

Remote Sensing-Based Risk Assessment of Heat Waves in the Ningxia Region: Postprint

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Abstract

Heat wave disaster risk information serves as an important reference for the prevention and control of extreme disaster events under conditions of global climate warming and rapid urbanization. To address the problem of incomplete assessment of heat wave hazard factors, based on multi-source satellite remote sensing data and socioeconomic statistical data, and by incorporating land surface temperature and meteorological data as heat hazard factors, the spatial distribution map of heat wave risk levels in Ningxia for July–August from 2014 to 2019 was calculated using an assessment model based on the Analytic Hierarchy Process (AHP) and map overlay method. The results demonstrate that: the overall heat wave risk in Ningxia is at a medium-high level, with the area proportion of moderate-high and high-risk regions increasing from 39.52% in 2014 to 62.65% in 2019; influenced by geographical latitude, topography, and climate, the heat risk distribution exhibits significant spatial variation, with overall risk in the north being higher than in the south (by approximately 13.27%), and risk in the west being higher than in the east (by approximately 12.30%); high-risk areas are concentrated in Zhongwei City and Shizuishan City, which is primarily the result of the combined effects of urban high temperatures and relatively low healthcare levels. The research findings can help inform the prevention of urban heat disasters and the formulation of emergency response plans for heat waves.

Full Text

Preamble

Assessing Heat Wave Risk in Ningxia Based on Remote Sensing

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Abstract

Disaster risk information for heat waves provides critical reference value for preventing and controlling extreme disaster events under conditions of global warming and rapid urbanization. To address the problem of incomplete assessment of heat wave hazard factors, this study evaluates the spatial distribution of heat wave risk levels in Ningxia from July to August between 2014 and 2019. The assessment integrates multi-source satellite remote sensing data and socio-economic statistical data, combining land surface temperature and meteorological data as hazard factors. An analytic hierarchy process and layer overlay method were employed to calculate risk indices. The results indicate that the overall heat wave risk in Ningxia is at an upper-medium level, with the proportion of high and higher-risk areas increasing from 39.52% to 62.65% during the study period. Influenced by geographic latitude, topography, and climate, the spatial distribution of heat risk shows significant regional differences, with northern regions exhibiting higher risk than southern regions (approximately 13.27% higher) and western regions showing slightly higher risk than eastern regions (approximately 12.30% higher). High-risk areas are concentrated in Zhongwei City and Shizuishan City, primarily due to the combined effects of urban heat islands and relatively lower medical service levels. These findings can inform urban heat disaster prevention and emergency response planning for heat wave events.

Keywords: heat wave; human settlement index; risk assessment; remote sensing; Ningxia

1. Introduction

The Fifth Assessment Report of the IPCC provides overwhelming evidence that global warming is an undeniable reality. The World Health Organization warns that if warming continues unabated, climate-related deaths worldwide are projected to increase dramatically by 2050. The synergistic effects of climate warming and urbanization have further intensified the scope and severity of heat wave events. Studies have shown that for every 1°C increase in average temperature, heat-related morbidity rates increase significantly across various regions. Heat waves not only cause direct mortality but also trigger surges in respiratory and

cardiovascular diseases, severely impacting public health and daily life while causing substantial damage to industrial and agricultural production, tourism, and transportation systems.

Consequently, heat waves have attracted increasing attention from governments and academia. Researchers have made substantial progress in understanding heat wave mechanisms, characteristics, risk assessment, epidemiology, and forecasting. For instance, Kuglitsch et al. analyzed heat wave trends in the eastern Mediterranean using intensity, duration, and frequency metrics, while Inostroza developed a heat wave risk assessment model for Santiago, Chile, incorporating daily morbidity rates, electricity demand, and water supply impacts. Zhang Xiaoyan et al. examined spatiotemporal variations in heat wave risk within the Dongting Lake basin, and Phung et al. investigated heat-related morbidity in the Mekong Delta using hierarchical Bayesian analysis.

In recent decades, under the backdrop of global climate change, Ningxia has experienced increasing frequency and intensity of high-temperature weather events. Previous studies have assessed spatial distributions of high-temperature days in Ningxia using meteorological data, analyzed spatiotemporal characteristics of heat waves in the Loess Plateau region, and examined temperature variation cycles. While these studies effectively reflect regional heat risk conditions and provide valuable disaster prevention insights, they have primarily focused on meteorological data analysis of heat wave intensity and frequency, with limited attention to socio-economic statistical data. Furthermore, spatial analysis precision has been constrained by the limited number and location of meteorological stations.

To address these limitations, this study employs multi-source remote sensing data and socio-economic statistics to conduct a kilometer-scale heat wave risk assessment for Ningxia during July-August 2014-2019. By extracting hazard factors, socio-economic vulnerability factors, and adaptation capacity indicators, and utilizing the analytic hierarchy process (AHP), we construct a comprehensive heat wave risk assessment model to explore spatial distribution characteristics and provide scientific support for urban heat disaster prevention and emergency response.

1.1 Study Area Overview

Ningxia is located in the upper and middle reaches of the Yellow River in northwestern China, bordering Shaanxi to the east, Inner Mongolia to the west and north, and Gansu to the south (Figure 1). Geographically positioned between 35°14' -39°23' N and 104°17' -107°39' E, the region covers a total area of 6.64×10^4 km². Characterized by a temperate continental arid and semi-arid climate with distinct seasons, the hottest month is July with average temperatures ranging from 16.9°C to 24.7°C. Annual precipitation varies significantly from south to north, ranging between 166.9-647.3 mm. As urbanization progresses, continuous urban expansion and population growth have intensified

the urban heat island effect, with cities and populations facing increasing heat-related risks.

Note: This figure was produced based on the standard map GS(2017)1267 downloaded from the National Surveying and Mapping Geographic Information Bureau's standard map service website, with no modifications to the base map boundaries. The same applies below.

Figure 1. Location and elevation of the study area

1.2 Data Sources and Preprocessing

The selected datasets include land surface temperature (LST), air temperature, atmospheric pressure, wind speed, precipitation, normalized difference vegetation index (NDVI), nighttime light data (DMSP/OLS), and socio-economic statistics such as permanent population, construction workers, air conditioner ownership per 100 households, hospital beds, and medical technicians for each district and county in Ningxia. For raster calculation convenience, all selected data were projected, resampled to 1 km resolution, and normalized. To minimize noise interference and ensure data quality, multi-temporal MODIS NDVI data were processed using the annual maximum value composite method, which effectively captures peak vegetation conditions:

$$NDVI_{max} = \text{Max}(NDVI_1, NDVI_2, \dots, NDVI_{23})$$

where $NDVI_{max}$ represents the annual maximum NDVI composite, and $NDVI_1, NDVI_2, \dots, NDVI_{23}$ are the 16-day NDVI values throughout the year.

Table 1. Detailed description of the data

Data Type	Time Resolution	Spatial Resolution	Source
MODIS LST	8 days	1 km	https://modis.gsfc.nasa.gov/
MODIS NDVI	16 days	1 km	https://modis.gsfc.nasa.gov/
DMSP/OLS Nighttime Light	Annual	1 km	http://ngdc.noaa.gov/eog/
DEM	-	30 m	http://www.gscloud.cn/search
Meteorological Data	Daily	-	http://data.cma.cn
Socio-economic Statistics	Annual	-	Ningxia Statistical Yearbook 2019

Note: LST = Land Surface Temperature; NDVI = Normalized Difference Vegetation Index; DEM = Digital Elevation Model. The same applies below.

2. Research Methods

Following the U.S. Environmental Protection Agency's ecological risk assessment guidelines and the IPCC Fifth Assessment Report, and building upon previous research, this study constructs a heat wave risk assessment framework for Ningxia based on "heat hazard—socioeconomic vulnerability—heat wave risk adaptation" (Figure 2).

Figure 2. Frame of heat wave risk assessment

2.1 Heat Hazard Factors

Heat hazard refers to external threats to the system, with temperature and precipitation being critical indicators. While meteorological stations provide air temperature data, their limited number and spatial distribution constrain large-scale analysis precision. Remote sensing has proven effective for monitoring environmental dynamics, and numerous studies have confirmed significant linear relationships between land surface temperature and air temperature. Therefore, this study uses both LST and meteorological data (temperature, precipitation, wind speed, and pressure) as remote sensing indicators for heat hazard assessment in Ningxia.

2.2 Socioeconomic Vulnerability Factors

Vulnerability factors represent the system's capacity to withstand risks. The human settlement index (HSI) serves as the primary vulnerability assessment indicator, supplemented by construction workers, population aged 65 and above, and permanent population as secondary indicators.

2.2.1 Human Settlement Index Factor To improve the spatial distribution accuracy of population conditions, this study integrates DMSP/OLS nighttime light data and NDVI to construct the human settlement index:

$$HSI = \frac{1 - DMSP_{nor} + DMSP_{nor} \times NDVI_{max}}{1 - DMSP_{nor} + NDVI_{max} + DMSP_{nor} \times NDVI_{max}} \times NDVI_{max} - 0.003DEM$$

where $DMSP_{nor}$ is normalized nighttime light data, $NDVI_{max}$ is the annual maximum NDVI composite, and DEM is elevation data.

2.2.2 Other Vulnerability Factors Disaster impacts are closely related to economic levels and population characteristics. Research indicates that higher per capita GDP correlates with greater economic vulnerability. Sensitive populations—including infants, elderly individuals, and outdoor workers—are more susceptible to high temperatures. Due to the lack of spatially explicit data for construction workers, elderly population proportion, and permanent population, we assume uniform values within each district and convert vector data to raster format using ArcGIS.

2.3 Heat Wave Risk Adaptation Factors

Adaptation factors represent societal responses to heat disasters, primarily reflected in resource allocation. Cities with better living conditions and advanced medical systems face reduced socioeconomic threats during heat waves. This study selects per capita GDP, air conditioner ownership per 100 households, urban hospital beds, and medical technicians as adaptation indicators. Similar to vulnerability data, these were processed using the same rasterization method due to limited spatialization approaches.

2.4 Assessment Methods

2.4.1 Analytic Hierarchy Process First, the heat wave risk components were structured into target (A), criterion (B), and indicator (C) layers. Indicators were pairwise compared based on relative importance to construct judgment matrices. After consistency verification, indicator weights were determined (Table 2). To ensure additivity, all indicator layer data were normalized to a uniform range of [0,1] using Matlab.

Table 2. Evaluation indexes and weight values of heat waves risk

Target Layer (A)	Criterion Layer (B)	Indicator Layer (C)	Weight
Heat Wave Risk	Heat Hazard B1	Land Surface	+0.46
		Temperature C1	
		Precipitation C2	+0.24
	Socioeconomic Vulnerability B2	Human Settlement	+0.31
		Index C3	
		Permanent	+0.06
		Population C4	
		Population Aged 65+ C5	+0.06
	Risk Adaptation B3	Construction	+0.06
		Workers C6	
		Per Capita GDP C7	-0.23
		Air Conditioner	-0.23
		Ownership C8	
		Hospital Beds C9	-0.23

Target Layer (A)	Criterion Layer (B)	Indicator Layer (C)	Weight
		Medical Technicians C10	-0.23

2.4.2 Layer Overlay Method Using ArcGIS 10.3 spatial overlay tools, criterion layer indicators were calculated as:

$$B_i = \sum_{i=1}^n \alpha_i C_i$$

where B_i represents criterion layer indicators, C_i are indicator layer factors, and α_i are their respective weights. After calculating criterion layer indicators, the spatial overlay tool was applied again to obtain the Ningxia heat wave risk index A :

$$A = 0.46B_1 + 0.31B_2 - 0.23B_3$$

where B_1 is the heat hazard indicator, B_2 is the socioeconomic vulnerability indicator, and B_3 is the risk adaptation indicator.

3. Results

3.1 Heat Wave Hazard Assessment

Based on the selected hazard indicators, rasterized data were loaded into ArcGIS 10.3 spatial overlay tools to calculate the weighted criterion layer indicator B_1 , producing the spatial distribution of heat hazard for July-August 2014-2019 (Figure 3). High and higher hazard areas are primarily distributed in Shizuishan City, western Yinchuan City, western Wuzhong City, and northern Zhongwei City—regions characterized by high population pressure, dense urban buildings, and extensive bare land and cultivated areas. In contrast, low and lower hazard areas are concentrated in Guyuan City, primarily due to its higher elevation (temperature decreases with altitude) and smaller proportion of built-up land, resulting in relatively weaker urban heat island effects.

Figure 3. Spatial distributions of hazard factors of heat wave

3.2 Socioeconomic Vulnerability Assessment

Using the selected vulnerability indicators, rasterized data were processed through ArcGIS 10.3 spatial overlay tools to calculate criterion layer indicator B_2 , generating the vulnerability spatial distribution (Figure 4). High and higher vulnerability areas are mainly found in western Wuzhong City, Zhongwei

City, and northwestern Guyuan City, where population densities are relatively high compared to surrounding areas. In 2018, some areas of Yinchuan City and Shizuishan City showed higher vulnerability due to accelerated urbanization and increased construction activities. Lower vulnerability areas are located in southern Yinchuan City and surrounding Shizuishan City, primarily comprising agricultural land and bare land with low population density.

Figure 4. Spatial distributions of vulnerability factors of heat wave

3.3 Heat Wave Risk Adaptation Assessment

Based on selected adaptation indicators, rasterized data were processed using ArcGIS 10.3 spatial overlay tools to calculate criterion layer indicator B_3 , producing the spatial distribution of heat wave risk adaptation (Figure 5). High adaptation areas are concentrated in central Yinchuan City, where superior medical services and higher air conditioner coverage enhance adaptive capacity. With continuous socioeconomic development, average risk adaptation across Ningxia has increased annually.

Figure 5. Spatial distributions of adaptation factors of heat wave

3.4 Risk Assessment and Spatial Analysis

The integrated assessment system was applied using AHP and spatial overlay of normalized indicators to obtain the Ningxia heat wave risk index. The natural breaks method classified risk levels into five categories: low (0.037–0.273), lower (0.273–0.350), medium (0.350–0.405), higher (0.405–0.465), and high (0.465–0.737) risk zones.

The results reveal that heat wave risk in Ningxia generally increases from north-east to southwest (Figure 6). High and higher-risk areas account for 62.65% of the total area, concentrated in central Ningxia at relatively low elevations. These regions feature high population density, extensive built-up areas, strong urban heat island effects, low vegetation coverage, and soils dominated by sierozem with low heat capacity. Combined with long sunshine hours and intense radiation, these factors cause rapid temperature increases. Additionally, relatively lagging economic development and high vulnerability contribute to elevated heat risks. The lowest risk areas are concentrated in southern and north-central Ningxia, where higher precipitation, greater humidity, and denser vegetation reduce hazard and vulnerability, while higher economic development and better living conditions enhance adaptation capacity.

Figure 6. Spatial distributions of the heat wave risk of Ningxia

Using Hongsipu District Government as the center, risk levels were analyzed along north-south and east-west transects (Figure 7). Central Ningxia shows substantially higher risk than other areas, with northern risk exceeding southern risk by an average of 12.30% annually. This pattern reflects decreasing precipitation and increasing evaporation from south to north, coupled with higher

elevations and vegetation coverage in the south that reduce heat hazard. Western risk is 13.27% higher than eastern risk, with both regions located in the central arid zone characterized by dry conditions, low vegetation coverage, and soils dominated by sierozem and aeolian sandy soil. However, denser population in the west results in slightly higher overall risk. The western profile shows smaller fluctuations, indicating less spatial variation in risk intensity.

Figure 7. Variations of heat risk index in different directions

Significant spatial variation exists among cities and counties (Figure 8). Zhongwei City exhibits the highest risk, with high and higher-risk areas comprising 92.16% of its territory, followed by Shizuishan City (74.58%) and Wuzhong City (61.56%). Yinchuan City and Guyuan City show relatively lower risk, with high and higher-risk areas accounting for 36.68% and 33.66%, respectively.

Figure 8. Area proportions of different heat risk levels of each district in Ningxia

4. Discussion and Conclusions

4.1 Discussion

This study evaluated heat wave disaster risk in Ningxia using 10 indicators selected according to regional climate characteristics and risk formation mechanisms. The results demonstrate increasing heat wave risk in Ningxia from 2014 to 2019, consistent with research showing rapidly increasing regional heat wave risks in China and particularly in northwestern regions. Studies indicate that northern Ningxia is among the fastest warming areas in China, with temperature increases of 0.36–0.42°C per decade, aligning with our findings.

Heat wave formation in Ningxia results from combined climatic, topographic, and anthropogenic factors. Compared with previous studies, our research incorporates population spatial distribution and socioeconomic factors, which are closely related to heat risk in Ningxia, thereby improving evaluation accuracy. However, heat wave occurrence is also influenced by land use patterns, urban air pollution, and individual health conditions, which should be considered in future research.

4.2 Conclusions

This study establishes a comprehensive heat wave risk assessment framework integrating remote sensing and socio-economic data. Key findings include:

1. Ningxia's heat wave risk is at an upper-medium level overall, with high and higher-risk areas increasing from 39.52% in 2014 to 62.65% in 2019, showing an expanding trend.

2. Significant spatial heterogeneity exists: northern risk exceeds southern risk by approximately 13.27%, western risk exceeds eastern risk by about 12.30%, and central regions show the highest risk.
3. High-risk areas are concentrated in Zhongwei and Shizuishan cities due to urban heat islands and relatively lower medical service levels.
4. Among cities, Zhongwei shows the highest risk (92.16% high/higher-risk area), followed by Shizuishan (74.58%) and Wuzhong (61.56%), while Yinchuan and Guyuan exhibit relatively lower risk.

These results provide scientific support for urban heat disaster prevention and emergency response planning in Ningxia.

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