



Article Spatiotemporal Characteristics of Freeze-Thawing Erosion in the Source Regions of the Chin-Sha, Ya-Lung and Lantsang Rivers on the Basis of GIS

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Abstract: Freeze-thawing erosion is mainly distributed in the tundra, which is one of the main factors affecting soil erosion and soil conservation and affects the economic development of relevant countries and regions. The study area was selected to the north of Tanggula Mountain and the south of Bayankera Mountain, to the east of The Qinghai-Tibet Plateau, as the headwaters of the Yangtze River and lancang River. The topography and climate were particularly prone to soil freeze-thawing erosion, and the ecological damage would seriously affect the production and life of people in the whole downstream area. Therefore, based on the analytic hierarchy process (AHP), this paper selects seven evaluation factors to analyze the temporal and spatial characteristics of freeze-thaw erosion in the study area and establishes a comprehensive weight evaluation model for freeze-thaw erosion. The results show that: (1) the evaluation model is effective, and the soil freeze-thawing erosion is strong in the whole research area; (2) the total area of the research area and the freeze-thawing erosion area are 418,843 km² and 375,514 km² respectively, the freeze-thawing erosion area accounting for 89.7% of the total research area, and the freeze-thawing erosion intensity ranged from 0.165 to 0.737; (3) the spatial distribution differs significantly, the freeze-thawing erosion intensity is mainly concentrated in high altitude areas, especially in the Tanggula Mountains; (4) slope, poor annual temperature, illumination, altitude and content of sand in soil accelerate soil freeze-thawing erosion, whereas vegetation index does not; wetness index enhanced the influence of vegetation coverage and sand content. (5) this research will provide scientific evidence for protection and restoration of ecological environment in the area.

Keywords: spatiotemporal characteristics; freeze-thawing erosion; source regions; AHP; GIS

1. Introduction

The silk road economic belt is known as the strategic energy and resource base in the 21st century. The economic belt includes countries and regions with high altitude and high latitude. The improvement of the environment can promote inter-regional connectivity and promote the level of regional cooperation [1]. Freeze-thawing is a kind of physical geological action and phenomenon of freezing and thawing of soil layer caused by frequent changes of temperature in alpine regions, which leads to the change of water volume in soil parent material pores or rock cracks [2]. Freeze-thawing changes surface runoff and soil permeability by changing soil water conductivity and soil water capacity. It directly affects the hydrological process of the frozen soil, changes the surface parameters, aggravates



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Copyright: © 2021 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/). soil degradation and seriously threatens the environment and land resources. The permafrost subsoil in the high-altitude area affects the water energy cycle in this area and the surrounding area [3]. Freeze-thawing erosion exacerbates soil degradation and seriously threatens the environment and land resources. It is a global environmental problem and limits the sustainable development of a global social economy [4–6]. Besides wind erosion and hydraulic erosion, freeze-thawing erosion is second type of soil erosion [7,8]. It is mainly distributed in high-altitude region of Northwest China, Qinghai Tibet Plateau and Northeast China. The permafrost area is the third largest in the world [9,10]. It is mainly mild and moderate. According to the second national survey of soil erosion types, the freeze-thawing erosion covers an area of 1,269,800 km², which accounts for 13.36% of the total land area in China [11].

Throughout the history and current situation of soil erosion research, the research on freeze-thawing erosion started late. In recent years, extreme climates have become more frequent. More and more scholars in the world have begun to pay attention to freezethawing erosion and have carried out a series of studies on freeze-thawing erosion [12]. Using the meteorological, Normalized Difference Vegetation Index (NDVI) and soil texture data of the Yili River valley, the model classification method was used to evaluate erosion characteristics [13]. Water content conditions affect the stability of soil aggregates [14]. By monitoring the soil temperature and moisture of the selected sites, the differences of the permafrost activity layer and the seasonal frozen permafrost freeze-thawing process in the source of Yellow River were analyzed in time and space [15]. The freeze-thawing erosion evaluation model was established by introducing dynamic influence factors and precipitation during the freeze-thawing period [16]. Five main factors (precipitation, annual temperature range, aspect, slope and vegetation coverage) affecting freeze-thawing erosion were selected for quantitative research, and the sensitivity degree and spatial distribution characteristics of freeze-thawing erosion in Qinghai Tibet Plateau were analyzed. The spatial distribution is significantly different [17]. Wu and Liu analysed the distribution range and freeze-thawing erosion evaluation system in the China Three Rivers, but the results obtained from the study were relatively rough [18]. The ecological sensitivity of the western Sichuan Plateau was evaluated by multifactor comprehensive analysis [19]. Using the normalized method and evaluation model of freeze-thawing erosion with graded weight, the precipitation, annual temperature difference, vegetation index, slope and solar radiation (the main factors affecting freeze-thawing erosion) were used for quantitative research and analysis [20]. By means of comprehensive evaluation index and relative grading evaluation, the freeze-thawing erosion intensity was graded, and the boundary definition and spatial distribution map of freeze-thawing erosion in Gansu Province of China were drawn [21].

This paper uses GIS technology to define the weight of freeze-thawing erosion evaluation factor by using an analytic hierarchy process, and it uses the comprehensive index and grading evaluation method to assess the freeze-thawing erosion intensity. In the meantime, the spatial distribution characteristics of its freeze-thawing erosion were analyzed. The research results are conducive to understanding the environmental conditions of countries along the new silk road economic belt, taking timely measures to slow down the degradation of frozen soil and reduce economic losses caused by geological disasters such as landslides and collapses.

2. Data and Methods

2.1. Research Area

The research area on the Tibetan plateau hinterland between the Bayan Kala Mountains and the Tanggula Mountains (30–36° N, 88–102° E) include Ganzi County, Dege County, Shiqu County, Sertar County, Qamdo County, Jomda County, Riwoqe County, Denqen County, Nyainrong County, Anduo County, Baqing County, Banma County, Dari County, Zadoi County, Yushu County, Chindu County, Nangqen County, Zhidoi County, Qumarleb County and southern Geermu City). The headwaters of the Chin-sha River, the Ya-lung River and the Lantsang River flow through the research area. The research area is in the hinterland of the Qinghai-Tibet Plateau and the middle and eastern border of the permafrost area, with high altitude, low temperature and mainly alpine grassland vegetation. Freeze-thawing erosion has a wide range and high intensity. Deji et al. found that the warming process in the northern Tibetan Plateau is stronger than that in the southern Tibetan Plateau [22]. Climate change of the Qinghai-Tibet Plateau is intense, and the area is one of the most significant warming areas [23]. With the warming of climate, the thickness of permafrost decreases and the thickness of active layer increases, leading to the gradual reduction of permafrost area, the permafrost edge area is gradually transformed into seasonal permafrost or even recede, and the alpine ecosystem and permafrost environment are constantly degraded. At present, there have been a lot of studies on the local climate effect of plateau snow cover and the regional climate effect of plateau vegetation change, but the regional climate effect of plateau freeze-thawing process at the regional scale is still a very small part of the study, and the soil freeze-thawing process has a great influence on regional climate, which is worth in-depth discussion [24].

The research area is a typical region of the alpine ecosystem in China, and the natural environment is harsh. The unique and fragile ecosystem and special hydrological characteristics play a great role in the hydrological cycle, ecological environment and climate change of the alpine region. The relationship between the frozen soil and the climate system is mutual. On the one hand, frozen soil is affected by climate system and responds to climate change. On the other hand, frozen soil has a negative effect on climate, freeze-thawing processes affect the climate system. Therefore, the freeze-thawing process and regional climate are the whole of mutual coupling and interaction. Research on freeze-thawing is of great significance to regional climate change and environmental change. From Resource and Environment Science and Data Center of Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, the land use type distribution map of the research area can be obtained, as shown in Figure 1.



Figure 1. Land use types in the research area.

2.2. Data Collection and Processing

The Digital Elevation Model (DEM) data used in the paper is provided by Geospatial Data Cloud site, Computer Network Information Center, Chinese Academy of Sciences (http://www.gscloud.cn/). Meteorological station data and temperature data came from the China Meteorological Science Data Sharing Service website (http://data.cma.cn/). NDVI data, land use type data, soil content data and soil moisture index data came from the Resource and Environment Science and Data Center of Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences (http://www.resdc.cn/).

Three steps were adopted to further process the source data. First, according to the data of temperature, precipitation and evaporation collected by meteorological stations in the survey region and its surrounding areas, the annual temperature range and wetting index of each station were calculated, and then the raster of the annual temperature and wetness index of the region were obtained by encryption with kriging weighting method. The calculated average annual temperature difference is added to the attributes of the site vector point data, and then the Kriging interpolation function in the ArcMap software is used to obtain the annual temperature difference raster image. Second, the georeference of each factor was unified using the Albers coordinate system of the D_Krasovsky_1940 datum, and all raster were cropped out of the same research area. Third, use the resampling function of ArcGIS software to resample all raster data to 1000 m spatial resolution images. The overview of major data used in this research is shown in Table 1.

Data Name	Туре	Resolution/m	Data/Year	The Data Sources
Study boundary Land use type	Vector Raster	500		Resource and Environment Science and Data Center Resource and Environment Science and Data Center
Meteorological dataset DEM	The text data Raster	90	2006–2016	National Meteorological Science Data Center Geospatial Data Cloud
NDVI	Raster	250	2006-2016	National Aeronautics and Space Administration Earth Observing System
Moisture index Sand content	Raster Raster	1000 1000	2006–2016 2006–2016	Resource and Environment Science and Data Center Resource and Environment Science and Data Center

Table 1. Overview of major data used in this research.

2.3. Definition of the Scope of the Freeze-Thawing Erosion Area

The freeze-thawing erosion area is an area characterized by intense freeze-thawing in a cold climate, where freeze-thawing is the most important erosivity and has a corresponding freeze-thawing erosion landform morphology [25]. Therefore, to determine whether a region belongs to the freeze-thawing erosion area, the most important thing is to see whether the erosion power of the region is dominated by freeze-thawing activity [26]. Now, there are many methods to observe the scope of freeze-thawing erosion area. A common method is to take the periglacial area as the lower limit of erosion area, but the lower boundary of the periglacial area is about 200 m lower than that of the permafrost area [10]. The lower boundary of the permafrost area is a range of -2.5 °C. Based on the previous research results [25], this study used the longitude (X), latitude (Y) and altitude (H) obtained from DEM data to calculate the boundary of the annual average temperature of -2.5 °C, and then subtracted 200 m to obtain the frozen melt and the lower bound of erosion. The calculation equation is:

$$H = \frac{66.303 - 0.920X - 0.144Y + 2.5}{0.005596} - 200,\tag{1}$$

where: *H* is the elevation (m) of the lower boundary of the freeze-thawing erosion area; *X* is the latitude (° E); *Y* is the longitude (° N).

The basic scope of freeze-thawing erosion area is determined by Equation (1), as shown in Figure 2.



Figure 2. Freeze-thawing erosion area in the research area.

2.4. Determining the Weight of the Freeze-Thaw Erosion Intensity Evaluation Factor

Climate warming and glacier change have also caused the melting of permafrost over a large area of the Qinghai-Tibet Plateau and the strengthening of freeze-thawing erosion. According to previous research, in general, the altitude is between permafrost and freeze-thawing erosion, and the higher the altitude is, the stronger the freeze-thawing erosion will be. Furthermore, the larger the annual temperature range, the stronger the freeze-thawing erosion. As the vegetation cover area and rainfall increases, the annual temperature difference decreases. Moreover, vegetation can improve soil structure, increase soil agglomeration and weaken the influence of sand on freeze-thawing erosion. The stronger the light, the faster the soil moisture evaporation, the greater the daily temperature difference, the more frequent the soil freezing and thawing and the stronger the freeze-thawing.

Studies have shown that freeze-thawing erosion is greatly affected by many factors, such as climate, hydrology, topography, vegetation and so on [20]. Therefore, this paper selected seven factors as the influencing factors of freeze-thawing erosion, including annual temperature range, elevation, slope, aspect, vegetation index, soil moisture index and sand content.

2.4.1. Annual Temperature Range

Annual temperature range refers to the difference between the maximum and the minimum monthly average temperature. Because the periodic change of soil temperature is the precondition of freeze-thawing erosion, the annual temperature range is the primary factor affecting the freeze-thawing erosion and the main index of ice and snow freezing depth [14]. The amplitude and frequency of temperature changes in soil (especially below 0 °C) directly affect the process of soil freezing and melting and further affect the physical properties of soil and soil erosion resistance stability [27]. It is difficult to obtain the temperature index (ground temperature difference) that affects freeze-thaw erosion, but soil temperature data has a strong correlation with the temperature, so the temperature change data can be used to reflect the severity of soil temperature change. Based on the temperature data from observation data of 34 meteorological stations in the research area and surrounding areas the annual temperature range was calculated between 2007 and 2016 in this paper. As there are few meteorological stations, they need to be encrypted. The distribution of annual temperature range is obtained by kriging interpolation, as shown in Figure 3a.



Figure 3. Distribution map of this region in different factors. (a) Annual temperature range. (b) Elevation. (c) Slope. (d) Aspect. (e) Vegetation coverage. (f) Moisture index. (g) Sand content.

2.4.2. Elevation

The altitude of the research area is 2918–6659 m, with obvious difference. Generally, the higher the altitude is, the lower the ground temperature is and the stronger the freeze-thawing erosion is, as shown in Figure 3b.

2.4.3. Slope

Slope affects the size of erosion displacement and the amount of freeze-thawing erosion. The higher the slope, the more material is transported and the farther it is transported [28]. Under the combined action of gravity and precipitation, the degree of freeze-thawing erosion will be greatly increased in areas with a large slope [29], as shown in Figure 3c.

2.4.4. Aspect

According to the interpretation and classification of remote sensing images, freezethawing erosion in the sunny slope is stronger than that in the shady slope. This is because of the strong solar radiation, the higher moisture evaporation and the higher daily temperature difference on the sunny slope that result in stronger soil freeze-thawing in the sunny slope [30], as shown in Figure 3d.

2.4.5. Vegetation Coverage

Vegetation index is also a significant factor, which can protect the surface, stabilize the soil and reduce freeze-thawing erosion [30]. Vegetation coverage was calculated according to NDVI data and is shown in Figure 3e. In this study, this index of vegetation coverage was obtained from the MOIDS NDVI dataset (2007 to 2016) (Equation (2)).

$$FC = \frac{NDVI - NDVI_{soil}}{NDVI_{veg} - NDVI_{soil}}$$
(2)

where *FC* is the fractional vegetation coverage, $NDVI_{veg}$ refers to the maximum value of pure vegetation at a confidential level (CL) of 0.95, and $NDVI_{soil}$ is the minimum value of pure bare soil (CL = 0.05).

Vegetation can protect the surface, improve soil stability and reduce the temperature difference between day and night, thus inhibiting the freeze-thawing erosion process. Vegetation coverage was calculated according to NDVI data, as shown in Figure 3e.

2.4.6. Moisture Index

It was found that moisture content affected the stability of soil aggregates. The moisture index is a representation of the degree of moisture. In contrast to the drying index, the basic form of the moisture index is the ratio of ground income moisture (precipitation) to expenditure moisture (evaporation and runoff). The higher the ratio is, the wetter the climate will be. Soil moisture index was used to replace precipitation to represent the effect of freeze-thawing erosion more accurately, as shown in Figure 3f. The moisture index can be calculated as follows:

$$M_i = R_i / ET_{oi} \tag{3}$$

where: M_i is moisture index; *i* is timing sequence; R_i is precipitation in a certain period; ET_{oi} is the reference evapotranspiration of the corresponding period.

2.4.7. Sand Content

Sandy soil refers to soil with a high content of sand in the composition of soil particles; it is one of the basic categories of soil texture. Compared with clay and silty sand, sandy soil has the largest particles. The larger the soil particles are, the more likely they are to be eroded. Therefore, the higher the content of sand in the soil, the weaker the soil erosion resistance. The sand content distribution map in this region is shown in Figure 3g.

2.5. Evaluation Factor Weight

AHP is a qualitative and quantitative, systematic and hierarchical analysis method. The influence factors will be grouped at the different hierarchical based on the correlation and subordinate relations and eventually form a multilevel analysis structure model [31,32].

Chen Qiong et al. took general soil erosion model as the basic idea, chose three rivers source region as the research object and used GIS method to carry out semiquantitative evaluation on different degrees of freeze-thawing erosion in this area. The semiquantitative model used in this paper is $A = R \times K \times L \times S \times C \times P$. This quantitative research model also subjectively assigns the weight of influence factors according to expert opinions. However, the AHP semiquantitatively assigns the weight of each factor according to the subjective judgment of experts and the importance of factors, which makes the weight allocation more reasonable. In this paper, based on the correlation of all factors and the premise of avoiding repeated superposition of single factors, the most direct factors causing freeze-thawing erosion were selected for study. Semiquantitative method can be authoritative according to the experience of experts, but it is easy to generate subjective preference, so the determination of factor weight needs to be further improved [26].

AHP is not only suitable for the situation of subjective and uncertainty information but also allows the logical use of experience, discernment and intuitive. The biggest merit of AHP is that it proposes the hierarchy itself, which enables us to seriously regard and weigh the relative importance of indexes.

Modeling with AHP can be generally carried out according to the following four steps:

- (1) building-up a hierarchical structure pattern
- (2) construct all comparison matrix in each level
- (3) single hierarchical sequencing and consistency test
- (4) overall hierarchical sequencing and consistency test

In this paper, by constructing a decision model of 7 factors affecting freeze-thawing erosion, the weight of each factor was obtained, and the consistency test of results is 0.001, far less than 0.1. Therefore, the weight obtained is scientific and accurate.

The judgment matrix and weight of evaluation factors is shown in Table 2.

The Evaluation Factors	Annual Temperature Difference (°C)	DEM (m)	Slope (°)	Aspect (°)	Vegetation Coverage (%)	Moisture Index	Sand Content (%)	Weight
Annual temperature difference (°C)	1	1	1/2	5	3	2	4	0.20
DEM (m)		1	1/2	5	3	2	4	0.20
Slope (°)			1	6	4	3	5	0.31
Aspect (°)				1	1/3	1/4	1/2	0.04
Vegetation coverage (%)					1	1/2	2	0.08
Moisture index						1	3	0.12
Sand content (%)							1	0.05

Table 2. Judgment matrix and weight of evaluation factors.

2.6. Evaluation Method of Freeze-Thawing Erosion Intensity

2.6.1. Index Normalization

Due to various factors with different dimensions and units, the process of calculation should first use each factor normalization. Factors that can promote freeze-thawing erosion were selected forward normalization, and those that can inhibit it were selected backward normalization, and then superimposed comprehensive calculation was carried out. The normalization method is (the upper branch of Equation (3) is the calculation method of forward index, and the lower branch of Equation (4) is the calculation method of backward index):

$$I_{i} = \begin{cases} (I - I_{\min}) / (I_{\max} - I_{\min}), & \text{if (forward index)} \\ (I_{\max} - I) / (I_{\max} - I_{\min}), & \text{otherwise} \end{cases}$$
(4)

where: I_i in Equation (3) is the normalized value of each factor; I is the value of each factor; I_{min} is the minimum value of each factor; I_{max} is the maximum value of each factor.

2.6.2. Comprehensive Index Evaluation Method

To evaluate the freeze-thawing intensity in the study area, the comprehensive index method was used in this paper in which multiple factors are superimposed to obtain the synthetic evaluation index [27].

The calculation equation of freeze-thawing erosion intensity is as follows:

$$FT = \sum_{i=1}^{n} W_i I_i / \sum_{i=1}^{n} W_i , \qquad (5)$$

where: FT is comprehensive evaluation index of freeze-thawing erosion; W_i is the weight corresponding to each factor; I_i is the normalized value of each factor; n is the number of evaluation factors.

The higher the comprehensive index value, the stronger the freeze-thawing erosion degree.

2.7. Freeze-Thawing Erosion Evaluation Factor Grading

This article selects a total of seven factors that influence freeze-thawing erosion to build the freeze-thawing erosion intensity evaluation system in the research area. Reference to the previous theoretical results and the corresponding scoring standards [16,21,28], the assignment of each factor is graded, as shown in Table 3.

Table 3. Grading criteria for freeze-thawing erosion sensitivity factors.

Evaluation Factor Type	Hierarchical Assignment of Indicators						
Evaluation Pactor Type	1	2	3	4	5		
Annual temperature difference (°C)	≤19	19–21	21–23	23–25	≥25		
Élevation (m)	≤ 4000	4000-4500	4500-5000	5000-5500	$\geq \! 5500$		
Slope (°)	≤ 3	3–8	8–9	9–12	≥ 12		
Acrest (^Q)	0–36	36-72	72-108	108-144	144-216		
Aspect ()	324-360	288-324	252-288	216-252			
Vegetation coverage (%)	≥ 80	60-80	40-60	20-40	≤ 20		
Moisture index	≤ -20	-20-0	0–20	20-40	≥ 40		
Sand content (%)	≤ 40	40-50	50-60	60–70	\geq 70		

3. Results

3.1. Comprehensive Evaluation of Freeze-Thawing Erosion Intensity

According to the comprehensive index evaluation method, the freeze-thawing erosion intensity in the study area was calculated to be between 0.165 and 0.737.

Soil loss per unit time and per unit area is usually taken as the grading basis of freezethawing intensity. However, there are few observational reports on freeze-thawing erosion loss, so the classification of freeze-thawing intensity is very difficult [26]. In this paper, the method of Natural Breaks in ArcGIS was used to assign the calculated results in grades. Natural Breaks Classification, which divides data at locations where there are relatively large differences in values, best groups similar values and maximizes differences between categories. The degree of freeze-thawing erosion is divided into different grades. The freeze-thawing erosion intensity was classified into five grades, namely, micro erosion, mild erosion, moderate erosion, strength erosion and severe erosion. The classification map of freeze-thawing erosion intensity in the study area was drawn, as shown in Figure 4.



Figure 4. Classification map of freeze-thawing erosion intensity.

The area results of freeze-thawing erosion intensity are shown in Table 4.

The Intensity of Erosion	Area (km ²)	The Proportion (%)
Nonfreeze-thawing erosion zone	43,329	
Micro erosion	30,448	8.44
Mild erosion	92,030	25.50
Moderate erosion	131,317	36.38
Strength erosion	83,287	23.07
Severe erosion	23,866	6.61

 Table 4. Evaluation results of freeze-thawing erosion intensity.

From the table, one can conclude that the area of nonfreeze-thawing erosion region is 43,329 km². The freeze-thawing erosion area accounts for 89.3% of the source regions. Among them, moderate erosion area is the largest, accounting for 36.38% of the total freeze-thawing erosion area, followed by mild erosion and strength erosion, accounting for 25.50% and 23.07% of the total freeze-thawing erosion area, respectively. Micro erosion and severe erosion accounts for a small proportion of the whole freeze-thawing erosion area 8.44% and 6.61% respectively.

3.2. Verification of the Freeze-Thawing Erosion Intensity Results

In order to verify the experimental results, regional data overlapped with the study area in the bulletin of soil and water conservation issued by the ministry of water resources of the People's Republic of China in 2017 was selected. The result of freeze-thawing erosion in Chindu County was compared with this experiment. It was found that the intensity distribution and spatial distribution of freeze-thawing erosion in Chindu County in 2017 were very similar to the results of this experiment; they gradually weakened from the mountainous areas in southwest China to the surrounding areas, as shown in Figure 5. Therefore, the experimental method in this paper is reliable, and the experimental results are accurate.



Figure 5. Comparison of freeze-thawing erosion (Chindu County). (**a**) The result of Bulletin of Soil and Water Conservation. (**b**) The research result of this paper.

3.3. Effect Comparison of Freeze-Thawing Erosion Intensity

Freeze-thawing process has a considerable effect on the water and energy cycle of the coupled earth-air system, and thus has an important climate effect. The increase of regional climate effect in freeze-thawing process will accelerate the degeneration of frozen soil [33], and freeze-thawing erosion is formed by the superposition of annual freeze-thawing action.

In this study, the superposition of freeze-thawing erosion effects in 2006 and 2016 with severe climate problems was selected for comparison. The freeze-thawing erosion area of Qinghai-Tibet Plateau is widely distributed, $16.394 \times 105 \text{ km}^2$, accounting for 63.68% of the total area, while the nonfreeze-thawing erosion area is mainly distributed in the Qaidam Basin, the lower reaches of the Yarlung Zangbo River Basin and the Hengduan Mountain area [16]. Wang Liyan et al. found that the freeze-thawing erosion area of the Qinghai-Tibet Plateau was $149.02 \times 104 \text{ km}^2$, the area sensitive to freeze-thawing erosion was $56.80 \times 104 \text{ km}^2$, and the area sensitive to moderate and above was $27.39 \times 104 \text{ km}^2$, accounting for 48.22% of the total area of freeze-thawing erosion. The area of moderate sensitive areas was $18.21 \times 104 \text{ km}^2$, accounting for 32.06% of the total area of freeze-thawing erosion freeze-thawing erosion-sensitive areas. The intensity sensitive area was $9.18 \times 104 \text{ km}^2$, accounting for 16.16% of the total area of freeze-thawing erosion-sensitive area for the total area of freeze-thawing erosion in 2016 is stronger than that in 2006, but the difference is relatively small.



Figure 6. Freeze-thawing strength in 2006 (a) and in 2016 (b).

Comparing the freeze-thawing erosion region in the two years, as shown in Figure 7, the freeze-thawing erosion intensity area ratio in 2006 and 2016 showed the same trend and similar proportion.



Figure 7. Freeze-thawing erosion intensity area ratio.

Freeze-thawing results in Dari county in different years were compared in this paper, as shown in Figure 8: freeze-thawing erosion spatial distribution was similar, but the freeze-thawing intensity in 2016 was stronger than that in 2006. In 2016, under the influence of super strong El Nino, extreme weather occurred frequently all over the world [34]. The average summer temperature in China broke the record, and the annual average temperature was relatively poor. The global average temperature was the highest in history, with heavy precipitation and severe flood disaster [35]. Therefore, in addition to human activities, the worse the annual temperature and the higher the wetness index, the stronger the effect of freeze-thawing erosion.



Figure 8. Freeze-thawing results in Dari county in 2006 (a) and in 2016 (b).

4. Discussion

The seven factors were reclassified by ArcGIS software for further analysis and to discuss the relationship between the erosion intensity of the study area and each single factor. By using superposition analysis, the relationship between freeze-thawing erosion area and different influencing factors in the study area is shown in Figure 9 and Table 3. The area distribution of freeze-thawing erosion intensity in different grades of each factor is shown in Figure 10 and Table 3.



Figure 9. Distribution of erosion area and the relationship between different influencing factors.





4.1. Analysis of the Effect of Annual Temperature Range on Freeze-Thawing Erosion Intensity

Sixty-six percent of the total freeze-thawing erosion area was distributed in the annual temperature range of \geq 23 °C. Among them, 53% were distributed in the temperature difference zone of 23–25 °C and 13% in the temperature difference zone of \geq 23 °C. The percentage of moderate erosion, strength erosion and severe erosion showed a significant increase with annual temperature range, while the percentage of micro erosion gradually decreased and even disappeared in the temperature difference zone \geq 23 °C. Therefore, in the area with temperature difference of \geq 23 °C, the freeze-thawing erosion intensity was stronger, and the influence of temperature difference was significant, as shown in Figures 9 and 10 and Table 3.

4.2. Analysis of the Effect of Different Elevations on Freeze-Thawing Erosion Intensity

The freeze-thawing erosion area with altitude above 4500 m accounts for 88%, while the freeze-thawing erosion area with altitude below 4000 m only accounts for less than 1%. Among them, the freeze-thawing erosion area with altitude of 4500–5000 m and above 5000 m accounted for 72% and 16% respectively. Severe erosion accounted for 6.6%, 15.6% and 72.4% respectively in the three height belts with altitude of 4500~5000, 5000~5500 and \geq 5500 m, as shown in Figure 9, Figure 10 and Table 3. With the increase of altitude, the area of freeze-thawing erosion increases, and the intensity of freeze-thawing erosion enhances. Especially with the increase of altitude, the proportion of severe erosion shows the growth movement.

4.3. Analysis of the Effect of Different Slopes on Freeze-Thawing Erosion Intensity

The intensity of freeze-thawing erosion increases with the increase of slope, and the percentage of area of severe erosion also increases. Freeze-thawing erosion occupies the largest freeze-thawing area in the slope zone of $3 \sim 8^\circ$, accounting for 57%, while the freeze-thawing erosion area in the slope zone of $\geq 8^\circ$ is relatively small. The erosion area of freeze-thawing intensity occupied by mild erosion and moderate erosion showed a downward trend with the increase of slope, while the erosion area of severe erosion and severe erosion showed the opposite trend. Slope has a great influence on the intensity of freeze-thawing erosion. Therefore, it is necessary to strengthen the protection of slopes to prevent the intensification of freeze-thawing erosion while controlling the large-scale reclamation of slope land.

4.4. Analysis of the Effect of Different Aspects on Freeze-Thawing Erosion Intensity

The freeze-thawing erosion area in the 144~216° aspect zone accounts for 56%, as shown in Figure 9, Figure 10 and Table 3. Mild erosion and moderate erosion occupy a larger area in each aspect. Micro erosion, mild erosion, moderate erosion, strength erosion and severe erosion tend to be stable with the increase of aspect. However, as the aspect moves southward, the freeze-thawing area increases, indicating that light can aggravate freeze-thawing erosion.

4.5. Analysis of the Effect of Different Vegetation Coverage on Freeze-Thawing Erosion Intensity

As the vegetation coverage decreases, the proportion of freeze-thawing erosion area of moderate erosion, strength erosion and severe erosion tended to increase, while micro erosion and mild erosion tended to decrease. When vegetation coverage $\leq 20\%$, there is no micro erosion, as shown in Figure 9, Figure 10 and Table 3. Because the land use types in this area are mainly grassland with weak inhibition to freeze-thawing erosion, there is still a large area of freeze-thawing erosion in this area despite of the high vegetation coverage. However, the intensity of freeze-thawing erosion decreases with the increase of vegetation coverage, which indicates that vegetation coverage still weakens freeze-thawing erosion to a certain extent. Therefore, the effect of vegetation can be utilized to increase the green area in this study area to reduce the damage of grassland and the cutting down of trees.

4.6. Analysis of the Effect of Different Moistures on Freeze-Thawing Erosion Intensity

The freeze-thawing erosion area distributed in the area with soil moisture index ≥ 0 accounted for 63%, as shown in Figure 9, Figure 10 and Table 3. As the moisture increases, the percentage of micro and mild erosion show an increasing trend, indicating that moisture degree inhibited freeze-thawing erosion in this region.

The moisture factor has no obvious effect on freeze-thawing erosion. The wetter the area is, the better the growth of vegetation. As the vegetation coverage increases, the inhibition of erosion is stronger, but the increase of soil water content strengthens the freeze-thawing erosion. Therefore, moisture factor enhances the effect of vegetation coverage and sand content. An increase in moisture factor strengthens the inhibitory influence of vegetation coverage on freeze-thaw erosion, while an increase in moisture factor strengthens the promoting effect of sand content on freeze-thaw erosion.

4.7. Analysis of the Effect of Different Sand Contents on Freeze-Thawing Erosion Intensity

The erosion area with sand content \leq 40%, 40~50% and \geq 50% accounted for 8%, 42% and 50% respectively. Thus, the freeze-thawing erosion area of the soil with sand content \geq 40% accounted for 92%, as shown in Figure 9, Figure 10 and Table 3, mainly because the study area was dominated by the alpine grassland climate, and the surface characteristics were mainly covered by a layer of grassland, with a large amount of sand in the soil. The area of strength erosion and severe erosion increased with the increase of sandy soil content in the soil. Therefore, the increase of sand content enhances the freeze-thawing erosion effect.

5. Conclusions

Seven factors including annual temperature range, elevation, slope, aspect, vegetation coverage, water index and sand content were selected in this study. Through the analysis of soil erosion intensity, spatial pattern and single factor, and compared with the data from the bulletin of soil and water conservation in China, the following conclusions are drawn.

(1) The intensity of erosion in the study area was mainly mild erosion, moderate erosion and strength erosion; micro erosion and severe erosion appeared to a lesser extent.

- (2) The spatial distribution of freeze-thawing erosion sensitivity is significantly different in different spatial patterns, and the intensity of freeze-thawing erosion is large in high altitude areas. The Tanggula Mountains contains the most of severe erosion area.
- (3) Annual temperature range, elevation, slope, aspect and content of sand in soil accelerate soil freeze-thawing erosion. Vegetation coverage inhibit freeze-thawing erosion. The increase of moisture index strengthened the role of NDVI and sand content. The increase of moisture index strengthened the inhibitory effect of NDVI but also strengthened the promoting effect of sand content. Under the comprehensive action of various factors, the melting of glaciers and the thaw of permafrost in the Qinghai-Tibet Plateau have accelerated the soil freeze-thawing erosion.
- (4) In this paper, the results of freeze-thawing erosion are compared with those published in the bulletin of soil and water conservation in recent years in Chindu County. The spatial distribution and intensity of freeze-thawing erosion are very similar, so the results are accurate.

Chen Qiong et al. [36] used A semiquantitative model $A = R \times K \times L \times S \times C \times P$ to evaluate the degree of freeze-thawing erosion in the three rivers source region. In 2005, the freeze-thawing erosion in three rivers source region was mainly distributed in most areas of northwest China, and the area with moderate erosion degree or above accounted for more than half of the whole area. It was the type of erosion with the most extensive and highest erosion degree in three rivers source region. The quantitative research model also judges the weight of impact factors subjectively according to expert opinions. In this paper, AHP semiquantitatively assigned the weight of each factor according to the subjective judgment of experts and the importance of factors, and concluded that from 2006 to 2016, the freeze-thawing erosion in the study area weakened from northwest to southeast and the erosion effect was enhanced compared with that of 2005. It was said that the freeze-thawing erosion area in many counties also increased. If the two models are combined and the weights of R and K factors are calculated by analytic hierarchy process, it may be better.

In recent decades, climate warming is the basic factor to accelerate the melting of glaciers. The deposition and accumulation of black carbon aerosols from greenhouse gases on the surface of glaciers further enhances freeze-thawing erosion. Therefore, it is an important measure to protect vegetation and reduce the destruction of vegetation by human activities to slow down the degradation of permafrost and freeze-thawing erosion. At the same time, it can control the emission of greenhouse gases and slow down the rate of climate warming without changing the light intensity and natural conditions of mountain structure. In addition, the discharge of industrial pollutants should be strictly controlled after reaching the standard. This paper studies the influence of seven types of factors on freeze-thawing erosion of Chin-sha river, Ya-lung river and Lantsang river in order to provide data support for freeze-thawing disaster monitoring and risk assessment in "One Belt and One Road" economic belt. The disaster risk brought by soil freeze-thawing erosion on the Qinghai-Tibet Plateau not only brings severe challenges to socioeconomic development of the belt and road region but also brings environmental risks to the water resources planning and management, sustainable development of plenty of countries in the "One Belt and One Road" region and it will affect the construction of a Community of a Shared Future for Mankind.

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