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Simulation of permafrost distributions in the Qilian Mountains using a multi-criteria approach

Wenjie Zhang [a,c], Weiming Cheng [a,*], Zhoupeng Ren [a,c], Yingbo Gao [b,c], Jin Chen [a], Baolin Li [a], Chenghu Zhou [a]

[a] State Key Laboratory of Resources and Environmental Information System (LREIS), Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences (CAS), Beijing 10010, China
[b] State Key Laboratory of Remote Sensing, Institute of Remote Sensing and Digital Earth, CAS, Beijing 10010, China
[c] University of Chinese Academy of Sciences, Beijing 100049, China

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ABSTRACT

Permafrost is a physical geographic phenomenon that is sensitive to temperature, and climate change has a great effect on alpine permafrost distributions. Based on topographic and meteorological factors and a benchmark map of alpine permafrost distribution, this paper puts forward a GIS-based empirical permafrost model. This model uses a multi-criteria approach to derive the permafrost distribution in 5-year intervals in the Qilian Mountains over the past 30 years. The simulation results show that: (1) the model can use multiple factors to simulate alpine permafrost, which can reduce dependence on field survey data. (2) The simulated distribution of alpine permafrost presents an overall degraded tendency, about 17.11% of which has decreased over the past 30 years. (3) Based on the climate change tendency, simulated Qilian permafrost will continue to degrade about 0.51×10^4 km^2 over the next 15 years.

1. Introduction

The cryosphere is not only a significant repository of paleoclimate and ancient environments, but an important indicator of climate change. As a main component of the cryosphere, permafrost, a physical geographic phenomenon, is extremely vulnerable to climate and environmental changes. Permafrost distribution change is one of the most sensitive indicators of climate change (Anisimov and Reneva, 2006; Guglielmin and Dramis, 1999; Jiang et al., 2003). Numerous studies have shown that the global climate changed much in the 20th century and the climate warming degraded alpine permafrost distributions heavily (Harris et al., 2003; Osterkamp, 2005; Vokelj et al., 2010). Melting permafrost could cause a series of changes, including local surface processes, hydrology, engineering infrastructure, and even local climate (Cheng and Wu, 2007; Etzelmüller et al., 2003; Yang et al., 2010). Therefore, understanding the spatial distribution and change of permafrost has become particularly urgent.

Change of permafrost can be simulated by formulating an appropriate quantitative model. As is widely known, field methods of investigating alpine permafrost, such as excavations and geophysical methods (Gerrard, 1990; King et al., 1992; Williams and Smith, 1989), are often expensive, time consuming and restricted in spatial extent. On the contrary, numerical simulation is potentially effective, because it does not wholly rely only on field surveys (Malevsky-Malevich et al., 2001). Hence, modeling techniques with Geographic Information Systems (GIS) have been used to simulate the distribution of permafrost frequently (Cheng et al., 2012; Etzelmüller et al., 2001a, 2001b; Heginbottom, 2002; Li and Cheng, 1999). Keller (1992) developed a GIS-aided program named Permafrost for investigating the distribution and automatically simulating and mapping alpine permafrost. Because of its scalability, simple operation and quantitative results, bottom temperature of snow cover (BTS) has been widely applied to simulate alpine permafrost distribution in many regions, such as the Alps (Hoelzle, 1992; Mühll et al., 2001) Canada (Lewkowicz and Ednie, 2004) and Japan (Ishikawa and Hirakawa, 2000). In recent years, the logistic regression model (LM) has received much attention (Etzelmüller et al., 2006; Zhao et al., 2012).

The Qilian Mountains on the northeastern Qinghai–Tibet Plateau (QTP) is one of the main areas of alpine mountain and high-altitude permafrost in China (Wu et al., 2009). Because of the influence of climatic warming, permafrost degradation has occurred in most permafrost regions in the QTP, especially the Qilian Mountains (Li et al., 2008). These mountains are the headwaters of the three largest inland river basins in Hexi Corridor (Jia et al., 2008). Thus, alpine permafrost degradation in these mountains can greatly affect water resources and even bring about flood disasters (Jin et al., 2000). Permafrost degradation can also cause other environmental deterioration, including destabilization of human infrastructure, biochemical processes, and desertification acceleration (Wang et al., 2000; Yang et al., 2010). Additionally, alpine permafrost areas in the Qilian Mountains have great prospecting potential for gas hydrate, which is characterized by a thinner permafrost zone

* Corresponding author. Tel.: +86 10 6488 9777; fax: +86 10 6488 9630.
E-mail address: chengwm@lreis.ac.cn (W. Cheng).

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and shallower depth (Lu et al., 2011; Zhu et al., 2010). Therefore, understanding the spatial distribution and change of Qilian Mountain permafrost has substantial social, economic and ecological significance.

Some research achievements regarding the permafrost distribution in the Qilian Mountains have been realized by previous studies. Much research has been done based on surveying points, but it does not simulate the permafrost distribution over the entire Qilian Mountain area (Li et al., 2009; Wang and French, 1995). Achievements of regional permafrost mapping mainly include: Map of Snow, Ice and Frozen Ground in China (Shi and Mi, 1988), Geomorphologic Atlas of People's Republic of China (1:1,000,000) (Edition Board of the Geomorphologic Atlas in People's Republic of China, 2009), and regional field surveying data from the QTP at the World Data Centre. These data portray the alpine permafrost distribution at different scales and periods, which provide the possibility of numerically simulating the permafrost distribution based on numerical permafrost models, including the altitude-response model (Cheng, 1984; Cheng et al., 2012; Li and Cheng, 1999) and LM (Zhao et al., 2012).

In this research, based on the Map of Snow, Ice and Frozen Ground in China at 1:4,000,000 (Shi and Mi, 1988), topographic and meteorological factors in each period, 5-year interval distributions of alpine permafrost over a recent 30-year period in the Qilian Mountains were simulated using a multi-criteria approach (MCA), according to the laws of our forecast, Qilian permafrost over the next 15 years will be predicted. This would provide more useful information for scientists and engineers for coming up with strategies in dealing with the permafrost-related issues in a positive manner.

2. Study area, data sources and methodology

2.1. Study area

The Qilian Mountains are in the northeast part of the QTP in western China. This is a rugged mountain range on the border of Qinghai and Gansu provinces (Fig. 1). The total area is about 19.96×10^4 km^2. With approximate coordinates 93.4°–103.4°E and 35.8°–40.0°N, it is characterized by higher elevations in the west and lower ones to the east. The topography is mainly controlled by faults, so rift basins and valleys have formed between mountains.

The Qilian Mountains are composed of northwest–southeast parallel mountain chains and broad valleys (Fig. 1). The altitude of the mountains varies from 3000 m to 5000 m, and most peaks exceed 4000 m. Mountains above 4500 m are covered with snow year-round and have modern glacial areas, with more than 500 glaciers. The glacial area is about 190 km^2 and its snow thickness is about 5–10 m (Sun, 1988).

The mountains are at the juncture of three climate regions of western China (monsoon, arid and QTP climates). Precipitation has a decreasing trend from east to west. Central and western areas have a continental semiarid alpine steppe climate, and the eastern area mainly has a continental arid desert climate. Average annual precipitation varies from more than 600 mm in the east to less than 100 mm in the west, which is one reason that the permafrost lower boundary gradually increases from east to west (Wu et al., 2009).

2.2. Data sources

In this study, the data used to create the simulation model includes two types, namely topographic and meteorological data. This is because both topographic and meteorological factors affect permafrost preservation.

2.2.1. Topographic factors

Considering the relationship between permafrost distribution and topographic factors, elevation, slope, aspect, longitude and latitude data were selected to simulate alpine permafrost in the Qilian Mountains.

Elevation controls alpine heat distribution in the mountains, thereby determining the distribution of high-altitude permafrost. In particular, extents of most alpine permafrost are represented by their upper and lower boundaries. Slope, indicating the obliqueness of the ground surface, directly influences geomorphology by determining the scale and intensity of the flow and energy transformation of ground materials (Tang et al., 2005; Zhou et al., 2009). Therefore, slope has a close relationship with the alpine permafrost distribution (Etzelmüller et al., 2001a). Aspect can generate differences in solar radiation energy, which can not only cause differences in land cover, but also lead to different permafrost lower bounds (Yang et al., 1993). Longitude reflects the "arid zonation" of alpine permafrost distribution in middle and low latitude regions (Cheng, 1984; Wu et al., 2009). Latitude controls

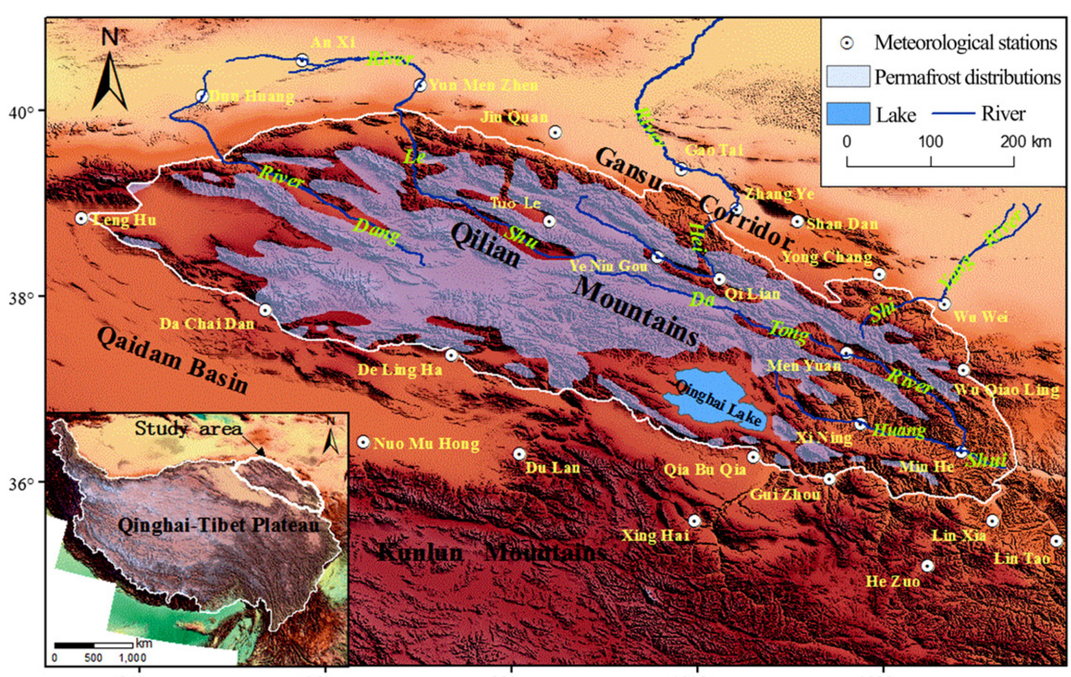

Fig. 1. Geographic setting, meteorological stations and permafrost distribution in Qilian Mountains.