Flash Flood Disaster Risk and Impact Zoning for Different Return Periods in the Yinchuan Section of Helan Mountains (Postprint)

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Abstract

To assess the degree of flash flood disaster risk and its impacts in the Yinchuan section of the Helan Mountains, this study utilizes high-resolution Digital Elevation Model (DEM), administrative divisions, water systems, and historical precipitation data from automatic weather stations, as well as socioeconomic information such as residential areas, schools, and bridges. By employing a combined method of Flo?odArea model simulation and ArcGIS spatial overlay statistical analysis, the research analyzes the distribution characteristics of flash flood disaster risk in the Yinchuan section of the Helan Mountains for different return periods, and its impacts on population, land use, and Gross Domestic Product (GDP). The results indicate: (1) In the Yinchuan section of the Helan Mountains, the areas of low-, medium-, and high-risk zones for flash flood disasters with 10–100 year return periods are 109.5–276.3 km^2, 45.0–231.0 km^2, and 13.4–204.3 km^2, respectively. The zonal area of flash flood disasters at the same risk level shows a significant increasing trend with increasing return period. (2) The risk zones for 10-year and 20-year flash flood disasters in the Helan Mountains are mainly located in the flash flood gullies and their adjacent areas at elevations of 1,130–1,450 m. The risk zones for 50-year flash flood disasters are primarily concentrated in the lower reaches of the flash flood gullies and the alluvial fan areas at elevations of 1,130–1,180 m in the piedmont. The risk zones for 100-year flash flood disasters cover the entire piedmont area at elevations of 1,120–1,350 m and the alluvial fan areas. With increasing return period, the flash flood disaster risk zones in the Helan Mountains exhibit a notable characteristic of slower (faster) expansion toward upstream (downstream) areas. (3) The total populations affected by 10-year, 20-year, 50-year, and 100-year flash flood disasters from the Helan Mountains in Yinchuan City are 7.30\$$\times 10^{\{4\}, 9.87\times 10}\{4\}, 1.65\times 10^{\{5\}, and 2.39\times 10}\{5\}$\$ people, respectively. With increasing flash flood return period, the total affected population shows a significant increasing trend, with the population growth rates in

low-, medium-, and high-risk zones ranging from -12.4%-20.5%, 48.6%-91.8%, and 163%-300%, respectively. (4) Farmland and grassland are the most severely affected by flash flood disasters from the Helan Mountains, with their combined proportion of the total affected land area ranging from 82.1%-86.9%. This is followed by construction land and cultivated land, which account for 4.4%-9.1% and 1.1%-4.6% of the total affected land area, respectively, representing key areas for flash flood disaster prevention in Yinchuan City. (5) The total GDP affected by medium- and high-risk zones for 10-year, 20-year, 50-year, and 100-year flash flood disasters from the Helan Mountains in Yinchuan City is 1.12\$$\times10^{\{9\},\,2.00\times10}\{9\},4.70\times10^{\{9\},\,and 8.74\times10}\{9\}$\$ yuan, respectively. When flash flood disasters exceeding the 50-year return period occur, agricultural and industrial sectors along the mountains, as well as basic public infrastructure, will suffer substantial economic losses.

Full Text

Risk and Impact Zoning of Different Return Period Flash Flood Disasters in Yinchuan Section of Helan Mountain

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Abstract: To assess the risk levels and impacts of flash flood disasters in the Yinchuan section of Helan Mountain, this study utilized high-resolution digital elevation models, administrative divisions, water system data, historical precipitation data from automatic weather stations, and socioeconomic information including residential areas, schools, and bridges. By combining the FloodArea model simulation with ArcGIS spatial overlay statistical analysis, we analyzed the risk distribution characteristics of flash flood disasters across different return periods and their impacts on population, land use, and gross domestic product (GDP) in the Yinchuan section of Helan Mountain. The results indicate: (1) For 10–100-year return periods, the low-risk, medium-risk, and high-risk zones covered areas of 109.5-276.3 km^2, 45.0-231.0 km^2, and 13.4-204.3 km^2, respectively. The zoned area for flash flood disasters at the same risk level showed a significant increasing trend as the return period increased. (2) Risk zones for 10-year and 20-year return periods were mainly located in flash flood channels and their adjacent areas at altitudes of 1,130–1,450 m. Risk zones for 50-year return periods concentrated in downstream channel areas and the alluvial fan region at altitudes of 1,130–1,180 m along the mountain front. Risk zones for 100-year return periods covered the entire mountain front area at altitudes of 1,120–1,350 m and the alluvial fan region. As the return period increased, risk zones exhibited a notable characteristic of slower expansion toward upstream (higher altitude) areas and faster expansion toward downstream (lower altitude) areas. (3) In Yinchuan City, the total population affected by 10-year and 100-year flash flood disasters was 73,000 and 987,000, respectively. With increasing return periods, the affected population showed a significant upward trend, with growth rates of -12.4% to 20.5% in low-risk areas, 48.6% to 91.8% in medium-risk areas, and 163% to 300% in high-risk areas. (4) Farmland and grassland were the most severely impacted land use types, together accounting for 82.1%-86.9% of the total affected area. Construction land and cultivated land followed, accounting for 4.4%-9.1% and 1.1%-4.6% of the total affected area, respectively. These areas represent key zones for flash flood disaster prevention and mitigation in Yinchuan City. (5) The total GDP affected by flash flood disasters in medium- and high-risk zones in Yinchuan City was 1.12 billion, 2.00 billion, 4.70 billion, and 8.74 billion yuan for 10-year, 20-year, 50-year, and 100-year return periods, respectively. During extreme 100-year flash flood events, agricultural and industrial industries, infrastructure, and public facilities along the Helan Mountain front would suffer severe economic losses.

Keywords: flash flood disaster; risk and impact zoning; FloodArea; Helan Mountain Yinchuan section; ArcGIS

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1 Introduction

Flash floods are sudden, rapidly rising surface runoff events in small mountainous watersheds triggered by precipitation, characterized by concentrated water volume, high flow velocity, strong destructive power, high potential for casualties, significant regional variation, and difficulty in prediction and prevention. Flash floods and associated debris flows and landslides are extremely destructive, causing severe damage to national economies and people' s lives and property, with challenging post-disaster recovery. According to the World Meteorological Organization' s survey of natural disaster losses across 134 major countries worldwide, flash flood disasters rank first or second in many nations. In China, flash flood disasters lead the world in activity intensity, outbreak scale, economic losses, and casualties. Since the 21st century, flash floods have occurred frequently in China, causing an average of 70%-90% of all flood-related deaths annually, with this proportion showing an upward trend. The hazards to industrial and agricultural development and people' s lives and property continue to increase.

Risk zoning assessment represents both an important component of flash flood disaster research and the foundation for disaster prevention efforts. Developed countries including the United States, United Kingdom, Sweden, and Japan began flash flood risk zoning research in the 1960s–1970s, achieving substantial results. China initiated flash flood disaster risk studies in the 1990s. Scholars have conducted macro-scale zoning and evaluation of national flash flood risks based on topographic and geological conditions, historical rainstorm disaster data by province, flood intensity, frequency, and national economic data. Building on this work, more detailed flood risk zoning maps have been developed for provinces, autonomous regions, and typical watersheds. These achievements have played important roles in flash flood early warning and prevention, providing effective non-engineering measures to avoid or reduce disaster losses.

Since the 21st century, Ningxia has experienced increasing trends in affected population, fatalities, and direct economic losses from flash floods, yet few studies have examined flash flood risk zoning within the region. The Yinchuan section of Helan Mountain receives an average annual rainfall of 150–400 mm and features over 40 major mountain torrent channels. With sparse vegetation, steep slopes, and extensive alluvial plains at the mountain front, flash floods occur frequently. Since 1949, approximately 30 major flash floods have occurred in the Yinchuan section, with 17 events since 2000. Rainstorm-induced flash floods in Helan Mountain pose a serious threat to lives, property, and urban safety in Yinchuan City.

This study utilizes topographic data, water system maps, historical precipitation and flood disaster data, and baseline data on population, economy, and land use types. By combining FloodArea model simulation with ArcGIS spatial analysis, we analyze and zone the risk levels of flash flood disasters in the Yinchuan section of Helan Mountain and assess the spatiotemporal distribution characteristics of impacts on Yinchuan's population and socioeconomic conditions across different risk levels. The results provide scientific basis and reference for developing flood control and disaster reduction plans for Helan Mountain, support government decision-making in flood prevention and loss reduction, and offer important theoretical guidance for enhancing flash flood defense capabilities in Ningxia.

2 Study Area and Methods

2.1 Study Area

The Yinchuan section of Helan Mountain was selected as the study area [Figure 1: see original paper]. Data sources included: basic information for various meteorological stations within the region (station names, IDs, geographic coordinates); hourly precipitation series from 6 national basic weather stations and 102 regional automatic weather stations in Xixia District, Jinfeng District, Xingqing District, Helan County, Yongning County, and Lingwu City; 30 m resolution digital elevation model (DEM) data; 1:50,000 scale administrative boundary and water system maps; geographic coordinates of meteorological and hydrological monitoring stations; and socioeconomic data including historical flood disasters, residential areas, population, land use, and GDP.

2.2 FloodArea Model and Experiments

The FloodArea model, developed by German company Geomer, is a two-dimensional unsteady flow hydrodynamic model built on raster data and embedded in the ArcGIS platform. The calculation is based on hydrodynamic methods that consider flow from each grid cell to its eight neighboring cells [Figure 2: see original paper]. The flow length to adjacent cells is considered equal, while diagonal cells are calculated using different length algorithms. The inflow/outflow volume for each grid cell is calculated using the Manning-Stricker formula, with flow direction determined by topographic slope. Inundation depth is the difference between water surface elevation and ground elevation. Unlike static flood risk maps, FloodArea simulates and calculates inundation extent and water depth at each time step, storing and displaying results as raster files.

In recent years, the combination of FloodArea hydrodynamic modeling with ArcGIS vector data spatial analysis has been widely applied in flash flood risk and impact zoning. Based on actual conditions of flash flood channels in the Yinchuan section of Helan Mountain' s eastern piedmont, we selected rainstorm inundation flash flood simulation experiments.

First, using the multi-probability distribution function fitting tool (MuDFiT software) and historical hourly precipitation data from automatic weather stations in the Yinchuan section of Helan Mountain, we fitted the precipitation series using different probability density distribution functions. Parameters were estimated via maximum likelihood method to calculate precipitation amounts for extreme events at different return periods (10-year, 20-year, 50-year, and 100-year). The most realistic precipitation values were selected as representative of extreme events for each return period. Kriging interpolation in ArcGIS was then used to generate rainfall raster surfaces covering the entire study area for different return periods. Second, using areal precipitation and hourly precipitation series data for the study area, we analyzed typical precipitation process durations, calculated hourly precipitation probabilities, determined hourly rainfall distribution patterns, and established typical precipitation processes for different return periods in the Yinchuan section of Helan Mountain. Finally, inputting the calculated areal precipitation for different return periods, hourly rainfall patterns, Manning coefficients, vegetation, and other underlying surface data into the FloodArea hydrological model, we conducted flash flood simulation experiments to obtain inundation raster data for different return periods in the Yinchuan section of Helan Mountain.

2.3 Zoning Assessment Methods

Based on the simulated inundation depth raster data for different return periods, we used ArcGIS mapping, data management, spatial analysis, data editing, and geoprocessing tools to analyze and assess flash flood disaster risk levels and their impacts in the Yinchuan section of Helan Mountain. First, we used ArcGIS mapping functions to create inundation maps for different return periods simulated by FloodArea. Based on inundation depth (h) and historical disaster data, flash flood disaster risk in the Yinchuan section of Helan Mountain was classified into three levels: low risk ($h \leq 0.6$ m), medium risk ($0.6 \text{ m} < h \leq 1.2$ m), and high risk ($h > 1.2$ m). Second, we used ArcGIS spatial interpolation to rasterize population, land use, and other indicator factors, distributing them across spatial grids. Based on refined land use types, we determined vulnerability coefficients for flash floods across different land types, extracted vulnerability coefficients for each grid cell, performed interpolation, and obtained vulnerability distributions for different land types in the Yinchuan section of Helan Mountain. These were overlaid with population and socioeconomic raster distribution data to analyze potential vulnerability of disaster-bearing bodies. Finally, using Zonal Statistics as Table and raster overlay analysis tools, we determined impact values of different risk levels on land use within the same grid cell based on reclassified data for different return periods, extracting values according to raster values. Using population data, we obtained impact values for inundation depth on three risk levels and population. Mapping tools were used to produce flash flood disaster risk impact zoning maps for the Yinchuan section of Helan Mountain.

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3 Risk and Impact Zoning Analysis

3.1 Flash Flood Disaster Risk Zoning for Different Return Periods

Based on the FloodArea model-simulated inundation depth raster data for typical flash flood processes at different return periods, overlaid with topography, flash flood channels, and natural village information, we produced risk zoning maps for the Yinchuan section of Helan Mountain [Figure 3: see original paper]. Spatial statistics indicate that for the entire Yinchuan section of Helan Mountain, low-risk, medium-risk, and high-risk areas for 10-year return period flash floods were 109.5 km^2, 45.0 km^2, and 13.4 km^2, respectively, accounting for 3.21%, 1.32%, and 0.39% of the total regional area. For 20-year return periods, low-, medium-, and high-risk areas were 142.6 km^2, 73.7 km^2, and 27.9 km^2, respectively (4.19%, 2.17%, and 0.82% of total area). For 50-year return periods, these values increased to 205.8 km^2, 145.0 km^2, and 86.7 km^2 (6.04%, 4.26%, and 2.54%). For 100-year return periods, low-, medium-, and high-risk areas reached 276.3 km^2, 231.0 km^2, and 204.3 km^2, respectively (8.12%, 6.79%, and 6.00%). Overall, at the same return period, zoned areas decreased significantly as risk level increased from low to medium to high. At the same risk level, zoned areas increased significantly as return period increased.

Risk zones for 10-year and 20-year flash floods were mainly located in flash flood channels and adjacent areas at altitudes of 1,130–1,450 m, including the Chaqigou, Helankou, Suyukou, Huangqikou, and Xiaokouzi channels. Risk zones for 50-year flash floods concentrated in downstream channel areas and the alluvial fan region at altitudes of 1,130–1,180 m along the mountain front.

Risk zones for 100-year flash floods covered the entire mountain front area at altitudes of 1,120–1,350 m and the alluvial fan region. As return periods increased, risk zones in the Yinchuan section of Helan Mountain expanded simultaneously toward higher and lower altitudes, with significantly faster expansion toward lower altitude downstream areas. The expansion capacity varied by risk level, following the order: high risk > medium risk > low risk.

3.2 Population Impact Zoning

To analyze and assess population impacts of flash flood disasters in the Yinchuan section of Helan Mountain, we overlaid natural village and community population data across the entire region. Figure 4 shows population impact zoning maps for different return periods. During 10-year flash flood events, villages near flash flood channels on both sides of the line from Nuanquan Farm to Nanliang Farm, Beifangjiaquan, Zhenbeibu, Junmachang, Lühua Brigade, and Nongken Bureau Experimental Station were significantly affected, with affected populations of 73,000 in low-risk zones, 28,000 in medium-risk zones, and 7,500 in high-risk zones. During 20-year events, villages near the line from Nuanquan Farm to Nanliang Farm, Beifangjiaquan, Zhenbeibu, Lühua Brigade, Nongji School, and Nongken Bureau Experimental Station experienced greater impacts, with affected populations of 92,000 in low-risk zones, 68,000 in medium-risk zones, and 28,000 in high-risk zones. During 50-year events, villages near the line from Nuanquan Farm to Chenjiagou, Hongliugou, Nanliang Farm, Beifangjiaquan, Zhenbeibu, District Cadre School, Lühua Brigade, Linfei Factory, Nongji School, Nongken Bureau Experimental Station, Pingjibao Farm, Dairy Farm, and Huangyangtan Farm were significantly affected, with affected populations of 300,000 in low-risk zones, 210,000 in medium-risk zones, and 75,000 in high-risk zones. During 100-year events, nearly all villages below 1,120 m altitude along the Helan Mountain front were severely affected, with affected populations of 670,000 in low-risk zones, 683,000 in medium-risk zones, and 556,000 in high-risk zones. During extremely rare 100-year flash flood events, villages below 1,120 m altitude along the entire mountain front were severely impacted, with total affected populations reaching 987,000, including 239,000 in low-risk zones, 390,000 in medium-risk zones, and 358,000 in high-risk zones.

As flash flood return periods increased, the total population affected by flash flood risks in the Yinchuan section of Helan Mountain showed a significant increasing trend. Growth rates varied significantly among risk levels: -12.4% to 20.5% in low-risk areas, 48.6% to 91.8% in medium-risk areas, and 163% to 300% in high-risk areas. The proportion of population affected by high-risk zones increased rapidly with return period, from 10.3% during 10-year events to 36.3% during 100-year events. Overall, the growth rate of affected population followed the pattern: high risk > medium risk > low risk.

3.3 Land Use Impact Zoning

Figure 5 shows land use impact zoning maps for different return periods in the Yinchuan section of Helan Mountain, derived by overlaying and spatially analyzing regional land use data. During 10-year flash flood events, the total area of all affected land use types was 168 km^2, with farmland and grassland most severely impacted (95 km^2 and 44 km^2, respectively). Construction land and cultivated land were secondarily affected, accounting for 4.4% and 9.1% of total affected area, respectively. Swamps, shrubland, bare land, and forest were relatively less affected, each accounting for less than 1%.

During 20-year flash flood events, the total affected land area was 244 km^2, with farmland, grassland, and cultivated land ranking as the top three affected types (134 km^2, 68 km^2, and 23 km^2, respectively). During 50-year events, 437 km^2 of various land types were affected, with farmland, grassland, and cultivated land accounting for 243 km^2, 124 km^2, and 37 km^2, respectively. During extreme 100-year events, the affected land area reached 614 km^2, with farmland, grassland, and cultivated land affected areas of 371 km^2, 148 km^2, and 42 km^2, respectively.

Statistical analysis of land use type proportions in low-, medium-, and high-risk impact zones across different return periods reveals that farmland and grassland are the most affected by Helan Mountain flash floods, together accounting for 82.1%–86.9% of total affected land area. Construction land and cultivated land follow, accounting for 4.4%–9.1% and 1.1%–4.6% of total affected area, respectively. During flash flood events, farmland, grassland, construction land, and cultivated land in downstream channel areas and along the mountain front are most affected, representing key areas for flash flood disaster prevention and mitigation in Yinchuan City.

3.4 GDP Impact Zoning

To further analyze socioeconomic impacts, Figure 6 shows GDP impact zoning maps for different return periods in the Yinchuan section of Helan Mountain. During 10-year flash flood events, agricultural industries on both sides of mid- to downstream channels were significantly affected, with affected GDP values of 229 million, 98 million, and 140 million yuan in low-, medium-, and high-risk zones, respectively. During 20-year events, infrastructure and agricultural industries in downstream villages were most severely impacted, with affected GDP values of 260 million, 165 million, and 350 million yuan across risk levels. During 50-year events, most agricultural industries along the Helan Mountain front were significantly affected, with some industrial and mining enterprises near flash flood channels also impacted, resulting in affected GDP values of 1.40 billion, 1.65 billion, and 3.15 billion yuan. During extremely rare 100-year events, all agricultural and industrial industries, infrastructure, and public facilities along the mountain front would be severely affected, with affected GDP values reaching 4.75 billion, 2.79 billion, and 3.99 billion yuan in low-, medium-, and high-risk zones, respectively.

In summary, as flash flood return periods increase, the total GDP affected in the Yinchuan section of Helan Mountain shows a significant increasing trend, particularly in medium- and high-risk zones with average growth rates of 82.1% and 86.9%, respectively—the fastest growth rates observed.

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4 Conclusions

(1) In the Yinchuan section of Helan Mountain, low-risk, medium-risk, and high-risk flash flood disaster areas were 109.5 km^2, 45.0 km^2, and 13.4 km^2 for 10-year return periods; 142.6 km^2, 73.7 km^2, and 27.9 km^2 for 20-year periods; 205.8 km^2, 145.0 km^2, and 86.7 km^2 for 50-year periods; and 276.3 km^2, 231.0 km^2, and 204.3 km^2 for 100-year periods, respectively. Overall, at the same return period, flash flood disaster zoned areas decreased significantly as risk level increased from low to high. At the same risk level, zoned areas increased significantly as return period lengthened. Risk zones showed simultaneous expansion toward higher and lower altitudes, with faster expansion toward downstream lower-altitude areas.

(2) Flash flood disaster risk zones in the Yinchuan section of Helan Mountain exhibit distinct spatial characteristics: flash flood channels and adjacent areas at altitudes of 1,130–1,450 m constitute 10–20-year risk zones; channels at 1,130–1,180 m and the mountain front alluvial fan region constitute 50-year high-risk zones; and the entire mountain front area at 1,120–1,350 m and the alluvial fan region constitute 100-year risk zones. As return periods increase, risk zones expand toward both higher and lower altitudes, with more rapid expansion toward lower altitudes.

(3) In Yinchuan City, total populations affected by 10-year and 100-year flash flood disasters were 73,000 and 987,000, respectively. As return periods increased, the affected population grew significantly, with growth rates of -12.4% to 20.5% in low-risk zones, 48.6% to 91.8% in medium-risk zones, and 163% to 300% in high-risk zones. The growth rate of affected population generally followed the pattern: high risk > medium risk > low risk.

(4) Farmland and grassland were the most severely impacted land use types, together accounting for 82.1%–86.9% of total affected area. Construction land and cultivated land accounted for 4.4%–9.1% and 1.1%–4.6% of total affected area, respectively. During flash flood events, farmland, grassland, construction land, and cultivated land in downstream channel areas and along the mountain front are priority areas for disaster prevention and mitigation.

(5) In Yinchuan City, GDP affected by flash flood disasters in medium- and high-risk zones totaled 1.12 billion, 2.00 billion, 4.70 billion, and 8.74 billion yuan for 10-year, 20-year, 50-year, and 100-year return periods,

respectively. During 100-year flash flood events, all agricultural and industrial industries, infrastructure, and public facilities along the Helan Mountain front would suffer severe impacts.

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