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Snow Disaster Risk Assessment Based on Long-Term Remote Sensing Data: A Case Study of the Qinghai–Tibet Plateau Region in Xizang

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Abstract: The risk analysis and assessment of snow disasters are essential foundational tasks in natural disaster management and profoundly impact the scientific and precise formulation of disaster prevention, preparedness, and mitigation strategies. Employing the theory and methodology of snow disaster assessment, this research focuses on historical and potential snow disasters in the Qinghai–Tibetan Plateau (QTP) Region. Utilizing a long-time-series snow depth remote sensing dataset, we extracted six assessment indicators for historical snow disaster risk factors and potential snow disaster risk factors. We determined the weights of these six assessment indicators using the entropy weight method. Subsequently, we established a snow disaster assessment model to evaluate the grade distribution of snow disasters in the study area. This method can effectively solve the problem of the sparse data distribution of meteorological stations and reflect degrees of snow disaster risk on a large spatial scale. The findings reveal that areas with a relatively high snow disaster risk are primarily concentrated in the western part of the Ali Region, the central part of Chamdo, and near the border in Southern Xizang. Additionally, regions with a high frequency of snow disasters are predominantly located at the junction of Nagchu, Chamdo, and Nyingchi in the eastern part of Xizang. These results contribute valuable insights into the risk assessment of snow disasters and facilitate the development of effective strategies for disaster management in the region.

Keywords: snow disaster; risk assessment; long-term remote sensing data; entropy weighting method

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Citation: Sun, X.; Miao, L.; Feng, X.; Zhan, X. Snow Disaster Risk Assessment Based on Long-Term Remote Sensing Data: A Case Study of the Qinghai–Tibet Plateau Region in Xizang. *Remote Sens.* **2024**, *16*, 1661. https://doi.org/10.3390/rs16101661

Academic Editors: Nan Xu, Armin Moghimi, Xin Li, Junfeng Xiong, Linyang Li and Arfan Arshad

Received: 5 March 2024
Revised: 27 April 2024
Accepted: 30 April 2024
Published: 8 May 2024

1. Introduction

The Qinghai–Tibetan Plateau (QTP) is the highest region on the Earth, and the Xizang Region is its centerpiece, with distinctive climatic and topographical terrain features that make the region more susceptible to extreme weather events, most characteristically snow disasters. Snow disasters may result in various troubles, such as avalanches, transportation disruptions, and damage to farmland, which pose great challenges to the lives of residents and agricultural production. Livestock snow disasters create tremendous losses regarding herdsmen's lives and properties. Further, disaster rescue and production recovery consume many manual and material resources and negatively affect economic development. In 2017, statistics revealed that a snow disaster struck parts of Shigatse and Shannan in Xizang, affecting 20,000 people. The disaster resulted in the deaths of nearly 900 large livestock and 37,000 sheep and incurred a direct economic loss exceeding CNY 15 million [1]. By assessing the risk of snow disasters, policymakers can gain a more comprehensive understanding of the spatial and temporal distribution patterns of snow disasters in Xizang, provide early warnings, and formulate effective preventive measures to minimize the adverse impacts of these disasters on local communities. Accurately locating the high-risk areas of snow disasters can provide powerful support and a scientific basis for disaster prevention, preparedness, and risk management in Xizang, which will help to ensure the safety of residents and maintain the stability of agricultural and animal husbandry production, as well as provide a solid foundation for sustainability.

Snow disasters are one of the top ten meteorological disasters worldwide, and they are broadly classified into the following three types according to their formation conditions, distribution range, and characteristics: avalanches, wind-blown snow (wind-snow flow), and snow accumulation [2]. Evaluating the risk of snow disasters is a fundamental task in disaster management. This assessment has profound importance in accurately formulating measures for disaster prevention and preparedness. It is crucial in organizing timely emergency relief efforts for snow disasters and making informed decisions for post-disaster recovery and reconstruction. In the QTP, snow disasters are a prevalent natural meteorological hazard during the winter and spring, occurring almost annually and most frequently between November and March of the following year [3]. Currently, no definitive solution is in place to completely eradicate the effects of snow disasters in the Xizang Autonomous Region (XAR). The only available approach is to prevent them and minimize their resulting losses to the greatest possible extent. Assessing natural disaster risks primarily involves analyzing the likelihood of historically occurring natural disasters and their potential future occurrences. This assessment combines factors such as the frequency and intensity of the causative elements and potentially hazardous environmental conditions [4].

To mitigate the losses incurred by snow disasters, numerous researchers have conducted extensive studies on the assessment of snow disasters, integrating various factors related to snow. The most commonly used methods include regression analyses, hierarchical analyses, and the percentile method. To illustrate, Tachiiri et al. employed the Normalized Difference Vegetation Index (NDVI) and the Snow Water Equivalent (SWE) as assessment indicators, utilizing a regression analysis to evaluate snow disasters in Mongolia [5]. Park et al. utilized the PSR method to analyze their proposed snow disaster risk indices. They applied a hierarchical analysis and the entropy weight method in determining indicator weights to identify the area vulnerable to snow disasters [6]. Yu et al. utilized nearly a century of observed data from weather stations in Korea to analyze snowfall frequencies. They employed a parameter-estimation method to assess risk in the provinces of Daegu, Gyeongbuk, and Gangwon in northeastern Korea [7]. Sturm et al. introduced a novel seasonal snow classification system. This system was based on the sequence of snow layers; it considered the thickness, density, crystal morphology, and granularity characteristics within each layer to establish grading criteria for the snowpack in the Alaskan Region [8].

Qi et al. devised a risk assessment index system for snow cover on highways. They integrated historical and potential disaster hazards, considering the specific characteristics of highway snow disasters in Shaanxi Province. This process enabled the classification of snow disaster risks on arterial highways into five distinct grades. They proposed a distribution pattern for snow disaster risks in Shaanxi Province, with their findings closely aligning with actual circumstances [9]. Xu et al. leveraged daily temperature and precipitation data from meteorological stations on the QTP to compile a snow disaster event dataset. By utilizing optimal marginal distribution and conjugate functions, they calculated joint regression periods and joint probabilities, effectively assessing the hazards of snow disasters in the region [10]. Lu et al. considered the snow depth, snowfall temperature, snow accumulation duration, and total snowfall to establish grading criteria for snow accumulation in the Nagqu Region. Their simulation and judgment of historical snow disasters basically matched the actual situation [11]. Zhou et al. introduced the concept of a snow disaster index. They believed that heavy snowfall, snow depth, low temperature, and persistent snow accumulation are the main factors causing snow disasters. Among these factors, persistent snow accumulation plays a dominant role [12].

Li et al. selected factors such as the average snowfall, stable snow depth, and average snow depth as the evaluation criteria for assessing regional snow disasters in Nagqu, Xizang. They applied a mathematical fuzzy comprehensive evaluation model to assess the risk level of snow disaster regions [13]. Li et al. calculated multi-year averages for cumulative snowfall indicators to represent the magnitude of the disaster risk and to analyze the intensity of disaster-causing events in a specific area [14]. Wang et al. employed the Principal Component Analysis (PCA) method to identify seven key factors that contributed over 85% of the snow disaster early warning information for the QTP. These factors included the average annual probability of snow disasters, cumulative snowfall days, livestock storage rate, continuous days with an average daily temperature below −10 °C, grassland burial index, grassland snow accumulation rate, and per unit livestock production value. They established a county-based early warning model for snow disaster livestock. Then, they proposed a qualitative risk assessment method for snow disasters in pastoral areas of the QTP with a resolution of 500 m [15]. Gao et al. constructed a potential risk assessment model based on the logistic regression of snow disaster events in Qinghai Province. They adopted the Back Propagation Artificial Neural Network (BP-ANN) method to establish an early warning snow disaster simulation model and validate it. The results indicated that the potential risk of snow disaster in Qinghai Province is positively correlated with three factors: the maximum snow depth, snow-covered days (SCDs), and slope [16]. Liu et al. conducted a comprehensive analysis of 18 indicators related to the hazard's harmfulness, the amount of physical exposure the hazard-bearing entities face, their sensitivity to the hazard, and the capacity to respond to a disaster on the QTP based on hazard harmfulness data collected from historical records and data from affected entities. The results indicated that the risk of snow disasters in the high-altitude areas of the central QTP is higher than in the plateau's peripheral areas [17]. Li et al. utilized ground remote sensing monitoring and national snow disaster assessment standards to carry out a quantitative assessment of snow disasters. They measured the early snowfall amount in the grasslands of Mengla County and produced a distribution map of the early amounts of snowfall during the disaster. The findings demonstrated that this forecasting method can assess the extent of a snow disaster's impacts [18].

Liang et al. utilized the spatial attributes of snow, grass, animals, and climatic factors to create two new quantitative metrics. These two indicators were used to estimate potential snow disaster levels and comprehensively assess the impacts of snow disasters on grassland animal husbandry. They formulated classifications and evaluation criteria for snow disasters. The results showed that their pixel-point index based on the grassland's yield, livestock carrying capacity, coefficient of available grassland area, and seasonal grazing utilization scenarios could quantitatively and comprehensively reflect the ability of grasslands to resist snow disasters [19]. Singh et al. first investigated changes in the Snow Cover Area (SCA) within the Bhagirathi River Basin using satellite imagery from a Moderate Resolution Imaging Spectroradiometer (MODIS) and the Gravity Recovery and Climate Experiment [20]. Liu et al. employed a multi-level synthesis method and a multi-objective linear weighting function method to establish early warning snow disaster models, snow disaster identification models, and risk assessment models. They predicted the ability of grassland and livestock in northern Xinjiang to resist snow disasters [21]. Sahu et al. investigated the evolution of glacial lakes in the Himalayan and Karakoram (H-K) mountain ranges using multi-temporal Landsat images from 1990 to 2020 [22]. Wang et al. analyzed the formation mechanisms of snow disasters, revealing their spatiotemporal characteristics, historical hazard occurrences, snowfall events, disaster-triggering environments, and livestock overloading, as well as the livestock's vulnerability and adaptability to snow disasters. They evaluated the Integrated Risk Index (IRI) of snow disasters on the QTP using ArcGIS 10.2 [23]. Novak et al. applied the method of probability distribution function (PDF) percentiles to determine the range of snowfall forecasts aligning with users' risk tolerance [24].

Most conventional snow disaster assessment techniques primarily rely on meteorological station data. However, for the vast area of Xizang, the distribution of meteorological stations is relatively sparse, and their data cannot adequately represent the entire region. Consequently, it is a challenge to effectively assess the degree of snow disasters risk on a large spatial scale. The current research focuses on the QTP region of Xizang and is conducted from the following two perspectives: the historical and potential risks of snow disasters. By extracting indicators for the risk assessment of snow disasters from the snow depth dataset, we establish a risk assessment model for snow disasters in the study area. Finally, we evaluate and delineate the risk zones for snow disasters in the study region. This method can effectively solve the problem of the sparse data distribution of meteorological stations and can reflect the degree of snow disaster risk on a large spatial scale.

2. Materials

2.1. Study Area

Xizang is located in the southwest of China, with an average altitude of over 4000 m above sea level. Its highest point, Mount Everest, reaches 8848.86 m. The terrain of Xizang is predominantly hilly, and the plateau is vast. The climate is cold, with low temperatures all year and an average minimum temperature of −2.4 °C. The lowest temperatures can reach −46.4 °C. The area of the autonomous region is 1,228,400 km^2, accounting for approximately one eighth of the total land area of China. Xizang consists of seven main regions, namely, Lhasa, Shigatse, Shannan, Chamdo, Nagqu, Nyingchi, and Ali. Snow cover occurs throughout the year in most parts of Xizang, so it is important to conduct a snow disaster risk assessment on a year-round time scale.

The QTP area is renowned for being the largest alpine meadow grassland livestock region and ranks among the top five in China. The grassland covers an area of approximately 53.3 Mha, ranking third in the nation. The natural conditions in this area are predominantly alpine. The grassland's quality is relatively better in the mountain valleys of southeast Xizang. The main livestock breeds in the region include Tibetan yaks, Tibetan sheep, and Tibetan horses. Although the QTP area plays a vital ecological role in China, it is also considered an ecologically vulnerable region, facing economic and social development challenges. Statistics reveal that snow disasters rank first among the various meteorological disasters in the study area and occur nearly every year. They cause substantial economic losses to local herders and animal husbandry in the QTP area [25]. Figure 1 shows the specific geographical location of the study.

2.2. Data Sources

The daily snow depth dataset of the QTP used for this research, between 1 January 2000 and 31 December 2018, was obtained from the National QTP Science Data Center [26,27]. This dataset combines high-temporal-resolution daily snow depth data and high-spatial-resolution, 8-day, cloud-free MODIS-based snow cover probability data to generate a 19-year snow depth product. Compared with the available passive microwave snow depth data, this dataset improves its spatial resolution to 0.05° through a new advanced temporal filter algorithm. Validations against the observed snow depth data from 92 meteorological stations suggest that the newly developed 0.05° snow depth product greatly improves upon the original 0.25° version, and the root mean square error (RMSE) and mean absolute error (MAE) values of the new 0.05° SD product are 1.54 and 0.67, respectively. The spatial reference coordinate system of the dataset is WGS-84, with a spatial resolution of about 5 km (0.05°) and a temporal resolution of days. Each pixel value represents the snow depth (in cm) within the corresponding area. Figure 2 depicts the spatial extent of the dataset, and the main parameters of the snow depth dataset are shown in Table 1.

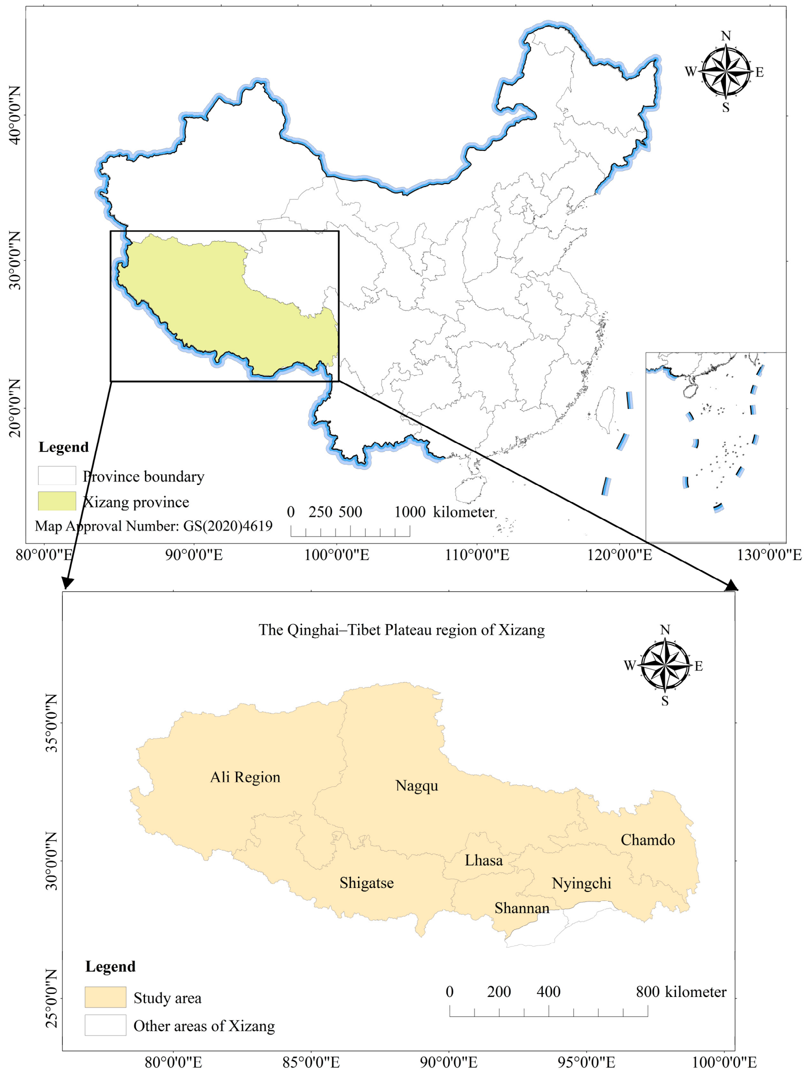

Figure 1. Sketch map of the study area.

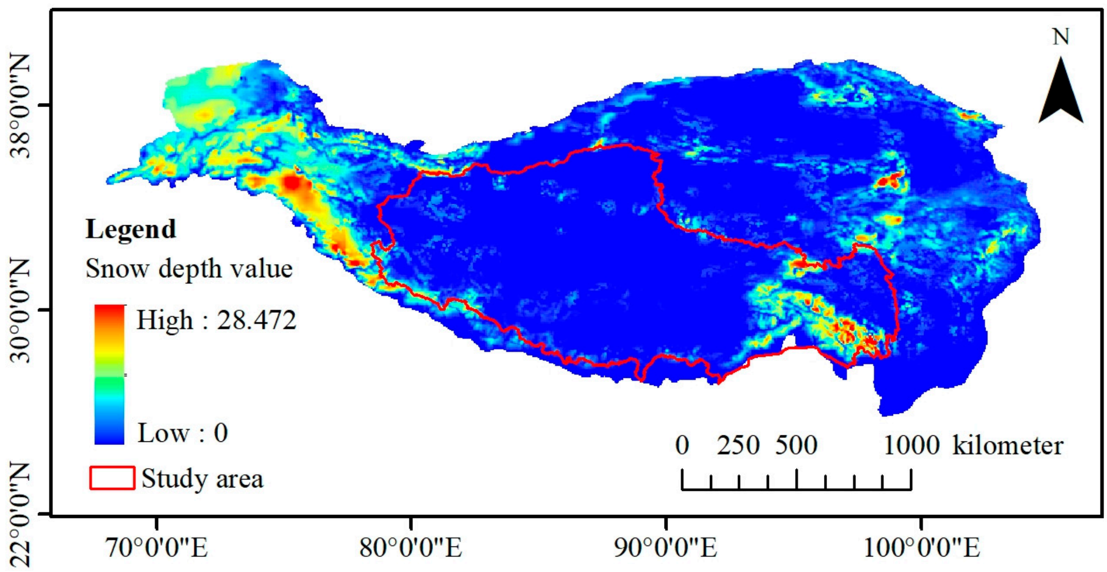

Figure 2. Scope of the dataset.

Table 1. Main parameters of the snow depth dataset.

Parameter	Value
Spatial resolution	0.05°
Time resolution	Day
Time scale	2000–2018
Coordinate system	WGS-84
RMSE	1.54 cm d^{-1}
MAE	0.67 cm d^{-1}

The study area of this research is the QTP region within the XAR. However, small portions of Xizang, including Mutuo, Mouna, and Chashu counties, are not situated on the QTP. Therefore, they are excluded from the snow disaster assessment study in this research, and their snow depth values are set as null or zero. The daily snow depth data for the study area from 2000 to 2018 were batch-extracted from the QTP snow depth dataset.

3. System Construction for the Risk Assessment of Snow Disasters

The construction of the snow disaster risk assessment model involves four main components, including the selection of snow disaster risk indicators, data preprocessing, the determination of the snow disaster risk indicator model, and the classification of snow disaster risk levels.

(1) Our research provides a comprehensive assessment of the snow disaster risk in Xizang, focusing on two key aspects: historical snow disaster risks and potential snow disaster risks, based on snow accumulation. Specifically, the index of historical snow disaster risk is determined using two disaster-causing factors, namely, the frequency of historical snow disasters and the intensity of snow disasters. Further, the potential snow disaster risk index is determined using four disaster-causing factors, namely, the multi-year average number of blizzard days, multi-year average maximum snow depth, multi-year average cumulative snowfall, and multi-year average snow depth.

(2) Different snow disaster risk assessment indicators have different dimensions, and direct quantitative calculations using the same standard may affect the assessment results due to the differences in the physical dimensions of individual indicators. In our research, data normalization was used to eliminate the dimensional differences of different disaster-causing factors.

(3) In order to measure the contribution of each snow disaster risk indicator to the results of the snow disaster risk assessment, the weight coefficients of each indicator in the assessment model must be determined. Our research uses the entropy weight method to determine the weight of each disaster-causing factor in our snow disaster risk assessment model.

(4) To facilitate the assessment and management of snow disaster risk, our research employs the percentile method to determine the threshold for the division of snow disaster risk levels and divides the snow disaster risk level into five levels in Xizang.

Based on the two indicators of historical snow disaster risk and the four indicators of potential snow disaster risk, we constructed a snow disaster risk assessment model for the Xizang area of QTP using the entropy weight method. Figure 3 depicts the methodology and data processing flow.

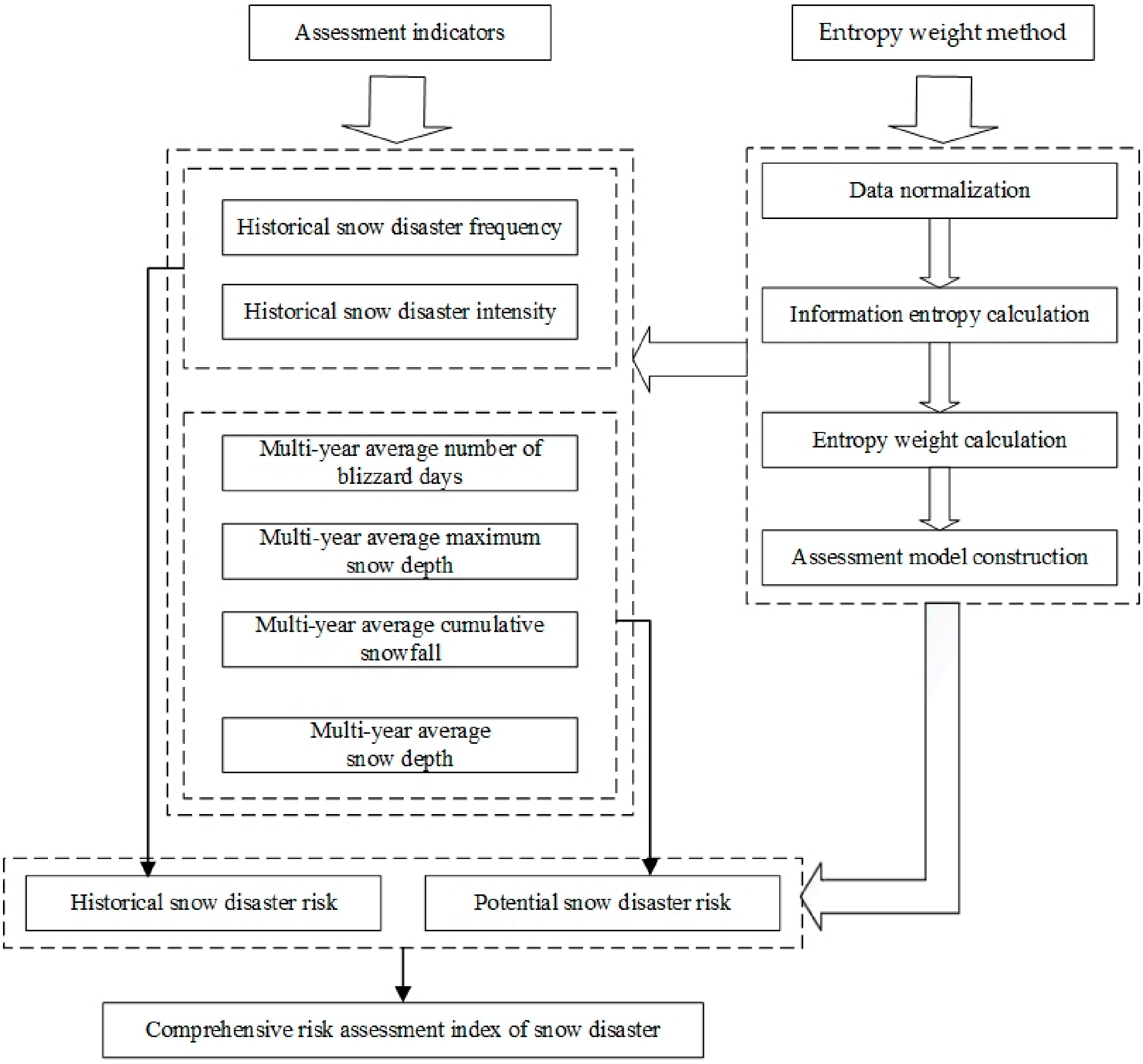

Figure 3. Flowchart of data processing.

3.1. Selection and Calculation Method of Snow Disaster Risk Indicators

Snow disasters are severe natural disasters with global implications, requiring a scientific hazard assessment for their effective prevention and response. However, variations in geography, objectives, methodologies, and data have led to various snow disaster evaluation systems across different regions and application scenarios. Disparities in data sources and quality can contribute to the differences in these evaluation systems. In addition, factors such as temporal and spatial resolution, accuracy, and data completeness influence the assessment results. The snow depth often results in many livestock deaths and severely influences the sustainable development of grassland animal husbandry due to heavy snowfall, deeper snow cover, longer snow cover days, and lower temperatures [23].

In this research, two indicators, namely, the historical and potential snow disaster risk indices, are employed to assess snow risk in Xizang, focusing on cumulative snowfall status. For historical snow disaster risk analyses, two disaster-causing factors are chosen, as follows: the frequency of historical snow disasters and the intensity of historical snow disasters. Similarly, the potential snow disaster risk is analyzed using four disaster-causing factors: the multi-year average number of blizzard days, multi-year average maximum snow depth, multi-year average cumulative snowfall, and multi-year average snow depth.

3.1.1. Historical Snow Disaster Risk Factors

Snow disasters are a natural phenomenon characterized by the widespread snow accumulation resulting from prolonged heavy snowfall. In this research, a snow disaster is defined from the perspective of its impact on livestock, by identifying the damage caused to livestock activities by snow events. In Xizang, livestock farming is widespread. When heavy snow covers the pasture, livestock fail to access the energy and nutrition provided by grazing, forcing them to rely on their stored fat reserves to endure the cold and sustain their basic life functions. This results in low-quality livestock, weight loss, and death, in severe cases. Consequently, economic losses occur in the affected pasture area. The forage grass in the QTP is relatively short, and livestock face difficulties in feeding when the snow depth exceeds 3 cm [25]. Therefore, an area is defined as experiencing a snow disaster when the snow depth reaches or exceeds 3 cm and persists beyond five days. All other conditions being equal, the regions with higher snow disaster intensities and frequencies are generally believed to be at higher risk of snow disasters. Using the grid unit of the snow depth dataset as the fundamental statistical unit, the frequency of historical snow disasters p and the intensity of historical snow disasters q are calculated using the following statistical methods.

(1) The frequency of historical snow disasters, represented as p, is determined by the number of years of snow disasters occurring within a specified basic statistical unit every ten years. The variable A_i indicates whether a snow disaster occurred in this statistical unit during the ith year. In the event of a snow disaster, it is recorded as 1; otherwise, it is recorded as 0. Equation (1) shows the expression for the frequency of historical snow disasters:

$$p = \frac{10}{n} \sum_{i=1}^{n} A_i \tag{1}$$

where n is the statistical time period and i is the specific year (i = 1, 2, 3, . . ., n).

(2) The intensity of historical snow disasters, denoted as q, is defined as follows: in year ith, if the jth statistical unit experiences one snow disaster, it is recorded as 1; otherwise, it is recorded as 0. The count is repeated if there are two or more occurrences. Here, D_{ij} represents the total number of snow disasters in the jth statistical unit in year ith. Equation (2) details the expression for the intensity of historical snow disasters as follows:

$$q = \frac{1}{n} \sum_{i}^{n} \sum_{j}^{k} D_{ij} \tag{2}$$

where i is the specific year (i = 1, 2, 3, . . ., n) and j is the statistical unit (j = 1, 2, 3, . . ., k).

3.1.2. Potential Snow Disaster Risk Factors

Throughout the entire process of a snow disaster, potential snow disaster factors play a crucial role. Snow disasters result from the combined interaction of factors such as snowfall and snow accumulation. This research selects the number of blizzard days, maximum snow depth, cumulative snowfall, and average snow depth as assessment indicators for the risk of potential snow disasters. The principal statistical methods used for evaluating these potential snow disaster risk factors are as follows:

(1) The multi-year average number of blizzard days, symbolized as I_{day}, is profoundly significant for a region. More blizzard days mean longer snow accumulation, increasing the likelihood of blizzards and resulting in more extensive damage. According to the guidelines for snow disasters in pastoral areas [28], a blizzard is defined as a weather event where snowfall accumulates by 10 mm or more within 24 h. In simple terms, if, in the ith year, the jth statistical unit receives a daily snowfall greater than 10 mm, the blizzard day is recorded as 1; otherwise, it is recorded as 0. If this phenomenon happens two or more times, it is counted repeatedly. Let S_{ij} represent the total number of blizzard days

in the *i*th year for the *j*th statistical unit. Equation (3) shows the formula for the average blizzard days over multiple years:

$$I_{day} = \frac{1}{n}\sum_{i=1}^{n}\sum_{j=1}^{k} S_{ij} \tag{3}$$

where i is the year (i = 1, 2, 3, . . ., n) and j is the statistical unit (j = 1, 2, 3. . ., k).

(2) The multi-year average maximum snow depth, denoted as I_{max}, holds substantial significance. The snow depth on the ground begins to impact the surrounding environment and potentially leads to snow-related disasters when it reaches a certain threshold. In a given area, the greater the snow depth, the higher the probability of experiencing a snow disaster. Thus, the potential harm is generally believed to be greater.

In this research, the maximum snow depth is defined as the highest depth of cumulative snowfall on the ground within a year. M_{ij} represents the maximum snow depth in the *j*th statistical unit during the *i*th year. Equation (4) shows the expression for the average maximum snow depth over multiple years:

$$I_{\max} = \frac{1}{n}\sum_{i=1}^{n}\sum_{j=1}^{k} M_{ij} \tag{4}$$

where i is the year (i = 1, 2, 3, . . ., n) and j is the statistical unit (j = 1, 2, 3, . . ., k).

(3) The multi-year average cumulative snowfall, denoted as I_{sum}, is calculated as follows: if the recorded snow depth in a specific area is greater than the snow depth on the previous day, snowfall is considered to have occurred on that day. The absolute difference in snow depths between the two days represents the snowfall amount that day. In weather forecasting, the snowfall amount is a common metric for measuring snowfall intensity.

U_{ij} represents the average cumulative snowfall in the *j*th statistical unit during the *i*th year. Equation (5) shows the expression for the average cumulative snowfall over multiple years:

$$I_{sum} = \frac{1}{n}\sum_{i=1}^{n}\sum_{j=1}^{k} U_{ij} \tag{5}$$

where i is the year (i = 1, 2, 3, . . ., n) and j is the statistical unit (j = 1, 2, 3, . . ., k).

(4) The multi-year average snow depth, denoted as I_{avg}, is calculated as follows: This research defines the average snow depth as the daily average of the ground snow depth within a calendar year. Here, J_{ij} represents the average snow depth in the *j*th statistical unit during the *i*th year. Equation (6) presents the expression for the average snow depth over multiple years:

$$I_{avg} = \frac{1}{n}\sum_{i=1}^{n}\sum_{j=1}^{k} J_{ij} \tag{6}$$

where i is the year (i = 1, 2, 3, . . ., n) and j is the statistical unit (j = 1, 2, 3, . . ., k).

3.2. Construction of the Risk Assessment Model

3.2.1. Indicator Normalization

Given that these various data are incomparable, owing to their different dimensions, quantifying the data without using dimensions is necessary to eliminate their influence. This study uses range transformation to normalize all sequence values to a specified value range, as follows:

$$y_i = \frac{x_i - \min(x_i)}{\max(x_i) - \min(x_i)} \tag{7}$$

where yi represents the value of the *i*th indicator after normalization and xi represents the value of the ith indicator. min(xi) and max(xi) represent the minimum and maximum values of the *i*th indicator, respectively.

3.2.2. Snow Disaster Risk Indicator Weights

The entropy weight method is an objective weighting technique that assigns weights to each evaluation criterion based only on their objective data. This method quantifies the contribution and importance of various indicators by assessing the information entropy of each indicator, thereby implementing a corresponding weight allocation. The greater the information entropy, the more information an indicator carries and therefore the smaller its weight should be, and vice versa. The entropy weighting method is usually applied in various domains, such as multi-criteria decision-making, risk assessment, and resource allocation. It can handle the complexity and uncertainty of multi-indicator data and can effectively cope with these multi-dimensional data problems. When determining indicator weights, the entropy weighting method can help avoid the influence of the subjective factors scored by traditional experts in the Analytic Hierarchy Process (AHP) [29]. In our research, the snow disaster risk assessment index involves multiple indicators, including the frequency of snow disasters, intensity of snow disasters, number of blizzard days, cumulative snowfall, and snow depth. The entropy weight method can measure the weight of each indicator through the calculation of their information entropy and weight allocation, which accurately reflects the degree of the contribution of each indicator to the snow disaster assessment. The process of calculating weights using the entropy weighting method is as follows:

(1) Calculating the information entropy for each indicator E_j:

$$E_j = -k\sum_{i=1}^{n} p_{ij} \times \ln(p_{ij}) \tag{8}$$

$$p_{ij} = \frac{x_{ij}}{\sum_{i=1}^{n} x_{ij}} \tag{9}$$

$$k = \frac{1}{\ln(n)} \tag{10}$$

where x_{ij} represents the ith sample value under the jth indicator and p_{ij} represents the proportion of the ith sample value under the jth indicator (i = 1, 2, 3, . . ., n; j = 1, 2, 3, . . ., m).

(2) Calculating the entropy weight for each indicator W_j:

$$W_j = \frac{D_j}{\sum_{j=1}^{m} D_j} \tag{11}$$

$$D_j = 1 - E_j \tag{12}$$

where D_j represents the coefficient of variation of the jth indicator (j = 1, 2, 3, . . ., m).

3.2.3. Classification of Snow Disaster Risk Levels

The percentile method is applicable to various types of data, including continuous and scattered data, and is not limited by the distribution pattern of that data. Therefore, it is highly generalizable and can be applied to the assessment of disaster events in different regions and time periods [30]. In this research, the percentile method is employed to investigate and establish threshold values for classifying snow disaster risk levels. The percentile method formula is as follows:

$$P_m = L + \frac{m/100 \cdot N - F_b}{f} \cdot i \tag{13}$$

where Pm represents the mth percentile, L represents the lower bound of the mth percentile group, N represents the total number of all groups, Fb represents the cumulative frequency of groups smaller than L, f represents the frequency of the mth percentile group, and ith represents the class width of the mth percentile group.

Referring to the grade of snow disasters in pastoral areas [28], the snow disaster risk levels in Xizang are categorized into five levels: high, relatively high, medium, relatively low, and low, as shown in Table 2. Here, the symbol "S" represents the risk assessment index of snow disasters.

Table 2. Snow disaster risk levels in Xizang.

Snow Disaster Risk Levels	Hazard Index
High	S > 80%
Relatively high	60% < S ≤ 80%
Moderate	40% < S ≤ 60%
Relatively low	20% < S ≤ 40%
Low	S ≤ 20%

3.3. Risk Assessment Model of Snow Disasters

In this research, the risk assessment of snow disasters in Xizang comprises two main components: historical and potential snow disaster risks. Historical snow disaster risk reflects the historical occurrence of snow disasters in a region. Generally, it is recognized that the higher the intensity and frequency of snow disasters, the higher the risk posed by them. Potential snow disaster risk is assessed by considering factors such as the number of blizzard days, snow depth, and cumulative snowfall. The higher the values of these potential factors, the greater the potential risk, indicating the likelihood of greater losses resulting from snow disasters in the area. By considering these two types of snow disaster risks, the snow disaster risk level in the study area can be assessed comprehensively. The snow disaster risk assessment model for Xizang is defined as follows:

$$S = A_1 S_1 + A_2 S_2 \tag{14}$$

$$S_1 = B_1 p + B_2 q \tag{15}$$

$$S_2 = C_1 I_{day} + C_2 I_{\max} + C_3 I_{sum} + C_4 I_{avg} \tag{16}$$

where S represents the snow disaster risk assessment index. S_1 and S_2 denote the historical and potential snow disaster risk indices, respectively. p and q signify the normalized assessment indicators for the frequency of historical snow disasters and the intensity of historical snow disasters. I_{day}, I_{max}, I_{sum}, and I_{avg} denote the normalized assessment indicators for the average number of snow disaster days, average maximum snow depth, average cumulative snowfall, and average snow accumulation depth over multiple years, respectively. A_1 and A_2 represent the weight coefficients corresponding to each evaluation indicator of snow disaster risk. B_1 and B_2 indicate the weight coefficients corresponding to each evaluation indicator of historical snow disaster risk. C_1, C_2, C_3, and C_4 represent the weight coefficients corresponding to each evaluation indicator of potential snow disaster risk.

4. Snow Disaster Risk Assessment in Xizang

This research assesses the snow disaster risk in Xizang from two perspectives: historical and potential snow disaster risks. The snow disaster risk in Xizang is then classified and assessed for its level of danger.

4.1. Historical Snow Disaster Risk

Based on the daily snow depth datasets, the annual occurrence of snow disasters in each statistical unit of Xizang was counted from 2000 to 2018. Subsequently, the frequency and intensity of these historical snow disasters were computed. After normalization, the entropy weight method was employed to establish the information entropy and weights of the two indicators, as illustrated in Table 3.

Table 3. Entropy weights of historical snow disaster indicators.

Indicators	Frequency of Historical Snow Disasters	Intensity of Historical Snow Disasters
Information entropy	0.96	0.94
Weight	0.40	0.60

As depicted in Table 3, the information entropies of the frequency of historical snow disasters and the intensity of historical snow disasters are 0.96 and 0.94, respectively. In terms of information entropy, the entropy of the intensity of historical snow disasters is lower than that of the frequency of historical snow disasters. However, it is worth noting that the larger the information entropy, the smaller the corresponding weight. The weight of the intensity of historical snow disasters is higher than that of the frequency of historical snow disasters, which are 0.60 and 0.40, respectively. This implies that the intensity of historical snow disasters exhibits a higher degree of specificity compared to the frequency of historical snow disasters in the risk assessment of snow disasters in Xizang. Therefore, the intensity of historical snow disasters plays a more crucial role in determining the value of the historical snow disaster risk index. Thus, we conclude that the intensity of historical snow disasters has a greater influence on the assessment of historical snow disaster risks in Xizang. Based on the results of the entropy weight calculation for the intensity of historical snow disasters and the frequency of historical snow disasters, combined with Equation (15), the calculation formula for the historical snow disaster assessment index can be expressed as follows:

$$S_1 = 0.40p + 0.60q \tag{17}$$

where p and q represent the normalized assessment indicators of the frequency of historical snow disasters and the intensity of historical snow disasters, respectively.

Utilizing Formula (17) to compute the historical snow disaster index, Figure 4 depicts the distribution of the historical snow disaster index in Xizang.

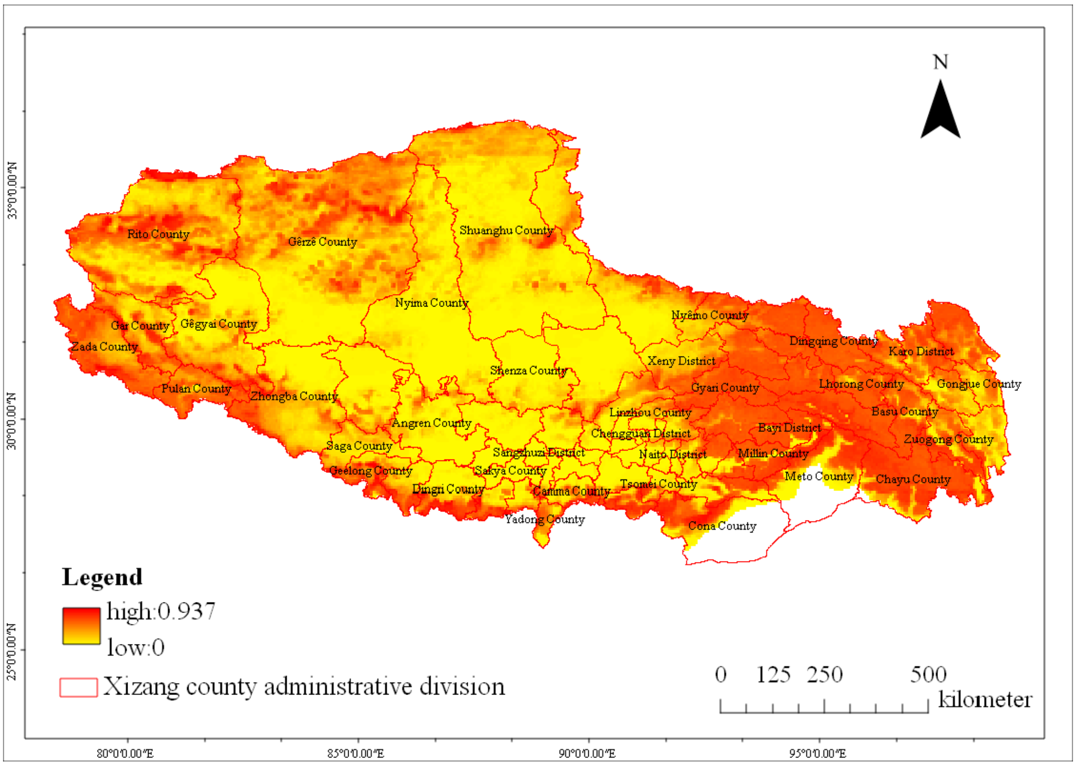

Figure 4. Distribution of historical snow disaster risk index in the study area.

As depicted in Figure 4, substantial regions in eastern Xizang are identified as high-risk zones for historical snow disasters, apart from two counties on the eastern border of Xizang and areas near the national border in the south. Additionally, the Gaize and Ritu counties in the Ali Region are also excluded from this high-risk zone. Notably, Nyingchi and Chamdo exhibit the highest level of risk, occupying the largest areas. Conversely, the risk levels in Shigatse and Nagqu, in Central Xizang, are relatively low.

4.2. Potential Snow Disaster Risk

Based on Formulas (3)–(6), the number of blizzard days, maximum snow depth, cumulative snowfall, and average snow depth were calculated for each year from 2000 to 2018. The average values over these 19 years for these four assessment indicators were then calculated.

After normalizing the four assessment indicators for the potential risk assessment of snow disasters according to Formula (7), the results were input into the entropy weight method formulas, Formulas (8)–(12). The information entropy and weights of the four indicators could then be calculated, as shown in Table 4.

Table 4. Entropy weight of potential snow disaster assessment indicators.

Indicators	Multi-Year Average Number of Blizzard Days	Multi-Year Average Maximum Snow Depth	Multi-Year Average Cumulative Snowfall	Multi-Year Average Snow Depth
Information entropy	0.9572	0.9667	0.9593	0.9265
Weight	0.22	0.18	0.21	0.39

According to the data presented in Table 4, the information entropy of the multi-year average number of blizzard days, multi-year average maximum snow depth, multi-year average cumulative snowfall, and multi-year average snow depth were 0.9572, 0.9667, 0.9593, and 0.9265, respectively. The average snow depth has the lowest information entropy, so its corresponding weight is the largest, at 0.39. This result indicates that the average snow depth plays a decisive role in potential snow disaster risk assessments, highlighting that persistent snow accumulation is the primary factor leading to snow disasters. Comparatively, the weights are 0.22, 0.18, and 0.21 for the multi-year average number of blizzard days, multi-year average maximum snow depth, and multi-year average cumulative snowfall, respectively. These three weights are much lower than that of the average snow depth at 0.39, indicating that their influence is relatively weaker. The common influencing factor between the number of blizzard days and accumulative snowfall is the snowfall amount. Consequently, their information entropy and weights in the snow disaster risk assessment are also quite similar. Based on the results of the entropy weighting calculations of the above four indicators, combined with Equation (16), the formula for calculating the potential snow disaster assessment index can be expressed as follows:

$$S_2 = 0.22I_{day} + 0.18I_{\max} + 0.21I_{sum} + 0.39I_{avg} \tag{18}$$

where I_{day}, I_{max}, I_{sum}, and I_{avg} represent the normalized multi-year average number of blizzard days, multi-year average maximum snow depth, multi-year average cumulative snowfall, and multi-year average snow depth, respectively. Using PIE 7.0 for thematic mapping, a distribution map was generated to illustrate the potential snow disaster index, as depicted in Figure 5.

As depicted in Figure 5, the areas with the highest potential snow disaster risk are primarily situated at the junction of Nyingchi and Chamdo. Conversely, other areas exhibit relatively low potential snow disaster levels.

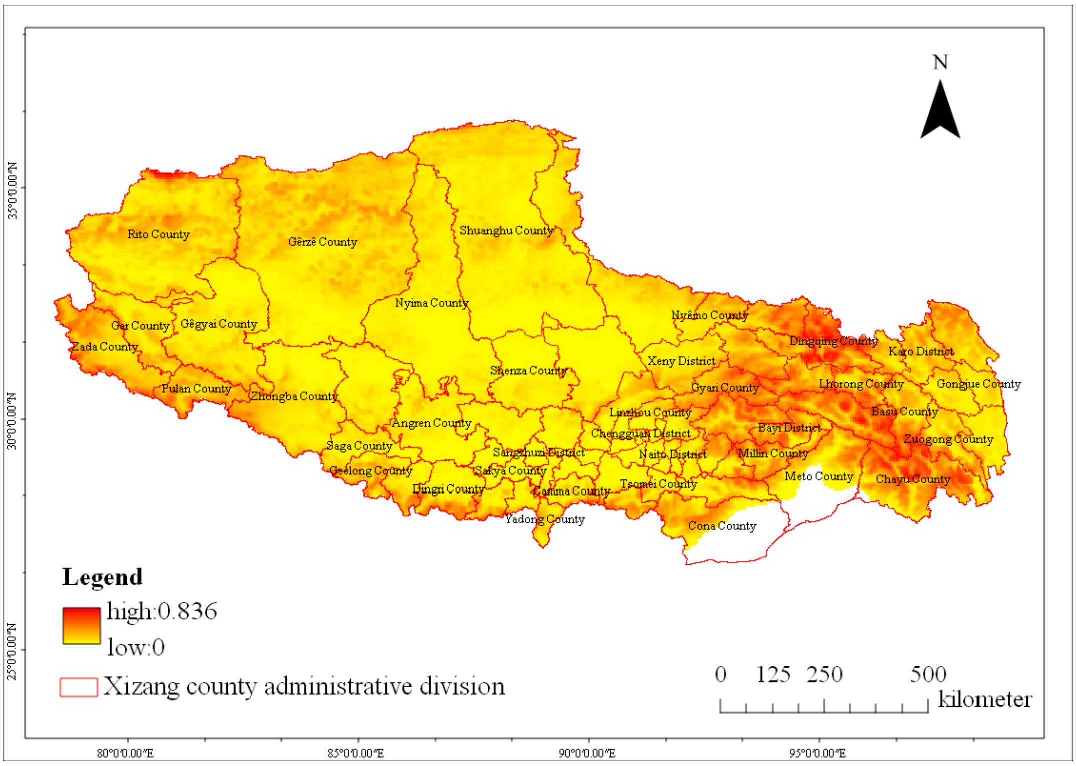

Figure 5. Distribution of potential snow disaster risk index in the study area.

4.3. Analysis of Snow Disaster Risk

When constructing the risk assessment model of snow disaster for Xizang, this research primarily considered historical and potential snow disaster risks. Based on Formulas (8)–(12), the information entropy and indicator weights presented in Table 5 can be calculated. As shown in Table 5, the influence of historical and potential snow disasters on the risk of snow disaster in Xizang is nearly equal. For ease of calculation, both were assigned a weight of 0.5.

Table 5. Entropy weights of risk assessment indicators of snow disasters.

Indicators	Historical Snow Disaster Risk Index	Potential Snow Disaster Risk Index
Information entropy	0.9555	0.9550
Weight	0.4974	0.5026

Therefore, the formula for calculating the risk assessment index of snow disasters in Xizang can be expressed as

$$S = 0.5S_1 + 0.5S_2 \tag{19}$$

where S_1 and S_2 are the normalized historical and potential snow disaster risk indices, respectively. Considering Formulas (17) and (18), Formula (19) can be expressed as follows:

$$S = 0.5(0.4p + 0.6q) + 0.5(0.22I_{day} + 0.18I_{\max} + 0.21I_{sum} + 0.39I_{avg}) \tag{20}$$

Based on Formula (20), the risk assessment index factors of snow disasters in Xizang can be calculated to depict the distribution of the comprehensive risk assessment index of snow disasters, as shown in Figure 6.

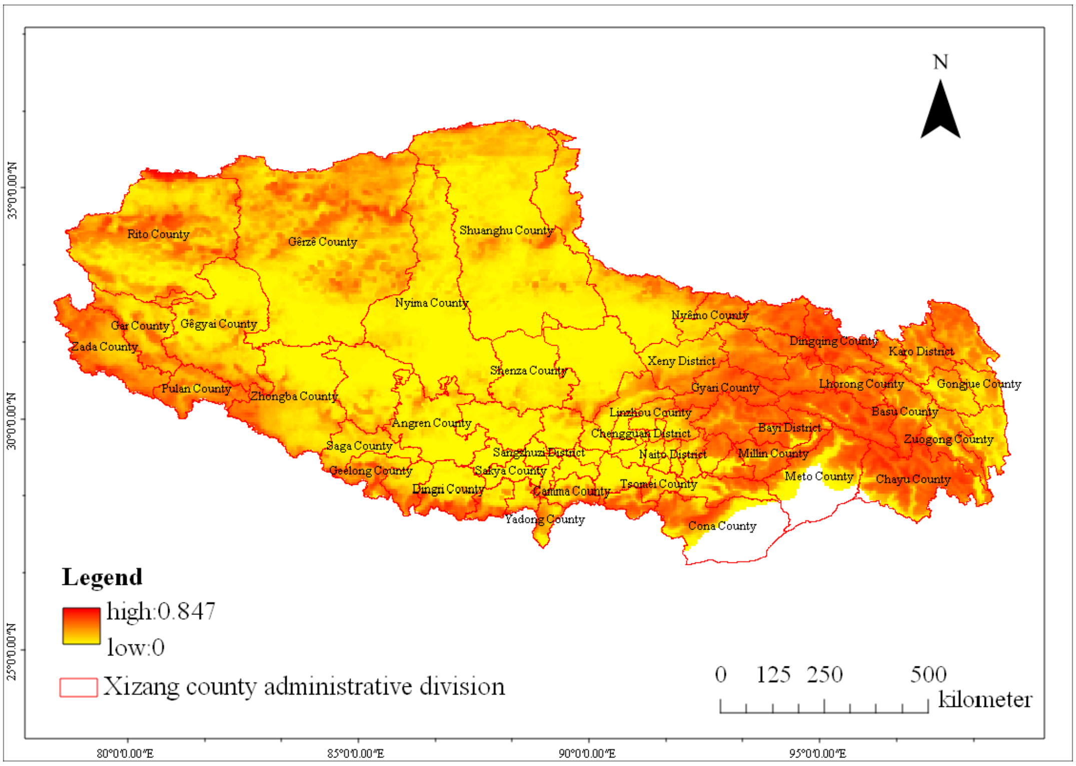

Figure 6. Distribution of the snow disaster risk index in the study area.

As depicted in Figure 6, the snow disaster assessment index in Xizang ranges from a maximum value of 0.847 to a value close to 0. After importing the assessment index into the PIE software, the percentile classification method (Equations (3)–(6)) was used to classify the assessment indices into five categories. In addition, four threshold values for the snow disaster risk levels were calculated, as presented in Table 6 below.

Table 6. Division values for risk assessment levels of snow disasters.

Percentile Values	Breakpoints
20%	0.019
40%	0.090
60%	0.219
80%	0.421

Utilizing the Xizang snow disaster risk level table (Table 2) as a reference, the distribution map of the Xizang snow disaster risk index was classified into five levels: high, relatively high, medium, relatively low, and low. Consequently, Figure 7 illustrates the snow disaster risk level map for Xizang.

Snow disaster risk assessment at a fine scale is extremely important for areas with a high frequency of snow disasters, especially areas such as Xizang, which are prone to snow disasters. Such assessments can provide more accurate and precise information on the degree of snow disaster risk and help to provide insight into the probability, intensity, and impact of snow disasters. By accurately locating potential risk areas, they provide a reliable reference for decision-makers and reduce the unpredictability of snow disasters. This enables decision-makers to gain a more comprehensive understanding of the potential impacts of snow disasters on the community and to develop specific, targeted prevention strategies.

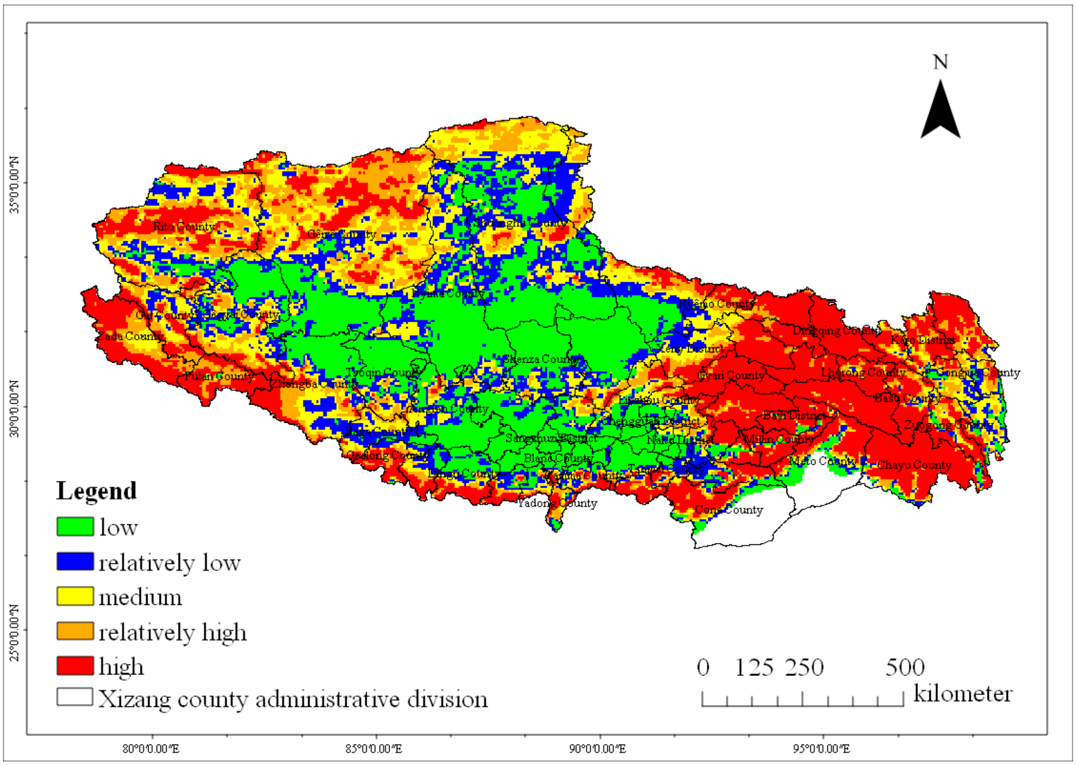

Figure 7. Snow disaster risk level map of Xizang.

To facilitate the analysis of the snow disaster risk in Xizang and provide guidance for disaster prevention in the region, the risk assessment index of snow disasters was statistically processed using county-level administrative units as the basic analytical units and using the average value method. Figure 8 shows a snow disaster risk level map for the county-level administrative areas of Xizang.

In the comprehensive results depicted in Figure 8, nine counties (districts) exhibit high levels of snow disaster risk, constituting 12.16% of the entire study area. These areas are predominantly situated in the eastern part of Xizang along the borders of three cities: Nagchu, Chamdo, and Nyingchi. Specifically, they encompass Dingqing and Bianba in Chamdo; Gongbu Jiangda, Bomi, and Chashu County in Nyingchi; and Nerong and Jiali County in Nagchu. Areas with high snow disaster risk levels tend to have more than 30 days of blizzards per year and up to 103 days. Moreover, the multi-year average maximum snow depth in these areas exceeds 20 cm and is up to 40 cm. These areas require high-priority attention in terms of disaster prevention and preparedness measures. A total of 24 counties (districts) have a relatively high risk of snow disasters, comprising 34.43% of the entire study area. These regions are predominantly located in the western part of the Ali Region, the central part of Chamdo, and the border region in Southern Xizang. The included counties are Jiangda, Leiwuqi, Luolong, Bashu, Zogong County, and the Kano District in Chamdo; Nerong and Ruoxian County in Nagqu; Mutuo and Mielin County in Nyingchi; Luozha County in Shannan; Gacha County in Lhasa; Mozhugongka County in Lhasa; Jilong, Nyalamu, Dingjie, and Yadong Counties in Shigatse; and Ritu, Gaer, Linda, and Pulan County in the Ali Region. In these regions, the number of blizzard days typically ranges from 14 to 30 days, and the multi-year average maximum snow depth ranges from 12 to 20 cm. A total of 18 counties (districts) exhibit a medium snow disaster risk level, accounting for 24.33% of the entire study area. These counties are predominantly located in the eastern part of the Ali Region, the northern part of Nagchu, and the northern part of Chamdo. Included are Chaya, Gongjue, and Mangkang County in Chamdo; Shuanghu, Amdo, and Senni County in Naqu; Dangxiong, and Linzhou County in Lhasa; Sannyi, Qusong, and Tsome County in Shannan; Zhongba, Saga, Tingri, Gangba, and Kangma

County in Shigatse; and Geji and Gaize County in the Ali Region. In the medium snow disaster risk level area, the number of blizzard days ranges from 10 to 14, while the multi-year average maximum snow depth ranges from 8 to 12 cm. A total of 15 counties (districts) exhibit a relatively low risk of snow disasters, comprising 20.27% of the entire study area. These areas are primarily situated at the junction of Shigatse and Shannan. They include Nyima, Shenzha, and Bango County in Nagchu; Langkazi and Naidong County in Shannan; Chengguan, Durlongdeqing, Dazi, District, and Nimu County in Lhasa; Ngongren, Shetong, Nanglin, and Bailang County in Shigatse; and Tsoqin County in the Ali Region. These areas often experience 6 to 10 blizzard days, with a multi-year average maximum snow depth ranging from 2 to 8 cm. As a result, the impact of snow disasters is relatively minor in these regions. A total of eight counties (districts) exhibit a low risk of snow disasters, accounting for 10.81% of the entire study area. These areas are primarily situated at the junction of Shigatse and Shannan. They include Qushui County in Lhasa; Lhatse, Sakya, Gyantse, Rinbu County, and Sangzhuzhi District in Shigatse; and Gonggar and Qiongjie County in Shannan. The number of blizzard days in these areas is less than 6, with a multi-year average maximum snow depth not exceeding 2 cm. There are generally no snow disasters in these areas, and they are suitable for human habitation.

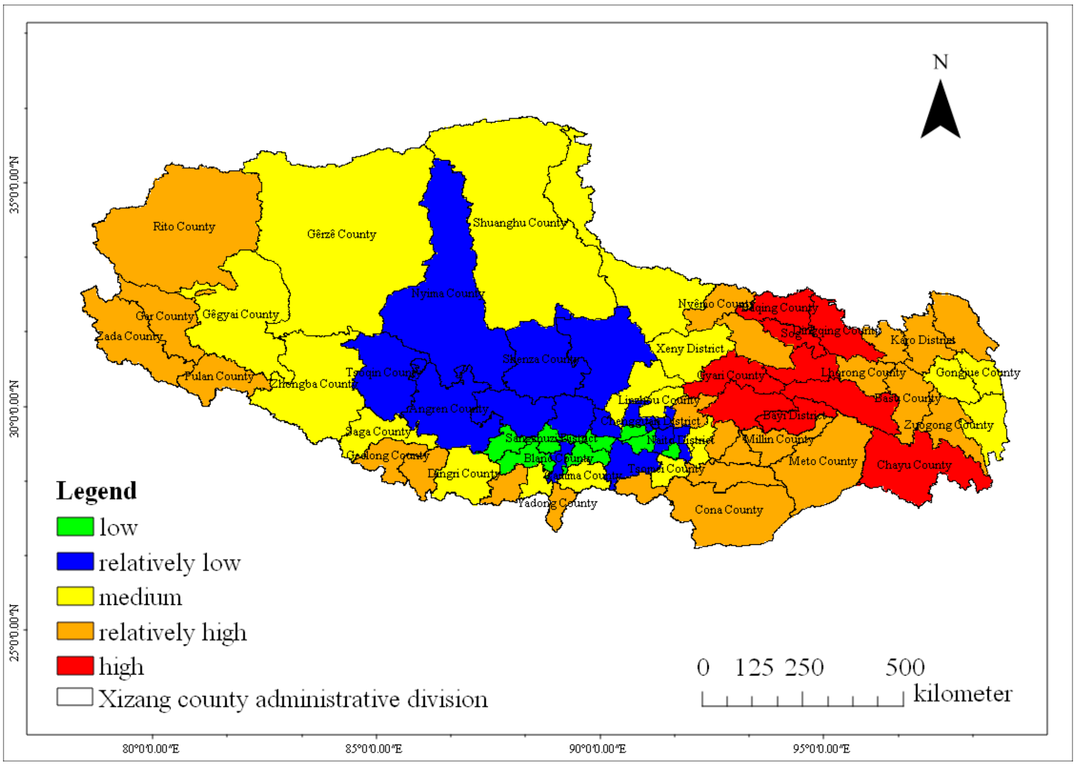

Figure 8. Snow disaster risk level map for county-level areas in Xizang.

5. Discussion

Some common machine learning models such as landslide susceptibility also exist in current natural disaster research. The performance of machine learning models is often measured in terms of metrics such as accuracy, which are evaluated and validated to ensure their ability to generalize to new data. Machine learning models commonly exhibit greater predictive power, but their internal mechanisms are more complex and require extensive computational resources and time to train and optimize. Considering the complexity of our assessment and the interpretability of our results, this research used the entropy weighting method to assess the snow disaster risk in the study area. We determined the weights of six snow-disaster-causing factors using the entropy weighting method and graded the degree of snow disaster risk in the study area.

5.1. Analysis of High-Risk Areas for Snow Disasters

The QTP, situated between the Himalayas and the Kunlun Mountains, stands as the world's highest plateau in terms of average elevation. Its geographical characteristics render the region highly susceptible to the impacts of climate change. Owing to its higher altitude and lower temperatures, snow depths on the QTP are both substantial and enduring [31,32]. The extended duration of snow cover stands out as a pivotal factor contributing to the heightened frequency of snow disasters on the QTP [33]. The plateau region contends with extremely cold temperatures and substantial snowfall during the winter months, resulting in a gradual accumulation of snow. This accumulation not only hampers ground transportation but also profoundly impacts pastoralism and agriculture in the plateau region [17,25,34]. For instance, the grazing activities of pastoralists and the cultivation efforts of farmers are influenced by the depth of snow cover, potentially resulting in the loss of herds and crops [35]. Consequently, as shown in Table 4, the information entropy value of the average snow depth is 0.9265, with the corresponding weight being the highest, at 0.39. This weight significantly exceeds those assigned to the number of blizzards, maximum snow depth, and cumulative snowfall. Hence, the average snow depth is the decisive factor in assessing potential snow disasters. This finding aligns with Zhou's perspective that persistent snow cover is the dominant factor causing snow disasters [12].

In areas of the QTP prone to snow disasters, these events have severely impacted local populations and their socio-economics. Consequently, it is crucial to identify areas at a high risk of snow disaster and implement specific measures to mitigate potential risks and damages in those high-risk areas. The analysis in Section 4 reveals that areas with relatively low snow disaster ratings are concentrated in the central part of Xizang, including the southwestern part of Nagchu and the northern part of Rikaze. Areas with higher snow disaster levels are predominantly located in the western part of the Ali Region, the central part of Chamdo, and areas near the border in Southern Xizang. Notably, the tri-city junction of Nagchu, Chamdo, and Nyingchi in eastern Xizang poses an extremely high risk, as indicated by all assessment indicators, which exhibit a certain degree of clustering. Xizang snow disaster statistics from 1960 to 2019 show that Nagchu has the highest frequency of snow disasters, totaling 189 occurrences, followed by the cities of Shigatse, Shannan, Ali, and Chamdo, with 179, 108, 90, and 85 snow disasters, respectively. Previous studies by other scholars have indicated that areas with a high comprehensive risk of snow disasters on the QTP are primarily concentrated in the central–eastern and southwestern parts of Xizang [23]. The central part of Shigatse, the southern part of Shannan, and the eastern part of Nagqu experience high snowfalls and snow depths [3]. Shigatse and Shannan are situated in the southern part of Xizang, while the area characterized by a high snowfall and snow depth in Nagqu is located in the central–eastern part of Xizang. This finding aligns with our research findings. In summary, our study indicates that the snow disaster level in Xizang is generally high, particularly in Nyingchi, Chamdo, Shannan, the eastern part of Nagchu, and the western part of the Ali Region. These areas are predominantly situated in the central–eastern and southern parts of Xizang and should be prioritized during snow disaster prevention and relief efforts in the future.

5.2. Limitations and Future Prospects

We utilized a long-time-series snow depth remote sensing dataset to enhance the spatial refinement of our research results. Compared with the weather station data traditionally used in hazard studies, this research reflected more accurately the regional heterogeneity of snow disasters in Xizang. However, there are some limitations to our research:

(1) In our research, the entropy weight method was employed to assess the weight of each indicator. The entropy weight method conforms to the laws of mathematics, with strict mathematical significance, but occasionally overlooks the subjective intentions of decision-makers. Therefore, the weights of indicators could be adjusted by incorporating subjective methods in future research, such as the AHP.

(2) Snow disasters have more complex and influential factors, and it is difficult to quantify the degree of a snow disaster risk. In selecting the indicators for snow disaster risk assessments, our research references the methods and findings of previous work, which is somewhat subjective. Therefore, the selection of snow disaster risk assessment indicators needs further improvement.

Most traditional technical systems for snow disaster risk assessments are based on meteorological station data. However, the distribution of meteorological stations is relatively sparse, and station data lack regional representativeness, which makes it difficult to effectively reflect the degree of snow disaster on a large spatial scale, such as in Xizang. In this research, a snow disaster risk assessment was conducted in the Xizang area of the QTP based on remote sensing images. Compared with snow disaster risk assessments based on meteorological station data, our research can reflect the degree of snow disaster risk on a large spatial scale, which makes up for the lack of regional representativeness in the station data due to the sparse distribution of meteorological stations. On the other hand, by integrating information from multiple resources, such as topographic, climate, and vegetation data, and combining spatial simulation and analysis with geographic information system methods, it is expected that we have accurately delineated potential snow disaster risk areas. Finally, our meteorological model simulation results are combined with statistical methods to fill in the gaps in weather station data while improving the comprehensiveness and accuracy of our assessment. Those comprehensive methods will provide a new direction for enhancing snow disaster assessment techniques in data-scarce environments and provide more reliable scientific support for future decision-making.

Our research selected key indicators such as the frequency of snow disasters, intensity of snow disasters, number of blizzard days, snow depth, and cumulative snowfall to construct a comprehensive assessment model for snow disasters in the Xizang area of the QTP. In future research work, this model could be refined and improved by adding more indicators. These indicators may include geographic and meteorological factors, such as elevation, wind speed, temperature, and other related variables. By incorporating more indicators, the robustness and accuracy of the model can be further improved, resulting in a more detailed understanding of snow disasters in the QTP, which is beneficial for formulating more detailed strategies for snow disaster prediction, mitigation, and responses.

6. Conclusions

Snow disasters are one of the main natural meteorological disasters occurring in the winter and spring seasons in the Xizang pastoral area, and they occur almost every year. The natural disaster situation in Xizang is still very complicated and severe, but the institutional mechanisms of disaster prevention, mitigation, and relief need to be improved continuously. This research developed a snow disaster assessment model for the XAR of the QTP based on a long-time-series snow depth remote sensing dataset. This model combined two indicators of historical snow disasters and four indicators of potential snow disasters and classified the snow disasters in the study area into five levels: high, relatively high, medium, relatively low, and low. A higher snow disaster risk level indicates a greater likelihood of significant harm occurring in these areas. Such issues include the pastures being more likely to be deeply covered with snow; difficulties in watering livestock; an obstruction of foraging; as well as the frostbite, starvation, disappearance, and even death of livestock. Hence, timely relief efforts and the reinforcement of disaster prevention and mitigation measures are crucial to safeguard the livestock in pastoral regions from the dangers of snow disasters. In disaster management and resource allocation, policymakers should prioritize enhancing the resilience of these high-risk areas by allocating additional supplies to those areas with high and relatively high snow disaster risk levels.

Our results indicate that the distribution of snow disaster classes across the study area from 2000 to 2018 was not uniform. Areas with a low snow disaster rating were primarily concentrated in Central Xizang, and areas with a high snow disaster rating were primarily distributed across the eastern–central and southern parts of Xizang. In the historical and potential snow disaster assessments of the study area, snow intensity and multi-year average snow depth had the highest weights in their respective assessments while also being considered the decisive factors in evaluating snow disaster risks. Finally, the most recent time point covered by the dataset is 2018, but our method remains applicable even if the dataset is updated in the future.

Author Contributions: Conceptualization, L.M. and X.S.; methodology, L.M. and X.F.; software, X.Z. and X.F.; validation, X.Z. and X.F.; formal analysis, X.S.; investigation, X.S., X.Z. and X.F.; data curation, X.Z. and X.F.; writing—original draft preparation, L.M. and X.S.; writing—review and editing, L.M., X.F. and X.S. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the Open Foundations of Jiangsu Province Engineering Research Center of Airborne Detecting and Intelligent Perceptive Technology (JSECF2023-14).

Data Availability Statement: The snow depth dataset for the Tibetan Plateau (2000–2018) data presented in the study is openly available from the Third Pole Environment Data Center at https://cstr.cn/18406.11.Snow.tpdc.271743 (accessed on 31 January 2022).

Acknowledgments: The authors would like to thank the National Tibetan Plateau Data Center for providing the snow depth dataset containing Tibetan Plateau data. We also thank the editors and reviewers for their constructive comments.

Conflicts of Interest: The authors declare no conflicts of interest.

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