Postprint: Analysis of Precipitation-Induced Flood Characteristics in Fifth-Level Watersheds of Shaanxi Province

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Abstract

Global warming-induced extreme climate events and their impacts on human society have consistently garnered significant attention. This study takes Shaanxi Province, which exhibits pronounced latitudinal zonality, as the research area, utilizing hydrological, meteorological, population (POP), Gross Domestic Product (GDP) spatial distribution data, and fundamental geographic information data. Employing statistical analysis, three-parameter power function methodology, K-S testing, and spatial analytical techniques, integrated with the "Shaanxi Province Rainstorm and Flood Disaster Risk Analysis System," we investigate the spatial heterogeneity of precipitation-induced flooding and exposure characteristics of underlying assets across fifth-level watersheds in the region, and examine the distribution of flood return periods under various precipitation scenarios. The results indicate: (1) Under heavy rainfall scenarios, flood distribution in Shaanxi Province demonstrates a pattern of less in the south and more in the north; under rainstorm scenarios, flood distribution is relatively lighter in the central and southwestern regions. (2) The isoline distribution of critical rainfall for return periods approximates contour patterns, with extreme isoline values exhibiting an upward trend. (3) The exposure degree of underlying assets for different return periods shows a decreasing trend in low-to-medium risk zones, while increasing in high and extremely high risk zones; the exposure quantity for 10-year return periods displays a rapid-then-slow rising pattern, whereas 100-year return periods exhibit a slow-then-rapid ascending trend. Based on fifth-level watersheds in Shaanxi Province, this research, through geospatial analysis combined with the structural framework of disaster systems, provides novel insights into analyzing spatial differentiation patterns of precipitation-induced flooding, thereby offering decision-making support for disaster prevention, mitigation, and watershed management efforts in Shaanxi Province.

Full Text

Abstract

Global warming has intensified extreme climate events, drawing widespread attention to their impacts on human society. This study focuses on Shaanxi Province, a region with pronounced latitudinal zonality, to investigate the spatial differentiation of precipitation-induced flooding and exposure characteristics of underlying surfaces across its five-level watersheds. Using hydrological, meteorological, population, and GDP spatial distribution data, combined with basic geographic information, we employed statistical analysis, the three-parameter power function method, K-S testing, and spatial analysis integrated with the "Shaanxi Province Rainstorm and Flood Disaster Risk Analysis System." The analysis examined spatial variations in flood-inducing precipitation and the exposure patterns of disaster-bearing bodies, while investigating the distribution of flood return periods across different precipitation scenarios. The results reveal three key patterns: (1) Under heavy rainfall scenarios, flood distribution exhibits a north-south gradient with more frequent events in northern regions; under rainstorm scenarios, flooding is less severe in central and southwestern areas compared to other regions. (2) The spatial distribution of critical surface rainfall for different return periods approximates contour patterns, with extreme values showing an increasing trend. (3) Exposure of disaster-bearing bodies demonstrates decreasing trends in low- and medium-risk zones, but increasing trends in high- and extremely high-risk zones. Specifically, the 10-year return period exposure shows a rapid-then-gradual increase, while the 100-year return period displays a gradual-then-rapid increase. Based on Shaanxi Province' s five-level watershed framework and integrated with the disaster system structure, this research provides a novel approach for analyzing spatial differentiation patterns of precipitation-induced flooding, offering decision-making support for disaster prevention, mitigation, and watershed management in the province.

Keywords: five-level watershed; spatial differentiation; critical surface rainfall; flooding

1. Study Area Overview

Shaanxi Province spans 31°42 -39°35 N and 105°29 -111°15 E, covering the Yellow and Yangtze River basins and encompassing 205 six-level watersheds [Figure 1: see original paper]. The province' s geomorphology is dominated by plateaus and mountains, with relatively small plains and basins, totaling 205,603 km^2. Watershed areas account for 97.7% of the provincial territory. The region exhibits a narrow north-south elongation: the northern Loess Plateau occupies 36.0% of the total area with elevations between 800–1,500 m; the central Guanzhong Plain comprises 19.0% of the area with elevations of 300–800 m; and the southern Qinba Mountains cover 45.0% of the area with elevations ranging from 1,000–3,000 m. Situated in the transitional zone between the humid southeast and arid northwest, Shaanxi experiences northerly winds in winter (dry and cold) and southerly winds in summer (warm and rainy). The climate is characterized by dry springs with low precipitation and rapid but unstable warming, frequent sandstorms, concurrent summer heat and rainfall with occasional droughts, cool and humid autumns with rapid cooling, and cold, dry winters with low temperatures and scarce rain and snow.

2.1 Data Sources

This study utilized multiple datasets: hydrological data, precipitation records, flood disaster archives, watershed boundary maps, population data, GDP spatial distribution data, digital elevation models (DEM), land use/cover change data, and other fundamental geographic information. Hydrological data were obtained through project implementation, including water level and discharge time series from major control stations in Shaanxi's five-level watersheds, various water level grades, and typical flood event data. Precipitation data comprised daily and hourly temperature and precipitation records from meteorological and hydrological stations (1951–2015), historical rainfall sequences, and rainfall data during flood events, all provided by the Shaanxi Provincial Meteorological Bureau. Flood disaster data were extracted from the Shaanxi Statistical Yearbook and the China Meteorological Disaster Canon (Shaanxi Volume). Watershed boundary data were acquired through project implementation. DEM data (30 m × 30 m resolution) were downloaded from the Geospatial Data Cloud (http://www.gscloud.cn/). Land use and cover change data (1 km × 1 km) were obtained from the National Geomatics Center of China (http://www.dsac.cn/). Land use status raster data for 2015 (100 m × 100 m resolution) were provided by the Chinese Academy of Sciences' Resources and Environmental Science Data Center (http://www.resdc.cn/), with analysis conducted at 30 m × 30 m resolution.

2.2.1 Fitting Maximum Precipitation for Different Return Periods

To address the limitation of single risk zoning in accommodating varying flood disaster severity levels, we introduced the return period concept for rainstorm flood risk assessment. Using multi-year observed daily precipitation data, we extracted annual maximum values to form an annual maximum (AM) series, obtaining maximum daily precipitation intensities for different return periods. We defined the precipitation value corresponding to a T-year return period as the precipitation extreme for that recurrence interval, calculated using distribution function fitting. By setting different return period parameters, we fitted 5–100 year maximum daily precipitation for all stations. The Kolmogorov-Smirnov (K-S) test was applied to evaluate goodness-of-fit, with p-values used to rank all distribution functions. Based on K-S test rankings, we identified the optimal distribution function for each station and calculated return period results accordingly.

2.2.2 Calculation of Critical Flood-Inducing Surface Rainfall

Determination of critical surface rainfall for different return periods employed the three-parameter power function method to establish relationships among water level, discharge, and precipitation. We performed univariate linear regression analysis between cumulative surface rainfall and discharge to quantify precipitation-discharge relationships, using discharge as the link to construct water level-precipitation relationships. Critical flood-inducing surface rainfall was ultimately determined based on flood control standard water levels. Optimal probability distributions were selected using K-S tests on maximum discharge values during flood events to determine different return period thresholds. Watershed surface rainfall was calculated using the Thiessen polygon method:

$$p = \frac{1}{A} \sum_{i=1}^{n} p_i \times a_i$$

where p is watershed surface rainfall (mm), p_i is precipitation at the ith meteorological station (mm), a_i is the area of the ith Thiessen polygon (km^2), A is total watershed area (km^2), and n is the number of meteorological stations within the watershed.

2.2.3 Flood Inundation Analysis for Different Return Periods

Based on hydrodynamic methods, we calculated inundation depth and extent for different return period floods using an eight-direction flow model that considers flow from eight neighboring grid cells. Flow velocity was calculated using the Manning-Stricker formula:

$$V = K \cdot r^{2/3} \cdot I^{1/2}$$

where V is velocity ($\mathrm{m \cdot s^{-1}}$), K is the coefficient for surface (open channel) roughness effects, r is hydraulic radius (m), and I is terrain slope. Slope between cells was determined by the difference between the lowest water level and highest terrain elevation. Flow direction was determined by terrain aspect, which reflects the direction of maximum elevation change. For any ground point, aspect indicates the steepest descent direction, calculated as:

$$\text{aspect} = 270 - \frac{360}{2\pi} \arctan\left(\frac{\partial z/\partial y}{\partial z/\partial x}\right)$$

where $\partial z/\partial x$ and $\partial z/\partial y$ represent elevation changes in east-west and north-south directions, respectively. Inundation depth was calculated as the difference between water level and ground elevation.

3.1 Spatial Differentiation of Floods Under Different Scenarios

Rainfall is a critical factor triggering floods. In Shaanxi Province, the distribution of rainstorm and heavy rainstorm days increases significantly from north to south. According to the national standard "Precipitation Grade" (GB/T28592-2012), precipitation is classified into six levels . Floods in Shaanxi are primarily induced by heavy rain, rainstorm, heavy rainstorm, and extreme rainstorm events. Given that extreme rainstorms cause severe flooding throughout the province, we used ArcGIS to process watershed baseline data, national rain gauge data, and return period critical surface rainfall datasets. We simulated flood distributions under heavy rain, rainstorm, and heavy rainstorm scenarios across Shaanxi' s five-level watersheds, analyzing underlying surface conditions including terrain slope, dominant soil types, and normalized difference vegetation index (NDVI). Soil texture classification based on sand and clay particle proportions includes ten categories: brown soil, cinnamon soil, black soil, chestnut soil, desert soil, lithosol, fluvo-aquic soil, bog soil, saline-alkali soil, and paddy soil.

Heavy rain scenario [Figure 2: see original paper]: The study area was divided into 205 zones, with 11 watersheds designated as safe zones. Flood distribution generally showed more events in the north and fewer in the south. Eight watersheds experienced 5-year return period floods, located on the southern edge of the Loess Plateau. Twenty watersheds experienced 10-year return period floods, distributed uniformly across the province. Vegetation cover varied significantly among watersheds, with terrain slopes ranging from 7.47° to 21.20°. Seven watersheds experienced 20-year return period floods, all distributed in northern Shaanxi, with relatively uniform vegetation cover. Watersheds with single soil types had average slopes of 13.66°, higher than those with multiple soil types (2.74°). Generally, higher vegetation cover correlated with steeper slopes. Under similar vegetation conditions, watersheds with more soil types exhibited steeper terrain. In the Loess Plateau, watersheds with similar soil composition showed that higher lithosol proportions correlated with steeper slopes, while in the Qinba Mountains, higher brown soil proportions corresponded to steeper slopes.

Rainstorm scenario [Figure 3: see original paper]: Safe zones were primarily located in the upper reaches of the Wei River mainstream (Jing River, Qishui River, and Baoji section), the Bao River tributary of the upper Han River, and the upper Jialing River basin in southern Shaanxi. Flood distribution showed 5-30 year return period floods concentrated in the Guanzhong Plain and southern Shaanxi, while 50-year return period floods were concentrated in the Loess Plateau with only the Ba River basin in the Guanzhong Plain. The pattern exhibited lighter flooding in central and southwestern regions. Analysis of underlying surfaces revealed that in flood zones where lithosol exceeded 50%, NDVI ranged 0.39-0.82 and slopes were relatively gentle (3.23°-16.17°). In zones where brown soil exceeded 50%, NDVI ranged 0.15-0.39 with steeper slopes (17.71°-26.72°). No 100-year return period floods occurred in these zones, indicating that under identical precipitation scenarios, watersheds with higher lithosol proportions experience larger return periods compared to those dominated by brown soil.

Heavy rainstorm scenario [Figure 4: see original paper]: All watersheds experienced floods of varying return periods, including 100-year events. The 5-year return period floods were concentrated in western Guanzhong and southern Shaanxi (31 watersheds), while 100-year return period floods were widely distributed (174 watersheds). The pattern showed lighter flooding in central, western, and southwestern regions, with more severe conditions elsewhere. Underlying surface analysis revealed that central and southwestern Shaanxi have relatively gentle slopes, mixed soil types, and good vegetation cover, which hinders rapid runoff concentration. In contrast, northern Shaanxi' s Loess Plateau has simple rainfall distribution patterns, while the Guanzhong Plain and southern Qinba Mountains show greater variation across return periods. During 100-year return period floods, rainfall distribution in northern Shaanxi increased from northwest to southeast, central areas showed inward-increasing patterns, and southern Qinba Mountains exhibited an eastward-increasing trend centered on Shangluo.

3.2 Distribution of Critical Surface Rainfall for Different Return Periods

Simulation of critical surface rainfall for different return periods, combined with custom zoning of rainfall isolines, reveals that denser isolines indicate greater spatial variation in values. Spatial distributions of critical surface rainfall across Shaanxi' s five-level watersheds show isoline patterns approaching contour lines, with extreme values increasing as return periods extend from 5 to 100 years [Figure 5: see original paper]. Maximum critical surface rainfall values occur in western Guanzhong, including the Qian River, Baoji section of the Wei River mainstream, Qishui River, and scattered Jing River basins. These areas feature flat terrain with gentle relief, predominantly cultivated land with permeable soils that enhance infiltration, resulting in smaller return periods. Minimum values occur in the Lu River, Shiwang River, and middle Beiluo River basins. The Lu River basin has large elevation differences and receives less precipitation in the northern Mu Us Desert, leading to larger return periods with less rainfall. The Shiwang River and middle Beiluo River basins have favorable runoff convergence conditions due to their surrounding-high, middle-low topography, enabling rapid water accumulation during rainstorms and resulting in larger return periods with relatively less precipitation.

3.3 Exposure of Disaster-Bearing Bodies Under Different Return Periods

As risk concepts deepen in disaster management, assessing exposure of disaster-bearing bodies has become crucial in international risk management frameworks. Using the "Shaanxi Province Rainstorm and Flood Disaster Risk Analysis System," we simulated flood inundation for different return periods. Following flood risk classification principles and overlaying disaster-bearing body distributions (population, GDP, land use), we evaluated potential losses and spatial risk distribution. Inundation depth was classified into five levels: <0.1 m, 0.1–1.0 m, 1.0–2.0 m, 2.0–3.0 m, and >3.0 m, corresponding to safe, low-risk, medium-risk, high-risk, and extremely high-risk zones [Figure 6: see original paper].

Comprehensive analysis shows that as simulated precipitation increases, both flood inundation extent and return periods increase, particularly evident in the Beiluo River middle reaches, Shiwang River, Wei River north bank, Ba River, Ju River, Huangfu River, Lu River, Hailiutu River, and Dali River basins. The Qinba Mountains in southern Shaanxi represent a warm-humid rainstorm center with large-area, long-duration, high-intensity rainfall events. In contrast, the Loess Plateau in northern Shaanxi, located in arid and semi-arid zones, experiences small-area, short-duration, high-intensity rainstorms with poor vegetation cover, leading to rapid runoff generation and flash floods.

Exposure statistics for the 100-year return period flood reveal varying exposure levels among different disaster-bearing bodies under different inundation depths . Population, GDP, cultivated land, and construction land exposure proportions were calculated for safe, low-risk, medium-risk, high-risk, and extremely high-risk zones. Results show that as return periods increase from 5 to 100 years, exposure proportions in safe, low-risk, and medium-risk zones decrease, while those in high-risk and extremely high-risk zones increase [Figure 7: see original paper].

Specifically, population exposure proportions decrease in low- and medium-risk zones but increase in high- and extremely high-risk zones. GDP exposure decreases in low-, medium-, and high-risk zones but increases in extremely high-risk zones. Cultivated land and construction land exposure proportions decrease in low- and medium-risk zones while increasing in high- and extremely high-risk zones. Under 10-year return period floods, exposure proportions for population, GDP, cultivated land, and construction land show rapid-then-gradual increases with inundation depth from 0–3 m, with population exposure increasing fastest and cultivated land slowest. Under 100-year return period floods, these proportions exhibit gradual-then-rapid increases, with population exposure again increasing fastest and cultivated land slowest [Figure 8: see original paper].

4. Discussion

Rainstorm-induced flooding represents the primary natural disaster factor in Shaanxi Province, significantly constraining and threatening socio-economic development. Investigating precipitation-flood characteristics and their impacts has become an urgent requirement for disaster prevention and mitigation. Previous studies primarily focused on single watersheds, administrative boundaries, rainfall duration, and rainfall grades to analyze flood spatial differentiation, mostly based on precipitation-induced flooding within specific return periods. This research, based on watershed boundaries, conducted spatial differentiation analysis of flood-inducing precipitation characteristics across 205 five-level watersheds in Shaanxi Province under 5–100 year return periods. We simulated flood distributions under heavy rain, rainstorm, and heavy rainstorm scenarios, and analyzed exposure conditions of disaster-bearing bodies based on existing disaster statistics. The findings reveal distribution characteristics of floods with different return periods induced by various precipitation scenarios across Shaanxi' s five-level watersheds, providing scientific basis and decision-making support for coordinated disaster prevention and mitigation efforts.

As one of Shaanxi' s most significant natural disasters, flood hazards require scientific prevention and control regardless of exposure conditions. Strengthening rainstorm-flood monitoring, early warning, and emergency response systems remains essential. This study provides a watershed-scale framework for understanding spatial heterogeneity in flood risk, though future research should incorporate dynamic land use changes and climate projections to enhance predictive capabilities.

5. Conclusions

1) Under heavy rainfall scenarios, flood distribution in Shaanxi Province exhibits a pattern of more events in the north and fewer in the south. Under rainstorm scenarios, flooding is less severe in central and southwestern regions compared to other areas.

2) The spatial distribution of critical surface rainfall for different return periods approximates contour patterns, showing a transition from relatively uniform to extremely non-uniform distributions. The extreme values of critical surface rainfall demonstrate an increasing trend as return periods extend from 5 to 100 years.

3) Exposure of disaster-bearing bodies shows consistent patterns across return periods: exposure proportions for population, GDP, cultivated land, and construction land decrease in low- and medium-risk zones while increasing in high- and extremely high-risk zones. The 10-year return period exposure exhibits a rapid-then-gradual increase, whereas the 100-year return period shows a gradual-then-rapid increase.

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