

# Evaluation of freeze–thaw erosion in Tibet based on the cloud model

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**Abstract** Freeze–thaw erosion can lead to accelerated soil loss, which is an important factor related to soil erosion in cold regions. Tibet is a typical region that is seriously affected by freeze–thaw erosion. Traditionally, the analytic hierarchy process (AHP) method is used to calculate the weight of the factors in evaluations of freeze–thaw erosion, but this method cannot accurately depict the fuzziness and randomness of the problem. To overcome this disadvantage, this study proposed an improved AHP method based on the cloud model for the evaluation of the factors impacting freeze–thaw erosion. To establish an improved evaluation method for freeze–thaw erosion in Tibet, the following six factors were selected: mean annual air temperature, mean annual ground surface temperature, average annual precipitation, aspect, vegetation coverage, and topographic relief. The traditional AHP and the cloud model were combined to assign the weights of the impacting factors, and a consistency check was performed. The comprehensive evaluation index model was used to evaluate the intensity of freeze–thaw erosion in Tibet. The results show that freeze–thaw erosion is extensive, stretching over approximately 66.1% of Tibet. Moreover, mild erosion and moderate erosion are the most widely distributed erosion intensity levels, accounting for 36.4% and 34.4% of the total freeze–thaw erosion, respectively. The intensity of freeze–thaw erosion gradually increased from slight erosion in the northwest to severe erosion in the southeast of the study region. The evaluation results for the intensity and distribution of freeze–thaw erosion in Tibet were confirmed to be consistent with the actual situation. In brief, this study supplies a new approach for quantitatively evaluating the intensity of freeze–thaw erosion in Tibet.

**Keywords** freeze–thaw erosion, cloud model, AHP, Tibet

## 1 Introduction

Freeze–thaw erosion occurs primarily in cold and high-latitude or high-altitude regions as a result of temperature changes (Zhang et al., 2005a). During freeze–thaw erosion, the soil body or rock is mechanically broken due to volume changes and is subsequently transported, migrated, and piled up under the effects of gravity and other forces (Eigenbrod, 1996; Tang, 2003; Zhang et al., 2005a). As the third-most frequently occurring type of erosion after water and wind erosion (Chai et al., 2015; Guo et al., 2017a), freeze–thaw erosion is common in areas experiencing soil erosion in China. According to the data from the third national soil erosion remote-sensing survey, the area experiencing soil erosion comprises 4.8474 million km<sup>2</sup>, of which freeze–thaw erosion accounts for 1.2782 million km<sup>2</sup>, and is 13.31% of the total land area in China (Jing, 2003a; Wei et al., 2012; Jing et al., 2016). Soil erosion occurs mostly in northeast China, the northwest Plateau, and the Qinghai-Tibet Plateau. In addition, freeze–thaw erosion is severe and extensive in Tibet, stretching across 0.905 million km<sup>2</sup> and accounting for 70.8% of the freeze–thaw erosion in China (Ministry of Water Resources, 2010; Zhang et al., 2010; Liu et al., 2013; Wang, 2014). Freeze–thaw erosion is also one of the main ecological and environmental problems in this region (Tao et al., 1999; Dong et al., 2000; Zhang et al., 2010; Wei et al., 2012; Li et al., 2015). Freeze–thaw erosion has adversely affected agricultural production, animal husbandry, and the lives of residents; has undermined the safety of roads and other projects; and has seriously hindered the sustainable development of the regional economy and society (Dong et al., 2000; Li et al., 2005; Li et al., 2008; Wang et al.,

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2017a). Furthermore, climate warming and environmental changes have accelerated the process of freeze–thaw cycles (Chen et al., 2015; Guo et al., 2017b). Therefore, it is important to dedicate increased attention to the prevention and treatment of freeze–thaw erosion and to the protection of Tibet’s ecological environment.

Over the years, scholars have conducted many valuable studies on freeze–thaw erosion. This work includes comprehensive and holistic research on the mechanisms underlying freeze–thaw erosion (Fan, 2003; Jing, 2003b; Zhang et al., 2009; Wei et al., 2012; Qian et al., 2014; Sun et al., 2019) and in-depth studies and discussions on specific areas in China (Zhang et al., 2005c; Wu and Liu, 2010; Zhang et al., 2012; Ouyang et al., 2014). Among these studies, most have used the AHP to assign the weights of the factors impacting freeze–thaw erosion (Zhang et al., 2006 and 2007; Kong and Yu, 2013; Chen et al., 2013a). Li et al. (2011) and Shi et al. (2012) used the AHP to calculate the weights of the evaluation factors and GIS to evaluate and analyze freeze–thaw erosion in the Three-River Headwaters Region. Lu et al. (2019) used the AHP and the comprehensive evaluation index model to analyze the spatial distribution characteristics of freeze–thaw erosion in the Yalu Tsangpo River basin.

The basic process for assigning the weights of indicators using the AHP consists of first selecting several of the important factors that affect a specific, complex decision-making target. Experts in relevant fields are invited to compare the impacting factors via subjective elements, such as personal knowledge and experience, and to construct the evaluation index judgment matrix. Finally, the weight of each impacting factor is calculated (Saaty, 1990 and 2008). The traditional AHP combines qualitative and quantitative methods, and thus, it is simple, practical, and easy to use. However, the importance of each impacting factor depends on the subjective experience of individual experts, which oversimplifies the internal relationships among the factors and ignores the fuzziness and randomness of the problem. Accordingly, the final results of the weight assignment are subjective. Many scholars have acknowledged this problem. Therefore, the AHP has been combined with other weight assignment methods, such as an entropy method and principal component analysis (PCA), to make the study of freeze–thaw erosion more objective (Guo et al., 2015 and 2017c). Moreover, previous studies of freeze–thaw erosion have not dealt with the fuzziness and randomness during the processes of obtaining the weights of all factors. Neither scholars in China nor abroad have paid enough attention to this issue.

The cloud model is effective in achieving a transition from qualitative to quantitative uncertainties. This model can be applied to decision support systems and comprehensive evaluations, and it increases the objectivity and effectiveness of qualitative evaluations (Wang et al.,

2005a; Fu et al., 2011; Ye et al., 2011). Jia and Xu (2014) presented a weighted approach to seismic risk assessment based on the cloud model and the AHP. By introducing the cloud model, Zhang et al. (2014) proposed an improved approach for the multihierarchical fuzzy comprehensive evaluation of reservoir-induced seismic risk, which improved the robustness and visualization of the assessment results. Song et al. (2016) established a method for evaluating vulnerability severity based on the cloud model and the AHP, which facilitated improvements in the processing efficiency of the vulnerabilities. Yang et al. (2018) proposed a cloud model-based approach for the practical risk assessment of mountain torrent disasters in Guizhou Province.

With an understanding of the issues mentioned above, this study combines the cloud model and the AHP to more quantitatively determine the weights of evaluation factors. Then, this study assesses this combined model using Tibet as a research area. This study supplies a reference for further research on the prevention and treatment of freeze–thaw erosion and offers suggestions for protecting the ecological environment.

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## 2 Materials and data

### 2.1 Study area

Tibet is located on the southwestern border of China (26°50′N–36°53′N, 78°25′E–99°06′E) and is bordered by Xinjiang to the north, Sichuan to the east, Qinghai to the north-east, and Yunnan to the southeast. Tibet is approximately 1.202 million km<sup>2</sup> in area, accounting for approximately 1/8 of the total land area of China. Surrounded by the Himalayas and the Kunlun and Tanggula Mountains, Tibet composes the main portion of the Qinghai-Tibet Plateau, the “roof of the world,” and is located in the south-western section of the Qinghai-Tibet Plateau with has an average elevation of more than 4000 m. The climate is unique, complex, and diverse with a highland climate of thin air and complex geology. Generally, the northwest region of Tibet is cold and dry, and the southeast region is warm and humid. The distribution of annual precipitation is notably uneven and gradually decreases from southeast to northwest. Because of the high altitude and low latitude, Tibet receives the largest amount of solar radiation of all areas in China, which gradually increases from the southeast to the northwest. The solar radiation varies seasonally, with the smallest values in December and the largest in May and June.

### 2.2 Data sources

Shuttle Radar Topography Mission-digital elevation model (STRM-DEM) data at a 90-m resolution were supplied by

the data center for resources and environmental sciences, Chinese Academy of Sciences (RESDC; available at Resource and Environment Science and Data Center). Topographic relief and aspect data with a spatial resolution of 90 m were obtained, based on the STRM-DEM, using ArcGIS software. China's annual normalized difference vegetation index (NDVI) spatial distribution data set from 1998 to 2018 (Xu, 2018), mean annual air temperature (1980–2015), and annual precipitation (1980–2015) were derived from the RESDC at a spatial resolution of 1 km. The meteorological ground surface temperature data (1980–2013) used here were obtained from the China Meteorological Science Data Sharing Service website. The mean annual ground surface temperature data were obtained using the kriging interpolation method with a spatial resolution of 250 m.

### 2.3 Evaluation factors

Sun et al. (1999) summarized the natural factors that contribute to freeze–thaw erosion: 1) temperature, given that the mean annual ground surface temperature and the ground surface temperature range in the region are decisive; 2) soil texture and soil moisture content; 3) vegetation, which can mitigate certain effects; and 4) terrain and aspect, which influence the type and degree of erosion. The operability and relevance of the pertinent indicators were determined based on previous studies, and the freeze–thaw erosion evaluation system was constructed with the following six indicators: mean annual air temperature, mean annual ground surface temperature, average annual precipitation, aspect, vegetation coverage, and topographic relief. Previous studies have analyzed the effects of these evaluation factors on freeze–thaw erosion (Li et al., 2011; Shi et al., 2012; Guo et al., 2015; Lu et al., 2019); therefore, the analyses of and the approaches to the six factors were not duplicated in this study. All of the classification factors are presented in Fig. 1.

It is worth noting that the edge effect is produced during the extraction of the terrain factors based on the digital elevation model (DEM). This effect creates inaccuracies in the statistical analysis of directional data and thus affects the analysis and decision-making process (Song et al., 2006). Accordingly, it was necessary to expand the range of the DEM. The indices were calculated with ArcGIS 10.2 software based on the DEM data set, and the spatial analysis tool was subsequently used to extract the study area.

## 3 Methods

### 3.1 Boundary definition of the freeze–thaw erosion region

Currently, the lower boundary of the ice edge zone or the permafrost zone is defined as the lower boundary of

freeze–thaw erosion. Based on previous research, Zhang et al. (2005b) proposed a method for defining the freeze–thaw erosion zone in Tibet. The method, which is recognized by many scholars, has universal applicability to the definition of the range of freeze–thaw erosion zones in Tibet (Li et al., 2011; Li et al., 2012; Guo et al., 2017a). The equation used to calculate the lower boundary elevation of the freeze–thaw erosion area is given as follows:

$$H = \frac{66.3032 - 0.9197X - 0.1438Y + 2.5}{0.005596} - 200, \quad (1)$$

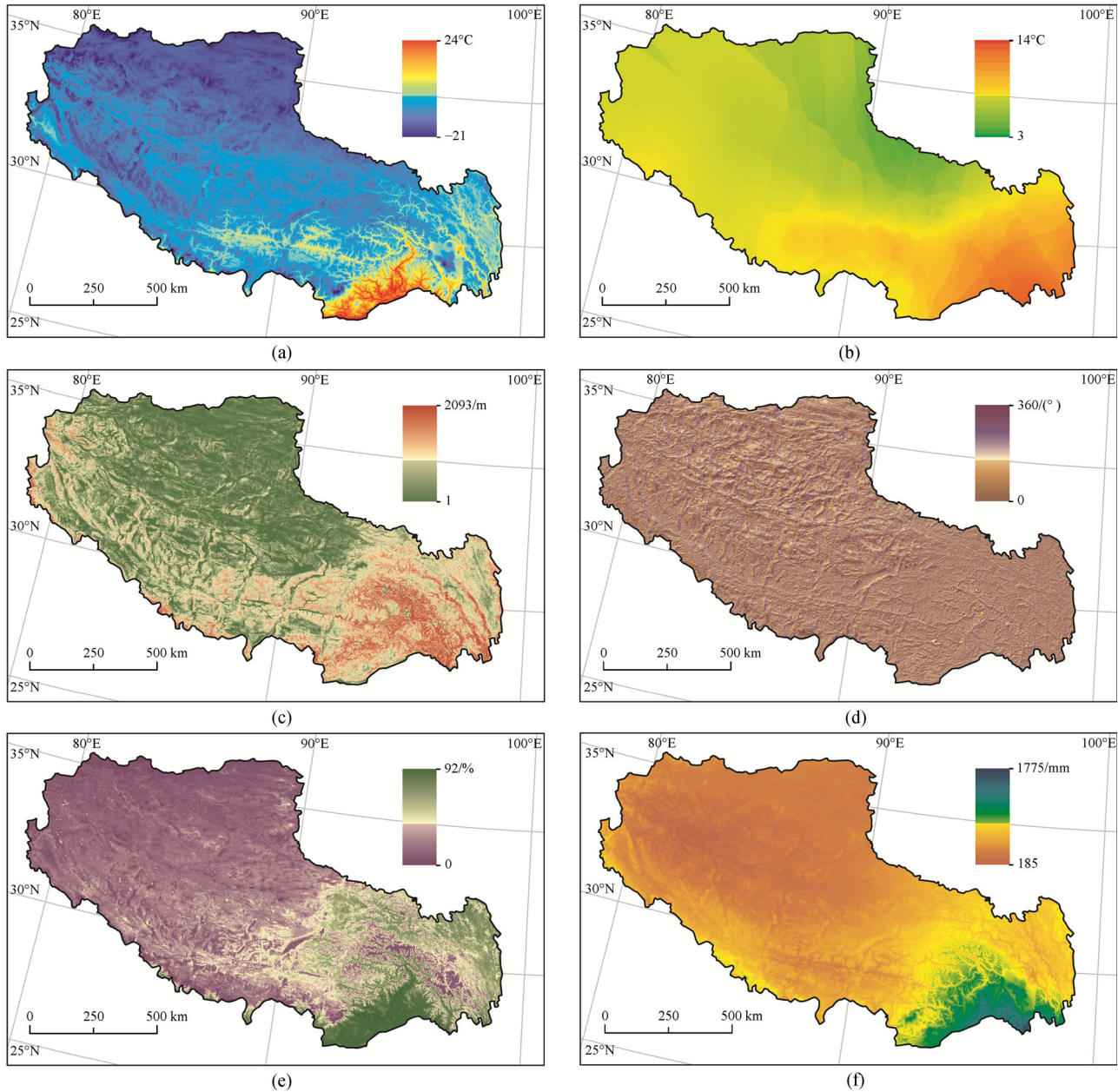
where  $H$  is the altitude of the lower boundary of the freeze–thaw erosion region (m),  $X$  is the latitude ( $^{\circ}$ ), and  $Y$  represents the longitude ( $^{\circ}$ ).

### 3.2 Cloud-AHP model

Currently, the AHP is widely used in the evaluation of freeze–thaw erosion. However, the assignment of the weights of impacting factors is subjective, as the weights are set artificially. At the same time, widespread uncertainty exists between qualitative concepts and quantitative data, especially fuzziness and randomness (Lv et al., 2003). Because of the uncertainty and fuzziness of language, Li et al. (2009) and Ye et al. (2011) established a cloud model to allow a transition of uncertainty from a qualitative to a quantitative aspect. This model can integrate fuzziness and randomness to obtain more accurate descriptions. Therefore, this study proposed that the improved AHP, which is based on the cloud model, can synthesize the conclusions of multiple experts to overcome the deficiency caused by the reliance on the subjective experience of individual experts. This approach can offer a more accurate and objective evaluation result.

#### 3.2.1 Feature importance profile based on cloud model

The following scenario is offered. A universe  $U = \{x\}$  ( $x = 1, 2, 3, \dots, 9$ ) is represented by three digital characteristics: expectation  $Ex$ , entropy  $En$ , and hyperentropy  $He$ . It is recorded as  $A(Ex, En, He)$ . Expectation ( $Ex$ ), the mathematical expectation of the cloud drops belonging to a concept in the universe, can be viewed as the value that best represents the qualitative concept. Entropy ( $En$ ) is a measurement of the uncertainty in a qualitative concept, and hyperentropy ( $He$ ) is the degree of uncertainty in entropy ( $En$ ), namely, the entropy of entropy (Li and Liu, 2004 and 2009; Jiang and Zhang, 2013). To establish the importance decision scale,  $Ex_0, Ex_1, \dots, Ex_8$  is equal to 1, 2, ..., 9, and the following 9 cloud models were used:  $A_0(Ex_0, En_0, He_0)$ ;  $A_1(Ex_1, En_1, He_1)$ ;  $A_2(Ex_2, En_2, He_2)$ ;  $A_3(Ex_3, En_3, He_3)$ ;  $A_4(Ex_4, En_4, He_4)$ ;  $A_5(Ex_5, En_5, He_5)$ ;  $A_6(Ex_6, En_6, He_6)$ ;  $A_7(Ex_7, En_7, He_7)$ ; and  $A_8(Ex_8, En_8, He_8)$ . The higher the value is, the more important the former value is than the latter (Fu et al., 2011). The digital characteristics



**Fig. 1** Distribution maps of various factors in Tibet. (a) Mean annual air temperature; (b) mean annual ground surface temperature. (c) topographic relief; (d) aspect; (e) vegetation coverage; (f) average annual precipitation.

of the importance scale cloud model are presented in Table 1.

The golden section method was adopted to calculate the  $En$  and  $He$  of each cloud model (Jia and Xu, 2014). The calculations are presented as follows:

$$\begin{aligned} En_0 &= En_2 = En_4 = En_6 = En_8 \\ &= 0.382\alpha \left( (x_{\max} - x_{\min}) / 6 \right) = 0.437, \quad (2) \end{aligned}$$

$$En_1 = En_3 = En_5 = En_7 = En_8 = En_0 / 0.618 = 0.707, \quad (3)$$

$$\begin{aligned} He_0 &= He_2 = He_4 = He_6 = He_8 \\ &= 0.382\alpha \left( (x_{\max} - x_{\min}) / 36 \right) = 0.073, \quad (4) \end{aligned}$$

$$He_1 = He_3 = He_5 = He_7 = He_0 / 0.618 = 0.118, \quad (5)$$

where  $x_{\max} = 9$ ,  $x_{\min} = 1$ ,  $\alpha = 0.858$ , and  $\alpha$  refers to the adjustment coefficient.

From the calculations, 9 judgment cloud models were obtained, as seen in Table 2. The importance of each element, based on the cloud model in the AHP index system, is shown in Fig. 2.

**Table 1** Importance scale

Degree of Importance	Definition
$A_0(Ex_0, En_0, He_0), Ex_0 = 1$	Equal importance of two elements.
$A_2(Ex_2, En_2, He_2), Ex_2 = 3$	Weak importance of an element compared with the other.
$A_4(Ex_4, En_4, He_4), Ex_4 = 5$	Strong importance of an element compared with the other.
$A_6(Ex_6, En_6, He_6), Ex_6 = 7$	Certified importance of an element compared with the other.
$A_8(Ex_8, En_8, He_8), Ex_8 = 9$	Absolute importance of an element compared with the other.
$Ex_1 = 2, Ex_3 = 4, Ex_5 = 6, Ex_7 = 8$	Intermediate values between two appreciations.

**Table 2** Nine judgment cloud models

Degree of importance	Importance scale	Cloud model
1	$Ex_0 = 1$	$A_0(1, 0.437, 0.073)$
2	$Ex_1 = 2$	$A_1(2, 0.707, 0.118)$
3	$Ex_2 = 3$	$A_2(3, 0.437, 0.073)$
4	$Ex_3 = 4$	$A_3(4, 0.707, 0.118)$
5	$Ex_4 = 5$	$A_4(5, 0.437, 0.073)$
6	$Ex_5 = 6$	$A_5(6, 0.707, 0.118)$
7	$Ex_6 = 7$	$A_6(7, 0.437, 0.073)$
8	$Ex_7 = 8$	$A_7(8, 0.707, 0.118)$
9	$Ex_8 = 9$	$A_8(9, 0.437, 0.073)$

calculated by Eq. (9)–(11), can be generated between them (Di et al., 1998; Li et al., 1998a and 1998b; Liu et al., 2005; Fu et al., 2011). The floating cloud  $C(Ex, En, He)$  expresses the blank language value of the qualitative concept described by clouds  $C_1$  and  $C_2$  (Di et al., 1999). When floating cloud  $C$  is floating toward  $C_1$ , it is increasingly affected by  $C_1$  but increasingly less affected by  $C_2$  until it totally overlaps at the position of  $C_1$ , and vice versa (Wang et al., 2005a, 2005b; Liu, 2011; Jiang, 2012; Jia and Xu, 2014):

$$Ex = \beta_1 Ex_1 + \beta_2 Ex_2, \tag{6}$$

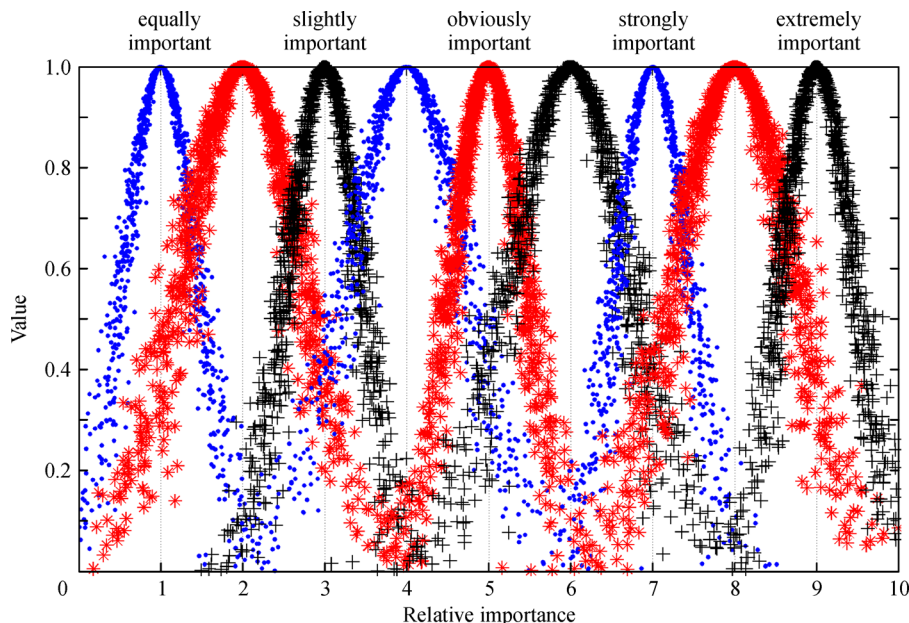
$$En = \frac{En_1(Ex_2 - Ex) + En_2(Ex - Ex_1)}{Ex_2 - Ex_1}, \tag{7}$$

$$He = \frac{He_1(Ex_2 - Ex) + He_2(Ex - Ex_1)}{Ex_2 - Ex_1}, \tag{8}$$

3.2.2 Acquisition of element importance based on group decision-making

The aggregation preference of the floating cloud was used to judge the importance of an element. The method is explained in the following scenario. A universe has two neighboring clouds:  $C_1(Ex_1, En_1, He_1)$  and  $C_2(Ex_2, En_2, He_2)$ , and a floating cloud  $C(Ex, En, He)$ , which is

where  $\beta_1$  refers to the adjustment coefficient, and its value is determined by experts based on specific circumstances. In the following,  $\beta_1 = k_1/(k_1 + k_2)$ ,  $\beta_2 = k_2/(k_1 + k_2)$ , and  $k_i$  ( $i = 1, 2$ ) represent the number of times that the  $i$ th



**Fig. 2** Nine cloud models used in assigning the weight of each factor in the analytic hierarchy process index system.

cloud model has been aggregated, and  $\beta_1 + \beta_2 = 1$ . If the expert determines that there is no need to intervene in the aggregation activity, then  $\beta_1 = \beta_2 = 0.5$ .

If there are  $m$  neighboring clouds, i.e.,  $C_1(Ex_1, En_1, He_1)$ ,  $C_2(Ex_2, En_2, He_2)$ , ...,  $C_m(Ex_m, En_m, He_m)$ , in a universe, then a floating cloud, namely,  $C(Ex, En, He)$ , which is calculated by Eqs. (12)–(14), can be generated for a qualitative concept by aggregating  $m$  clouds. Thus,  $C(Ex, En, He)$  is affected by the synthetic effect of the  $m$  clouds (Jiang, 2012; Wang and Liu, 2012):

$$Ex = \beta_1 Ex_1 + \beta_2 Ex_2 + \dots + \beta_m Ex_m, \tag{9}$$

$$En = \frac{\beta_1 En_1 Ex_1 + \beta_2 En_2 Ex_2 + \dots + \beta_m En_m Ex_m}{\beta_1 Ex_1 + \beta_2 Ex_2 + \dots + \beta_m Ex_m}, \tag{10}$$

$$He = \sqrt{He_1^2 + He_2^2 + \dots + He_m^2}, \tag{11}$$

$$\begin{pmatrix} a_{11} & a_{12} & \dots & a_{1n} \\ a_{21} & a_{22} & \dots & a_{2n} \\ \dots & \dots & \dots & \dots \\ a_{n1} & a_{n2} & \dots & a_{nn} \end{pmatrix} = \begin{pmatrix} A_{11}(1,0,0) & A_{12}(Ex_{12},En_{12},He_{12}) & \dots & A_{1n}(Ex_{1n},En_{1n},He_{1n}) \\ A_{21}(Ex_{21},En_{21},He_{21}) & A_{22}(1,0,0) & \dots & A_{2n}(Ex_{2n},En_{2n},He_{2n}) \\ \dots & \dots & \dots & \dots \\ A_{n1}(Ex_{n1},En_{n1},He_{n1}) & A_{n2}(Ex_{n2},En_{n2},He_{n2}) & \dots & A_{nn}(1,0,0) \end{pmatrix}, \tag{12}$$

where the elements on the diagonal  $A_{ij} = (1, 0, 0;$  note:  $i = j)$  mean that the same factors are of equal importance. If the latter factor is more important than the former, then the importance of the reciprocal scale is expressed as  $a_{ij} = \frac{1}{a_{ji}}$ :

$$a_{ij} = A_{ij} = \frac{1}{a_{ji}} = \frac{1}{A_{ji}} = \frac{1}{A_{ji}(Ex, En, He)} = \left( \frac{1}{Ex}, \frac{En}{(Ex)^2}, \frac{He}{(Ex)^2} \right). \tag{13}$$

The square root method is used to calculate the relative weights of the expectation, fuzziness, and randomness of the elements. If there are  $n$  neighboring clouds, i.e.,  $C_1(Ex_1, En_1, He_1)$ ,  $C_2(Ex_2, En_2, He_2)$ , ...,  $C_n(Ex_n, En_n, He_n)$ , in a universe, the multiplication operation is introduced in cloud model computing, and the calculated result is  $C(Ex, En, He)$ , where

$$Ex = Ex_1 Ex_2 \dots Ex_n, \tag{14}$$

$$En = |Ex_1 Ex_2 \dots Ex_n| \cdot \sqrt{\left(\frac{En_1}{Ex_1}\right)^2 + \left(\frac{En_2}{Ex_2}\right)^2 + \dots + \left(\frac{En_n}{Ex_n}\right)^2}, \tag{15}$$

$$He = |Ex_1 Ex_2 \dots Ex_n| \cdot \sqrt{\left(\frac{He_1}{Ex_1}\right)^2 + \left(\frac{He_2}{Ex_2}\right)^2 + \dots + \left(\frac{He_n}{Ex_n}\right)^2}. \tag{16}$$

where  $\beta_m$  refers to the adjustment coefficient, and its value is determined by experts based on specific circumstances. In the following,  $\beta_1 = k_1/(k_1 + k_2 + \dots + k_m)$ ,  $\beta_2 = k_2/(k_1 + k_2 + \dots + k_m)$ , ...,  $\beta_m = k_m/(k_1 + k_2 + \dots + k_m)$ ,  $k_i (i = 1, 2, \dots, m)$  represents the number of times that the  $i$ th cloud model has been aggregated, and  $\beta_1 + \beta_2 + \dots + \beta_m = 1$ . If the expert determines that there is no need to intervene in the aggregation activity, then  $\beta_1 = \beta_2 = \dots = \beta_m = \frac{1}{m}$ .

### 3.2.3 Cloud model and analytic hierarchy process based on the scale of the judgment matrix

Based on group decision-making, the judgment matrix for comparison of the importance of each element based on the cloud model is constructed as follows:

Thus,  $W_i^{(0)}(Ex_i^{(0)}, En_i^{(0)}, He_i^{(0)})$ , which is calculated by Eqs. (17)–(19), is obtained, and the results are given as follows:

$$Ex_i^{(0)} = \frac{Ex_i}{\sum Ex_i} = \frac{\left(\prod_{j=1}^n Ex_{ij}\right)^{\frac{1}{n}}}{\sum_{i=1}^n \left(\prod_{j=1}^n Ex_{ij}\right)^{\frac{1}{n}}}, \tag{17}$$

$$En_i^{(0)} = \frac{En_i}{\sum En_i} = \left\{ \left( \prod_{j=1}^n Ex_{ij} \right) \sqrt{\sum_{i=1}^n \left( \frac{En_{ij}}{Ex_{ij}} \right)^2} \right\}^{\frac{1}{n}} / \sum_{i=1}^n \left\{ \left( \prod_{j=1}^n Ex_{ij} \right) \sqrt{\sum_{i=1}^n \left( \frac{En_{ij}}{Ex_{ij}} \right)^2} \right\}^{\frac{1}{n}}, \tag{18}$$

$$He_i^{(0)} = \frac{He_i}{\sum He_i} = \left\{ \left( \prod_{j=1}^n Ex_{ij} \right) \sqrt{\sum_{j=1}^n \left( \frac{He_{ij}}{Ex_{ij}} \right)^2} \right\}^{\frac{1}{n}} / \sum_{i=1}^n \left\{ \left( \prod_{j=1}^n Ex_{ij} \right) \sqrt{\sum_{j=1}^n \left( \frac{He_{ij}}{Ex_{ij}} \right)^2} \right\}^{\frac{1}{n}}. \tag{19}$$

The desired consistency check is performed using the consistency indices  $C$  and  $R$ , which are calculated by Eqs. (20)–(21).

$$C = (\lambda_{\max} - n)/(n - 1), \tag{20}$$

$$\lambda_{\max} \approx \frac{1}{n} \sum_{i=1}^n \left( \sum_{j=1}^n Ex_{ij} W_{i1} / W_{1j} \right). \tag{21}$$

The consistency ratio (*CR*) is obtained by Eq. (22), and the *CR* is required to be less than 0.1:

$$CR = C/R < 0.1, \tag{22}$$

where *R* is the average of the consistency index of the same-order random judgment matrix.

### 3.3 Evaluation model of freeze–thaw erosion

Thus far, studies of freeze–thaw erosion have mainly adopted the hierarchical weighting evaluation model, which is suitable for large-scale macroresearch. In this model, different factors are measured with different units, and the classification scheme is highly subjective. The classification schemes have a great influence on the evaluation results (Shi et al., 2012; Wang et al., 2017b); therefore, standardization is needed to eliminate the differences in the variables due to differing units. The variables can be processed using Eqs. (23) and (24) to change them into unitless variables (0–1):

$$I_{i_p} = \frac{I - I_{\min}}{I_{\max} - I_{\min}} \times 100\% \quad (\text{positive}), \tag{23}$$

$$I_{i_n} = \frac{I_{\max} - I}{I_{\max} - I_{\min}} \times 100\% \quad (\text{negative}), \tag{24}$$

where *I* refers to the value of each factor, *I<sub>i</sub>* (*I<sub>i\_p</sub>* and *I<sub>i\_n</sub>*) is the standardized value of factor *I*, *I<sub>min</sub>* refers to the minimum value of factor *I*, and *I<sub>max</sub>* is the maximum value of factor *I*.

The comprehensive evaluation index model is written as follows:

$$FT = \sum_{i=1}^n W_i I_i / \sum_{i=1}^n W_i, \tag{25}$$

where *FT* is the freeze–thaw erosion index, *W<sub>i</sub>* is the

weight of factor *i*, *I<sub>i</sub>* is the value of evaluation factor *i*, and *n* is the number of evaluation factors in the given study of freeze–thaw erosion.

The *FT* was divided into different levels by using the natural breaks method in the ArcGIS software. The natural breaks method is a data classification method designed to determine the best arrangement of values into different classes (Chen et al., 2013b; Khamis et al., 2018). The natural breaks method is based on natural grouping inherent in data, and the classification interval is identified such that similar values are grouped most appropriately and the differences between each class are maximized. Each feature is divided into multiple classes, and for each of these classes, the boundary is set at the position where the data value difference is relatively large. The working principles and steps of the natural breaks method are described in previous studies (Basofi et al., 2015; Fariza et al., 2017).

## 4 Evaluation of freeze–thaw erosion intensity

### 4.1 Weight assignment of evaluation factors based on the cloud-AHP model

Based on previous studies, the judgment matrix consisting of each index and the freeze–thaw erosion intensities can be determined according to the relative importance of each evaluation index in affecting the intensity of freeze–thaw erosion. The weight of each factor is subsequently calculated via the AHP, and the consistency check is performed. Two comparison matrices, P1 and P2, are obtained, as seen in Table 3.

Based on the above comparison matrix, the language judgment scale of factors *i1* and *i2* based on the cloud model can be obtained as *A<sub>1</sub>* = (3, 0.707, 0.118) and *A<sub>2</sub>* = (2, 0.437, 0.073), respectively. After the aggregation, the cloud model of importance judgment between *i1* and *i2* is (2.5, 0.572, 0.096). Similarly, the judgment matrix, which is calculated by Eqs. (9)–(11), can be obtained through aggregation, as seen in Table 4.

**Table 3** Comparison matrix of evaluation factors

	P1						P2					
	<i>i1</i>	<i>i2</i>	<i>i3</i>	<i>i4</i>	<i>i5</i>	<i>i6</i>	<i>i1</i>	<i>i2</i>	<i>i3</i>	<i>i4</i>	<i>i5</i>	<i>i6</i>
<i>i1</i>	1	3	4	1	2	1	1	2	3	1/2	1	1/2
<i>i2</i>	1/3	1	2	1/2	1/2	1/2	1/2	1	2	1/2	1	1/2
<i>i3</i>	1/4	1/2	1	1/4	1/3	1/4	1/3	1/2	1	1/3	1/2	1/3
<i>i4</i>	1	2	4	1	2	2	2	2	3	1	1	1
<i>i5</i>	1/2	2	3	1/2	1	1/2	1	1	2	1	1	1/2
<i>i6</i>	1	2	4	1/2	2	1	2	2	3	1	2	1

Notes: *i1* refers to the mean annual air temperature, *i2* refers to the mean annual ground surface temperature, *i3* refers to the aspect, *i4* refers to the vegetation coverage, *i5* refers to the average annual precipitation, and *i6* refers to the topographic relief.

**Table 4** Judgment matrix

	<i>i1</i>	<i>i2</i>	<i>i3</i>	<i>i4</i>	<i>i5</i>	<i>i6</i>
<i>i1</i>	(1, 0, 0)	(2.5, 0.572, 0.096)	(3.5, 0.572, 0.096)	(0.75, 0.055, 0.009)	(1.5, 0.219, 0.037)	(0.75, 0.055, 0.009)
<i>i2</i>	(0.417, 0.094, 0.016)	(1, 0, 0)	(2, 0.437, 0.073)	(0.5, 0.109, 0.018)	(0.75, 0.055, 0.009)	(0.5, 0.109, 0.018)
<i>i3</i>	(0.292, 0.053, 0.009)	(0.5, 0.109, 0.018)	(1, 0, 0)	(0.292, 0.053, 0.009)	(0.417, 0.094, 0.016)	(0.292, 0.053, 0.009)
<i>i4</i>	(1.5, 0.219, 0.037)	(2, 0.437, 0.073)	(3.5, 0.572, 0.096)	(1, 0, 0)	(1.5, 0.219, 0.037)	(1.5, 0.219, 0.037)
<i>i5</i>	(0.75, 0.055, 0.009)	(1.5, 0.219, 0.037)	(2.5, 0.572, 0.096)	(0.75, 0.055, 0.009)	(1, 0, 0)	(0.5, 0.109, 0.018)
<i>i6</i>	(1.5, 0.219, 0.037)	(2, 0.437, 0.073)	(3.5, 0.572, 0.096)	(0.75, 0.055, 0.009)	(2, 0.437, 0.073)	(1, 0, 0)

Notes: *i1* refers to the mean annual air temperature, *i2* refers to the mean annual ground surface temperature, *i3* refers to the aspect, *i4* refers to the vegetation coverage, *i5* refers to the average annual precipitation, and *i6* refers to the topographic relief.

**Table 5** Calculation of importances

$W_i$	$W_i^{(0)}$
(1.395, 1.162, 0.862)	(0.204, 0.2, 0.2)
(0.734, 0.642, 0.476)	(0.107, 0.111, 0.111)
(0.416, 0.363, 0.27)	(0.061, 0.063, 0.063)
(1.694, 1.436, 1.066)	(0.248, 0.247, 0.247)
(1.009, 0.852, 0.632)	(0.148, 0.147, 0.147)
(1.583, 1.351, 1.002)	(0.232, 0.233, 0.233)

As shown in Table 5, the relative weight  $W_i^{(0)}$  is calculated according to Eqs. (17)–(22).

The consistency check of the expectations is calculated as follows:

$$\begin{bmatrix} 1 & 2.5 & 3.5 & 0.75 & 1.5 & 0.75 \\ 0.417 & 1 & 2 & 0.5 & 0.75 & 0.5 \\ 0.292 & 0.5 & 1 & 0.292 & 0.417 & 0.292 \\ 1.5 & 2 & 3.5 & 1 & 1.5 & 1.5 \\ 0.75 & 1.5 & 2.5 & 0.75 & 1 & 0.5 \\ 1.5 & 2 & 3.5 & 0.75 & 2 & 1 \end{bmatrix} \begin{bmatrix} 1.395 \\ 0.734 \\ 0.416 \\ 1.694 \\ 1.009 \\ 1.583 \end{bmatrix}$$

$$= \begin{bmatrix} 8.657 \\ 4.542 \\ 2.566 \\ 10.6 \\ 6.258 \\ 9.888 \end{bmatrix}$$

$$\lambda_{\max} \approx 6.211,$$

$$C = (\lambda_{\max} - n)/(n - 1) = (6.211 - 6)/(6 - 1) = 0.042,$$

$$I = CR = C/R = 0.042/1.26 = 0.034 < 0.1.$$

According to the consistency check,  $CR$  ( $CR = 0.034$ ) is less than 0.1, and the judgment matrix satisfies consistency. The weight vector, i.e., the weight of all indices affecting freeze–thaw erosion, is shown in Table 6.

**Table 6** Weighting of freeze–thaw erosion indicators

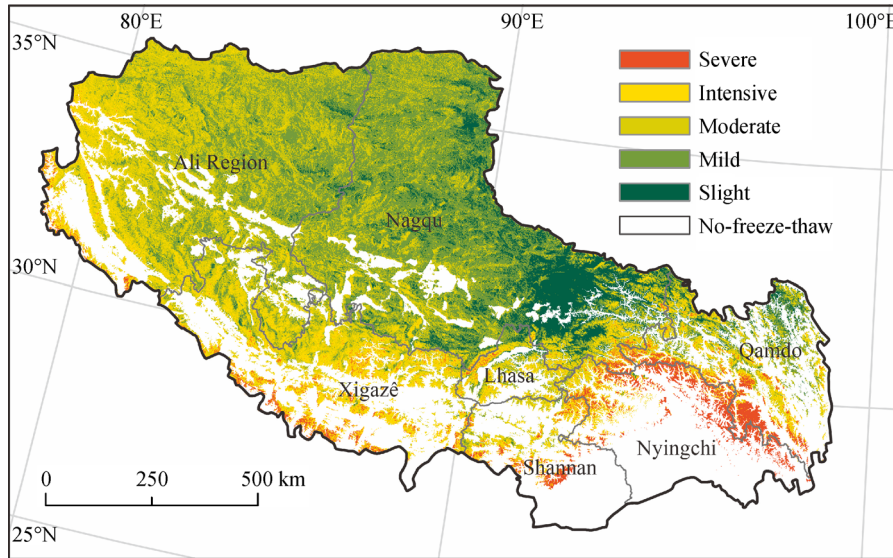
Index	<i>i1</i>	<i>i2</i>	<i>i3</i>	<i>i4</i>	<i>i5</i>	<i>i6</i>
Weight	0.204	0.107	0.061	0.248	0.148	0.232

## 4.2 Evaluation of freeze–thaw erosion intensity

The distribution map of the freeze–thaw erosion intensity in Tibet was developed through the combination of ArcGIS 10.2 software and the comprehensive evaluation model. The freeze–thaw erosion intensity indices ranged from 0.194 to 0.710. To facilitate analysis of the spatial pattern of freeze–thaw erosion, based on the distribution map, the freeze–thaw erosion intensity comprehensive index was divided into slight erosion ( $0.194 < I < 0.33$ ), mild erosion ( $0.33 \leq I < 0.377$ ), moderate erosion ( $0.377 \leq I < 0.425$ ), intensive erosion ( $0.425 \leq I < 0.489$ ), and severe erosion ( $I \geq 0.489$ ) by using the natural breaks method in the ArcGIS software (see Fig. 3).

Figure 3 indicates that freeze–thaw erosion is widely distributed in Tibet and covers approximately 66.1% of the total area of Tibet. Freeze–thaw erosion is discontinuously distributed in Ali Region and Nagqu, and the no-freeze–thaw region is mainly concentrated in the southern and southeastern regions (Xigazê, Shannan, and Nyingchi). Mild erosion and moderate erosion are the most widely distributed intensities, at 36.4% and 34.4% of the total area of freeze–thaw erosion, respectively. Slight erosion, which is distributed mostly in Nagqu, accounts for 9.4% of the total area of freeze–thaw erosion. Intensive erosion, which accounts for 15.1% of the total area of freeze–thaw erosion, is discontinuously distributed in the central region. Severe erosion, which is concentrated mostly in Nyingchi and Qamdo, accounts for 4.7% of the freeze–thaw erosion area.

The freeze–thaw erosion area in Tibet is mainly concentrated in the temperature zone with a mean annual air temperature of  $< -0.5^\circ\text{C}$ ; the no-freeze–thaw-erosion region is mainly distributed in zones with mean annual air temperatures of  $-0.5^\circ\text{C}$  to  $3.5^\circ\text{C}$  and  $> 11.4^\circ\text{C}$ . Moreover, severe erosion is mainly concentrated in regions with mean annual air temperatures of  $3.5^\circ\text{C}$ – $11.4^\circ\text{C}$ . In terms of average annual precipitation, freeze–thaw erosion is mainly concentrated in areas with average annual pre-



**Fig. 3** Distribution and classification map of freeze–thaw erosion intensity.

precipitation values of < 1076 mm; in zones with annual precipitation values  $\geq 1076$  mm, severe erosion occurs. Although annual precipitation is higher in the southeast (Shannan and Nyingchi), most of the area in the southeast (Shannan and Nyingchi) belongs to the no-freeze–thaw erosion category due to the low altitude and high vegetation coverage. The freeze–thaw erosion area is mainly concentrated in the vegetation belt with vegetation coverage of < 70%. In short, the results suggested that the spatial distribution of freeze–thaw erosion intensity gradually increased from slight erosion in the northwest to severe erosion in the southeast region.

### 5 Validation of results

To evaluate the efficacy of the results, previous studies on freeze–thaw erosion in Tibet were used as the basis for comparative verification. In addition, 212 sampling points were collected from high-definition Google Earth images to evaluate the experimental results through visual interpretation. Zhang et al. (2005a, 2006, 2007, and 2008) and Li et al. (2005) conducted many research

studies on freeze–thaw erosion in Tibet. With respect to the spatial distribution, the results of this paper confirm those of previous studies. Recent research on freeze–thaw erosion on the Tibetan Plateau (Guo et al., 2015 and 2017a) has resulted in similar conclusions to ours.

In addition, based on previous studies (Li et al., 2011; Guo et al., 2015 and 2017c), an error analysis matrix was constructed comprising the observation points collected from Google Earth images and the evaluation results of this paper, thus facilitating analysis of the accuracy of various freeze–thaw erosion intensity values (see Table 7).

As shown in Table 7, the evaluation accuracy ranged from 0.794 to 0.909, which demonstrates the validity of the classification. The values for mild erosion were the most precise. The accuracies of the values for intensive erosion were much lower. Nevertheless, the overall precision was 87.7%, thus confirming the high efficiency and accuracy of this freeze–thaw erosion model for Tibet.

### 6 Conclusions

In this study, the weights of the evaluation factors were

**Table 7** Error matrix of freeze–thaw erosion categories

Erosion severity	Evaluation results for freeze–thaw erosion					Total	Evaluation accuracy
	11	12	13	14	15		
11	27	3	2	1	1	34	79.4%
12	1	50	2	2	0	55	90.9%
13	1	3	54	1	2	61	88.5%
14	1	1	0	36	2	40	90.0%
15	0	1	1	1	19	22	86.3%
total	30	58	59	34	41	212	-

Note: 11 refers to slight erosion, 12 refers to mild erosion, 13 refers to moderate erosion, 14 refers to intensive erosion, and 15 refers to severe erosion.

calculated by an improved AHP based on the cloud model. In addition, the freeze–thaw erosion intensity indices in Tibet were evaluated by a combination of ArcGIS software and a comprehensive evaluation model. The results indicate that freeze–thaw erosion is widely distributed in Tibet. Mild erosion and moderate erosion are the most widely distributed, followed by intensive erosion. The intensity of the freeze–thaw erosion gradually increased from slight erosion in the northwest to severe erosion in the southeast of the study region. Upon verification, the evaluation results were found to be consistent with the actual data.

This study introduced cloud model theory and used the aggregation algorithm of the cloud model to synthesize the opinions of many experts in the process of assigning the factor weights. This approach overcomes the deficiencies of the traditional AHP, which relies on the subjective experience of individual experts. This method allows for a more accurate and objective description of the fuzziness and randomness of the factors impacting freeze–thaw erosion. Thus, the weight of each factor in the evaluation of freeze–thaw erosion can be objectively reflected, and the objectivity and reliability of the evaluations can be improved. The results of the evaluation were consistent with reality. This research is of great importance to the study of freeze–thaw erosion and supplies scientific data to support soil and water conservation and ecological and environmental protection in areas undergoing freeze–thaw erosion.

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