Emergy-Theory-Based Evaluation of Typhoon Disaster Risk in China’s Coastal Zone

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Abstract: The evaluation of typhoon disaster risk is a widely discussed global topic. Currently, the index system method has become a common approach for the evaluation of typhoon disaster risk. However, the indices within the system are calculated independently, and subjective human factors significantly influence the assignment of index weights. The existing studies lack purely quantitative assessment methods, which makes the studies less precise and more difficult for other researchers to replicate. To bridge this gap, this study employs emergy analysis methods based on thermodynamics to develop a typhoon disaster risk evaluation index system for China’s coastal zone. Without the interference of weights and other human factors, the system contains various quantitative indices, including aggregate impelling energy, typhoon intensity emergy, adaptability emergy, the vulnerability index, and the integrated typhoon hazard index. Subsequently, these indices and socioeconomic data were spatialized, and the evaluation of typhoon disaster risk was conducted at the city grid level in the coastal zone of China. The findings reveal that the high-risk areas for typhoon disasters in China are concentrated in prefecture-level cities along the southeast coast. The typhoon disaster risk index is higher in the southern region compared to the northern region, with a decreasing trend in the distribution of the integrated typhoon hazard index from coastal to inland areas. The aim of this study is to use a new quantitative evaluation method (emergy) to evaluate typhoon disasters. It also serves as a theoretical foundation and technical support for national and local governments in the formulation of policies for disaster prevention and reduction.

Keywords: typhoon; disaster; emergy; risk evaluation; coastal zone

1. Introduction

In the Anthropocene era and amidst globalization, it is widely accepted that global warming and sea-level rise are ongoing phenomena [1]. The occurrence and severity of natural disasters, including typhoons, rainstorms, floods, and storm surges, have escalated [2]. Meteorological disasters pose the greatest threat to human safety and property. Apart from floods, typhoons inflict the most widespread damage and result in the greatest losses globally [3]. China’s coastal areas are heavily affected by typhoons, causing direct economic losses of USD 5.15 billion every year [4,5]. Typhoon disasters account for 90% of the direct economic losses caused by marine disasters [6,7]. In Ningbo, Zhejiang Province, China, the direct economic losses incurred because of Typhoon Fitow in 2013 were estimated to be around USD 5 billion [8]. China experiences more typhoons annually than any other Asian country. Some studies predict that by the 2050s, China’s coastal regions...
will experience an increase of two to three intense typhoons annually, amplifying the impact of the typhoon disaster chain [8,9]. The southeast coast of China, despite its dense population and thriving economy, is also the most typhoon-prone region in the country. Hence, for such areas, typhoon risk evaluation is crucial for potential loss prevention and mitigation [4].

Given the importance of typhoon risk evaluation, scholars worldwide have extensively studied this topic. Last century’s focus in typhoon risk research primarily centered on gales [10]. In the 1990s, the United States Federal Emergency Management Agency (FEMA) designed a risk evaluation system for individual hurricanes primarily using semi-quantitative and qualitative methods [11]. The US National Weather Service (NWS) conducted extensive studies on sea-level rises resulting from meteorological disasters like hurricanes, heavy rains, and floods. This research represents the earliest storm surge risk evaluation based on hurricane paths [12]. Over the past two decades, disaster risk science has gradually developed and improved, with increased research on typhoon disaster risk. The United Nations Environment Program (UNEP) introduced an index system and assessment framework to gauge global typhoon disaster risks [13]. Shi proposed a risk assessment model that considers hazards, exposed entities, and the environment, which has become the foundation for many Chinese researchers [14]. At present, most studies use the index system method combined with a Geographic Information System (GIS) to assess regional typhoon disaster risk. There is also a lot of research on typhoons in China’s coastal zone. The relationship between precipitation and typhoons in China’s coastal zone over the past 40 years has been studied, and the results show that there is a significant relationship between the increase in precipitation and the increase in the number of typhoons [15]. Li studied the changes of typhoons in China’s coastal zone from 2001 to 2020. The results show that the area affected by typhoons in China’s coastal zone increased significantly from 2011 to 2020 [3]. Research on hazard factors centers on the intensity and frequency of typhoons [16]. The vulnerability assessment of typhoon disasters mainly includes the resistance and recovery ability of the region after a typhoon [17]. For example, some researchers used two typical typhoons to explore vulnerability changes, finding that rainfall intensity and wind intensity were the most critical factors [18]. Liu used the index system method to analyze the typhoon hazard risk in Hainan Province, China, with mitigation capacity as a key factor [4]. Most previous studies have used the analytic hierarchy process, expert scoring method, and empowerment method to deal with evaluation indices, which usually introduce subjective factors [19]. For instance, in expert scoring methods, seasoned experts’ ratings often diverge from those of newer researchers, potentially compromising result accuracy [20,21]. Subjective factors (such as weight) often contribute to poor accuracy and reproducibility of research [14]. The available qualitative and semi-quantitative disaster risk assessment methods are usually hard to replicate by other researchers, because they have different calculations of index weights. In addition, existing studies cannot integrate social, economic and natural environmental factors well, with each relatively separated, thus hindering the reflection of inter-relationships between indices [22,23]. All in all, there are three main aspects of the research gap: first, the subjective factor leads to a decline in accuracy. Second, the current assessments are hard to replicate. Third, most of the current studies are qualitative or semi-quantitative. Current research methodologies lack a purely quantitative, replicable, and unbiased approach to the evaluation of typhoon disaster risks.

In response to the identified gaps, our study addresses them based on emergy theory, which integrates hazard risks, exposed entity vulnerability, and environmental sensitivity. The aim of our research is to establish a typhoon disaster risk assessment index system using the emergy method and use it to assess the typhoon disaster risk in China’s coastal zone, to make a certain contribution to disaster reduction. This system incorporates aggregate impelling emergy, vulnerability emergy, typhoon intensity emergy, adaptability emergy, and an integrated typhoon hazard index. All indices in the study are quantitative indicators, which have no weight and can be easily replicated by other researchers. The
evaluation framework aims to minimize human biases in test outcomes. The comprehensive risk of typhoon disasters in China’s coastal areas is quantitatively assessed at the municipal level from the perspective of emergy. This research marks the inaugural large-scale application of emergy theory in disaster studies. It offers insights for post-typhoon disaster relief and emergency decision making.

2. Materials and Methods

2.1. Study Site

This study encompasses 12 provincial-level administrative regions along China’s coast, excluding Taiwan due to data accessibility issues. These regions include Hainan, Guangxi Zhuang, Fujian, Guangdong, Shanghai, Zhejiang, Jiangsu, Shandong, Tianjin, Hebei, Beijing, and Liaoning. Refer to Figure 1 for the research area’s scope.

China’s economically prosperous and densely populated coastal areas rank among the most typhoon-impacted globally. Spanning latitudes N18-43°, the coast covers three primary climatic zones: warm temperate, subtropical, and tropical. These regions predominantly fall within the East Asian monsoon realm, including South Asian tropical, tropical, and subtropical monsoon climates. Notably, Guangdong, Guangxi, and Hainan fall under the tropical monsoon climate zone, characterized by annual average temperatures of 13.5–24 °C, precipitation between 1300 and 2500 mm, and sunshine duration of 1500–2300 h. In comparison, Fujian, Shanghai, Zhejiang, southern Jiangsu, Guangdong, and northern Guangxi feature subtropical monsoon climates with temperatures around 13–22 °C, precipitation levels of 800–2000 mm, and sunshine hours of 1400–2500. The general climate trend in these areas is warm and humid winters and hot, rainy summers. Conversely, Liaoning, Hebei, Tianjin, Beijing, northern Jiangsu, and western Shandong experience temperate monsoon climates with temperatures ranging from −11 to 20 °C, precipitation levels of 400–800 mm, and sunshine hours between 1500 and 2600. They typically have warm, rainy summers and cold, dry winters. Abnormal monsoon patterns have heightened the typhoon risk in China’s coastal zones [24].
2.2. Data Collection

Based on emergy theory, the overall risk of typhoon disasters in China’s coastal zones was assessed using the following data sources:

(1) Data regarding typhoon position, track, intensity, maximum wind speed, longitude, latitude (recorded every two hours), and the range of category 7 typhoon wind circle (or level 7 wind circle, which means the maximum average speed of a typhoon’s wind exceeds 17.1 m per second) from 2011 to 2021 were sourced from China Typhoon Net http://typhoon.nmc.cn/web.html (accessed on 4 May 2023).

(2) Land use data were sourced from the Resources and Environment Sciences and Data Center of China https://www.resdc.cn/ (accessed on 20 May 2023), while vector and raster data detailing provincial and municipal boundaries were retrieved from the National Basic Geographic Information System http://www.ngcc.cn/ngcc/ (accessed on 20 May 2023).

(3) The 2021 Statistical Yearbook provided economic, social, and demographic data for the provinces in the study [25]. These data encompass year-end total population, population density, per capita GDP, fixed-asset investment, and counts of clinical personnel and students per 10,000 residents.

(4) Emergy empower density data were derived from Huang et al.’s study [26], while emergy currency ratio data were sourced from Brown et al.’s research [27].

(5) Typhoon loss data spanning 2011–2021 for each province and city were gathered from the China Meteorological Disasters Canon and the China Meteorological Disasters Yearbook.

2.3. Theoretical Foundations of Emergy Disaster Risk Evaluation

Discussing emergy inevitably leads to H.T. Odum, a renowned American ecologist from the 1980s, who pioneered the theory of emergy and its associated accounting procedures. The initial emergy theory was formulated for ecosystems and economic systems, offering a new quantitative accounting method for the ecological economics of its era. The essence of the emergy accounting method (EMA) lies in the redefinition of measurement standards across diverse energy forms. EMA quantifies the aggregated environmental prerequisites of resources employed within a given process. Additionally, EMA serves as a unifying metric, facilitating the coherent integration and translation of various resource inputs and maintaining data on their quantity and quality, all without artificial weightings. The emergy method standardizes all energy flows (exergy) from material and energy resources into common units, typically solar energy. The computation employs conversion factors termed unit emergy values (UEVs) or “transformities” that encapsulate the distinct characteristics of every flow introduced to a specific subsystem. By this logic, the biosphere’s efforts produce resources, and emergy quantifies the effort required to yield a unit of a given good or offering. Since all energy forms stem directly or indirectly from solar radiation, energy resources differ in their offering cost and serve as an index of resource quality. According to solar-based quality parameters, EMA standardizes diverse, systemically available energy forms into a common solar energy metric. EMA’s foundational formula is as follows:

\[ U = \sum \tau_i \times B_i \]  

where \( U \) (sej) denotes the emergy coming from the sun, \( \tau_i \) (sej/g or sej/J) stands for unit emergy values, and \( B_i \) (J or g) signifies input flow energy. This equation facilitates the construction of an inventory table by itemizing input energy and converting it to an aggregate emergy unit.

The emergy biosphere baseline is integral to the emergy method. This reference baseline approximates the annual emergy accessible to the geobiosphere, underpinning all environmental activities and forming the basis for resource calculations. Recent studies have updated the emergy reference baseline to \( 12.0 \times 10^{24} \text{SEJ/year} \) [27,28]. In our analysis, if the
preceeding GEB (9.44 × 10^24 sej/year) [29] is utilized, a multiplier of 1.28 is applied to align with the updated figure.

An important part of applying new methods to new fields is the formation of a hypothesis and validation. The research hypothesis is whether the emergy method is applicable to the field of typhoon disaster risk assessment, regardless of heavy rain and flooding. After constructing the indicators, we first evaluate the typhoon hazards in China’s coastal zone and finally compare them with existing traditional studies to see if similar conclusions or results can be reached to prove the truth of the hypothesis.

2.3.1. Typhoon Disaster Risk Evaluation Process Based on the Emergy Method

Emergy analysis has evolved significantly in recent years and has been applied across diverse fields and industries. Common emergy analysis entails the following steps: (1) collect and analyze comprehensive data and information pertaining to the ecological landscape, social assets, and economic activities in the nation; (2) construct a comprehensive system diagram that clearly defines the boundaries of the studied system and illustrates its intersystem components with emergy symbols to represent its constituent elements, operations, and energy flows [30]; (3) develop an accounting table for emergy evaluation and convert all flows into emergy units to compute the total emergy (U); (4) calculate the emergy of all components, including products, resource and economic value, etc.; (5) establish an emergy index system for region-specific research content and analysis of the region; and (6) analyze the outcomes by considering the computed indices and offering policy recommendations.

As depicted in Figure 2, this study’s framework integrates catastrophe risk evaluation theory with the emergy analysis processes mentioned earlier. The initial step involves gathering all necessary data, including typhoon parameters (path location, strength, and bi-hourly maximum wind speeds), socio-economic metrics (year-end total population, GDP per capita, population density, and fixed-asset investments), and emergy datasets. Second, based on the system boundaries, the system diagram depicted in Figure 3 can be built to study the energy and information flow process of typhoon disasters in the nature-agricultural subsystem and urban subsystem. Third, an index system (refer to Table 1) is established to evaluate typhoon-related disaster risks. This index system includes metrics such as aggregate impelling emergy, the vulnerability index, typhoon intensity emergy, adaptability emergy, and the integrated typhoon hazard index. Fourth, based on the calculated indices, risk maps for typhoon disasters within the study area are developed. Lastly, utilizing the delineated risk maps, the evaluation of typhoon disaster risks across China’s coastal regions is conducted.

![Figure 2. Steps of emergy evaluation of typhoon disaster risk.](image)

2.3.2. System Diagram of Emergy Typhoon Risk Assessment

Natural disasters influence ecological, economic, and social systems, largely attributed to the influx of disorderly energy from the disaster system into more structured systems [31]. The theoretical foundation of emergy analysis lies in the establishment of
the relationship among ecological, human, social, and economic systems. Figure 3 delineates the interplay and distinctions among energy, information, and money flows across disaster, ecological, and economic subsystems. During a typhoon, the energy it carries, symbolizing the aggregate impelling energy (E1) or disorderly energy, poses risks to the impacted region or orderly structures. The vulnerability of agricultural (E2) and urban systems (E3) denote their respective energy losses during severe weather occurrences, with the combined energy loss represented as agricultural–urban system vulnerability (E4). The vulnerability of natural systems (E5) is characterized by the energy of undeveloped land. The vulnerability (E6) denotes the ratio of energy within the subsystem to that of undeveloped land. For a given typhoon intensity, this ratio correlates positively with the resultant damage. Typhoon intensity energy (E7) quantifies the capacity of a typhoon disaster in a particular area to impact ecological, social, and economic systems over a unit of time. Adaptability denotes the systematic ability of a system to recover, evolve, and adapt in a perpetually shifting environment. Key determinants of adaptability encompass population and socio-economic variables, collectively representing the system’s adaptability energy (E8). The integrated typhoon hazard index (E9) is derived from the ratio of typhoon intensity emergy to adaptability emergy, signifying the severity of regional typhoon disaster risk.

2.3.3. Index System of Typhoon Risk Evaluation

The socio-economic damage caused by typhoons arises from the collision between disordered energy and organized systems. The integrated typhoon hazard index directly correlates with typhoon intensity emergy and adaptability emergy and indirectly with aggregate impelling emergy and the vulnerability index. As outlined in Section 2.3.2, the emergy analysis approach requires an initial delineation of a system diagram for disaster risk evaluation, followed by the development of an emergy analysis index system. To
illustrate the quantitative interplay among these direct and indirect determinants, we created an emergy index system specific to typhoon risk evaluation. Table 1 details definitions and units associated with these novel indices. To enhance the clarity of our results, we adjusted our previous calculation methodologies and introduced refinements to the emergy evaluation index system [33]. The calculation methodology for each specific index will be elaborated upon in the following sections.

Table 1. The index system of typhoon hazard evaluation in China’s coastal zone.

<table>
<thead>
<tr>
<th>Index</th>
<th>Unit</th>
<th>Calculation Process</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aggregate impelling emergy ($U_A$)</td>
<td>sej</td>
<td>The typhoon’s power × unit emergy values [30]</td>
</tr>
<tr>
<td>Vulnerability index</td>
<td>-</td>
<td>$\sum$ Emergy of several forms of land use/undeveloped land emergy 1 [27]</td>
</tr>
<tr>
<td>Typhoon intensity emergy</td>
<td>sej</td>
<td>Aggregate impelling emergy × vulnerability index</td>
</tr>
<tr>
<td>Adaptability emergy</td>
<td>sej</td>
<td>$\sum$ (Holistic socio-economic and population-related aspects × unit emergy values) 2 [32]</td>
</tr>
<tr>
<td>Integrated typhoon hazard index</td>
<td>-</td>
<td>Typhoon intensity emergy/adaptability emergy</td>
</tr>
</tbody>
</table>

1 Several forms of land use mean forest, cultivated, traffic, residential, and undeveloped land. The energy value of each land use is calculated by multiplying the area of the land use by empower density, which describes the ratio of a country or city’s overall energy consumption to its area per unit of time. 2 Holistic socio-economic and population-related aspects include GDP, fixed-asset investment, clinical personnel, and university students for every 10,000 individuals.

Similar to hazard risk in disaster science, the total driving emergy represents the overall energy intensity of a typhoon affecting a specific region over a period. This index quantifies the total energy contained during a disaster event (such as a typhoon) by converting it into solar emergy units. The aggregate impelling emergy $U_A$ (sej) for each city in the study area from 2011 to 2022 is equal to the typhoon energy $E_T$ (J) multiplied by unit emergy values $\tau$ ($UEV$ (sej/J)) of the typhoon. Its calculation formula is as follows:

$$U_A = E_T \times \tau$$  \hspace{1cm} (2)

Regarding the calculation of $\tau$, we derived a value of 8414 sej/J from prior research, adjusted to account for the updated emergy reference baseline [27]. In this research, the total energy ($E_T$) of each typhoon in each prefectural city along China’s coast from 2011 to 2021 is derived by considering the duration of typhoons within the category 7 typhoon wind circle and the inherent energy associated with this wind circle. The energy value in the typhoon’s category 7 wind circle comes from the study by Gao [33]. The time the level 7 wind circle passed through each city over the past decade is obtained through statistics from the China Typhoon Network.

Guided by emergy theory, our constructed vulnerability index reflects the vulnerability concept of entities impacted by hazards in disaster risk science. The vulnerability index quantifies the susceptibility of several forms of land use to typhoon-related hazards, signifying the extent to which these types are affected. Broadly, land use categories associated with intense economic and social activities exhibit higher emergy content due to elevated energy density power [34]. For example, the total land emergy of an urban system is much higher than that of undeveloped land. In energy theory, the total emergy of different land uses, rather than GDP, represents the “true” wealth of the region [32]. The “real” wealth, represented by emergy, differs fundamentally from monetary assets, which essentially serve as media of circulation. Employing the ratio of emergy across multiple land use forms to that of undeveloped land as the vulnerability offers a standardized dimension to assess the vulnerability of prefecture-level cities to typhoon hazards. The formula for calculating the vulnerability index of each city in the study area is as follows:

$$S = \frac{\sum (\rho \times L)}{\left(\rho \times L_{un}\right)}$$  \hspace{1cm} (3)
where $S$ (sej/m²) is the vulnerability index, $q$ stands for the empower density of various land-types, $L$ (m²) is the area of various land-types, and $L_{un}$ (m²) is the undeveloped land area.

Typhoon intensity emergy characterizes the potential impact on a regional system during extreme meteorological events or other abrupt “disorderly” energy surges. In other words, typhoon intensity emergy reflects the disaster-causing ability and risk degree of typhoon disasters in a specific region to the natural system, human social system, and economic system within a unit time. Its calculation formula is as follows:

$$I_T = U_A \times S$$

(4)

where $I_T$ (sej) is the typhoon intensity emergy, $S$ (sej) stands for the vulnerability, and $U_A$ (sej) is aggregate impelling emergy. The formula reveals that a high-intensity typhoon in a low-sensitivity area will not necessarily yield a significant value for this index. According to disaster risk science, regional disaster intensity and the risk-causing potential correlate with both hazard and exposure. Similarly, under emergy theory, typhoon intensity emergy is positively correlated with the aggregate impelling emergy and vulnerability of the influenced region.

Adaptability emergy ($A$) encompasses the system’s adaptive process in a fluctuating environment, promoting structured recovery and evolution. This emergy comprises elements that are beneficial for both disaster prevention and mitigation. As indicated in the preceding table, metrics for adaptability emergy include GDP, fixed-asset investment, and the number of clinical personnel and university students per 10,000 individuals. Adaptability emergy within a system exhibits elasticity and varies across diverse natural, social, and economic contexts. For example, a city or system with a robust economic foundation can swiftly recover post-disaster due to ample financial resources, often emerging even more economically vibrant [35]. Conversely, an intense disaster could devastate the entire economic infrastructure of a less-developed city. Thus, GDP and fixed-asset investment largely determine a city’s adaptability emergy [36]. Beyond economic considerations, certain social and demographic variables, such as the quantity of clinical personnel and university students in a city, significantly influence adaptability emergy. Clinical personnel in a city signify its post-disaster emergency response capability, whereas a higher count of university students suggests a more educated populace [37]. An abundance of clinical personnel correlates with fewer post-typhoon casualties, and a well-educated population typically adopts superior disaster prevention strategies. Hence, a greater number of these essential personnel enhances a city’s capacity to mitigate and manage disasters. Adaptability emergy computations are detailed in Table 2.

<table>
<thead>
<tr>
<th>Type of Factors’ Emergy</th>
<th>Unit</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Economic factor emergy</td>
<td>sej</td>
<td>The monetary amount of gross domestic product × unit emergy values [27]</td>
</tr>
<tr>
<td></td>
<td>sej</td>
<td>Amount of money invested in fixed assets × unit emergy values [28]</td>
</tr>
<tr>
<td>Social factor emergy</td>
<td>sej</td>
<td>Clinical personnel per unit (10,000 individuals) × unit emergy values [30]</td>
</tr>
<tr>
<td></td>
<td>sej</td>
<td>University students per unit (10,000 individuals) × unit emergy values [30]</td>
</tr>
<tr>
<td>Adaptability emergy (A)</td>
<td>sej</td>
<td>Economic factor emergy + social factor emergy</td>
</tr>
</tbody>
</table>

The integrated typhoon hazard index ($V$) directly influences typhoon disaster risk and is shaped by the aggregate impelling emergy, the vulnerability index, typhoon intensity emergy, and adaptability emergy. Based on emergy theory, this index offers an intuitive reflection of typhoon disaster risk for a specified region. It is calculated as the ratio of typhoon intensity emergy ($I_T$) to adaptability emergy ($A$). The formula is as follows:

$$V = \frac{I_T}{A}$$

(5)
3. Results

3.1. Aggregate Impelling Emergy of Typhoon Disaster Risk Evaluation

The aggregate impelling emergy for a typhoon disaster reflects the cumulative energy intensity affecting a specific area over a given time span. We determined the typhoon's aggregate impelling emergy for each city within our study domain. Based on ArcGIS's map algebra method and the grid computation principle in spatial analysis, we generated our results. These findings are presented in Figure 4 according to the natural-breakpoint classification approach.

![Figure 4. Spatial distribution of aggregate impelling emergy across coastal China's prefecture-level cities.](image)

The results indicate that every city in the coastal provinces has experienced typhoon disasters over the past decade, albeit with differing accumulations of aggregate impelling emergy. Particularly noteworthy is that Guangdong, Fujian, Guangxi, Hainan, and Zhejiang Provinces exhibit a relatively high accumulation of typhoon-driven emergy. Conversely, Liaoning, Hebei, Beijing, Tianjin, and Shandong demonstrate a lower accumulation of typhoon-driven emergy.

3.2. Vulnerability Index of Typhoon Disaster Risk Evaluation

In emergy analysis theory, the “disordered” energy from typhoons and other natural disasters, upon entering natural and human social systems, can cause varying degrees of damage to the system’s “ordered” structures. Typhoons cause disasters in systems with an “orderly” structure, which encompasses the majority of the system’s emergy. Beyond the emergy of the highly mobile population, the system also comprises emergy from buildings, roadways, diverse infrastructure, forested areas, grasslands, and cultivated crops. Hence, the system exhibits a significant accumulation of “real” wealth. Similar to the concepts of vulnerability and exposure in disaster risk science, the vulnerability in this study denotes the potential extent to which the subsystem is impacted by disaster events (e.g., typhoons). Fundamentally, assessing typhoon disaster vulnerability involves determining the potential degradation of “real” wealth within an “orderly” system. We consolidated six land use types—residential, construction, forest, cultivated, grassland, and undeveloped—and applied this categorization to all cities within our study domain. Based
on the algorithm outlined in Section 2.3.3, we processed raster data in ArcGIS to derive the spatial distribution of the vulnerability index for coastal Chinese cities, as depicted in Figure 5.

![Spatial distribution map of vulnerability of prefecture-level cities in coastal China.](image)

**Figure 5.** Spatial distribution map of vulnerability of prefecture-level cities in coastal China.

### 3.3. Typhoon Intensity Emergy of Typhoon Disaster Risk Evaluation

During extreme typhoon events, characterized by “disordered” energy bursts, the typhoon intensity emergy determines the potential impact on the region’s system. The index value corresponds to the product of the aggregate impelling emergy and the vulnerability index. A larger index value signifies a higher potential for disaster loss in the region. Based on the typhoon intensity emergy Formula (4) from Section 2.3.3, along with the aggregate impelling emergy results from Section 3.1 and vulnerability results from Section 3.2, the effective typhoon intensity energy for each coastal city in China was evaluated, with the outputs in ArcGis presented in Figure 6.
3.4. Adaptability Emergy Index of Typhoon Disaster Risk Evaluation

Guided by both disaster risk science and emergy analysis principles, the adaptability emergy in this study encompasses emergy from two sources: aiding in disaster prevention and minimizing disaster-related losses. Proactive measures involve enhancing protective measures based on historical data before disasters strike, including aspects like road traffic management, building wind resistance, infrastructure, seamless lifelines, and early-warning systems. Another crucial factor in measuring adaptability is the system’s capability to swiftly and effectively harness external and natural energies to repair its “disordered” structures, thereby restoring an “orderly” configuration. We assessed the emergy values associated with university students and clinical personnel in coastal cities nationwide. Although we computed these indices at the city level for comparative purposes, results are presented at the provincial level, and the final adaptability emergy is aggregated at the city level. Additionally, we calculated the GDP emergy and fixed-asset investment emergy, as shown in Figure 7. Utilizing ArcGis’s map algebra tool and the grid calculation within the spatial analysis model, we aggregated the aforementioned indices to derive the final adaptability emergy for China’s coastal cities. These results are presented using the natural-breakpoint grading method in Figure 8.
3.5. Integrated Typhoon Hazard Index of Typhoon Disaster Risk

The integrated typhoon hazard index serves as a comprehensive measure of the total typhoon risk in a given region, encapsulating the impact of disaster events on the system. A higher integrated typhoon hazard index indicates greater potential losses in the event of a typhoon occurrence within the region. In this study, the integrated typhoon hazard index is calculated by deriving the ratio of typhoon intensity emergy to adaptability emergy. The calculation method is shown in Table 1. This index encompasses various factors such as driving energy, the vulnerability index, and adaptability energy, with the ultimate typhoon disaster risk contingent upon both typhoon intensity emergy and adaptability emergy. Using the calculation method from Section 2.3.3 and integrating the evaluation results from Sections 3.3 and 3.4 on typhoon intensity emergy and adaptability emergy, we assessed the integrated typhoon hazard index for prefecture-level cities along China’s coast. The processed results are depicted using ArcGIS in Figure 9.
4. Conclusions

Based on the spatial patterns of typhoon-driven emergy in coastal cities, two main observations are evident: (1) Emergy distribution diminishes from the coast inward. (2) With Jiangsu Province as a reference, areas south of Jiangsu tend to have higher emergy values, while areas to its north generally exhibit lower values.

The vulnerability index assessment reveals the following: (1) Prefecture-level cities in China’s coastal regions, such as Shanghai, Beijing, the Pearl River Delta, and cities like Putian and Xiamen in Fujian Province, exhibit elevated vulnerability indices due to their economic development and population density. (2) South of Shanghai, the vulnerability index tends to diminish from the coastline moving inland, possibly due to elevated inland terrains and limited economic development. (3) The area north of Shanghai presents a higher average vulnerability index compared to the southern provinces, possibly due to the relatively level terrain up north and a substantial, uniformly dispersed, rural populace.

After an analysis of the spatial distribution patterns of typhoon intensity emergy, vulnerability, and aggregate impelling emergy in coastal cities, the following insights can be obtained: (1) Coastal cities south of Shanghai typically exhibit a high accumulation of typhoon intensity emergy, indicating both significant aggregate impelling emergy and vulnerability index in these regions. (2) Northern regions of Shandong Province display low levels of typhoon intensity. This can be explained by their high vulnerability levels and comparatively lower aggregate impelling emergy from typhoons. (3) Typhoon intensity emergy values in China’s coastal cities exhibit a decreasing trend from the coast to inland areas. This trend is primarily influenced by two factors. Firstly, the driving emergy values associated with typhoon disasters diminish rapidly post-landing, attributed to factors like terrain, leading to a consistent decrease in aggregate impelling emergy accumulation. Secondly, the distribution patterns of population and economic accumulation in China’s coastal cities diminish from the coast to inland areas. Consequently, this leads to a parallel decrease in the distribution pattern of the vulnerability index.

Through the evaluation of adaptability emergy in coastal prefecture-level cities in China, we discerned the overall accumulation and spatial distribution of adaptability emergy allocated for disaster prevention and mitigation in each city. The primary findings are as follows: (1) In China’s coastal prefecture-level cities, regions with significant accumulations of adaptability emergy coincide with areas of high population and economic density, notably the Beijing–Tianjin–Hebei region, Shanghai, Jiangsu, Zhejiang, the
Shandong Peninsula, Guangdong, the Hong Kong and Macao region, and the Yangtze River Delta. (2) Areas with lower adaptability emergy accumulation in China’s coastal prefecture-level cities are found in northern Hebei, eastern and western parts of Liaoning, northern Guangdong, and northern Guangxi. (3) Excluding key areas such as the Beijing–Tianjin region, Shanghai, Guangzhou, and the Shandong Peninsula, the distribution of adaptability emergy in China’s coastal prefecture-level cities typically exhibits a central concentration, with both a southward and northward diminution.

The outcomes of the integrated typhoon hazard index in the evaluation of typhoon disaster risk are as follows: (1) High-risk areas for typhoon disasters in China predominantly cluster in the southeastern coastal prefecture-level cities, particularly in the coastal regions of Hainan, Guangdong, Guangxi, and Fujian. This observation aligns with the fact that the annual average frequency of typhoon disasters in these areas surpasses that in other regions. Given the high population density and economic activity in the coastal zones, the potential losses are significant. (2) With the central region of Jiangsu Province as a demarcation, the integrated typhoon hazard index is higher in the southern coastal regions of Jiangsu and lower in its northern areas. (3) The integrated typhoon hazard index diminishes from the coast to the inland areas, possibly due to the increasing elevation from the coastal regions to the interior.

5. Discussion

Typhoon disasters in China’s coastal areas account for the most significant losses compared to other calamities. Currently, numerous studies focus on the evaluation of typhoon disaster risks. However, most research methods assign subjective weights to evaluation indices, potentially compromising the accuracy and objectivity of the results. Implementing a more objective (unweighted) evaluation method for typhoon disaster risk can enhance result reliability and potentially serve as a backup theory for the evaluation of other hazard risks.

In this research, we employed the ecological emergy theory (unweighted approach) for the initial evaluation of typhoon disaster risk in China’s coastal zones. Through the application of a series of emergy indices, our analysis revealed elevated risk levels in densely populated and economically affluent areas in southern Jiangsu Province, with diminished risk observed in northern and inland parts of Jiangsu. The index system we devised aligns with the contemporary mainstream approaches to typhoon disaster risk evaluation systems (including the international meteorological disaster risk evaluation system), which involves multiplying hazard, exposure, and vulnerability results to derive the final typhoon disaster risk evaluation. For instance, the aggregate impelling emergy can illustrate hazard analysis, vulnerability emergy can represent exposure, and adaptability and emergy can encapsulate vulnerability. From the perspective of hazard risk, Hong’s classification of typhoon risk in China’s southeastern coastal areas aligns closely with our findings on aggregate impelling emergy [38]. Yin’s research, which focused on exposure in typhoon disaster risk evaluation, identified heightened risk in densely populated southeastern coastal areas, thereby corroborating our findings from vulnerability index analysis [39]. Sajjad’s evaluation of coastal cities’ adaptability closely resembled our findings relating to adaptability emergy [40]. Consequently, emergy theory exhibits high accuracy in typhoon disaster risk assessment, capturing essential components of conventional assessment methodologies. Currently, the emergy method is applied to flood hazards to assess flood risk in Ya’an City, Sichuan Province, China [41]. The applicability of the emergy method in flood disaster risk assessment is demonstrated [42]. After comparing these traditional findings, the emergy method is suitable for typhoon disaster risk assessment without considering flooding and rainfall. The emergy method can improve the accuracy of assessment based on not involving subjective factors, and even has a broad development prospect in all fields of disaster risk science [43].

The use of the emergy method for disaster risk evaluation is a nascent approach with limitations during practical application. For instance, our method of calculating typhoon
emergy in this study relies on a generalized estimate derived from Odum’s foundational calculations. Given the variations in underlying surface climate, elevation, and other factors, there is potential to enhance the accuracy of typhoon energy estimations, thereby refining the results of aggregate impelling emergy. Local communities and stakeholders could enrich the emergy analysis. For example, multi-scale data on disaster resilience practices will make the assessment more nuanced [44,45]. Additionally, we utilized data with a spatial resolution of 1 km, leaving room for improvement in resolution. Examining extended temporal and spatial data series (spanning over 30 years) would enhance the reliability of our conclusions. Our next work will focus on improving assessment accuracy and simulation predictions to address typhoon disaster risks under global climate change.

We believe it is an effective approach to apply emery theory to disaster risk evaluation. In prior research, Wu utilized emergy to assess flood disaster risk in Zhengzhou [46]. Based on the outcomes from the integrated typhoon hazard index, Jiangsu Province appears as a significant demarcation, with the northern region bearing considerably less risk than its southern counterpart. The causes behind this phenomenon will be a focus of our future research. A fundamental reason for a disaster occurrence lies in the disruptive energy it channels into the human social system. From this viewpoint, emergy theory serves as an advantageous method for disaster studies. Its capacity to standardize diverse energy units facilitates streamlined analysis and computation, particularly during the energy flow. Therefore, we posit that emergy theory holds vast applicability within the disaster realm, encompassing aspects like energy intensity computation across varied disasters, disaster loss quantification, and urban tangible wealth loss evaluation, among others. The methodical integration of emergy theory into disaster research, combined with the adoption of more granular and precise standards, is poised to foster enhanced interdisciplinary synergy between the two domains in future endeavors.

Recognizing that disaster risk evaluations inevitably incorporate human factors or weights, we advocate the utilization of emergy theory to evaluate typhoon disaster risks in China’s coastal areas. By transmuting energies from both the disaster and social systems into a standardized solar energy metric for computation and scrutiny, this approach diminishes human biases, enhances evaluative dependability, and offers new investigative paradigms for energy as well as disaster risk studies.

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