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The Human Threat to River Ecosystems at the Watershed Scale: An Ecological Security Assessment of the Songhua River Basin, Northeast China

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Abstract: Human disturbances impact river basins by reducing the quality of, and services provided by, aquatic ecosystems. Conducting quantitative assessments of ecological security at the watershed scale is important for enhancing the water quality of river basins and promoting environmental management. In this study, China's Songhua River Basin was divided into 204 assessment units by combining watershed and administrative boundaries. Ten human threat factors were identified based on their significant influence on the river ecosystem. A modified ecological threat index was used to synthetically evaluate the ecological security, where frequency was weighted by flow length from the grids to the main rivers, while severity was weighted by the potential hazard of the factors on variables of river ecosystem integrity. The results showed that individual factors related to urbanization, agricultural development and facility construction presented different spatial distribution characteristics. At the center of the plain area, the provincial capital cities posed the highest level of threat, as did the municipal districts of prefecture-level cities. The spatial relationships between hot spot locations of the ecological threat index and water quality, as well as the distribution areas of critically endangered species, were analyzed. The sensitivity analysis illustrated that alteration of agricultural development largely changed the ecological security level of the basin. By offering a reference for assessing ecological security, this study can enhance water environmental planning and management.

Keywords: human threat; river ecosystem integrity; ecological security assessment; watershed scale; ecological threat index; Songhua River Basin

1. Introduction

Serious ecological problems around the world have threatened the sustainability of social-economic-natural ecosystems, calling for urgent needs and actions to ensure ecological security [1]. Ecological security is defined by two factors: one is whether the ecosystem itself is intact, that is, whether its own structure is damaged, and whether its function is sound; second is whether the ecosystem is safe for humans, that is, whether the ecosystem services provided meet the needs of human survival and development [2]. The definition indicates that ecological security is the overall reflection of ecosystem integrity and health [1]. Based on Karr et al. [3], species distribution and abundances of river ecosystems are affected by alterations in the principal drivers (i.e., energy source, physical habitat, flow regime, water quality, and biotic interactions), which might be used as substitutes to evaluate the ecosystem integrity [4]. Human disturbances impact the ecological security of watersheds by decreasing the integrity of river ecosystems, where the processes involved are complex at both temporal and spatial scales [5]. Compared with many terrestrial and marine ecosystems, the biodiversity of river ecosystems is highly threatened or has already been diminished due to the growing need for water resources, and the impacts of climatic warming and land-use changes [6,7]. The sustainability of river ecosystems stands to be further affected by increasing human threats [8].

Human activities change the ecosystem processes, composition, and structure at multiple spatial scales, making evaluation of ecological security more complicated [9]. Thus, during the evaluation process, it is critical to assess the severity of stresses on ecosystem integrity [10]. Ecological security assessment is the identification and judgment of ecosystem integrity and sustainability to maintain ecosystem health under all kinds of risks [11], and it offers a means to compare and weigh the threats posed by human disturbance [12]. Evaluation of ecological threats at large scales can improve the conservation efficiency for watersheds and enhance the management capacity of administrators, thus playing a positive role in integrated management of the watersheds [13]. Many scholars have endeavored to advance such evaluations and have made some progress. Mattson and Angermeier [14] proposed the Ecological Risk Index Protocol to quantify 12 threats of the upper Tennessee River Basin based on human impacts and ecological integrity. Falcone et al. [15] qualified 33 potential disturbance factors generated from available GIS data, which was applied to the Western United States. Vörösmarty et al. [8] selected 23 factors from four themes to diagnose threats over worldwide fresh water from both human water security and biodiversity perspectives by the method of expert assessing. Further, by comparing studies on ecological security and risk assessments that were applied at various spatial scales [16–18], it has been demonstrated that data acquisition and analytical methods vary, and one approach does not appear to be more advantageous than another. Paukert et al. [19] developed the ecological threat index (ETI) in order to identify regions of greatest potential threat to aquatic biota for the Lower Colorado River Basin, an index that was confirmed to be both simple and objective. On that basis, considering the distance decay effect, the modified ecological threat index was improved by assigning distance weightings, with the aim of assessing different effects of human threats at different distances to rivers [20].

The Songhua River Basin (SRB) is one of China's seven major basins, with a population of approximately 60 million. The SRB is an important base for industry and food production in China because of its abundant resources and fertile land [21]. The strategy *Revitalizing the Northeast Old Industrial Base* has put forward a long-term plan for the whole basin, which identified that maintenance of the basin's ecological security will preserve food security and water resource in the northern part of China [22]. The goal of this study was to assess the spatial human threat to the SRB, as well as to discuss the impact of each factor on the result of the integrated assessment. The ecological threats posed to the current water quality or species distribution also demanded analysis to enhance the ability of water resource conservation and watershed management.

2. Data and Methods

2.1. Study Area

Located in Northeast China (41°42′ N–51°38′ N, 119°52′ E–132°31′ E), the SRB has a drainage area of 561,200 km^2, is 920-km wide and 1070-km long [23]. There are two sources for the Songhua River: the northern source is the Nen River and the southern source is the Westward Songhua River (formerly known as the Second Songhua River). It is called the Songhua River since the two branches converge into the Sancha River near Fuyu County, Jilin Province. The main stream then flows east into the Heilongjiang River in Tongjiang City [24].

The elevation of the SRB gradually increases from the center to the border, ranging from 44 to 2667 m above sea level (Figure 1). The basin is bounded by the Greater Khingan Mountains in the northwest, the Lesser Khingan Mountains in the northeast, the Wanda Range, the Laoye Range, the Zhangguangcai Range and Changbai Mountains in the southeast, and hilly areas in the southwest divide the Songhua

River and the Liao River basins [25]. The elevation of Mount Baiyun, the main peak of Changbai Mountains, lying in the southern part of the SRB, is the highest (2667 m above sea level), while in the middle the Song-Nen Plain, a major agricultural area, is the lowest at only 40–200 m above sea level.

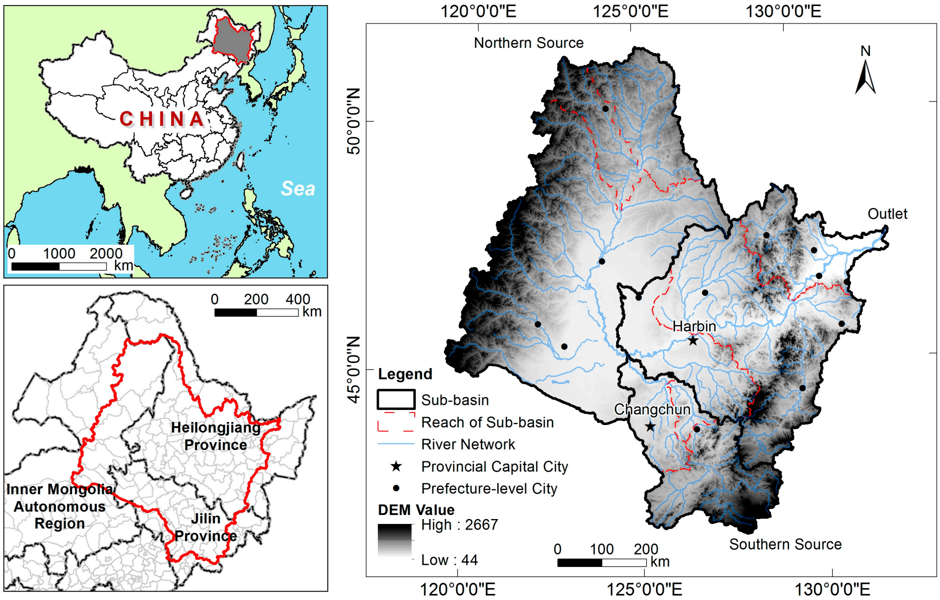


Figure 1. Location of the Songhua River Basin (SRB).

As it is the responsibility of all the administrative districts to conserve their river ecosystems for watershed management, both the watershed boundary and the administrative boundary should be taken into consideration during the process of river ecosystem restoration and planning [26]. Referring to the administrative divisions, the SRB is located in Heilongjiang Province, Jilin Province, and Inner Mongolia Autonomous Region. Using the hydrology model of ArcGIS 10.2 software (Redlands, CA, USA) and adjusting the value of flow accumulation, the SRB was divided into three sub-basins (the value of flow accumulation = 10 million) based on the digital elevation model (DEM, resolution is 78.84 m) [27]. Each sub-basin was then divided into upper, middle, and lower reaches (the value of flow accumulation = 5 million) along the rivers. In total, nine reaches intersected 127 counties of the SRB, creating 204 polygons as assessment units (AUs), with an average area of 2751.0 km^2.

2.2. Human Threat Factors

Human threat factors were selected from three aspects, urbanization, agricultural development, and facility construction, for the following reasons. First, both industrialization and urbanization processes threaten the river ecosystem by altering land use and producing wastes, resulting in growing and long-lasting problems [28]. Moreover, as the commodity grain base of China, agricultural development of the SRB has a significant impact on local ecosystems [29]. In addition, artificial facility construction has impacted the river regime, directly acting on the security of river ecosystems [30]. Considering the availability of data, and based on the eco-environment status of the SRB, we chose ten human threat factors that were determined to be related to river ecosystems in previous studies [31,32]. These factors specifically included population (total number of inhabitants), secondary industrial output (annual revenue in CNY, Chinese Yuan Renminbi), urbanized and industrialized areas (residential areas and industrial estates), large animals (sum number of cattle, horses, donkeys, mules, and camels), fertilizer (consumption of nitrogen, phosphate, potash, and compound), pesticides (consumption of chemical pesticides), agricultural area (tillage of agriculture land), reservoir storage (storage capacity of large and medium reservoirs), traffic land (roads > 30 m in width), and mining and manufacturing sites (sum number of pollution points). On top of that, statistical data were all collected from the provincial statistical yearbooks [33–35], and land-use data were provided by the Resource and Environment Science Data Center, Chinese Academy of Sciences, while reservoir storage capacity and water quality data was derived from the Water Resources Bulletin of Song-Liao Basin [36]. Critically endangered species and their distribution data were gathered from three volumes of China Species Red List [37]. In all of these data sources, 2010 was set as the base year to ensure the data collection of the total AUs. For each AU of the whole basin, threat factor data was converted to a density value [19]. Density of point factors (i.e., population, large animals, and mining and manufacturing sites) was calculated as the number of factors per square km. For quantitative factors (i.e., secondary industrial output, fertilizer, and pesticides), density was calculated as quantity (i.e., revenue in CNY and weight) of a factor per square km. Density of land use (i.e., urbanized and industrialized areas, agricultural area, and traffic land) was calculated as a percentage of total land use. Reservoir storage density was calculated as total storage volume (m^3) per square km. Based on the DEM, all of these density values of threat factors were transformed to grid layers in order to calculate the threat frequency in each AU.

2.3. Threat Frequency and Severity

Threat frequency and severity are the two essential elements needed to compute the ETI. The former is used to identify the intensity of human activity. It was assumed that human activities close to the rivers had a greater impact on the river ecosystem. So, each of the grid layers of all the threat factors was multiplied by the raster layer of distance from each grid of the AUs to the downstream river center along the flow path. Using the hydrology tool "Flow Length" of ArcGIS 10.2 (Redlands, CA, USA) [27], such distance was calculated and then scored as 5 (0–2 km), 4 (2–5 km), 3 (5–10 km), 2 (10–20 km) or 1 (>20 km) [20,38]. Independent of threat frequency, threat severity is used to indicate the stresses of the factors on the variables of river ecosystem integrity (i.e., water quality, physical habitat, biotic interactions, flow regime, and energy source), and the severity weightings were assigned using the scoring system in Mattson and Angermeier [14]. The scores were determined according to previous studies [16,20,39] and published reports of the SRB. Then the scores of all the ecosystem integrity variables were summed up to obtain a cumulative severity score for each factor (Table 1).

Table 1. Threat severity weightings assigned to individual threat factors.

Threat Factors	Classification	Unit	Water Quality	Physical Habitat	Biotic Interactions	Flow Regime	Energy Source	Total
Population	Urbanization	No./km^2	3	3	3	3	2	14
Secondary industrial output	Urbanization	CNY (10^4)/km^2	3	3	3	2	1	12
Urbanized & industrialized areas	Urbanization	%	3	3	2	2	3	13
Large animals	Agricultural development	No./km^2	1	1	1	1	3	7
Fertilizer	Agricultural development	kg/km^2	3	0	1	0	2	6
Pesticides	Agricultural development	kg/km^2	2	0	3	0	1	6
Agricultural area	Agricultural development	%	2	3	2	2	3	12
Reservoir storage	Facility construction	m^3/km^2	3	3	3	3	3	15
Traffic land	Facility construction	%	2	2	1	1	2	8
Mining & manufacturing sites	Facility construction	No./km^2	3	3	2	2	1	9

Note: A score of 0 suggests no influence, whereas a score of 3 suggests severe influence on the variables of ecosystem integrity.

2.4. Calculation and Analysis Methods

The ETI for an AU is the sum of all the threat factors calculated by severity weightings after the frequency was obtained, and the specific formulas are as follows:

$$gF_i = \sum_{j=1}^{n} (T_{ij} \times D_{ij}) \quad (1)$$

where T_{ij} is the threat density value of grid j of factor i, and D_{ij} is the distance weighting of grid j of factor i, while gF_i is the frequency value of factor i. Then the frequency values of the factors were standardized, as shown in Equation (2), giving scores that range from 0% (the lowest) to 100% (the highest). Thus, F_i is the threat frequency for individual factors, which enables one to facilitate comparisons among different factors.

$$F_i = \frac{gF_i - gF_{i\ min}}{gF_{i\ max} - gF_{i\ min}} \times 100\% \quad (2)$$

$$gETI = \sum_{i=1}^{n=10} (F_i \times S_i) \quad (3)$$

where S_i is the severity weighting of factor i shown in the last column in Table 1, and $gETI$ is the ecological threat value of an AU. Then the ecological threat values were standardized as shown in Equation (4), giving scores that range from 0% (the lowest) to 100% (the highest). So, ETI is the ecological threat index of an AU, which provides the opportunity to compare with those of other AUs. All the threat frequencies for individual factors and the ETI were finally ranked as low (0%–25%), moderate (25%–50%), high (50%–75%), and very high (75%–100%) based on a four equal quartiles method in order to make the spatial distribution visible in maps.

$$ETI = \frac{gETI - gETI_{min}}{gETI_{max} - gETI_{min}} \times 100\% \quad (4)$$

For the sake of demonstrating the spatial distribution of the threat frequency and the ETI in the whole basin, 204 AUs were analyzed by spatial and traditional statistical methods. Using the Getis-Ord General G statistic tool, a high/low clustering analysis of the frequency for individual factors and the ETI was undertaken, respectively. This tool could be used to measure the concentration of high or low values in a statistical manner at the global scale for a targeted study area. The Getis-Ord General G tool is an inferential statistic, meaning that the results of the analysis are interpreted within the context of the null hypothesis, to wit, there is no spatial clustering of feature values. After processing by this tool, the null hypothesis could be rejected if the returned p-value is small and statistically significant. Then, the sign of the z-score is used to judge the high values clustering (positive) or the low values clustering (negative) [27]. By summarizing the level at which spatial phenomena cluster, the level of threat clustering for different regions can be compared [40]. Furthermore, hot spot analysis was performed to identify where the frequency for different factors or the ETI with either high or low values clustered spatially at the local scale by use of the Getis-Ord Gi* statistic tool [41]. By looking at each feature within the context of neighboring features, this tool identifies a statistically significant hot spot when a feature has a high value and is surrounded by other features with high values as well [27].

A sensitivity analysis was conducted to determine the influence of threat factors on the overall ETI. After adjusting the original frequency values for individual factors by an increase or a decrease of 10% in both positive and negative directions, the ETI was recalculated and then the sensitivity was calculated according to Equation (5) [42]. Similarly, conditions were set by adjusting the factors classified into three aspects, respectively, urbanization, agricultural development, and facility construction. So, the changes of ETI under different conditions were calculated along with the sensitivity. Based on the sorted sensitivity, the threat factors with high sensitivity were identified in order to provide a basis for the basin's ecological threat control.

$$SS_x = \frac{|ETI_0 - ETI_x|}{ETI_0} \times 100\% \quad (5)$$

where ETI_0 is the original ETI value, and ETI_x is the ETI value after adjusting; therefore, SS_x is the sensitivity after adjusting correspondingly.

3. Results

3.1. Frequency for Individual Factors

The distribution frequency for the ten individual factors among the 204 AUs is shown in Figure 2. Unsurprisingly, there were distinct characteristics of the spatial patterns of these factors. The AUs with high and very high frequency of population, urbanized and industrialized areas, and fertilizer were concentrated in the plain area in the southwest part of the SRB, while the AUs with high and very high frequency of secondary industrial output, large animals, and pesticides were mostly located in the south-central part. In addition, reservoir storage, traffic land, and mining and manufacturing sites were distributed throughout the entire basin where the AUs with high and very high frequency were dispersed. Compared with the above factors, the AUs with high and very high frequencies of agricultural area were clustered in the north-central part. Except for reservoir storage, the frequency of the remaining factors was also higher among the downstream AUs near the outlet of the SRB. The AUs with high and very high frequency of the factors related to urbanization (population, secondary industrial output, and urbanized and industrialized areas) connected the provincial capital cities, Harbin and Changchun, with the surrounding areas. However, the frequency for factors associated with agricultural development (large animals, fertilizer, pesticides, and agricultural area) was weak around the provincial capital cities. The factors linked to facility construction (reservoir storage, traffic land, and mining and manufacturing sites) mainly relied on the geographic distribution of natural resources and development demand, so that they were more spatially dispersed. Thus, it could be inferred that the intensity of human activity from different aspects displayed diverse spatial characteristics, which was linked with the social-economic-natural complex ecosystems.

High/low clustering analysis of frequency patterns for individual factors was conducted to confirm the statistical clustering characteristics. The results showed that the pattern of mining and manufacturing sites did not appear to be significantly different from random distribution, while there was less than a 1% likelihood that the high-clustered patterns of the remaining nine factors could be the result of random chance, which reflected the aggregation effect of high frequency AUs in space (Table 2). As for the significant high-clustered factors, the analysis was performed by Getis-Ord Gi* statistic, and their specific hot spot locations were identified. The hot spot area of large animals was the smallest, while that of fertilizer was the largest, and the hot spots of pesticides were the most scattered. There were hot spots of both agricultural area and traffic land located at the outlet of the basin. Though the areas and locations differed, the AUs of hot spots were mainly distributed in the southwest and central parts of the SRB, especially at the junction of the three sub-basins, as shown in the last column in Table 2.

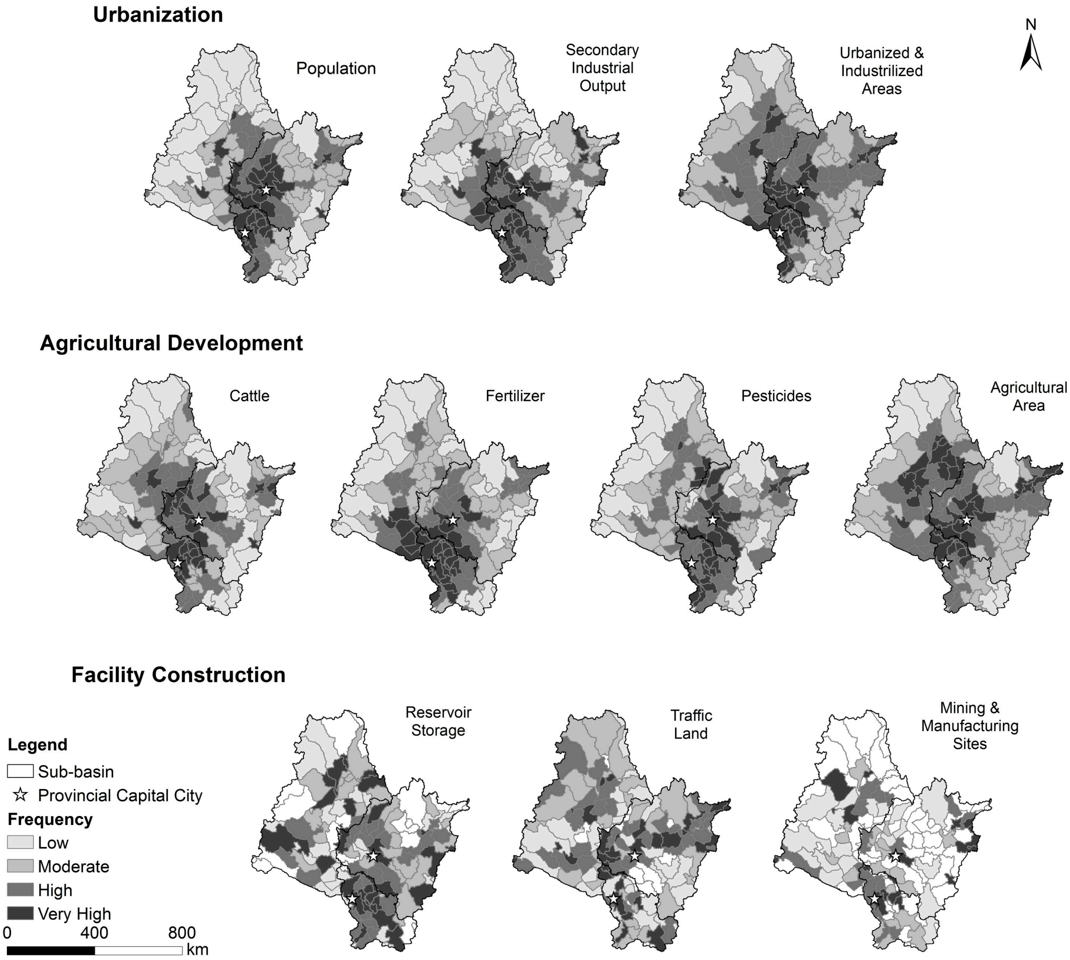
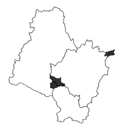


Figure 2. Spatial distribution of frequency for the 10 individual factors, with low, moderate, high, and very high values sorted by quartile in ascending order.

Table 2. Getis-Ord General G statistic results of frequency for the factors and their hot spot locations.

Threat Factor	*z*-Score	*p*-Value	Hot Spot Location
Population	6.436	0.000	
Secondary industrial output	4.157	0.000	
Urbanized & industrialized areas	4.736	0.000	
Large animals	3.362	0.001	

Table 2. *Cont.*

Threat Factor	z-Score	p-Value	Hot Spot Location
Fertilizer	13.239	0.000	
Pesticides	9.084	0.000	
Agricultural area	9.075	0.000	
Reservoir storage	7.775	0.000	
Traffic land	4.445	0.000	
Mining & manufacturing sites	0.208	0.835	Random

Note: z-Score is a standard deviation while p-value is a probability.

3.2. Integrated ETI of the SRB

Based on the frequencies for the ten threat factors and severity weightings on ecosystem integrity, the ETI of the river ecosystem among the 204 AUs in the SRB was assessed (Figure 3). The AUs with very high scores were mainly located in the plain area, in the southwestern part of the SRB, and formed a pattern of high-level threat centering on the provincial capital cities of Changchun and Harbin. The ETIs of the municipal districts of prefecture-level cities were also high, reflecting the fact that the river ecosystem in the regions mentioned above might be under great pressure from human activity, especially from the urbanization process. Close to the northwest and southeast boundaries of the SRB, the mountainous regions had less threat potential to threats because of the wide land area, high elevation and low activity intensity, which ameliorated local human disturbance. As for the entire watershed, midstream and downstream in the Westward Songhua River sub-basin and upstream in the Mainstream Songhua River sub-basin were areas where the threat to the river ecosystem was concentrated. Given the z-score of 7.513, the Getis-Ord General G statistic revealed that there was less than a 1% likelihood that the high-clustered pattern of the ETI could be the result of random chance. The hot spot locations were also identified by the Getis-Ord Gi* statistic, which is shown by the red boundary in Figure 3. The 21 AUs of hot spots were mainly distributed at the junction of the three sub-basins as well.

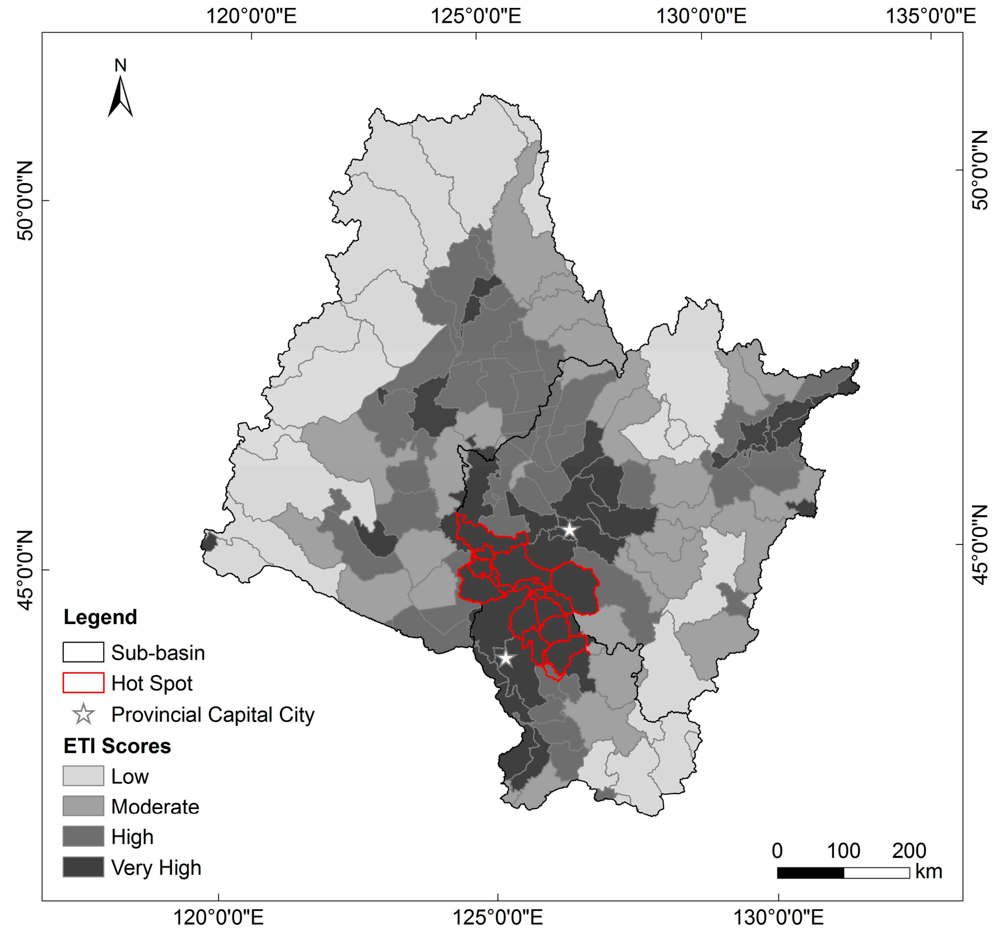


Figure 3. Spatial distribution of the ecological threat index (ETI) in the SRB, with low, moderate, high, and very high values sorted by quartile in ascending order with the hot spot locations.

Water retains the ability to self-purify, so the current situation of water quality reflects the buffering capacity of watersheds against the potential ecological threats. The water quality of rivers in the Nen River sub-basin was better than that in the other two sub-basins, given that water quality of the tributaries of the Westward Songhua River and most rivers in the Mainstream Songhua River sub-basin were poorer than Grade III (Figure 4). It could be seen that the hot spot locations of ETI covered the rivers with poor water quality so that their buffering capacity against ecological threats would be low. On the other hand, due to the higher requirements on habitat quality, the distribution areas of endangered species are more susceptible to ecological threats. In the SRB, most of the critically endangered species were primarily distributed in mountainous regions, and some seasonal migratory birds (such as the white crane) were also distributed in the plain area of the Nen River sub-basin (Figure 4). Fortunately, the hot spot locations of ETI did not coincide with the species distribution areas; thus, their susceptibility to ecological threats was not high. However, the distribution areas of the critically endangered species in the southern part of the basin, which was adjacent to the hot spot locations of ETI, deserved more concern about their present habitat quality.

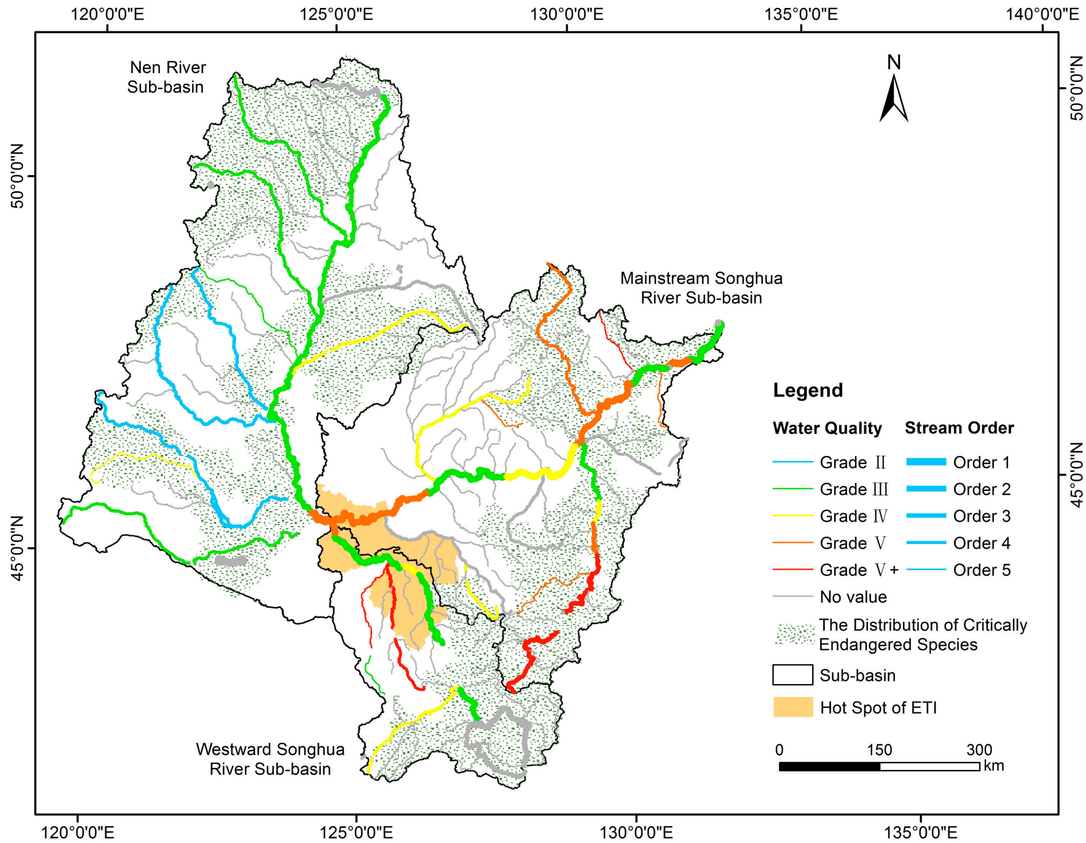


Figure 4. The spatial relationships between hot spot locations of ETI and water quality as well as the distribution of critically endangered species in the SRB.

3.3. Impact of Individual Factors on the ETI

Since the ETI spatial distribution would be driven mostly by threat factors, the impact of individual factors on the ETI was explored by sensitivity analysis. The analysis results were essentially the same in positive and negative directions, as the relationship between the ETI and frequency of each factor was linear. Comparing the sensitivity of different factors (Table 3), it was observed that the ETI was most sensitive to the factor of agricultural area (2.91%), followed by the factor of population (2.32%), while the factor of mining and manufacturing sites was the lowest (0.05%). For other factors, the sensitivity ranged from 0.22% to 1.40%. Results of sensitivity under different conditions illustrated that the ETI was most sensitive to agricultural development, indicating that alteration of agricultural development largely changed the ecological security level in the SRB, while the alteration of facility construction had less influence on the result of ecological security assessment. Therefore, during the management of ecological threats, factors with high sensitivity should be emphatically considered. In addition, the overall regulation of agricultural development would be distinctly beneficial to controlling basin's ecological threats.

Table 3. Sensitivity in a positive direction of individual factors and under different conditions listed in descending order.

Threat Factor	Sensitivity (%)	Condition	Sensitivity (%)
Agricultural area	2.91	Agricultural development	5.14
Population	2.32		
Pesticides	1.40		
Urbanized & industrialized areas	1.10	Urbanization	4.06
Secondary industrial output	0.63		
Traffic land	0.57		
Fertilizer	0.47		
Large animals	0.37	Facility construction	0.84
Reservoir storage	0.22		
Mining & manufacturing sites	0.05		

4. Conclusions and Discussion

Except for mining and manufacturing sites, which were distributed randomly in accordance with the distribution of natural resources, other threat factors demonstrated high frequency aggregation effects in the study area. Areas with intensive human activities were mainly located in places with better geographic conditions and easy resource access; in particular, urban areas (provincial capital cities and the surrounding areas) were superimposed over multiple factors. There were high levels of industrial development and population aggregation in these areas, and increasing urbanization and land-use change will lead to more serious threats on the river ecosystems of the cities. Hence, future priority areas for watershed management should focus on urban areas and their surroundings.

The distribution of ETI is mainly driven by the frequency of threat factors, instead of their severity. The hot spot analysis of the high-clustered factors helped to identify the spatial locations of the hot spot areas; thus, the basin's ecological threat level could be lowered by reducing the high threat frequency of these areas. Furthermore, the hot spot analysis of threat factors and the ETI also indicated that most hot spots tended to aggregate at the junction of the three sub-basins. This phenomenon probably resulted from the decrease in flow length to the main rivers in that area, which leads to the increase of distance weightings. A conclusion could be drawn that the junction of the three sub-basins is the key area of the SRB for maintaining and conserving the river ecosystem. Additionally, the junction areas with high ETI scores included the lower reaches of the Nen River sub-basin and the Westward Songhua River sub-basin, and the upper reach of the Mainstream Songhua River sub-basin. Generally, as for the river ecosystem, ecological threats on the upper reach would accumulate in the middle and lower reaches. Therefore, the plan and management of the upper reach of the three sub-basins, especially the Mainstream Songhua River sub-basin, should be given considerably stricter attention.

The spatial relationships between hot spot locations of ETI and water quality as well as the distribution areas of critically endangered species were analyzed. Based on the results, a number of targeted countermeasures on watershed management should be proposed. It is imperative to improve the water quality of rivers in the Westward Songhua River sub-basin and the Mainstream Songhua River sub-basin, in order to enhance their buffering capacity against ecological threat. In accordance with the provisions, sewage treatment facilities need to be invested and equipped, and the total amount of wastewater discharge must be controlled for reducing the pollution load into local waters. The authorities should strengthen the management of the existing wildlife reserves within the SRB and monitor the susceptible reaches and regions where critically endangered species inhabit or reproduce.

The sensitivity analysis pointed out that, under different conditions, the ETI was most sensitive to agricultural development, so that regulating agricultural development is the most effective way to control the basin's ecological threats. Since the SRB is an important food production region in China, agricultural development slowdown is unlikely. However, it is necessary to promote the development of sustainable agriculture so as to reduce the agricultural non-point source pollution to the aquatic ecosystems [43]. The sensitivity analysis also helped to find the factors with low sensitivity to the ETI as well. Thus, during the practical assessing and applying processes, the factors with low sensitivity (such as mining and manufacturing sites in our study) might be removed empirically in order to lower the complexity of the evaluation system and to reduce the workload of data analysis and processing.

Previous methods, both for river ecosystems conservation and for species maintenance, have focused chiefly on a restoration model involving physical, chemical and biological processes of the natural area [44]. Since river ecosystems are vulnerable to integrated development of their watersheds, ecological plans that have combined human threats (e.g., reservoir and land use) at certain landscape scales with water resource protection have attracted much attention. Scholars have gradually reached a consensus on the importance of reducing human threats during ecological restoration for the purpose of protecting the ecosystems more effectively [45]. The modified ecological threat index method used here, taking the distance decay effect into consideration, provides a valuable means to assess ecological security. This study determined the spatial pattern of ecological threats and identified the hot spot areas, offering guidance for conserving and managing the SRB, which will be a useful reference for analogous basins to control their ecological threats and to protect their water environment.

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