counties, followed by high and extreme exposure levels, and the percentage of slight and light exposure levels was the least, whereas the area of high exposure level was the largest, accounting for 51.0% of the total area. In 2018, low exposure levels showed the largest number of counties, followed by high and extreme exposure levels. Moderate exposure level had the least number of counties, occupying 9.1% of the total counties with a decreased rate of 36.4% compared with 2006. The counties with a slight exposure level were non-existent and the high level still had the greatest area proportion.

We found that an upward trend in the exposure index, a mean value increased from 0.28 in 2006 to 0.30 in 2018. The spatially distributed map showed the total number ratio of light, high and extreme exposure levels had increased from 2006 to 2018, while the total percentage of the slight and moderate levels had descended, manifesting a gradually raised trend of exposure in the Qilian Mountains. Additionally, the exposure level of the two years presented a decreased trend from the northwest to the southeast. The counties with high and extreme exposure levels were primarily located in the northwest, covering the municipal district of Haixi, Delingha and Tianjun, with the exposure of 0.40, 0.45 and 0.53 in 2018, respectively. While the moderate and below exposure levels were mainly situated in the middle and southeast of the regions, including Qilian, Minle, Tianzhu, etc., except for Liangzhou. To probe the variation tendency of exposure, we calculated the changing rate from 2006 to 2018 in the Qilian Mountains, a significant raising tendency mainly occurred in the northwest portion of Subei and Sunan, with the rate of 31.1% and 35.2%, respectively. The downward trends were largely concentrated in the middle part of Gangcha, Menyuan, Qilian, etc.

4.2.2 Spatial characteristics of sensibility

As shown in Figures 6c and 7c, we classified the results of sensibility assessment into five levels, including slight (0–0.2], light (0.2–0.4], moderate (0.4–0.6], high (0.6–0.8] and extreme (0.8–1]. In 2006, the moderate and high sensibility levels played a significant role in the study region, the total numbers of counties and area ratios were 9.0% and 95.0%, respectively. Slight and extreme sensibility levels covered the counties with the fewest number and area. In 2018, eight counties presented moderate and high sensibility levels, which occupied 90.3% of the total area, indicating a slow descent compared with 2006. Besides, the number of counties with extreme sensibility level had increased by 1, with a total of 2. The number and area proportion of slight sensibility level counties remained minimum with the values of 1 and 2.6%, respectively.

The spatially distributed sensibility level of the two years demonstrated that moderate, high and extreme levels were dominated. The sensibility index showed a tendency of increasing during 2006–2018, with a mean value rising from 0.59 to 0.68, at a high level. The spatial distribution of sensibility was significantly different, showing that the sensibility level increased from the northwest to the southeast in 2006.

Compared with 2006, the spatially distributed sensitivity of 2018 presented high and extreme levels, which had replaced extreme and moderate levels, and the distribution range of high and extreme sensitivity was dominated. One high sensitivity county, four extreme sen sitivity counties and five moderate sensitive counties of 2006 changed into two high sensitivity counties, seven extreme sensitivity counties and one moderate sensitivity county in 2018, respectively. The number of counties with the moderate level was constant but its

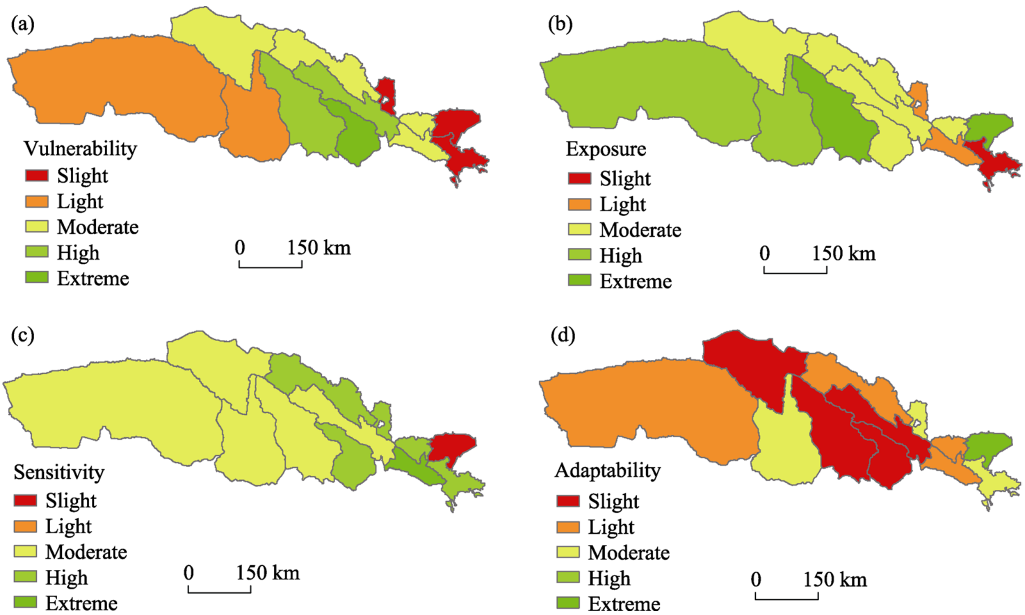

Figure 6 Spatially distributed vulnerability level of the glacier changes in the Qilian Mountains in 2006

sensitivity increased significantly. To be specific, Delingha, Tianjun, Qilian and Subei changed from moderate to extreme sensitivity; Gangcha became from extreme to high sensitivity, with a sensitivity index as high as 0.85; for the municipal district of Haixi, the sensitivity index increased from 0.42 to 0.58, but its level did not change. In addition, only the sensitivity of Liangzhou was always at a level of slight. In general, the sensitivity of glacier change in the Qilian Mountains was mainly dominated by moderate or above levels, accounting for 97.4% of the total area.

4.2.3 Spatial characteristics of adaptability

We divided the adaptability into five levels: slight (0–0.2], light (0.2–0.4], moderate (0.4–0.6], high (0.6–0.8] and extreme (0.8–1], based upon the results of adaptability and regional characteristics. The adaptability of 2006 and 2018 was mainly dominated by slight and light levels in the Qilian Mountains, including seven counties with a percentage of 82.3%. Four counties had moderate and above adaptability levels and one county showed a high level, the counties of moderate adaptability changed from three to two and high adaptability increased from zero to one. The mean adaptability index of all counties increased from 0.34 in 2006 to 0.37 in 2018, with a level of slight, but the corresponding adaptability showed an upward trend.

The spatially distributed map showed that low values of adaptability were concentrated in the northwest and central regions, and high values were scattered (Figures 6d and 7d). Significant differences in adaptability occurred in northwestern, central and southeastern regions. The adaptability in northwestern, central, and southeastern regions showed obvious differences, slight and light value of adaptability mainly distributed in the municipal district of Haixi, Gangcha, Tianjun and Subei. Among them, Gangcha had the lowest adaptability, with a value of 0.05 in 2006 and 0.12 in 2018, respectively. The moderate and above adaptability levels were located in Delingha, Minle, Tianjun and Subei. The sorted adaptability was generally low, and the area proportion of moderate and above adaptability levels accounted for 17.7%.

4.2.4 Spatial characteristics of vulnerability

The vulnerability index of 2006 was in the range of 0.08–3.04. The vulnerability level of the Qilian Mountains was dominated by slight, light and moderate levels, which accounted for 79.4% of the total area. The central region had a significantly higher vulnerability level compared with other regions, among which Gangcha was at a high vulnerability level, Tianjun and Qilian presented extreme level; the northwestern and southeastern regions had a relatively lower vulnerability, among those, the municipal district of Haixi and Delingha were in slight vulnerability level. Tianzhu, Liangzhou and Minle were at a light vulnerability level. The distribution of moderate vulnerability level was relatively scattered, which was mainly situated in Subei, Sunan and Menyuan. In brief, the glacier change vulnerability of the Qilian Mountains decreased in space from the center to the northwestern and southeastern regions (Figure 6a).

The vulnerability index of 2018 ranged from 0.07 to 2.70, and the overall vulnerability was led by moderate and high levels, which accounted for 82.3% of the total area. Compared with 2006, the central area was still seriously vulnerable with extreme vulnerability level, but the area of high level had increased. The municipal district of Haixi had evolved from low to high vulnerability levels. Sunan and Subei had changed from moderate to high vulnerability levels, and the impact of glacier change on the system was significantly enhanced. Liangzhou and Tianzhu in the southeast still belonged to low vulnerability levels. The vulnerability showed a decreasing trend in space from the central to the northwestern and southeastern regions, that is, the central region had high and extreme vulnerability. The northwestern region presented moderate and high vulnerability, and the southeastern region showed slight and light vulnerability (Figure 7a).

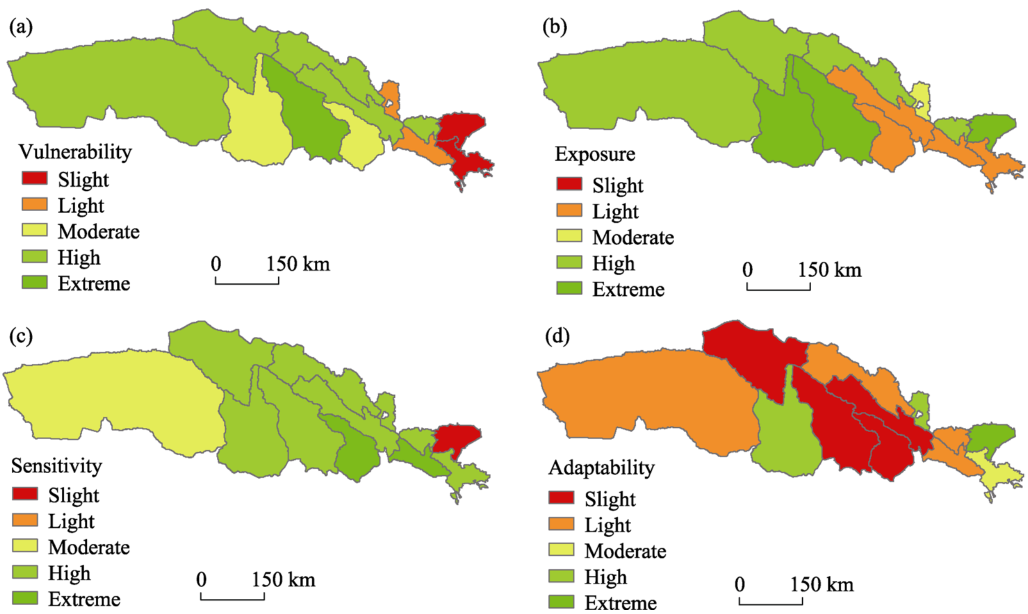

Figure 7 Spatial distributed the vulnerability level of the glacier changes in the Qilian Mountains in 2018

In terms of quantity, the corresponding county area proportions of different vulnerability levels in the Qilian Mountains were significantly different for the two studied years. In 2006, the proportions of counties with slight, light, moderate, high and extreme vulnerability levels were 6.4%, 51.0%, 22.0%, 15.9% and 4.7%, respectively, among which the area of low vulnerability level was the largest and high vulnerability level was the smallest. In 2018, the proportions of areas with slight, light, moderate, high and extreme vulnerability levels were 5.1%, 2.4%, 17.3%, 65.0% and 10.2%, respectively. Among them, the area of counties with extreme and light vulnerability levels accounted for the largest and smallest proportion, respectively. Indicating the area proportion of counties with slight and light vulnerability decreased from 57.4% to 7.5%, and the area proportion of counties with high and extreme vulnerability increased from 20.6% to 76.2%. Apparently, glacier change vulnerability has increased, which was mainly located in moderate, high and extreme vulnerability levels, the changing patterns of vulnerability presented typical stage and regional complex characteristics.

4.2.5 Characteristics of vulnerability transformation matrix

We calculated glacier change vulnerability transformation matrix of the Qilian Mountains for the whole period, which can reflect the area conversion relationship of different glaciers change vulnerability levels in a certain period. Besides, the two-dimensional matrix includes areas where the level of vulnerability has not changed. The glacier change vulnerability conversion matrix is:

$$F_{ij} = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1x} \\ a_{21} & a_{22} & \cdots & a_{2x} \\ \vdots & \vdots & \vdots & \vdots \\ a_{x1} & a_{x2} & \cdots & a_{xx} \end{bmatrix} \tag{12}$$

where a is glacier area, x is the number of glacier change vulnerability levels, i is the levels of glacier change vulnerability before conversion, j is the levels of glacier change vulnerability after conversion, F_{ij} is the area of the vulnerability levels within a conversion period.

From 2006 to 2018, the area of glacier change vulnerability from slight to moderate vulnerability level was 2904.11 km^2, but the area of slight vulnerability level was 11,883.84 km^2. The area of light vulnerability converted to a moderate vulnerable level was 26,138.91 km^2, whereas the area from light to high vulnerability level was relatively large (91,848.23 km^2). The moderate vulnerability level area changed into light and high levels. The vulnerable area of light transforming into an extreme level was 23,518.52 km^2, and the unchanged area of light vulnerability level was 13,134.26 km^2. The area of extreme vulnerability level becoming moderate level was 10,959.84 km^2 (Table 3).

From 2006 to 2018, the areas with increased glacier change vulnerability classification approached 82.1% of the total area, whereas the unchanged and reduced area proportion of

Table 3 Glacier change vulnerability transformation matrix in 2006–2018

2006	2018				
	Slight	Light	Moderate	High	Extreme
Slight	11883.84	0.00	2904.11	0.00	0.00
Light	0.00	0.00	26138.91	91848.23	0.00
Moderate	0.00	5550.26	0.00	45363.25	0.00
High	0.00	0.00	0.00	13134.26	23518.52
Extreme	0.00	0.00	10959.84	0.00	0.00

vulnerability levels accounted for 10.8% and 7.1% of the total area, respectively. Consequently, the overall glacier change vulnerability of the study area in the entire period had increased gradually, and the glacier was continuing to retreat. For the internal change of varying vulnerability levels, the vulnerability level of light had the greatest percentages with an increased vulnerability of 51.0%. The area proportion of moderate and high vulnerability levels were subjected to increased vulnerability at 19.6% and 10.2% of the total area.

Hence, the vulnerability of glacier change reflected the influencing degree to the socio-economy adversely affected by glacier change, especially the percentage of increased vulnerability level indicated the temporal trend of the vulnerability of glacier changes. For this reason, we should focus on the regions with increased vulnerability levels to formulate the corresponding countermeasures when studying the vulnerability of glacier changes in a certain region.

5 Discussion

5.1 Reliability of glacier variations

As we know, remote sensing images and glacier boundary delineating methods may cause the difference in glacier area, this study used visual interpretation to delineate glacier boundary based on existing glaciological knowledge, which was the most credible method to retrieve glacier boundary (Raup *et al.*, 2007). Nevertheless, the reliability of our study should be evaluated. Three approaches can be used to evaluate the reliability of glacier boundary delineation, including validation of the glacier boundary using ground-based field surveys, previous similar results and the interpretation of higher resolution remote sensing images. Here we mainly compared our results with previous similar studies since the lack of in-situ surveys. An updated GAMDAM glacier inventory over high-mountain Asia provided that the total glacier area in the Qilian Mountains was 1625.61 km^2 from 1997 to 2004 (about 90.0% of the total glacier number were delineated during the period 2000–2002), which was very close to our result (1626.01±71.53 km^2 in 1998, most of the images acquired in 1998, 1999 and 2000) (Sakai, 2019), confirming the reliability of glacier area in 1998. In addition, He *et al*. (2019) compiled a new inventory of glaciers in the Qilian Mountains using Landsat Operational Land Imager (OLI) images acquired in 2015 and identified 2748 glaciers that covered an area of 1539.30±49.50 km^2, which was thus similar to our results (1554.85±68.42 km^2 in 2018, most of the images acquired in 2017 and 2018). The difference between the two results was only 15.55 km^2 (accounting for 1.0% of the total glacier area in 2018) and was within the error range of the glacier inventory (1489.80– 1588.80 km^2). The relatively larger glacier area in our studies may be related to the interpretation method and remote sensing images. Considering the uncertainty of each study, glacier variations provided in this study were promising.

5.2 The behavior of glacier variations

Glaciers in the Qilian Mountains presented a shrinking trend with obvious regional differences during the study period. Solid precipitation is the mass requirement for glacier development, and low air temperature is the basic condition for glaciations. As mentioned above, the Qilian Mountains belong to a typical continental climatic setting, rain and heat occur simultaneously during the summer months (May to September), and the glaciers are typical summer-accumulation types. The distribution of precipitation and the concentration-time of maximum precipitation within a year will also influence the accumulation and ablation of glaciers. The heat entrapped by the liquid water components in summer precipitation will enhance glacier melting. Air temperature of the 11 counties generally increased, especially in the recent 10 years, whereas precipitation showed a slight increase for most counties. The continuous increase of air temperature was the main factor for the accelerated shrinkage of glaciers in the Qilian Mountains. The obvious decreases in glacier volume in Tianjun, Delingha and Sunan glaciers were mainly due to the increase in summer temperatures (Figure 8).

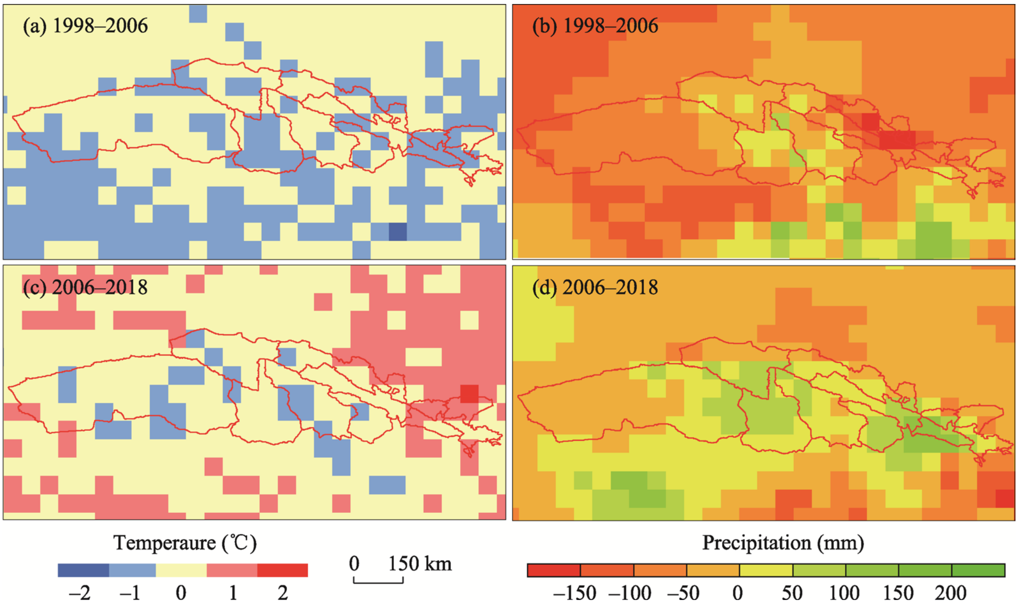

Figure 8 Variations of summer (May-September) temperature (a, c) and annual precipitation (b, d) in the Qilian Mountains during 1998–2018

Geographical conditions are another important consideration affecting glaciations. The relative altitude difference of the mountains above the snow line determines the number, scale and shape of glaciers. The higher the mountain altitude is, the lower the temperature is, the more water vapor is intercepted, and the larger the glacier accumulation area is possible. Therefore, the altitude of the glacier peak determines the amount of mass supply, while the altitude of the glacier terminus determines the amount of ablation (Cuffey and Paterson, 2010). Such as, the absolute reduction of glacier area and volume was large in Sunan, which may be attributed to the low altitude of the glacier terminus and peak, resulting in relatively strong melting at the ablation area and small mass supply at the accumulation area (Figure 9).

In addition, surface albedo plays a key role in the feedback process between air temperature and glacier ablation. The increased air temperature strengthened the deterioration and melting of snow and ice, the melting of glaciers accelerated, the equilibrium line increased, and glacier ablation area increased, leading to the decrease of glacier surface albedo, which further resulted in glacier mass loss (Qu *et al.*, 2014). For example, the equilibrium line altitude of the Qiyi Glacier had shown an increasing trend in the recent 50 years and the accumulation area ratio had decreased, resulting in the decrease of the average surface

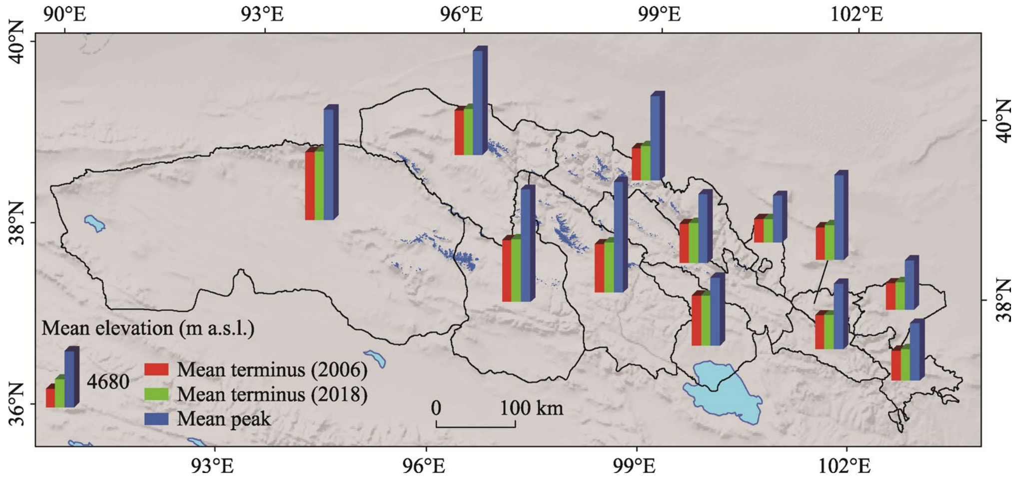

Figure 9 Spatial distribution of mean terminus and peak of glaciers in different counties

albedo (Xu *et al*., 2012). What's more, light-absorbing substances in the atmosphere, such as black carbon, organic carbon, and the dust settled on glacier surfaces will also reduce the albedo (Ming *et al*., 2013). The contribution of black carbon and dust in snow and ice to albedo reduction is about 15%–40% during the ablation season of Laohugou Glacier No.12 in the Qilian Mountains, which caused net ablation is up to 200–400 mm w.e. (Zhang and Kang, 2017). Hence, glacier surface ablation and albedo feedback mechanism under global warming are the major factors for accelerated glacier ablation (Tedesco *et al*., 2011). As one of the basic physical parameters, the increase of glacier temperature will reduce cold storage and accelerate glacier melting (Sun *et al*., 2017). The latest studies suggested that the thickness of Laohugou Glacier No.12 at the ablation area was larger, which caused a greater contribution to the bottom strain heat. At the same time, the warm ice in the grain-snow region was transported downstream and inside of the glacier, resulting in the presence of warm ice at the bottom of the ablation area, which also further resulted in glacier mass loss (Ding *et al*., 2019).

5.3 Spatial patterns of vulnerability differences

The index of glacier change vulnerability in the region between the municipal district of Haixi and Sunan increased by approximately 0.72 and 0.51, respectively, from 2006 to 2018, which was the greatest change in the whole Qilian Mountains. The increased vulnerability rate of Delingha, Tianjun, Tianzhu, Minle and Subei was lower than the municipal districts of Haixi and Sunan. On the contrary, the index of glacier change vulnerability in Qilian, Gangcha, Menyuan and Liangzhou had decreased with the largest value of 2.14.

The above results indicated that the regions with increased glacier change vulnerability exhibited high exposure, high-sensitive system environment and low-level adaptability. High exposure areas mainly had the characteristics of high glacier coverage, high relative and absolute changes of glacier area and volume. Socio-economic aspects are characterized by the continuous improvement of economic development level, accelerated urbanization process and the increase of population density, which makes the natural volume and socio-economic volume increase under the interaction of nature and social economy, resulting in a significant increase in the system's exposure to glacier changes (Ding and Yang, 2019). On the one hand, air temperature and precipitation changing rates of the highly sensitive area are closely related to glaciers, air temperature determines the glacier melting and solid precipitation dominates glacier accumulation, the combined functions of air temperature and precipitation determine the formation, development and evolution of the glaciers (Ding and Xiao, 2013). On the other hand, glaciers and their run-off supply directly affect the utilization of water resources in agricultural activities and indirectly affect the yield and value of crops. Various production activities are also closely related to water resources in the process of economic development. In short, regions with high glacier changing sensitivity have obvious changes in air temperature and precipitation, relatively low levels of socio-economic and agricultural development, and a highly sensitive system environment. The adaptability of glacier changes highly was connected with the level of regional socio-economic development. The level of entire regional economic development and whether it has the economic ability to take high-level and high-tech adaptive measures are the key considerations to deal with the impact of glacier change. Besides, the development levels of education, healthcare and agriculture also indirectly reflect the regional economic strength. Therefore, regions with low-level adaptability mainly meant that their socio-economic development is relatively slow, and the existing economic strength still needs to be enhanced. In contrast, most areas with reduced glacier change vulnerability had low-exposure and low-sensitivity system environments and high-level adaptability, except for Liangzhou. The glacier area coverage rate of Liangzhou was only 6.0%–7.0%, the absolute change rate of glacier area and volume was small but its relative change rate was relatively large. In addition, the population density of the county was relatively high, the level of urbanization continued increasing and the economic development was good, which had led to a relatively large natural and socio-economic volume and high exposure. Therefore, Liangzhou owned the lowest sensitivity and the highest level of adaptability although it had a high degree of exposure. The interaction of the three groups of dimensions resulted in low vulnerability.

5.4 Effectiveness of the vulnerability division and the results

In this study, three groups of dimensions—exposure, sensibility and adaptability—were synthesized using a vulnerability evaluation model to reflect multiple features of glacier change vulnerability in the Qilian Mountains. However, different division methods of glacier change vulnerability may have an uncertain impact on the outcomes. The natural breaks method, also known as the Jenks natural breaks classification method (Smith *et al*., 2015), is a classic analysis tool used to present and identify regional spatial differentiation characteristics in geographic research. The division is based on the univariate classification method in clustering analysis. When the number of classes is determined, the data breaks between classes are calculated iteratively to minimize differences in the classes and maximize differences between the classes. This method is used as the basis for the establishment of discontinuities and the natural classification of sub-regions to group the similar values in the data most appropriately and eliminate the interference of human factors as far as possible to keep the statistical characteristics of the data.

This study used the classification method to classify the glacier change vulnerability into five grades, in order to evaluate the precision of the division results. The comparative research on the different partition methods found the natural breaks method had advantages in high accuracy, simple algorithm and strong generalization, which was suitable to analyze the spatial distribution of glacier change vulnerability in the Qilian Mountains. Previous studies also adopted the natural breaks method to classify the vulnerability of glaciers to climate change (Yang *et al*., 2015). Therefore, the division results were reliable.

6 Conclusions

Taking the Qilian Mountains in China as an example, we analyzed the spatial and temporal characteristics of glacier changes based on remote sensing images and the Second Chinese Glacier Inventory. We estimated the basic organizational framework and evaluation index system of glacier change vulnerability from exposure, sensitivity and adaptability, which covered the factors of physical geography, population status and socio-economic level, to reveal the spatial and temporal evolution characteristics of glacier change vulnerability.

Our results suggested that glacier area and volume decreased by 71.12±98.98 km^2 and 5.59±4.41 km^3, respectively, from 1998 to 2018. The reduction of glacier area below 4800 m was relatively large with an area shrinking rate of 2.5%. Glacier area showed a decreasing trend in all aspects, and the area in the northward aspects (northwest, north and northeast) had the largest decrease (50.08±2.20 km^2). Different counties exhibited remarkable discrepancies in glacier area reduction, Tianjun exhibited the largest area decrease (19.27±26.67 km^2), Minle had the least glacier shrinkage with a reduced area of 0.11±0.21 km^2, other counties were in between.

Spatially, the vulnerability level decreased from the central region to the northwestern and southeastern regions with the highest level in the central region. The northwestern region came the second, and the southeast was the lowest. In terms of time, the vulnerability areas of slight and light levels decreased significantly, the areas of high and extreme levels increased significantly, and the rating presented an obvious increase, which mainly concentrated in medium, high and extreme vulnerability levels. The changes in glacier vulnerability had typical characteristics of phases and regional complexity.

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