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ECOLOGICAL SENSITIVITY EVALUATION BASED ON GIS: A CASE STUDY IN HENGSHUI, CHINA

Qunying Gao¹, Nor Fadzila Binti Aziz², Norlaila Binti Mohd Zanuri³

^{1,3} *Centre for Marine and Coastal Studies (CEMACS),*

² *School of House, Building and Planning,*
UNIVERSITI SAINS MALAYSIA

Abstract

Hengshui City, located in China, serves as an ecological barrier for the coordinated development of the Beijing-Tianjin-Hebei region. The city prioritizes ecological civilization construction and actively promotes pollution control and ecological restoration. This study examines nine ecological factors from three categories: natural resources, terrain, and social factors. These factors include the digital elevation model (DEM), slope, rainfall, land use and cover (LUCC), normalized vegetation index (NDVI), net primary productivity (NPP), population, night light (NL), and soil erosion (SE). Using data from 2010 to 2020, we constructed an evaluation index system. We conducted a comprehensive analysis and evaluation of the ecological sensitivity of Hengshui City by combining the Analytic Hierarchy Process (AHP) with Geographic Information Systems (GIS). The results indicate that the comprehensive ecological sensitivity of Hengshui City can be categorized into four levels: mild sensitivity, moderate sensitivity, high sensitivity, and extreme sensitivity. Overall, Hengshui City exhibits mainly mild ecological sensitivity, with minimal changes in area over the study period. These research findings provide valuable insights for maintaining the health of Hengshui City's ecosystem and optimizing ecological management strategies.

Keywords: Ecological sensitivity, GIS, Hengshui city

¹ Corresponding author. Email: lailazanuri@usm.my

INTRODUCTION

Since the onset of the Industrial Revolution, urbanization has accelerated significantly worldwide. In China, the trajectory of economic development has entered a new phase characterized by rapid urbanization. This swift urbanization has brought about numerous urban environmental challenges (Wu, 2014), most notably the substantial increase in urban construction land outpacing the growth rate of the urban population (Guan et al., 2018). Early scholarly inquiries into urban ecology primarily focused on experimental physiology, integrating studies on flora and fauna, outdoor energy flow cycles, and related domains (Bi et al., 2020). Over time, urban ecology has evolved into a pivotal field in interdisciplinary studies, encompassing human ecology, environmental psychology, and ecological functions (Niu et al., 2020).

Ecological sensitivity refers to the degree to which ecosystems reflect human disturbances and natural environmental changes. It serves as a critical indicator of ecosystem stability (J. Yu et al., 2020) and quantifies regional ecological environmental changes. Research outcomes in this field can provide a scientific basis for policymakers in formulating regional environmental policies (T. Yu et al., 2020). Ecologically sensitive areas are regions particularly vulnerable to environmental changes and human activities. These areas include natural reserves, biodiversity hotspots, regions rich in water resources, and areas susceptible to natural disasters (Liang & Li, 2012). In such regions, environmental degradation can lead to biodiversity loss, land degradation, and water pollution, adversely affecting human livelihoods and economic development (Xu et al., 2014). Therefore, safeguarding and managing ecologically sensitive areas is crucial. This requires comprehensive consideration of factors such as the natural environment, biodiversity, and socio-economic dynamics, and the formulation of corresponding protection policies and management measures to achieve sustainable ecosystem development.

LITERATURE REVIEW

Hengshui City plays a crucial role in bridging and linking the coordinated development of the Beijing-Tianjin-Hebei region, thereby promoting regional economic integration and sustainable development. However, in recent years, there has been a noticeable lack of attention from experts and scholars, both domestically and internationally, regarding the ecological sensitivity of Hengshui City. Instead, research has predominantly focused on the evaluation of human settlements (L. Yu et al., 2022), the optimization of landscape patterns (L. Yu et al., 2022), the management of groundwater resources (Sun et al., 2020; Zhao et al., 2020), and the analysis of heavy metal pollutants (W. Liu et al., 2022).

The concept of ecological sensitivity emerged in the 1960s and gained momentum in the 1970s with technological advancements facilitating further research into evaluation methods. Despite these developments, significant

shortcomings remain. Current evaluation methods often depend on a limited set of indicators, such as land use type and vegetation coverage, thereby neglecting the diversity and complexity of ecosystems (Khan et al., 2022; Tsou et al., 2017; Wei et al., 2023). Additionally, data acquisition and technological constraints limit the effectiveness of these methods. Although remote sensing and GIS technologies are widely used in ecological sensitivity assessments, issues with spatial and temporal data resolution persist, hindering the ability to achieve high precision and timeliness (Chen et al., 2022; Meraj et al., 2022; Yilmaz et al., 2020). Furthermore, current methods inadequately address the dynamic nature of ecosystems. They predominantly rely on static analyses, failing to account for ecological changes over varying time scales (X. Liu et al., 2023; Ran et al., 2022).

RESEARCH METHODOLOGY

Study area

Hengshui City is located in the southeastern part of Hebei Province, with geographical coordinates ranging from 37°03' to 38°23' N and 115°10' to 116°34' E. The city comprises 11 districts and counties (Figure 2), with the municipal government situated in Taocheng District, approximately 250 kilometers from Beijing, the capital of China. Hengshui spans a total land area of 8,815 square kilometers and is part of the planned "1+9+3" Jingnan District within the Bohai Rim Economic Circle and the Capital Economic Circle. It is also a member city of the Mayor's Joint Conference for Cooperation in the Bohai Rim region, known as the "Golden Cross Intersection."

Geographically, Hengshui City is positioned within the alluvial plain of Hebei Province, featuring an average elevation of 12 to 30 meters. The terrain slopes from southwest to northeast, with elevation differences mainly ranging between 30 to 50 meters. Hengshui experiences a typical temperate monsoon climate, characterized by four distinct seasons and significant variations in temperature, dryness, and humidity. The city receives an average annual precipitation of 524 millimeters.

As of 2021, Hengshui City has a permanent population of 4.2129 million, with 2.306 million urban residents (54.74% of the total population) and 1.9067 million rural residents (45.26% of the total population).

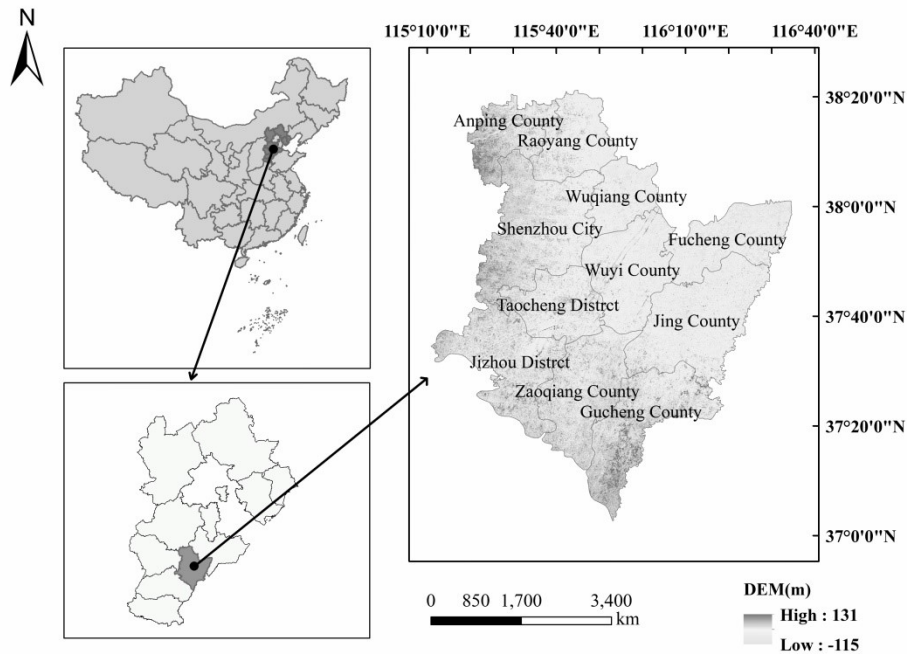


Figure 1: Administrative division map of Hengshui City

Data sources

The statistical data for the research area are derived from the "Hengshui Municipal People's Government Statistical Bulletin," the "Hengshui City Environmental Quality Bulletin," and the "Hengshui Statistical Yearbook." The vector data represent the dataset prior to integration and optimization. The Digital Elevation Model (DEM) is sourced from the geospatial data clouds available at [<http://www.gscloud.cn>] (<http://www.gscloud.cn>), specifically the ASTERGDEM30M dataset. Altitude and slope information are extracted from this dataset using ArcGIS software.

The vegetation index is comprised of remote sensing images obtained from the Landsat8 OLI-TIRS satellite digital product, also accessed through the geospatial data cloud platform. These images are processed using the Remote Sensing Image Processing Platform (ENVI).

For reference purposes, administrative divisions and high-definition image maps of Hengshui City are utilized.

Research method

Utilizing a hybrid methodology that integrates single-factor evaluation and multi-factor comprehensive evaluation techniques, our study aims to establish robust criteria for accurately assessing the ecological sensitivity of Hengshui City. This

involves a meticulous single-factor assessment of ecological sensitivity, using predefined sensitivity grading levels as benchmarks (the sensitivity factors and corresponding grading scores are presented in Table 1). After the initial assessment, the Analytic Hierarchy Process (AHP) will be employed to determine the weight values assigned to each evaluation factor. These weights, as shown in Table 1, are synthesized from ratings provided by 15 experts, relevant literature, and previous academic research in the region. These weight values will then be used to compute comprehensive ecological sensitivity data (Song et al., 2010; Ying et al., 2007).

Subsequently, a comprehensive analysis and evaluation of ecological sensitivity will be conducted, encompassing the entire geographic domain of Hengshui City. This systematic approach is expected to yield valuable insights into the region's ecological dynamics, thereby informing decision-making and proactive environmental management strategies.

Table1: Evaluation index and classification criteria of ecological sensitivity assessment

Single factor indicator	Evaluation criterion	Ecological sensitivity grading	Score	Weight
Digital Elevation Model (DEM): m	>28	Extremely sensitive	5	0.0485
	24-28	Highly sensitive	4	
	21-24	Medium sensitive	3	
	17-21	Low sensitive	2	
	<17	Non sensitive	1	
Slope:°	>4	Extremely sensitive	5	0.0692
	3-4	Highly sensitive	4	
	2-3	Medium sensitive	3	
	1-2	Low sensitive	2	
	0-1	Non sensitive	1	
Rainfall: mm/year	>510	Extremely sensitive	5	0.0765
	480-510	Highly sensitive	4	
	450-480	Medium sensitive	3	
	420-450	Low sensitive	2	
	<420	Non sensitive	1	
Land use and land cover (LUCC):km ²	Forest land	Extremely sensitive	5	0.113
	waters	Highly sensitive	4	
	Grassland	Medium sensitive	3	
	Cultivated land	Low sensitive	2	
	Construction land	Non sensitive	1	
Normalized vegetation index (NDVI)	>0.8	Extremely sensitive	5	0.1685
	0.6-0.8	Highly sensitive	4	
	0.4-0.6	Medium sensitive	3	
	0.2-0.4	Low sensitive	2	
	<0.2	Non sensitive	1	
Net primary productivity (NPP): g*c/m ²	<210	Extremely sensitive	5	0.1646
	210-250	Highly sensitive	4	
	250-290	Medium sensitive	3	
	290-320	Low sensitive	2	
	>320	Non sensitive	1	

Single factor indicator	Evaluation criterion	Ecological sensitivity grading	Score	Weight
Population: people	>22000	Extremely sensitive	5	0.0671
	22000-9100	Highly sensitive	4	
	3000-9100	Medium sensitive	3	
	600-3000	Low sensitive	2	
	<600	Non sensitive	1	
Night light index (NL)	>0.8	Extremely sensitive	5	0.0743
	0.6-0.8	Highly sensitive	4	
	0.4-0.6	Medium sensitive	3	
	0.2-0.4	Low sensitive	2	
	<0.2	Non sensitive	1	
Soil erosion intensity (SE)	Highly erosion	Extremely sensitive	5	0.2184
	Relatively erosion	Highly sensitive	4	
	Medium erosion	Medium sensitive	3	
	Mild erosion	Low sensitive	2	
	Slightly erosion	Non sensitive	1	

Based on the availability of data and to eliminate the influence of a single evaluation indicator, we selected common indicators such as land use and plant coverage, as well as natural and social impact indicators such as terrain, slope, and precipitation. This selection was intended to enrich and enhance the diversity of ecosystems. Additionally, we utilized GIS technology to screen spatial image data with a resolution of 30 x 30 meters, ensuring high resolution and accuracy of the spatial data. We then analyzed the dynamic changes in ecological sensitivity across three periods: 2010, 2015, and 2020.

ANALYSIS AND DISCUSSION

Single-factor sensitivity assessment and analysis

DEM sensitivity

The DEM factor serves as the cornerstone among the evaluation criteria for assessing ecological sensitivity in secondary forests, exerting direct or indirect influence on factors such as slope and vegetation coverage (Khan et al., 2022). Consequently, the DEM factor occupies a pivotal position in the appraisal of ecological sensitivity within secondary forest ecosystems. Based on the distribution of elevations across diverse administrative regions within Hengshui City, the sensitivity levels of the DEM have been categorized into five grades, as outlined in Table 1. Sensitivity classification maps for the years 2010, 2015, and 2020 were generated by assigning values to the designated study area, as depicted in Figure 2.

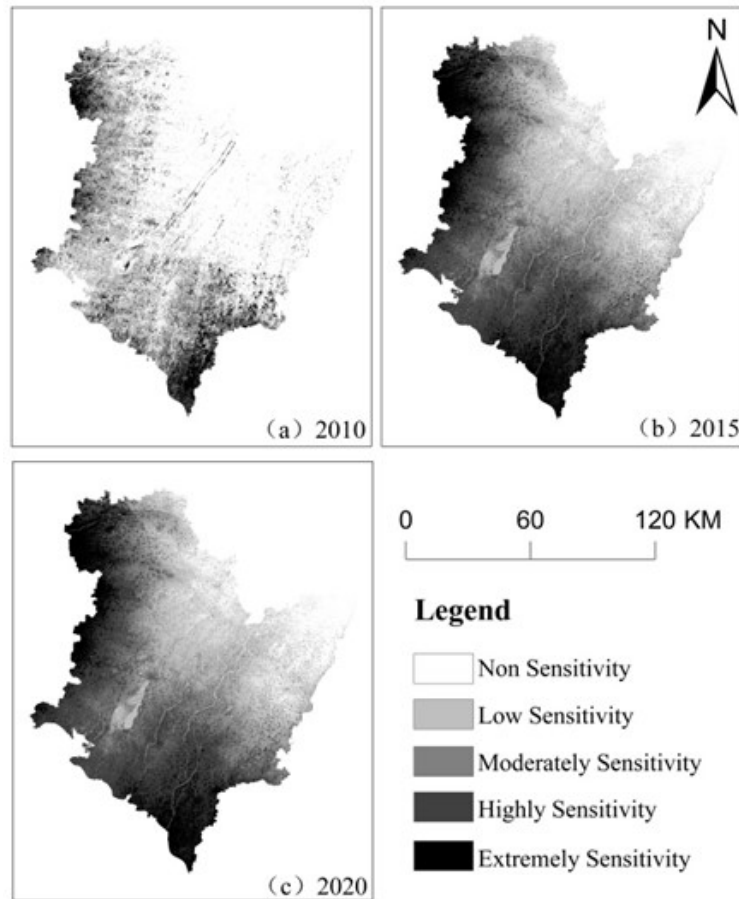


Figure 2: The influencing factors of DEM

Analysis of both charts and maps reveals that in 2010, elevation sensitivity throughout Hengshui City predominantly fell within the non-sensitive and low-sensitive categories, covering a total area of 6913.11 km², approximately 78.42% of the total land area. However, starting in 2015, there was a continuous decline in the area covered by regions classified as low-sensitivity, while conversely, areas classified as high-sensitivity and extremely high-sensitivity notably increased. Minimal disparities were observed in the areas and proportions of sensitivity levels between 2015 and 2020.

Furthermore, the northeastern part of Hengshui City features relatively flat terrain and lower sensitivity, whereas the western and southern regions exhibit greater elevation variations compared to the northeastern part, indicating higher sensitivity levels. This observation implies a direct correlation between

terrain fluctuation and sensitivity levels, where increased terrain variations correspond to heightened sensitivity.

Slope sensitivity

Based on the analysis of slope distribution across various regions of Hengshui City, we have categorized the sensitivity assessment into five distinct levels. This classification system has facilitated the creation of a slope factor ecological sensitivity classification map (Figure 3).

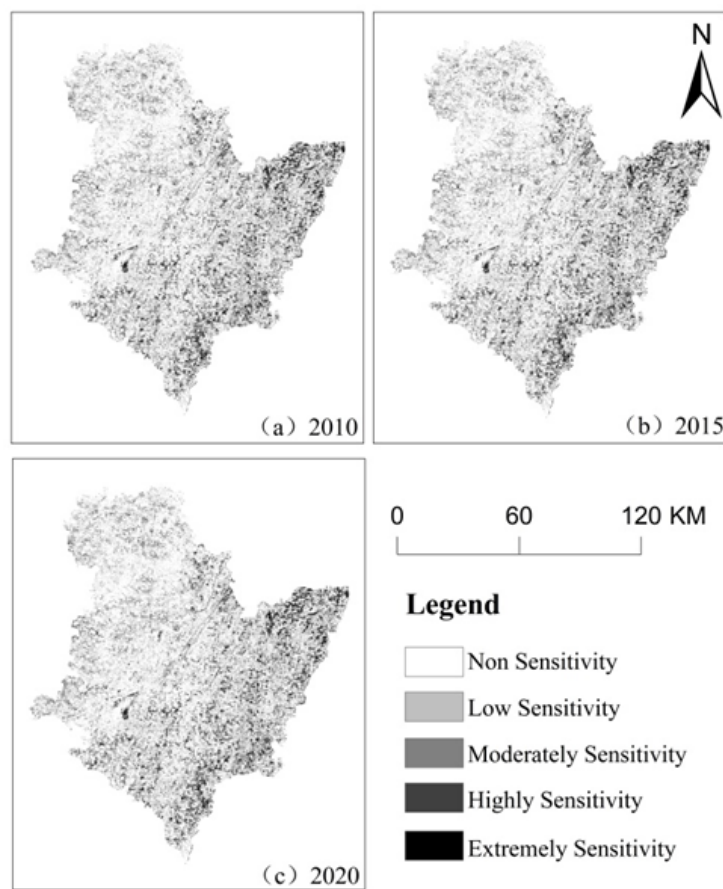


Figure 3: The influencing factors of Slope

Upon examining this map, it becomes apparent that Hengshui City is characterized by predominantly flat terrain, with minimal variations in slope gradients. Remarkably, spanning from 2010 to 2020, the sensitivity levels associated with the slope factor consistently indicate a low degree of sensitivity, showing negligible fluctuations across all data levels.

NDVI sensitivity

NDVI (Normalized Difference Vegetation Index) stands as a pivotal metric in the assessment of ecological sensitivity within the designated study area(Wei et al., 2023). It effectively captures the nuances of vegetation growth and coverage across Hengshui City. Drawing from the vegetation cover data obtained from various sectors within Hengshui City, the NDVI sensitivity is stratified into five distinct levels, culminating in the development of an NDVI sensitivity classification map, as depicted in Figure 4.

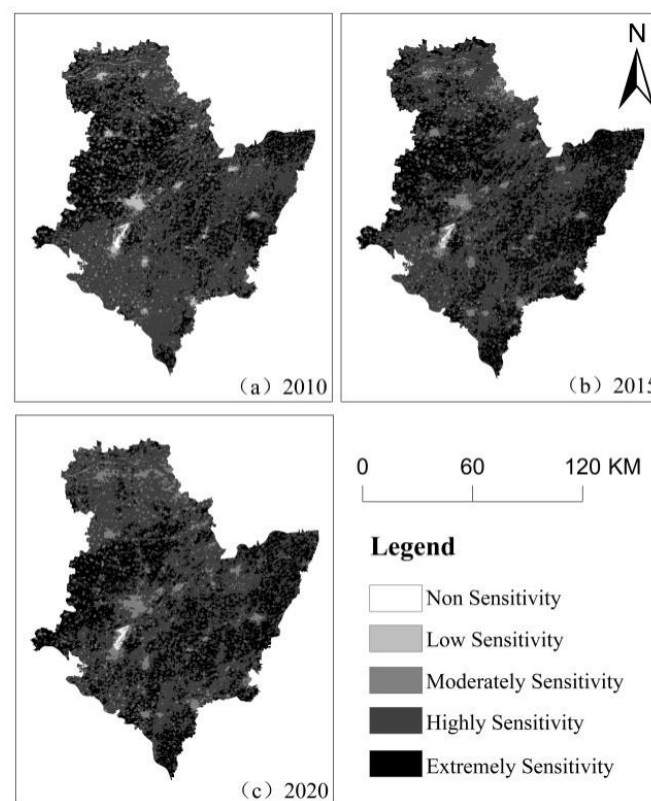


Figure 4: The influencing factors of NDVI

Upon examining the map and its corresponding dataset, it is evident that from 2010 to 2020, Hengshui City predominantly exhibits areas characterized by high and extremely high sensitivity according to NDVI assessments. Specifically, in 2010, sensitive regions covered 7746.66 square kilometers, representing 90.15% of the total land area. By 2015, these areas expanded to 8215.70 square kilometers, accounting for 93.20% of the total area. By 2020, sensitive regions further extended to cover 8270.53 square kilometers, constituting 93.82% of the

total land area. Noteworthy is the concentration of low-sensitivity areas across all three time periods, primarily localized within the water surface region of Hengshui Lake.

NPP sensitivity

NPP, short for Net Primary Productivity, refers to the surplus energy derived by vegetation through photosynthesis, after subtracting the energy consumed via metabolic processes. This metric serves as a fundamental gauge for ecosystem productivity and energy conversion efficiency, holding paramount significance in understanding ecological functionality and vitality. Typically, elevated NPP values indicate robust vegetative growth and heightened energy utilization efficiency within an ecosystem, while diminished NPP values may suggest constraints or compromised ecological health. Similarly, the assessment of NPP sensitivity in Hengshui City is stratified into five tiers, as illustrated in Figure 5.

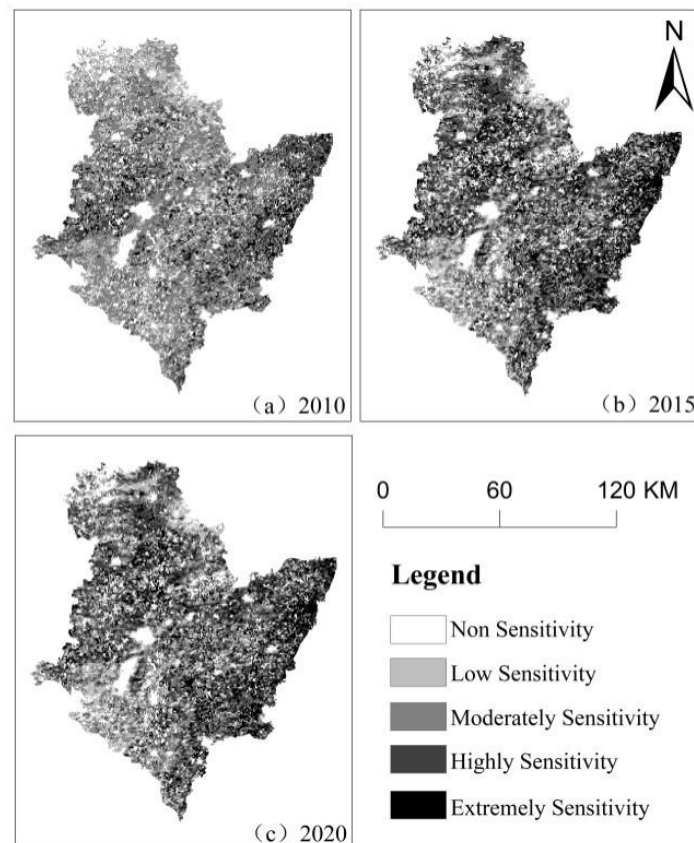


Figure 5: The influencing factors of NPP

Overall trends indicate a shift in Hengshui City's NPP sensitivity from moderate to heightened levels during the period from 2010 to 2020.

Integrated Sensitivity Assessment and Analysis

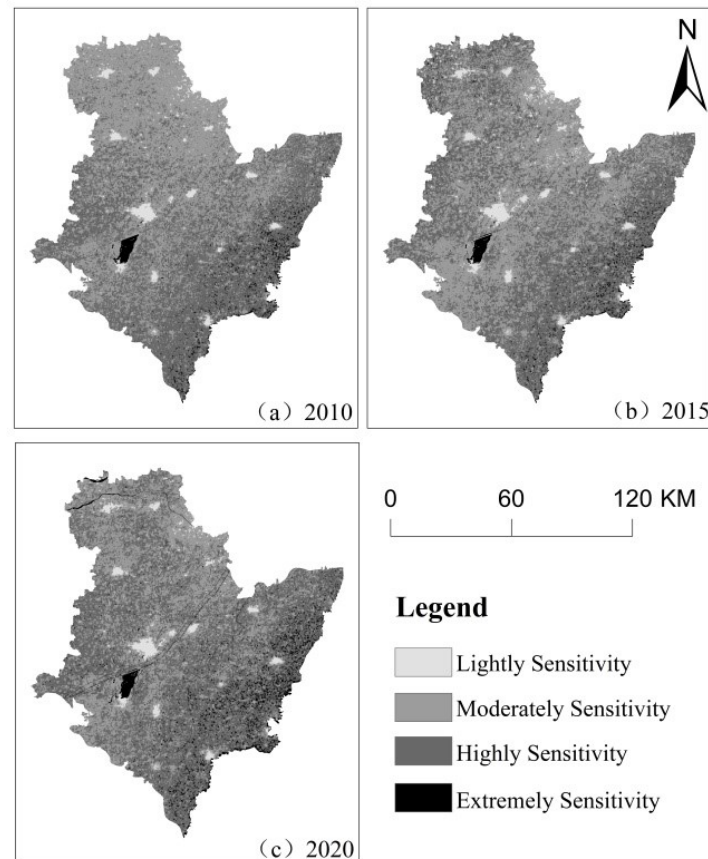


Figure 6: Distribution of comprehensive ecological sensitivity

Using GIS software and employing Analytic Hierarchy Process (AHP) analysis, we determined the weights of various sensitivity factors outlined in Table 1. All imagery underwent normalization using fuzzy tools to mitigate the impacts of dimensional variations on the data. Subsequently, GIS methodologies were used to overlay the weighted single-factor sensitivity indicators, resulting in the ecological sensitivity distribution of Hengshui City for the years 2010, 2015, and 2020. Combining all data outcomes, the ecological sensitivity of Hengshui City was categorized into four tiers: mild sensitivity, moderate sensitivity, high sensitivity, and extreme sensitivity (Figure 6).

Analysis of graphical and tabular representations reveals that in 2010, Hengshui City exhibited ecological sensitivity levels including moderate sensitivity (4472.05 km², 50.73%), severe sensitivity (3919.01 km², 44.46%), mild sensitivity (217.26 km², 2.46%), and extreme sensitivity (206.67 km², 2.34%). By 2015, the ecological sensitivity profiles of Hengshui City showed a decline in the following order: moderate sensitivity (4405.36 km², 49.98%), severe sensitivity (3928.08 km², 44.56%), mild sensitivity (284.39 km², 3.23%), and extreme sensitivity (197.17 km², 2.24%). In 2020, the area of severe sensitivity in Hengshui City expanded to 4764.87 km², representing 54.05% of the total area, while the territory characterized by moderate sensitivity decreased to 3377.37 km², accounting for 38.31%. Meanwhile, the region classified as extreme sensitivity (466.26 km², 5.69%) saw a slight increase, and the area designated as mild sensitivity (206.10 km², 2.34%) remained relatively stable.

CONCLUSION

Hengshui City demonstrates a high ecological sensitivity overall. The northern region exhibits moderate sensitivity, indicating a stable ecological environment conducive to moderate development and utilization. In the southeastern region, which shows notably high and extensive ecological sensitivity, factors such as NDVI and NPP exert significant influence. Upholding the prevailing ecological conditions in these areas is imperative, prioritizing vegetation conservation and natural preservation.

The area of extreme sensitivity is relatively small but densely concentrated, primarily within the Hengshui Lake Nature Reserve. This concentration is due to the reserve's abundant natural resources and high vegetation coverage. However, once the ecological equilibrium is disrupted, restoring it becomes challenging within a short timeframe. Therefore, these regions require considerable attention and scrutiny from relevant authorities.

The precision of ecological sensitivity research concerning Hengshui City is somewhat constrained by limitations in temporal and spatial resolutions, as well as data disparities. Acquiring data specific to the Hengshui Lake Nature Reserve presents a formidable challenge, receiving marginal emphasis in this study. Future scientific endeavors aim to leverage advancements in artificial intelligence and big data analytics to procure datasets of higher accuracy. These efforts seek to facilitate a more thorough investigation into areas exhibiting high and extreme ecological sensitivity within Hengshui City.

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