Characteristics and Model of Rainstorm Flood Disaster Risk Index Along Qinghai Highways: Postprint

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Abstract

Utilizing daily precipitation data from ground meteorological observations, geographic information data, and socioeconomic data from 50 national meteorological stations and 39 highway traffic meteorological stations in Qinghai Province from January 2012 to December 2021, and based on the analysis of occurrence and development patterns, spatiotemporal distribution characteristics of rainstorm floods along highways, and spatial distribution characteristics of rainfall days with different intensities, this study employed methods such as the Analytic Hierarchy Process and natural breakpoint method to summarize the spatial characteristics of hazard factor risk index, disaster-forming environment risk index, exposure risk index, disaster prevention and mitigation capacity risk index, and comprehensive risk index. Furthermore, using factors including disaster-forming environment, meteorological risk, and disaster prevention and mitigation capacity for rainstorm flood disasters along highways, a risk model for highway rainstorm flood disasters was constructed. The results indicate that: (1) The spatial distribution of rainfall days with different intensities along highways in Qinghai Province generally exhibits a decreasing trend from southeast to northwest, with sections from the highest risk zone to the sub-highest risk zone including the Xining-Tianjun section of National Highway G315 and the Xining-Ebao Ridge section of G227, among others. (2) The vulnerability risk of the rainstorm flood disaster-forming environment gradually decreases from the southeast and northeast to the west, with sections of higher vulnerability risk including the Qilian section of National Highway G227 and the Gonghe-Nangqian section of G214, among others. (3) The highest risk zones of exposure are mainly concentrated in the Minhe-Gonghe section of National Highway G109 and the Xining-Ebao Ridge section of G227, among others. (4) Areas with higher disaster prevention and mitigation capacity are mainly distributed in sections such as Xining, Haidong, eastern Haibei, and western Haixi in Qinghai Province. (5) The risk model for highway rainstorm flood disasters in Qinghai Province is classified

into five levels: lowest risk (Level 1), sub-lowest risk (Level 2), medium risk (Level 3), sub-highest risk (Level 4), and highest risk (Level 5). This risk model can be applied in meteorological disaster risk management operations, providing scientific basis for disaster prevention, mitigation, and relief efforts of local transportation departments.

Full Text

Preamble

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Characteristics and Model of Rainstorm and Flood Disaster Risk Index Along Qinghai Highways

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Abstract: Based on daily precipitation data from meteorological observations, geographic information data, and socioeconomic data, this study analyzes the occurrence and development patterns, spatiotemporal distribution characteristics, and spatial distribution features of rainfall days at different intensities along highways. Using the analytic hierarchy process and natural breakpoint method, we summarize the spatial characteristics of risk indices for rainstorm and flood disaster-causing factors, disaster-pregnant environments, disaster-bearing bodies, disaster prevention and mitigation capabilities, and comprehensive risk indices. By incorporating factors related to the disaster-pregnant environment, meteorological risk, and disaster prevention/mitigation capacity for rainstorm and flood disasters along highways, we construct a risk model for rainstorm and flood disasters along Qinghai highways. The results show: (1) The spatial distribution of rainfall days at different intensities along Qinghai highways generally decreases from southeast to northwest, with the highest to second-highest risk zones for disaster-causing factor hazards including the Tianjun section of National Highway G315 and the Xining-Ebaoling section of National Highway G227. (2) The vulnerability risk of the disaster-pregnant environment gradually decreases from the southeast and northeast to the west, with higher vulnerability risk sections including the Qilian section of National Highway G227 and the Gonghe-Nangqian section of National Highway G214. (3) The highest risk zone for exposure of disaster-bearing bodies is concentrated in the Minhe-Gonghe section of National Highway G109 and the Xining-Ebaoling section of National Highway G227. (4) Areas with higher disaster prevention and mitigation capabilities are mainly distributed in Xining, Haidong, eastern Haibei, and western Haixi. (5) The risk model classifies rainstorm and flood disaster risk into five levels: lowest risk (Level 1), low risk (Level 2), medium risk (Level 3), high risk (Level 4), and highest risk (Level 5). This model can be applied in meteorological disaster risk management operations, providing a scientific basis for disaster prevention, mitigation, and relief efforts by local transportation departments.

Keywords: rainstorm and flood disaster; disaster-causing factor; disaster-pregnant environment; disaster-bearing body; disaster prevention and mitigation capacity; risk model; Qinghai Province

Introduction

In recent years, global climate warming has led to a significant increase in extreme weather events and meteorological disasters worldwide. Meteorological disasters occur when meteorological conditions exceed the bearing capacity of disaster-bearing bodies, resulting in losses. These disasters are related not only to meteorological conditions but also to the vulnerability of the disaster-bearing bodies themselves. When meteorological conditions reach critical thresholds, corresponding disasters may occur; these thresholds are referred to as critical meteorological conditions for disaster-causing. Natural disasters comprise two fundamental elements: first, they are events occurring in nature, and second, these events can directly cause losses or catastrophes to human society. Among natural disasters, rainstorm and flood disasters are among the most severe, accounting for 40% of economic losses from all natural disasters. Meteorological disaster risk assessment involves quantitatively evaluating rainstorm and flood risks, studying their spatial distribution patterns, and establishing disaster-specific prevention and mitigation service models, which are crucial for reducing meteorological disaster risks and mitigating losses. Road traffic operation and management are increasingly sensitive to meteorological conditions. Qinghai, as part of the main Qinghai-Tibet Plateau, represents a sensitive and fragile region for climate and environmental changes in China. Previous research on rainstorm and flood disasters in Qinghai has primarily focused on occurrence patterns and impact mechanisms, with relatively few studies on risk assessment and zoning, mainly due to difficulties in obtaining geographic data, basic information, and incomplete technical methodologies.

Bao Guangyu et al. studied the spatiotemporal distribution characteristics of road icing in Qinghai and established a forecasting model for ground temperature and snow depth, dividing meteorological impact levels for traffic safety operations based on road icing duration. They also investigated the variation characteristics of road surface temperature in the Qaidam hinterland of the Beijing-Tibet Expressway and its relationship with temperature elements, as well as the risk zoning method for heavy snowfall disasters along Qinghai highways. Domestic and international scholars have conducted related research, such as risk assessment studies on rainstorm and flood disasters in the Huaihe and Datong River basins, and risk assessment methods based on cloud models or GIS in Xinjiang, Jiangxi, and Sichuan. However, research on rainstorm and flood disaster risks along Qinghai highways triggered by heavy rainfall remains in its initial stage. By the end of 2021, Qinghai's highway mileage reached 3610.07×10^3 km, including 3790×10^3 km of expressways. Under the combined influence of precipitation and terrain, mountain floods and debris flows frequently occur along highways in Qinghai.

Therefore, this study utilizes precipitation data, topographic relief, vegetation coverage, population density, per-unit-area cultivated land, per-unit-area large livestock numbers, per-unit-area usable grassland area, and per-capita GDP along Qinghai highways to conduct applied research on heavy precipitation risk technology in highway traffic professional meteorological services, aiming to enhance the scientific content and forecasting service capabilities of meteorological services.

1.2 Data Sources

This study uses daily precipitation data from 50 national meteorological stations and 39 traffic meteorological stations along Qinghai highways from January 2012 to December 2021 to calculate rainfall days at different intensities. The average values of indicators such as land area, sown area, population, GDP, and livestock numbers for various cities and counties in Qinghai were obtained from the *Qinghai Statistical Yearbook*. Vegetation coverage, river network data, topographic elevation, and administrative division data were extracted from 1:250,000 GIS maps provided by the National Information Center. Basic information on rainstorm and flood disasters, disaster types, and integrated data were sourced from the Qinghai Meteorological Disaster Database. Ten national highways and eight provincial highways in Qinghai were selected for the rainstorm and flood disaster risk model study. The distribution of research routes and meteorological stations is shown in [Figure 1: see original paper].

1.3 Research Methods

Statistical methods including dimensionless processing, analytic hierarchy process, natural breakpoint method, and comprehensive index method were applied to normalize indicators and eliminate dimensional differences. The normalization formulas for rainstorm and flood hazard, vulnerability, and exposure indicators are:

$$D_{ij} = 0.5 + 0.5 \times \frac{A_{ij} - \min(A_i)}{\max(A_i) - \min(A_i)}$$

where D_{ij} is the normalized value of the i-th indicator at station j; A_{ij} is the i-th indicator value at station j; and $\max(A_i)$ and $\min(A_i)$ are the maximum and minimum values of the i-th indicator, respectively.

To reduce meteorological disaster risk, disaster prevention and mitigation capabilities must be enhanced, so the normalization formula for disaster prevention and mitigation capacity differs from other indicators:

$$D_{ij} = 1.0 - 0.5 \times \frac{A_{ij} - \min(A_i)}{\max(A_i) - \min(A_i)}$$

All evaluation factor indices were calculated using the weighted comprehensive evaluation method, which considers the influence degree of each indicator on the overall factor:

$$V_t = \sum_{i=1}^{n} W_i \times D_{it}$$

where V_t is the total value of evaluation factor t; W_i is the weight of indicator i; D_{it} is the normalized value of indicator i for factor t; and n is the number of evaluation indicators.

The analytic hierarchy process was used to calculate factor weights, which objectively quantifies subjective judgments using a specific scale. When establishing the rainstorm and flood risk forecasting model, the weighted comprehensive evaluation method was applied based on natural disaster risk assessment principles and evaluation indicator systems:

$$MDRI = a \times V_{\text{hazard}} + b \times V_{\text{exposure}} + c \times V_{\text{vulnerability}} + d \times V_{\text{prevention}}$$

where $MDRI$ is the comprehensive model for rainstorm and flood disaster risk forecasting, representing the degree of rainstorm and flood risk (higher values indicate greater risk); V_{hazard}, V_{exposure}, $V_{\text{vulnerability}}$, and $V_{\text{prevention}}$ are the hazard index, exposure index, vulnerability index, and disaster prevention/mitigation capacity index calculated using formula (3), respectively; and a, b, c, and d are the weights of the evaluated factors.

1.4 Selection and Calculation of Risk Indicators

Different grades of precipitation along Qinghai highways were selected as the disaster-causing factor risk index for rainstorm and flood disasters. Vegetation coverage, topographic relief, and river network density were chosen as the disaster-pregnant environment risk index. Population density, per-unit-area cultivated land, per-unit-area large livestock numbers, and per-unit-area usable grassland area were selected as the disaster-bearing body risk index. Per-capita

GDP was chosen as the indicator for disaster prevention and mitigation capacity risk index. All indicators and weights were calculated using the analytic hierarchy process, as shown in .

According to Qinghai Provincial Meteorological Disaster Standards, precipitation $ $50.0 mm is defined as a rainstorm, 25.0–49.9 mm as heavy rain, 10.0–24.9 mm as moderate rain, and 0.1–9.9 mm as light rain. Based on this standard, rainstorms occur infrequently along major highways in Qinghai. Therefore, precipitation days $ $25.0 mm are collectively referred to as heavy rainfall days for highway contexts. Due to the low average annual heavy rainfall days at highway meteorological stations, the annual cumulative heavy rainfall days, annual average light rain days, and annual average moderate rain days were calculated and standardized as disaster-causing factors for rainstorm and flood disaster risk.

2.1.1 Spatial Distribution Characteristics of Different Rainfall Days

The spatial distribution of rainfall days along Qinghai highways generally shows a decreasing trend from southeast to northwest. The most affected highway sections include: the Huangzhong, Guinan, Darlag, and Jiuzhi sections of Provincial Highway S101; the Henan and Zeku sections of Provincial Highway S203; the Datong and Menyuan sections of National Highway G227; the Haiyan and Gangcha sections of National Highway G315; and the Nangqian section of National Highway G214.

The spatial distribution of annual cumulative heavy rainfall days along Qinghai highways ([Figure 2: see original paper]) shows that the main affected sections include: the Tianjun section of National Highway G315; the Ebaoling section of National Highway G227; the Gonghe and Xiewu-Nangqian sections of National Highway G214; and the Maqin, Baima, and Jiuzhi sections of Provincial Highway S101. The spatial distribution of annual average light rain days ([Figure 2: see original paper]) indicates that the main affected sections include: the Qilian section of National Highway G227; the Haiyan and Gangcha sections of National Highway G315; and the Nangqian section of National Highway G214. The spatial distribution of annual average moderate rain days ([Figure 2: see original paper]) reveals that the main affected sections include: the Ebaoling section of National Highway G227; the Gonghe and Xiewu-Nangqian sections of National Highway G214; and the Henan section of Provincial Highway S203.

2.1.2 Spatial Distribution Characteristics of Disaster-Causing Factor Risk Index

Using three indicators—annual cumulative heavy rainfall days, annual average light rain days, and annual average moderate rain days—the spatial distribution of the rainstorm and flood disaster-causing factor risk index was calculated

([Figure 3: see original paper]). The natural breakpoint classification method divided the hazard levels into highest risk, high risk, medium risk, low risk, and lowest risk zones. The results show that the hazard of rainstorm and flood disaster-causing factors along Qinghai highways exhibits an east-high, west-low pattern, consistent with the spatial distribution of rainfall days at different intensities. The highest to high-risk zones for disaster-causing factors include: the Tianjun section of National Highway G315; the Ebaoling section of National Highway G227; the Jiuzhi section of National Highway G214; and the Henan section of Provincial Highway S203.

2.2 Spatial Distribution Characteristics of Disaster-Pregnant Environment Risk Index

The spatial distribution of rainstorm and flood disaster-pregnant environment risk index along Qinghai highways ([Figure 3: see original paper]) shows that vulnerability risk gradually decreases from the southeast and northeast to the west. Areas with higher vulnerability risk are mainly located in Haibei, Hainan, northern Guoluo, and northeastern Yushu. Lower vulnerability risk areas are primarily in the western and northwestern regions. In eastern Qinghai, including southern Huangnan, southern Guoluo, and the Qinghai Lake area, the disaster-pregnant environment shows medium and low risk levels. Highway sections with higher vulnerability risk include: the Qilian section of National Highway G227; the Nangqian section of National Highway G214; the Maqin section of National Highway G0615; and the Gonghe section of National Highway G109.

2.3 Spatial Distribution Characteristics of Disaster-Bearing Body Risk Index

Disaster-bearing bodies are the entities threatened by rainstorm and flood disasters. Using population density, per-unit-area cultivated land, per-unit-area large livestock numbers, and per-unit-area usable grassland area, the spatial distribution of the disaster-bearing body risk index was calculated ([Figure 4: see original paper]). The highest risk zone for exposure of disaster-bearing bodies is concentrated in eastern Qinghai, where population is relatively dense and major agricultural areas are located. This region features complex road infrastructure including bridges and tunnels, with high volumes of local and through traffic. The highest risk sections for disaster-bearing body exposure include: the Minhe-Gonghe section of National Highway G109; the Xining-Ebaoling section of National Highway G227; the Gangcha section of National Highway G315; the Xinghai section of National Highway G214; the Guide section of National Highway G310; and the Maixiushan section of Provincial Highway S306.

2.4 Spatial Distribution Characteristics of Disaster Prevention and Mitigation Capability Risk Index

Disaster prevention and mitigation capability refers to the ability of regions affected by rainstorm and flood disasters to resist and recover from disasters, which is related to local economic development levels. Higher per-capita GDP indicates stronger economic capacity and thus stronger disaster prevention and mitigation capability. The spatial distribution of disaster prevention and mitigation capability risk index along Qinghai highways ([Figure 4: see original paper]) shows that higher capability regions are mainly distributed in Xining, Haidong, eastern Haibei, and western Haixi. Highway sections with higher disaster prevention and mitigation capability include: the Xining-Gonghe and Golmud sections of National Highway G109; the Gangcha and Dachaidan-Mangya sections of National Highway G315; the Qilian section of National Highway G227; the Guide section of National Highway G310; the Xunhua and Tongren sections of Provincial Highway S202; and the Xining-Guide and Xunhua sections of Provincial Highway S101.

2.5 Comprehensive Risk Index Grade Distribution Characteristics

Based on quantitative analysis of various risk indicators for rainstorm and flood disasters along Qinghai highways, the comprehensive risk index was divided into five risk levels: highest risk, high risk, medium risk, low risk, and lowest risk zones. The spatial distribution of the comprehensive risk index ([Figure 5: see original paper]) shows that high to highest risk sections include: the Minhe-Gonghe section of National Highway G109; the Ebaoling section of National Highway G227; the Gangcha section of National Highway G315; the Xinghai section of National Highway G214; the Maqin and Baima-Jiuzhi sections of Provincial Highway S101; the Xunhua section of Provincial Highway S202; and the Tongren section of Provincial Highway S306.

2.6 Rainstorm and Flood Disaster Risk Model

Based on the analysis of occurrence patterns, spatiotemporal distribution characteristics, and spatial distribution of rainfall days at different intensities along major highways in Qinghai, we summarized the risk indices for disaster-causing factors, disaster-pregnant environments, disaster-bearing bodies, disaster prevention and mitigation capabilities, and comprehensive risk levels. By incorporating factors related to the disaster-pregnant environment, meteorological risk, and disaster prevention/mitigation capacity for rainstorm and flood disasters along highways, and revealing the relationship between precipitation and rainstorm/flood disasters, we normalized the values of disaster-pregnant environment, disaster-bearing body, and disaster prevention/mitigation capacity indices. Building upon the comprehensive characteristics of disaster-causing factor hazards, we added correction coefficients for the disaster-pregnant environment, disaster-bearing bodies, and disaster prevention/mitigation capacity to develop the rainstorm and flood disaster risk model for highways.

The weighted comprehensive evaluation method was applied according to the formula, establishing the rainstorm and flood disaster risk model for Qinghai highways. The model index levels were divided into five grades (Level 1 to Level 5), representing lowest risk, low risk, medium risk, high risk, and highest risk, respectively ().

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3 Conclusions

(1) The spatial distribution of rainfall days at different intensities along Qinghai highways generally decreases from southeast to northwest. The most affected sections include the Huangzhong, Guinan, Darlag, and Jiuzhi sections of Provincial Highway S101; the Henan and Zeku sections of Provincial Highway S203; the Datong and Menyuan sections of National Highway G227; the Haiyan and Gangcha sections of National Highway G315; and the Nangqian section of National Highway G214.

(2) Higher hazard from rainstorm and flood disaster-causing factors leads to higher flood risk, with different precipitation grades reflecting disaster intensity and impact duration. The highest to high-risk zones for disaster-causing factors include the Tianjun section of National Highway G315, the Jiuzhi and Ebaoling sections of National Highway G214, and the Henan section of Provincial Highway S203.

(3) The vulnerability risk of the disaster-pregnant environment gradually decreases from southeast and northeast to west. Higher vulnerability risk sections include the Qilian section of National Highway G227, the Nangqian section of National Highway G214, and the Maqin section of Provincial Highway S101.

(4) The highest risk zone for exposure of disaster-bearing bodies is concentrated in the Minhe-Gonghe section of National Highway G109 and the Xining-Ebaoling section of National Highway G227, as well as the Gangcha, Xinghai, Guide, Xunhua, and Maixiushan sections.

(5) Regions with higher disaster prevention and mitigation capabilities are mainly distributed in Xining, Haidong, eastern Haibei, and western Haixi. Highway sections with higher capability include the Xining-Gonghe and Golmud sections of National Highway G109, the Gangcha and Dachaidan-Mangya sections of National Highway G315, the Qilian section of National Highway G227, the Xinghai section of National Highway G214, and the Xining-Guide, Xunhua, and Tongren sections of Provincial Highway S101.

(6) Based on quantitative assessment of various risk indicators, the compre-

hensive risk index for rainstorm and flood disasters along highways was divided into five risk levels. The highest risk zones are mainly distributed in eastern Qinghai. High to highest risk sections include the Minhe-Gonghe, Ebaoling, Gangcha, and Xinghai sections of National Highways G109, G227, G315, and G214, respectively, as well as the Maqin-Baima-Jiuzhi section of Provincial Highway S101 and the Xunhua and Tongren sections of Provincial Highways S202 and S306.

(7) Based on the spatial distribution characteristics of disaster-causing factor risk index, disaster-pregnant environment risk index, disaster-bearing body risk index, disaster prevention and mitigation capability risk index, and comprehensive risk index levels, we constructed a rainstorm and flood disaster risk model for highways. The model index is divided into five grades (Level 1 to Level 5), representing lowest risk, low risk, medium risk, high risk, and highest risk, respectively.

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Note: Figure translations are in progress. See original paper for figures.