Resilience Assessment of Urban Complex Giant Systems in Hubei Section of the Three Gorges Reservoir Area Based on Multi-Source Data

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Abstract: Due to a lack of guidance in urban systems thinking, China’s rapid urbanization has intensified the interactions and coercive effects between the various urban space subsystems. As a result, “urban diseases” such as environmental pollution, frequent earthquakes, and unbalanced urban-rural development have spread. As a complex giant system, the exploration of urban resilience enhancement is critical to ensuring the joint spatial development of cities and towns. Based on the PSR model, this study screens 38 indicators in five levels of the natural-material-economic-social-intelligent regulation subsystem of the Three Gorges Reservoir Area urban giant system, and constructs a multi-source data resilience assessment framework. Likewise, it employs the Geodetector model to investigate the key factors impacting the resilience mechanism. The results demonstrate that: (1) between 2011 and 2020, the overall resilience in the Hubei section of the Three Gorges Reservoir Area increased from low to high and the coupled characterization of the “pressure-state-response” increased at different rates, with the state layer increasing the most; (2) the frequency of geological hazards, urbanization rate, and total number of early warning and monitoring of geological hazards are the key factors that contribute to changes in spatial resilience; (3) enhanced resilience is the result of the synergistic effects of different driving factors. Our model is used to assess the resilience of the urban system, assisting decision-makers in planning strategies to respond to urban system problems effectively and improve urban resilience.

Keywords: multi-source data; resilience; urban giant system; Three Gorges Reservoir Area; PSR model; Geodetector

1. Introduction

Rapid urbanization in China has resulted in the aggregation of urban population and physical infrastructure, as well as the emergence of various urban diseases. Following the beginning of the Reform and Opening-up period in 1978, approximately 600 million people have moved from rural to urban areas, the urbanization rate has increased from 17.92% to 64.72 %, and the ratio of urban GDP to national GDP has increased from 36% to 80% [1]. However, industrial wastewater emissions have increased from 23.35 to 75.85 billion tons, and urban diseases such as water pollution, air pollution, and unbalanced urban-rural development have gradually spread, making urban issues more prominent [2,3].

Academicians Wu [4] and Zhou [5] proposed at the beginning of the 21st century that the city is a complex giant system with multiple forms and layers of subsystem interactions. Therefore, based on the method of mathematical analysis of multi-source data, it is necessary to employ the methodological guidance of system science and investigate the interaction mechanism in order to infer the overall macro-level resilience of giant systems. In this study, the natural, economic, social, and physical environment and the intelligent regulation system comprise an urban complex giant system. Figure 1 depicts the composition of the
interconnected and interdependent subsystems. The natural environment subsystem is the foundation and support of the giant system, in which water resources, land resources, atmospheric resources, and flora and fauna resources provide the energy for its healthy and sustainable operation. This subsystem absorbs the harmful effects of human physical-space construction and socio-economic development. The physical space subsystem is the carrier, providing the hardware facilities for economic and social activities, and the construction of physical facilities and affects the structure, function, and efficiency of the giant system. As content, the social and economic subsystems include various human production and life, and their efficient operation benefits the giant system. However, if their development is too sloppy, this increases the pressure on their operation, causing each subsystem to exceed its carrying capacity. As a coupler connecting each subsystem, the intelligent regulation subsystem is capable of self-feedback and self-response, and its positive coordination effect on the subsystems manifests itself in the appropriate exploitation of the natural environment, the scientific construction of the physical space, and the healthy guidance of high-quality socio-economic development.

Figure 1. Composition relationship of the urban complex giant system (drawn by author G.C.).

The rapid urbanization of urban complex giant systems disrupts the functions and structures of the subsystems, and the “type-characteristic elements” of these disruptions are complex and diverse. Simultaneously, the level of interactive stresses between systems worsens, endangering human health and the safety of urban systems. How to construct a framework for assessing the resilience of the urban giant system using system science methodology, as well as how to study and evaluate the main controlling elements of the resilience enhancement among subsystems, is a pressing issue that must be resolved.

Multi-source data refers to data sets with various sources, characteristics, properties, and structures that are complex, heterogeneous, dynamic, and widely dispersed [6–8]. Current urban research primarily consists of the organic fusion of traditional data [9] and emerging data [10]. Typically, to create a multi-source heterogeneous database, academics combine a variety of emerging data sources with traditional data. In subsequent research on urban spatial planning, this database is utilized for tasks such as identifying the primary and secondary centers of polycentric cities [11], defining the dominant functional areas of cities [12], examining urban hierarchy [13,14], and evaluating cities from multi-level and multi-element perspectives [15–19]. In the modern era, emerging multi-source data provide more viable data sources for the quantitative study of urban systems, compensating for the
limited research scale of traditional data. The continuous enhancement of the multi-source data method promotes the development of urban systems in fine-grained research.

The study of resilience advances through the stages of engineering resilience [20], ecological resilience [21], and evolutionary resilience [22]. With the deepening of resilience research, the concept of resilience has been applied to the study of urban systems in order to increase their capacity to withstand stress and recover from internal and external disturbances. Urban resilience, as defined by the Resilience Alliance [23], is the capacity of a complex urban system to self-organize, self-learn, and self-adapt when exposed to various types of disturbances, while retaining its original structure and function. In recent years, scholars from various countries have developed single-dimensional and multi-dimensional resilience assessment components for various assessment objects of urban systems, such as the single-dimensional resilience framework of “resilience—absorption—recovery” proposed by Bruneau et al. [24] and the multi-dimensional Disaster Resilience of Place (DROP) model proposed by Cutter et al. [25]. Currently, urban resilience assessment favors the combination of qualitative and quantitative assessment methods [26–28] based on a systems science orientation. By using data from multiple sources, a more objective index system can be established. Indexes are quantified by assigning values to more precisely evaluate the spatiotemporal evolution of urban system resilience.

In recent years, there has been a breakthrough in urban resilience assessment methods due to the intensification of relevant research and the development of information technology. However, the index systems proposed by Chinese scholars tend to be more directive and less exhaustive [29–32]. As a result, they lack analysis from the perspective of resilience processes and at the urban system level. Additionally, they focus less on resilience mechanisms in urban complex giant systems.

This study is guided by the methodology of system science [33–35] and supported by emerging multi-source data derived from the PSR model. It employs its “cause–effect–response” logic to determine the causal logic of resilience process, i.e., the three-stage coupling effect of “stress drivers—multidimensional system state—intelligent regulation”. Simultaneously, this is combined with mathematical and statistical methods to construct a multidimensional spatial resilience assessment framework for cities and towns, quantitatively analyze the spatiotemporal evolution of resilience, and identify the key factors.

2. Study Area and Data Sources
2.1. Study Area

The Three Gorges Reservoir Area is the region affected by inundation during the Three Gorges Project 175m impoundment [36,37], which spans Hubei Province and Chongqing City. This paper focuses on the “head” section of the Three Gorges Reservoir Area, which includes Yiling District, Zigui County, and Xingshan County in Yichang, Hubei Province, as well as Badong County in Enshi Autonomous Prefecture (Figure 2). The construction and development of towns in the Three Gorges Reservoir Area went through three stages: the Immigrant New Town period, the Post-Three Gorges period, and the Yangtze River Protection period. The Three Gorges Project spurred the development of new towns for immigrants in the Three Gorges Reservoir Area over 15 years (1994–2009). This period was characterized by rapid and haphazard urbanization, low and resource-dependent economic development, structurally and functionally incomplete urban infrastructure, and an urban management system devoid of technological sophistication [38,39]. In response, the State Council issued the “Three Gorges Follow-up Project” in 2010 to assist towns in the Three Gorges Reservoir Area in optimizing and improving their structure and functions, as well as enhancing urbanization quality. With the further promotion of Yangtze River Protection and Yangtze River Economic Belt Strategies, the Three Gorges Reservoir Area, as an essential environmental function area, is the core driving force for promoting the healthy and sustainable development of the area by improving the multidimensional coupling resilience between the subsystems of “natural environment-socio-economic—physical space—intelligent regulation” in urban space [40,41].
Based on the development status of new towns for immigrants in the Three Gorges Reservoir Area over time, this paper investigates the multidimensional coupling characteristics and mechanisms of the urban giant system during the post-Three Gorges period and Yangtze River Protection period in order to quantify its multidimensional coupling resilience state. Therefore, the study period was from 2011 to 2020.

2.2. Data Sources

The indicator data for evaluating the urban resilience in this study are characterized by multiple sources and levels, which are categorized and classified into two types: traditional data and emerging data. The use of various data in the assessment indicators and their pre-processing methods are identified below.

(1) Traditional Data

(1) Open Government Data. These data were primarily obtained from the 2010–2020 Yichang Statistical Yearbook, the Enshi Prefecture Statistical Yearbook, the China County Statistical Yearbook, the environmental quality bulletin of each county, the national economic and social development statistical bulletin of each county, the 14th Five-Year Plan for urban–rural development of each county, and other relevant statistics and general planning information. Natural resources and socio-economic data were extracted for calculation purposes. Certain data were calculated results, and missing data from individual years were interpolated from adjacent years.

(2) Remote Sensing and Geospatial Data. The ESA Sentinel series data source (https://scihub.copernicus.eu/, accessed on 15 April 2022) was used to collect Sentinel II image data.
for the respective years, and software such as ENVI was used for manual interpretation of urban arable land, forest, and other land-use forms, which were used as basic data for the processing and calculation of certain natural resource indicators.

(2) Emerging Data

① Smart Facility Monitoring Data. These data were primarily derived from geological hazard monitoring points, climate monitoring points, and environmental noise monitoring points in each county and district. By interpolating data from adjacent years, missing data for certain years were reconstructed.

② Application Programming Interface Data. Such data were primarily derived from the geospatial open data platforms of Baidu Maps (https://lbsyun.baidu.com/, accessed on 15 April 2022) and Gaode Maps (https://lbs.amap.com/, accessed on 15 April 2022), where data related to material space were extracted; relevant calculations were performed using POI data, etc.

3. Research Method and Index System Construction

3.1. The “Pressure-State-Response” P-S-R Model

Urban resilience focuses on process characteristics. It emphasizes the ability to maintain sustainable development, stability, and risk monitoring and regulation through internal buffering, self-regulation operation, and self-healing properties after facing various natural or social disturbances, especially when suffering from sudden or more serious disasters. Based on the PSR model proposed by the Organization for Economic Cooperation and Development (OECD) and the United Nations Environment Programme (UNEP) [42], this paper describes the three stages of the cyclic chain relationship of “stress driver—multidimensional system state—intelligent regulation” (Figure 3) to the process attributes of urban resilience development.

![Figure 3. Internal Logic Analysis of the PSR model (self-drawn by author G.C.).](image)

The pressure layer is used to determine the threat level of natural disasters or human activities and other disaster-causing factors, as well as the possibility of exposing the metropolis to unpredictable disturbances. The state layer describes and reflects the self-adaptive, self-regulating, and self-restoring state of the structure and function of a subsystem under the influence of disturbances. When the system’s state falls below a critical threshold, the city system becomes hugely vulnerable to significant impacts. It
enters a state of disorder before its main body is able to take countermeasures. The response layer reflects the capacity to resume regular operation following a crisis and adjust to the new environment through intelligent regulation and management [43,44].

3.2. Construction of Urban Resilience Index System

As shown in Table 1, based on the main contents of the above urban complex giant system facing disturbances, a multi-dimensional and multi-source data evaluation system of urban resilience was developed by combining a total of five dimensions: natural environment, economic, social, and physical space, and intelligent regulation subsystems, with a total of 38 indicators.

Table 1. Urban resilience index system in Hubei section of Three Gorges Reservoir Area (compiled by authors G.L, G.C. and Z.W.). Note: "+" and "−" indicate positive and negative correlations between indicators and urban resilience.

<table>
<thead>
<tr>
<th>Guideline Layer</th>
<th>Criteria Layer</th>
<th>Index Layer</th>
<th>$W_{ij}$</th>
<th>$W_{ij}$</th>
<th>$W_{ij}$</th>
<th>$W_{ij}$</th>
<th>Index Direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural disaster disturbance data</td>
<td>R1 Frequency of geological hazards in the reservoir area</td>
<td>0.0236</td>
<td>0.0273</td>
<td>0.0255</td>
<td>−</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>R2 Average annual rainfall (mm)</td>
<td>0.0087</td>
<td>0.0249</td>
<td>0.0168</td>
<td>−</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>R3 Frequency of extreme weather</td>
<td>0.0088</td>
<td>0.0304</td>
<td>0.0196</td>
<td>−</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>R4 Rate of good air quality (%)</td>
<td>0.0114</td>
<td>0.0298</td>
<td>0.0206</td>
<td>+</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pressure</td>
<td>R5 Industrial wastewater emissions per unit of GDP (million tons/billion yuan)</td>
<td>0.0120</td>
<td>0.0284</td>
<td>0.0202</td>
<td>−</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>R6 Industrial SO$_2$ emissions per unit GDP (tons/billion yuan)</td>
<td>0.0079</td>
<td>0.0260</td>
<td>0.0170</td>
<td>−</td>
<td></td>
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</tr>
<tr>
<td></td>
<td>R7 Agricultural fertilizer use per unit of GDP (tons/billion yuan)</td>
<td>0.0130</td>
<td>0.0264</td>
<td>0.0197</td>
<td>−</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>R8 Average regional ambient noise dB (A)</td>
<td>0.0094</td>
<td>0.0215</td>
<td>0.0154</td>
<td>−</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>R9 Frequency of major safety accidents</td>
<td>0.0112</td>
<td>0.0256</td>
<td>0.0184</td>
<td>−</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Man-made disaster disturbance</td>
<td>R10 Percentage of paddy and dryland area (%)</td>
<td>0.0530</td>
<td>0.0309</td>
<td>0.0420</td>
<td>+</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>R11 Percentage of cultivated land on &gt;25 slopes (%)</td>
<td>0.0224</td>
<td>0.0298</td>
<td>0.0261</td>
<td>−</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>R12 Effective irrigated area (thousand hectares)</td>
<td>0.0617</td>
<td>0.0240</td>
<td>0.0429</td>
<td>+</td>
<td></td>
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<td></td>
<td>R13 Absolute elevation difference (m)</td>
<td>0.0321</td>
<td>0.0374</td>
<td>0.0348</td>
<td>−</td>
<td></td>
<td></td>
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<td></td>
<td>R14 Forest coverage rate (%)</td>
<td>0.0164</td>
<td>0.0283</td>
<td>0.0223</td>
<td>+</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Natural Environment Representation</td>
<td>R15 Per capita GDP (billion yuan/10,000 people)</td>
<td>0.0327</td>
<td>0.0266</td>
<td>0.0296</td>
<td>+</td>
<td></td>
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<tr>
<td></td>
<td>R16 Percentage of primary and secondary industries (%)</td>
<td>0.0151</td>
<td>0.0217</td>
<td>0.0184</td>
<td>−</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>R17 Urbanization rate (%)</td>
<td>0.0148</td>
<td>0.0201</td>
<td>0.0174</td>
<td>+</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>R18 Urban registered unemployment rate (%)</td>
<td>0.0094</td>
<td>0.0208</td>
<td>0.0151</td>
<td>−</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>R19 Urban population density (10,000 people per 10,000 km$^2$)</td>
<td>0.0649</td>
<td>0.0408</td>
<td>0.0529</td>
<td>−</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Socio-Economic Representation</td>
<td>R20 Road network density (km/100 km$^2$)</td>
<td>0.0198</td>
<td>0.0190</td>
<td>0.0194</td>
<td>+</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>R21 Number of students in general secondary schools per 10,000 people</td>
<td>0.0451</td>
<td>0.0322</td>
<td>0.0387</td>
<td>+</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>R22 Number of beds in medical institutions per 10,000 people (beds per 10,000 people)</td>
<td>0.0214</td>
<td>0.0221</td>
<td>0.0218</td>
<td>+</td>
<td></td>
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<tr>
<td></td>
<td>R23 Number of beds in adoption-type institutions per 10,000 people (beds per 10,000 people)</td>
<td>0.0233</td>
<td>0.0190</td>
<td>0.0211</td>
<td>+</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>R24 Park green space per 10,000 people (hectares per 10,000 people)</td>
<td>0.3840</td>
<td>0.0300</td>
<td>0.0342</td>
<td>+</td>
<td></td>
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<tr>
<td></td>
<td>R25 Percentage of villages benefiting from piped water (%)</td>
<td>0.0202</td>
<td>0.0244</td>
<td>0.0223</td>
<td>+</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>R26 Rural electricity consumption per 10,000 people (million kWh per 10,000 people)</td>
<td>0.0309</td>
<td>0.0303</td>
<td>0.0306</td>
<td>+</td>
<td></td>
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<tr>
<td></td>
<td>R27 Gas penetration rate (%)</td>
<td>0.0116</td>
<td>0.0257</td>
<td>0.0187</td>
<td>+</td>
<td></td>
<td></td>
</tr>
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</table>
Table 1. Cont.

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<thead>
<tr>
<th>Guideline Layer</th>
<th>Criteria Layer</th>
<th>Index Layer</th>
<th>( W_{ij} )</th>
<th>( W_{2j} )</th>
<th>( W_{3j} )</th>
<th>Index Direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adaptability</td>
<td>R28 Energy consumption reduction rate per unit of GDP (%)</td>
<td>0.0149</td>
<td>0.0245</td>
<td>0.0197</td>
<td>–</td>
<td></td>
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<tr>
<td></td>
<td>R29 Plantation area ratio (ha/km(^2))</td>
<td>0.0299</td>
<td>0.0267</td>
<td>0.0283</td>
<td>+</td>
<td></td>
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<tr>
<td></td>
<td>R30 Integrated utilization rate of industrial solid waste (%)</td>
<td>0.0130</td>
<td>0.0301</td>
<td>0.0216</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td></td>
<td>R31 Number of environmental management projects completed in the year</td>
<td>0.0711</td>
<td>0.0211</td>
<td>0.0461</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>Response</td>
<td>R32 Ratio of social security investment to regional GDP (%)</td>
<td>0.0349</td>
<td>0.0262</td>
<td>0.0306</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td></td>
<td>R33 Percentage of environmental spending (%)</td>
<td>0.0288</td>
<td>0.0228</td>
<td>0.0258</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td></td>
<td>R34 Percentage of public safety spending (%)</td>
<td>0.0246</td>
<td>0.0273</td>
<td>0.0260</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>Resourcefulness</td>
<td>R35 Total number of R &amp; D personnel (people)</td>
<td>0.0484</td>
<td>0.0229</td>
<td>0.0356</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td></td>
<td>R36 Ratio of R&amp;D internal expenditure to GDP (%)</td>
<td>0.0332</td>
<td>0.0239</td>
<td>0.0285</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td></td>
<td>R37 Total number of early warning and monitoring of geological hazards</td>
<td>0.0549</td>
<td>0.0280</td>
<td>0.0414</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td></td>
<td>R38 Integrated broadband coverage rate (%)</td>
<td>0.0070</td>
<td>0.0233</td>
<td>0.0152</td>
<td>+</td>
<td></td>
</tr>
</tbody>
</table>

3.3. The Entropy Weight-CRITIC Method

3.3.1. Data Standardization

Using the technique of extreme difference standardization, the data were made dimensionless. According to the positive or negative effect on resilience, the indicators were categorized as positive and negative [45]. Positive indicators imply that the greater the evaluation indicator data, the stronger the resilience. On the contrary, negative indicators implies that the greater the evaluation indicator data, the weaker the resilience.

Positive indicators:

\[
X'_{ij} = \frac{x_{ij} - \min(x_j)}{\max(x_j) - \min(x_j)} \tag{1}
\]

Negative indicators:

\[
X'_{ij} = \frac{\max(x_j) - x_{ij}}{\max(x_j) - \min(x_j)} \tag{2}
\]

where \( X'_{ij} \) is the \( j \)th indicator of a county in the \( i \)th year, \( \max(x_j) \) and \( \min(x_j) \) are the maximum and minimum values of the \( j \)th indicator for each county in all years, and \( X'_{ij} \) is the standardized value of the \( j \)th indicator in the \( i \)th year for a county.

3.3.2. Determining the Indicator Weights

Following is the formula for calculating weights using the entropy weighting approach [46,47]:

\[
Y_{ij} = \frac{X'_{ij}}{\sum_{m=1}^{m} x_{ij}} \tag{3}
\]

\[
e_j = -k\sum_{i=1}^{m} (Y_{ij} \times \ln Y_{ij}), \quad k = \frac{1}{\ln m}, 0 \leq e \leq 1 \tag{4}
\]

\[
d_j = 1 - e_j \tag{5}
\]

\[
W_{ij} = \frac{d_j}{\sum_{j=1}^{n} d_j} \tag{6}
\]

where \( Y_{ij} \) stands for the proportion of the \( j \)th indicator in the \( i \)th year, \( e_j \) stands for the entropy of the \( j \)th indicator, \( d_j \) stands for the redundancy of the indicator information entropy, and \( W_{ij} \) stands for the entropy weight of the \( j \)th indicator. The entropy weight \( W_j \) represents
the degree of difference between indicators; the greater the value, the more significant the indicator’s impact on the comprehensive decision. If $Y_{ij} = 0$, then $Y_{ij} \times \ln Y_{ij} = 0$ is defined.

For computing the weights using the CRITIC technique [48,49], the influence of several of the more correlated indicators can be avoided, and the overlap of indicator data can be minimized using the following formula:

$$S_j = \sqrt{\frac{\sum_{i=1}^{m} (X_{ij} - \bar{X}_j)^2}{m - 1}}$$  \hfill (7)

$$\bar{X}_j = \frac{\sum_{i=1}^{m} X_{ij}}{m}$$  \hfill (8)

$$R_j = \frac{\sum_{i=1}^{n} (1 - r_{ij})}{n}$$  \hfill (9)

$$C_j = S_j \sum_{i=1}^{n} (1 - r_{ij}) = S_j \times R_j$$  \hfill (10)

$$W_{2j} = \frac{C_j}{\sum_{j=1}^{n} C_j}$$  \hfill (11)

where $S_j$ stands for the standard deviation of the $j$th indicator, $r_{ij}$ stands for the correlation coefficient between evaluation indicators $i$ and $j$, and $W_{2j}$ stands for the weight derived using the CRITIC approach.

The combination of the two methods described above can more accurately reflect indicator weights, assuming that both methods are equally important, by setting $x = y = 0.5$ [50–52]. Following is the formula for calculating the entropy-CRITIC combination weights:

$$W_j = \alpha W_{1j} + \beta W_{2j} \alpha = \beta = \frac{1}{2}$$  \hfill (12)

### 3.3.3. Overall Resilience Scores

Using statistical methods, the results of each index were compiled into resilience scores that reflect the relative scale of the spatial resilience of cities and towns in the Three Gorges Reservoir Area. Using the weighted summation index method, the resilience scores of the three processes of “pressure–state–response” and the overall resilience scores were obtained. The following is the formula:

$$P = \sum_{j=1}^{9} W_j X'_{ij}$$  \hfill (13)

$$S = \sum_{j=10}^{27} W_j X'_{ij}$$  \hfill (14)

$$R = \sum_{j=28}^{38} W_j X'_{ij}$$  \hfill (15)

The value of $j$ in the formula is from Table 1. $j = 1–9$ represents the 1st–9th indicators, which all belong to the pressure layer; $j = 10–27$ represents the 10th–27th indicators, which all belong to the state layer; and $j = 28–38$ represents the 28th–38th indicators, which all belong to the response layer.

### 3.4. Evaluating the Controlling Elements of Resilience

The Geodetector model [53,54] is a statistical method used to detect spatial dissimilarity and investigate its driving forces. It consists of four modules, including the Factor Detector, Interaction Detector, Risk Detector, and Ecological Detector. It can be downloaded for free at http://geodetector.cn/, accessed on 9 May 2022. In this study, the Factor Detector was utilized to identify the most critical controlling elements for the resilience of the Complex Giant System in the Three Gorges Reservoir Area. The Interaction Detector was employed to screen the forms of interactions between the indicators, and the $q$ value was
utilized to assess the effect of the internal driver X on the attribute Y, i.e., the degree of coupled coercion. The following is the formula:

\[ q = 1 - \frac{1}{N_\sigma^2} \sum_{h=1}^{L} N_h \sigma_h^2 = 1 - \frac{SSW}{SST} \]  

(16)

In the equation, the value interval of q is [0, 1], and the greater the value of q, the greater the influence degree of factor X on attribute Y; \( h = 1, \ldots, L \) represents the stratification of factor X; \( N_h \) and N represent the number of samples in the detection region and the entire region, respectively; \( \sigma_h^2 \) and \( \sigma_2 \) represent the variance of Y values in the detection region and the entire region, respectively; and SSW and SST represent the sum of variance within the stratum and the variation of the entire region, respectively.

4. Results and Discussion
4.1. Spatiotemporal Evolution and Urban Resilience Characteristics in Counties
4.1.1. The Temporal Evolution of the Resilience Characteristics in Counties

As shown in Figure 4, the trend of overall resilience change in the Hubei section of the Three Gorges Reservoir Area is divided into four stages: the small fluctuation stage from 2011 to 2014, the steep increase stage from 2014 to 2015, the steady increase stage from 2015 to 2019, and the slight decrease stage from 2019 to 2020.

![Figure 4](image-url)

Figure 4. Time series of urban spatial resilience changes in the Hubei section of the Three Gorges Reservoir Area from 2011 to 2020 (self-drawn by author G.C.).

From an overall perspective, the resilience of cities and towns in the Hubei section of the Three Gorges Reservoir Area increased from 0.3432 in 2011 to 0.5277 in 2020. It shows an increase of 0.1845 or 53.76% in 10 years, indicating that the overall resilience increased significantly between 2011 and 2020. This is due to the post-Three Gorges Period after 2010, the Three Gorges Follow-up Project [55], and the Plan for Major Function-oriented Zones [56], which gradually emphasized the coordinated development of the “natural environment-socio-economic—physical space construction” of the urban system and provided crucial strategic support for the improvement of urban resilience. What is striking in this figure is the rapid increase in overall resilience in 2015, with an annual increase of 17.29%. The main cause is the establishment of the Leading Group for Promoting
the Development of the Yangtze River Economic Belt in 2014, which promoted urbanization and industrial transformation. From a process perspective, the resilience level of the pressure layer is similar to that of the response layer, showing a slightly fluctuating growth trend, which indicates that the disturbances in the urban system are decreasing and the capacity to cope with disturbances is improving. However, from 2012 to 2014, the resilience of both the pressure layer and the state layer declined in a similar trend; from 2015 to 2016, that of the pressure layer decreased from 0.646 to 0.644, and from 2019 to 2020 that of the response layer decreased from its highest value of 0.1480 to 0.1313. Moreover, the resilience level of the state layer has been steadily increasing, with a significant increase in 2017–2018 from 0.2244 to 0.2548, indicating a gradual improvement in the robustness of the spatial urban system in the Hubei section of the Three Gorges Reservoir Area.

4.1.2. The Spatial Evolution of the Resilience Characteristics

The results show that the urban spatial resilience in the Hubei section of the Three Gorges Reservoir Area increased from 2011 to 2020. In addition, the spatial distribution of resilience changed significantly (Figure 5).

In 2011, Xingshan County had the highest overall resilience level, followed by Zigui County and Yiling District, while Badong County had the lowest. During the small fluctuation stage from 2011 to 2014, the overall resilience of the Yiling District increased slightly from 0.3609 to 0.4189, while the other three counties experienced small decreases. During the steep increase stage from 2014 to 2015, Xingshan increased from 0.4028 to the highest value of 0.4957 among four counties in 2015, while Badong increased from 0.2571 to 0.3321, indicating that overall resilience of both these two counties improved significantly. During the steady increase stage from 2015 to 2019, the overall resilience of the Yiling District was relatively high compared to other three counties, gradually rising from 0.4649 to 0.6473. During the slight decrease stage from 2019 to 2020, Yiling showed a downward trend but remained higher than the other three counties. On the contrary, Badong was the lowest before 2019, then increased in 2019–2020, overtaking Zigui.

The main reason for the spatial variation in overall resilience changes is that 2011 was the early year of the post-Three Gorges Period when urban construction and development were relatively unstable. There was little variation in socio-economic status, material space status, or regulatory adaptability among counties and districts. However, with the delineation of the ecological conservation area, the construction of the Yangtze River Economic Belt, and accelerating urbanization, the agglomeration effect of different resources has become more apparent. The development gap between Yiling District and other counties in terms of “natural-social-economic-material-management” has grown increasingly prominent, leading to a spatial pattern of the highest resilience in Yiling District which is slightly different than the remaining regions.

4.2. Identification of Resilience Main Controlling Influence Factor

4.2.1. Analysis of Resilience Main Controlling Influence Factor

The Geodetector model was used in this paper because it has better computational accuracy for small sample sizes. SPSS software was used to disaggregate the continuous data into five categories, the Geodetector tool was employed to examine the contribution of each influence factor quantitatively, and the $q$ value for each factor was calculated. The higher the $q$ value, the greater the influence of factor $X$ on attribute $Y$, and the lesser the opposite; thus, $q > 0.5$ indicates that $X$ has a significant influence on $Y$ [57,58]. The top five indicators with $q > 0.5$ in the pressure layer, state layer, and response layer were selected as the most influential controlling elements on the spatial resilience of cities and towns in the Hubei section of the Three Gorges Reservoir Area (Table 2).
Figure 5. Spatial evolution of overall resilience in the Hubei section of the Three Gorges Reservoir Area from 2011 to 2020 (self-drawn by author G.C.).
Table 2. Top five factors of pressure, state, and response layers affecting spatial resilience of cities and towns (compiled by author G.C.).

<table>
<thead>
<tr>
<th>Pressure Factor</th>
<th>State Factor</th>
<th>Response Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1 0.6807</td>
<td>R17 0.7207</td>
<td>R37 0.7185</td>
</tr>
<tr>
<td>R7 0.5922</td>
<td>R27 0.7193</td>
<td>R35 0.6175</td>
</tr>
<tr>
<td>R6 0.4058</td>
<td>R15 0.6532</td>
<td>R31 0.4779</td>
</tr>
<tr>
<td>R3 0.2409</td>
<td>R26 0.5901</td>
<td>R38 0.4416</td>
</tr>
<tr>
<td>R4 0.2076</td>
<td>R24 0.5796</td>
<td>R29 0.2722</td>
</tr>
</tbody>
</table>

According to the detection results, the top five indicators of the pressure layer with high \( q \) values are the frequency of geological hazards in the reservoir area (R1) and agricultural fertilizer use per unit of GDP (R7); the top five indicators of the state layer all have high \( q \) values, which are urbanization rate (R17), gas penetration rate (R27), per capita GDP (R15), rural electricity consumption per 10,000 people (R26), and park green space per 10,000 people (R24). The top five indicators of the response layer with high \( q \) values are total number of early warnings and monitoring of geological hazards (R37), and total number of R&D personnel (R35). This implies that these factors are more likely to affect the improvement of resilience. Consequently, it is beneficial to take corresponding measures to improve the spatial resilience of towns and cities, such as improving their monitoring and early warning systems to effectively reduce geological disaster losses, refining infrastructure construction in towns and cities, accelerating the industrial transformation, promoting economic development to raise the per capita GDP, rationalizing the use of agricultural fertilizers, and enhancing the quality of research and development personnel.

4.2.2. Types of Interactions between Influence Factors

The “interaction detector” of Geodetector was employed to determine the interactions among factors on the resilience enhancement of complex giant systems. The interaction types included 325 groups of two-factor enhancement types and 416 groups of non-linear enhancement types, suggesting that all two-factor interactions affect the resilience enhancement of the study area. The top ten groups of interaction factors (Table 3) included six groups of two-factor enhancement types and four groups of non-linear enhancement types with interaction values greater than 0.9, indicating a high level of interaction. These factors are represented by the total number of R&D personnel (R35) and road network density (R20). When the total number of early warning and monitoring of geological hazards (R37), urbanization rate (R17), total number of R&D personnel (R35), and gas penetration rate (R27) were linked with other factors, the number of groups with interaction greater than 0.9 were 16, 12, 9, and 8, indicating that they were more probable to interact than other factors.

Table 3. Ten sets of interactions for spatial resilience of cities and towns in the Hubei section of the Three Gorges Reservoir Area (compiled by author G.C.).

<table>
<thead>
<tr>
<th>Factor Interaction</th>
<th>( Q(C_i) )</th>
<th>( Q(C_j) )</th>
<th>( Q(C_i \cap C_j) )</th>
<th>Value Comparison</th>
<th>Interaction Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>R35 ( \cap ) R20</td>
<td>0.6175</td>
<td>0.2494</td>
<td>0.9583</td>
<td>( &gt;R35 + R20 )</td>
<td>Enhance, Nonlinear</td>
</tr>
<tr>
<td>R37 ( \cap ) R35</td>
<td>0.7185</td>
<td>0.6175</td>
<td>0.9565</td>
<td>( &gt;\max (R37, R35) )</td>
<td>Enhance, bi-</td>
</tr>
<tr>
<td>R27 ( \cap ) R20</td>
<td>0.7193</td>
<td>0.2494</td>
<td>0.9561</td>
<td>( &gt;\max (R27, R20) )</td>
<td>Enhance, bi-</td>
</tr>
<tr>
<td>R37 ( \cap ) R7</td>
<td>0.7185</td>
<td>0.5922</td>
<td>0.9445</td>
<td>( &gt;\max (R37, R7) )</td>
<td>Enhance, bi-</td>
</tr>
<tr>
<td>R37 ( \cap ) R10</td>
<td>0.7185</td>
<td>0.3728</td>
<td>0.9437</td>
<td>( &gt;\max (R37, R10) )</td>
<td>Enhance, bi-</td>
</tr>
<tr>
<td>R23 ( \cap ) R17</td>
<td>0.0897</td>
<td>0.7207</td>
<td>0.9428</td>
<td>( &gt;R23 + R17 )</td>
<td>Enhance, Nonlinear</td>
</tr>
<tr>
<td>R20 ( \cap ) R7</td>
<td>0.2494</td>
<td>0.5922</td>
<td>0.9413</td>
<td>( &gt;R20 + R7 )</td>
<td>Enhance, Nonlinear</td>
</tr>
<tr>
<td>R37 ( \cap ) R15</td>
<td>0.7185</td>
<td>0.6532</td>
<td>0.9403</td>
<td>( &gt;\max (R37, R15) )</td>
<td>Enhance, bi-</td>
</tr>
<tr>
<td>R35 ( \cap ) R25</td>
<td>0.6175</td>
<td>0.5563</td>
<td>0.9395</td>
<td>( &gt;\max (R35, R25) )</td>
<td>Enhance, bi-</td>
</tr>
<tr>
<td>R26 ( \cap ) R20</td>
<td>0.5901</td>
<td>0.2494</td>
<td>0.9388</td>
<td>( &gt;R26 + R20 )</td>
<td>Enhance, Nonlinear</td>
</tr>
</tbody>
</table>
4.3. Discussion

(1) The development of a comprehensive and systematic multi-source data index system is the foundation of research evaluating the urban spatial system. Through analysis of multidimensional coupling characteristics and process mechanisms among the subsystems, a comprehensive evaluation system consisting of 38 indicators was constructed based on the principles of indicator selection and previous studies. Furthermore, entropy weight-CRITIC was utilized to calculate the resilience of each subsystem. This study aims to capture as much of the actual resilience situation in the study area as possible. While the research methodology and procedure are applicable to the existing urban resilience studies in China, there are limitations. This paper discusses the urban giant system from the natural, social, economic, physical and intelligent regulation levels; however, it lacks analysis and discussion of communities and people. Future work should improve the indicator system from multiple perspectives and levels and employ more accurate and objective quantitative analysis methods.

(2) The Geodetector model has both benefits and drawbacks. It is excellent at predicting spatial heterogeneity and identifying its underlying driving forces, and was therefore used to examine the main factors influencing the spatial resilience of cities and towns in the Hubei section of the Three Gorges Reservoir Area as a whole. However, its properties make it difficult to analyze the factors influencing resilience in different counties. As a result, future research should concentrate on simulating the development scenarios of resilience and identifying the crucial factors impacting resilience in each county.

(3) Emerging data serves as a supplement to traditional data in urban resilience assessment. However, because the accessibility of emerging data varies significantly across regions in China, there may be a lack of emerging data, such as monitoring data of smart facilities, in certain counties and regions. Therefore, the application of emerging data in urban resilience assessment has limitations. How to efficiently integrate traditional data with emerging data, improve the existing database, and provide more diverse data support for future urban resilience assessment are questions that need further consideration in future research.

(4) The level of overall resilience in the Hubei section of the Three Gorges Reservoir Area is increasing. Nonetheless, there are a few years in Figure 4 where there is a degree of decline; for example, the overall resilience in 2020 decreased by about 0.006 compared to 2019. This is due to the impact of the COVID-19 pandemic in 2020, a significant public health event, which somewhat constrained the intelligent control capacity, resulting in a significant decrease in resilience in the response layer from 2019 to 2020. Therefore, the ability to adapt and recover from the effects of urban resilience is essential when urban spaces are exposed to uncertain disturbances.

5. Conclusions

Utilizing the PSR model and combining the characteristics and mechanical process of resilience in the Hubei section of the Three Gorges Reservoir Area, a 38-indicator evaluation system for urban resilience was developed in this study. Meanwhile, the Entropy Weight-CRITIC method and GIS software were used to analyze the spatiotemporal evolution characteristics, and the Geodetector model was employed to identify the primary driving factors and the interactions between factors in the study area. The main conclusions are as follows. (1) In terms of time-series change, the overall resilience in the Hubei section of the Three Gorges Reservoir Area shows an upward trend from low to high; there are differences in the annual growth rate and annual trend, with the overall resilience in 2014–2015 exhibiting the most significant growth level. In terms of the PSR process, the resilience of the state layer increases the most. (2) Regarding spatial evolution characteristics, Xingshan County has a higher initial overall resilience level than the other three counties and districts, and the variation among counties and districts is insignificant. After four stages of change from 2011 to 2020, the variation in the four counties gradually
increases, and the overall resilience level of Yiling District eventually surpasses that of the other three counties. (3) The results using the factor detector indicate that nine factors, such as urbanization rate, total number of early warnings, and monitoring of geological hazards, are more likely than other indicators to influence urban resilience. (4) The results of the interaction detector indicate that the resilience enhancement of the complex giant system in the Hubei section of the Three Gorges Reservoir Area is attributable to the synergistic effect of multiple driving factors, as opposed to a single factor.

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