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Evaluation and simulation for ecological risk based on emergy analysis and Pressure-State-Response Model in a coastal city, China

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Abstract

The objective of this study is to evaluate and simulate the ecological risk level of a coastal city, Tianjin's urbanization through an emergy synthesis model. In this study, an ecological risk index system was developed corresponding to the factors of urban ecosystem risk including in Pressure-State-Response model (PSR). Thus, an emergy-based ecological risk evaluation model (EERM) was proposed to evaluate and simulate the risk levels for urban expansion, which offers an integrated evaluation tool in view of urban ecosystem pressure, state and response. Emergy analysis methods are explained, illustrated and used to diagram the urban ecosystem, to evaluate environmental and economic inputs and harvested yield, and to assess the sustainability of the Tianjin during 1995 to 2009. The results have shown that, from 1995 to 2009, the pressure rating of the urban ecology risk in this area had been rising continually. These results comply with relevant laws of correlativity between urbanization and ecological protection in this research area. It is hoped that the evaluation and simulation for ecological risk will provide scientific basis for appraisal of the security and sustainable development of urbanization.

Keywords: emergy analysis; Pressure-State-Response Model; Tianjin; ecological risk

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1. Introduction

Urban ecosystem depends on input of resource from the nature and output of waste to the nature [1]. As open thermodynamic system, urban ecosystem is complex unequal system [2]. A safe urban system is important for economic development and social stability [3, 4]. However, rapid economic growth may increase the risk status of many urban ecosystems [5]. If go along with this trend, it will not only harm people health and economic development, but also bring about the breakdown of urban ecosystems [6, 7]. Since the 1990s, increasing efforts have been made to set the research of urban ecological risk as a new branch of environmental management research [8-10].

Based on the assessment concept from the fields of management science, the basic definition of urban ecological risk assessment can be considered as the determination of the probability of some adverse effect occurring to an urban ecological system [11]. Despite large number of urban ecological risk assessment methodologies based on most indicators found in the literatures, comprehensive studies evaluating the urban ecological risk in the biophysical perspective via the process and mechanism of urban ecosystem development and energy flows inside urban system are still few [10, 12, 13]. New methodology is sought to bridge the gap between economy and energy in an internal perspective on the urban ecological risk during the rapid urbanization process in order to analyze the ecological risk in energy of complex urban ecosystem.

PSR framework, a process and systematic analysis approach, affirms that human activities bring pressures on the environment. That may change the state of the environment. Human society then responds to the changes with environmental or economic policies to prevent, reduce or mitigate environmental damage [14-16]. Emergy analysis, a thermodynamic-based environmental accounting approach, converts all materials, energy sources, human labor and services into emergy unit [17, 18]. When one urban ecosystem is affected, the energy flows in the whole urban system will change, which may result in ecological risk [19]. Fath [20] mentioned that energy flowing in ecosystem are necessary to keep all growth and development activities. Campbell et al. [21] also pointed out that there is fundamental connection between emergy and response of systems, therefore, selective pressures might make emergy particularly suitable indicator for ecosystem risk.

Urban ecosystems are related to the human activities. Relative measures of urban ecological risk should reflect the anthropogenic effects of human decision making and activities on the ecological risk. Consequently, the estimation of urban ecological risk needs different characteristic, which can mark systematic features including emergy pressure, emergy state and emergy response. The conventional concept of emergy may account for the environmental services supporting process as well as for their convergence through a chain of energy and matter transformations in spatial and temporal perspective [22]. Hence, much can be gained from examining urban ecosystem by transformations and emergy flows analysis, because the ecological processes through direct, indirect, and cumulative impacts often result in variation of urban ecological risk. So far, various systems have been evaluated by emergy analysis on regional scales [23-25]. Considering the inherent laws of urban ecosystem in which the social metabolism exchanges energy and materials with the environment, the research of urban ecological risk should be focused on seeking for mechanisms that predominate the constraint and scarcities of the ultimate driving forces [26].

In this paper, we intended to integrate pressure-state-response model and emergy analysis to analyze the urban ecological risk (Section 1 and Section 2). Another aim of this paper is to statistically analyze the anti-risk ability of a typical coastal city in China, Tianjin city (Section 3).

2. Materials and methods

2.1. Study area

Tianjin is a metropolis and one of the five national central cities in China. It is governed as one of four direct-controlled municipalities under direct administration of the central government.

Tianjin is located in Northern China along the coast of the Bohai Gulf, with latitude ranging from 38° 34' to 40° 15' N, and longitude ranging from 116° 43' to 118° 194' E, and surrounded by Hebei Province on all directions except for the sea and is bordered by Beijing to the northwest. It lies at the northern end of the Grand Canal of China, which connects with the Yellow River and Yangtze River. The municipality is generally flat, and swampy near the coast, but hilly in the north, where the Yan Mountains intrude into northern Tianjin. The highest point is at an altitude of 1078 m.

Fig.1. Location of Tianjin city

Tianjin features four seasons, typical climate of East Asia. Winter in Tianjin is cold, windy, very dry, and reflecting the influence of the vast Siberian anticyclone, and summer is hot and humid for the monsoon. Spring in the city is dry and windy, occasionally seeing sandstorms blowing in from the Gobi Desert, capable of lasting for several days. Monthly average temperatures range from −3.5 to 26.6 °C from January to July, with an annual average of 12.6 °C [27]. With precipitation being generous only during June and September, and a low annual total of 540 mm, the city lies within the humid continental zone, with parts of the municipality being semi-arid [28].

The nominal GDP for Tianjin was 750 billion yuan (US$110 billion) in 2009, a year-on-year increase of 16.5%. In 2009, per capita GDP was 62,403 Yuan (US$9,136). The manufacturing sector was the largest (54.8%) and fastest-growing (18.2%) sector of Tianjin's economy. Urban disposable income per capita was 21,430 Yuan, a real increase of 10.3% from the previous year. Rural pure income per capita was 10,675 Yuan, a real increase of 10.4% from the previous year. Farmland takes up about 40% of Tianjin Municipality's total area. Wheat, rice, and maize are the most important crops. Fishing is important along the coast. Tianjin is also an important industrial base. Major industries include petrochemical industries, textiles, car manufacturing, mechanical industries, and metalworking. Tianjin also has deposits of about 1 billion tonnes of petroleum, with Dagang District containing important oilfields. Salt production is also important, with Changlu Yanqu being one of China's most important salt production areas. Geothermal energy is another resource of Tianjin. Deposits of manganese and boron under Tianjin were the first to be found in China.

In terms of urban population, it is the sixth largest city of the People's Republic of China, and its urban land area ranks 5th in the nation, only after Beijing, Shanghai, Guangzhou, and Shenzhen. At the end of 2009, the population of Tianjin was 12.28 million, of which 9.8 million were residential holders of Tianjin permanent residence. Among Tianjin permanent residents, 5.99 million were urban, and 3.81

million were rural. The population will grow up to 14 million, of which 11.5 million will be urban population.

2.2. Pressure-State-Response analysis methodology

The Pressure-State-Response (PSR) model, developed by OECD, provides a mechanism to monitor the status of the environmental and economic. The PSR cycle also provides a framework for investigation and analysis of processes involved in urban ecological risk. It has gained international prominence and can be applied at a sub-national level, for sectoral analysis, at regional, local and other sub-national levels, and at an individual project level. The framework arises from a simple set of questions [29] (Table 1).

Table 1. Pressure-State-Response (PSR) model framework

Questions ?	Indicators	What these observations show
What is happening to the state of the environment and of natural resources?	Indicators of State	Changes or trends in the physical or biological state of the natural world
Why is it happening? What social, political, economic, market and other forces are involved?	Indicators of Pressure	The range of stresses or pressures from human activities that result in environmental change
What are we doing about it, or what can be done about it?	Indicators of Response	Actions adopted in response to environmental problems and concerns. These responses will themselves become pressures.

2.3. Emergy analysis methodology

Emergy is used as the principal conceptual tool for expressing the inter-relationship of energy flows and resource quality, and for linking natural environment system and human economy system together [30, 31]. The emergy analysis is a type of embodied energy analysis that can provide common units (emergy) for comparison of environmental and economic goods by summing the energy of one type required directly or indirectly for production of goods [31]. In emergy analysis, the quality of each form of energy is taken into account by multiplying each quantity of energy by its solar transformity, which is defined as solar emergy per unit energy (sej/j) [31]. Energy of high transformity has more emergy and is high in its quality of effect [32].

Annual average changes in urban emergy flows and storages were converted to equivalent emergy-dollars (emdollars) to gain perspective on the ecological risk [33]. More information was shown in table 2.

Table 2. Definitions of emergy analysis concepts

Concepts	Definition
Emergy	Energy of a single type required directly and indirectly for transformations in order to generate a product or service.
Solar emergy	Solar energy required directly and indirectly to produce a product or service(units of solar emjoules, sej).
Transformity	Emergy per unit energy required for a given product or service in a system.
Solar transformity	Solar emergy per unit energy, units are solar emjoules/joule (sej/J).
Emergy per	Emergy of a single type required to generate a flow or storage of a
unit mass	unit mass of a material (units of sej/g).
Empower	Emergy flow per unit time, usually per year (units of sej/yr).
Solar empower	Solar emergy flow per unit time, usually per year (units of sej/yr).
Emergy/money ratio	Ratio of emergy flow to money flow, commonly for a state or nation, calculated as annual emergy use divided by the value of the gross national product (unitsof sej/$).

In this study, we used emergy analysis to quantitatively evaluate urban ecological risk in Tianjin city to find out the patterns of sustainable development.

2.4. Emergy evaluation indices

Diagramming was conducted with energy system symbols [33]. Pathways may indicate casual interactions, show material cycles, or carry information, but always with some energy (Fig. 2).

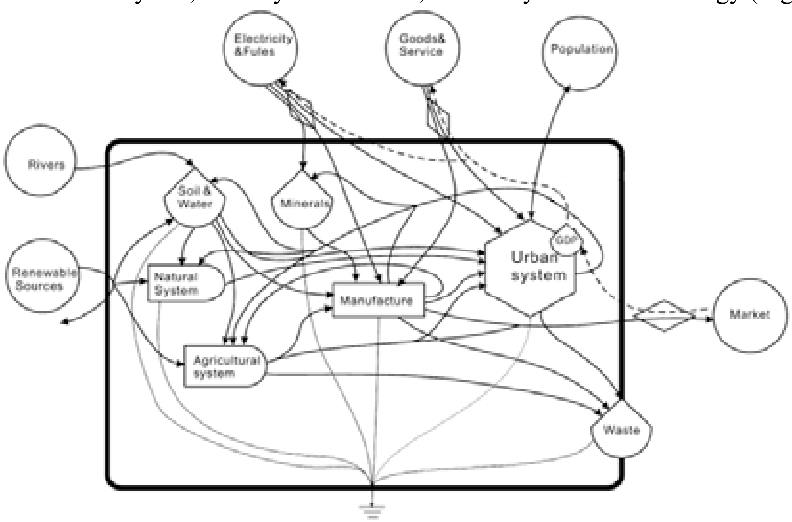

Fig.2. Systems diagram of energy flow in urban system

Emergy evaluation proposed by H.T.Odum provides several indicators that can be used to assess a system's performance, or to monitor one system in time such as product quality, environmental stress to surrounding system, short and long term sustainability for production [34]. Here, we selected several indicators to depict the research. The main indicators were listed as follows:

The environmental loading ratio (ELR) is the ratio of nonrenewable emergy (N+I) to renewable emergy (R) as follows:

$$ELR=(N+I)/R \tag{1}$$

Environmental loading ratio (ELR) represents the unbalance between non-renewable and renewable resources used in a process. Low ELR reflects relatively small environmental loading, while high ELR suggests great loading.

The Emergy yield ratio (EYR) is emergy of yield divided by the emergy of all the feedback from the economy (e.g. tourism income, several funds and services in this study), i.e. (in this system the output emergy is calculated by summing emergy inputs).

$$EYR=(R+N+I)/I \quad (2)$$

Emergy yield ratio (EYR) shows the importance of the local resources with respect to exogenous ones [35]. EYR of each system is a measure of its net contribution to the economy [36].

2.5. Urban ecological risk index

The urban ecological risk index is to assess ecological risk of urban ecosystem by using a emergy-based sustainability index (ESI), which combining both social-economic yield and environmental impact as below [37]:

$$ESI = \frac{EYR}{ELR} \quad (3)$$

where EYR is net emergy yield ratio and ELR is environmental loading ratio.

The ESI was calculated as the ratio of the emergy yield ratio to the environmental loading ratio, and measures the production of a system relative to the environmental pressure [37, 38].

3. Results and discussion

3.1. Pressure-State-Response Model for ecological risk of Tianjin city

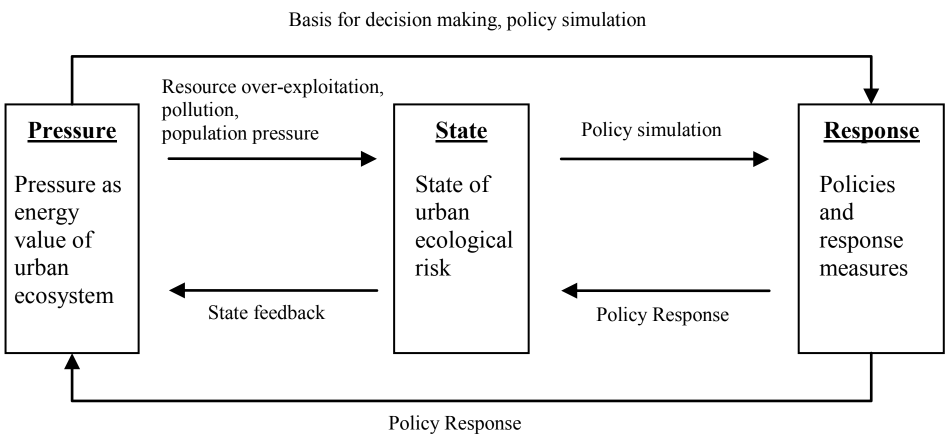

Fig.3. PSR framework of Tianjin ecological risk in emergy

To determine the driving mechanism of urban ecological risk, Pressure-State-Response Model analysis is used to describe the relationship of emergy index and urban ecosystem risk levels, with the framework shown in Fig. 3.

The PSR model of Tianjin ecological risk is made up series reference points. PSR framework of Tianjin ecological risk in emergy is shown in Fig.3, and the index of the model is listed in Table 3. The PSR model of Tianjin ecological risk is based on functional causality and points to the linkages between the pressure of energy value and the state of urban ecological risk, however these cannot be considered as a one-to-one, linear, relationship, as changes in the system often results from a complex chain of interactions of pressures.

Table 3. Index of Tianjin ecological risk PSR model

Factor	Index	Sub-index
Pressure	Resource Emergy Pressure (PRE)	Environmental renewable emergy flow (R)
	Environment Emergy Pressure (PEE)	Enviromental nonrenewable emergy flow (N)
	Socioeconomic Emergy Pressure (PSE)	Emergy intput to system (I)
		Emergy output of the system (O)
State	Urban Resource State (SUR)	Total emergy flow of the system (U)
	Urban Environment State (SUE)	Renewable emergy ratio (RER)
	Urban Socioeconomic State (SUS)	Emergy yield ratio (EYR)
		Environmental loading ratio (ELR)
Response	Resource utilization Response (RR)	Emergy density (ED)
	Environmental Protection and Management Response (RE)	Emergy per population (EPP) Emergy self-sufficiency rate (ESR)
	Social and economic Policy Response (RS)	

3.2. Emergy evaluation of Tianjin city ecosystem

Emergy indicators (Table 4) were calculated by aggregating data from Tables 4. These Indicators, which relate flows from the economy to flows of the environment, were used to compare net yields and environmental loading, and to evaluate sustainability, as well as to identify more sustainable methods.

In 2009, renewable emergy resources in Tianjin, which are from solar, rain, wind, geothermal heat and fluvial energy and emergy of nonrenewable resources (mud and sediment and water) are 1.51×10^{22}Sej and 1.36×10^{23}Sej, respectively. Among renewable resources energy of rain chemical, vaporization and fluvial chemical contribute the most. The total environmental input can be determined as 9.91×10^{22} Sej, and esmergy output of system contribute 5.57×10^{22} Sej. The renewable emergy is large lower than non-renewable emergy corroborating that the supplementary nonrenewable emergy contributes a lot to the total emergy. Further, much of the emergy from outside sources cannot be typed as to renewability. Compare with emergy output, emergy output intput is higher, with a difference of 4.34×10^{22}Sej.

The emergy density of Tianjin city is 1.51×10^{13} Sej, and emergy per capita is 1.46×10^{16} Sej. It indicates that Tianjin city is a high emergy density and high emergy per capita city (higher than that of other cities about magnitudes, see Liu's study [39], and emergy flow plays an important role in Tianjin urban system operation. The emergy self-sufficiency is about 50%, which means a half of emergy come from outside.

From Table 4, we can conclude that the environmental loading ratio is an indicator of the state of urban systems on the environment [37]. It should be pointed out that portions of the system state may due to the stress from outside the area of analysis [38]. The environmental loading ratio is 15.57, which is high. That maybe because population growth and vigorously construction that damages the environment. Recently, it appears that Tianjin city is seriously lack of capability for sustaining ecological balance. Emergy yield ratio (EYR) is the ratio of the emergy yield to that required for processing [33]. It is an indicator of the system relationship, and in this urban system the EYR is 2.52.

Table 4. Emergy indicators of Tianjin city ecosystem

Name of index	Expression	Value (sej)
Environmental renewable emergy flow	R	1.51×10^{22}
Enviromental nonrenewable emergy flow	N	1.36×10^{23}

Emergy intput to system	I	9.91×10^{22}
Emergy output of system	O	5.57×10^{22}
Total emergy flow of the system	U=R+N+I-O	1.79×10^{23}
Emergy density	ED = U/area	1.51×10^{13}
Emergy per capita	EPC=U/population	1.46×10^{16}
Emergy self-sufficiency rate	ESR=(R+N-O)/U	0.53
Renewable emergy ratio	RER=R /U	0.08
Emergy yield ratio	EYR=(R+N+I)/I	2.52
Environmental loading ratio	ELR=(I + N)/R	15.57

3.3. Anti-risk ability of Tianjin ecosystem

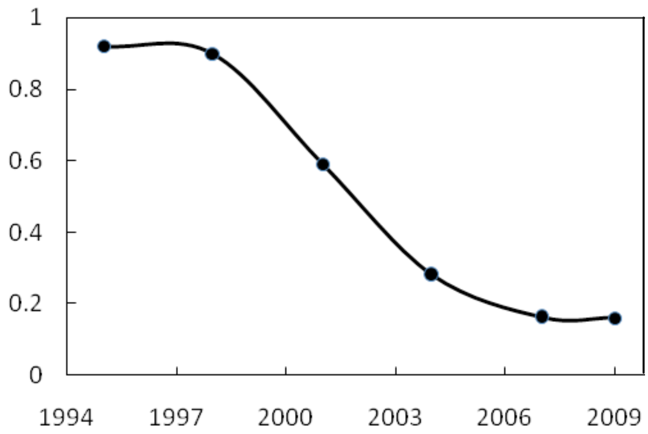

Fig.4. Urban ecological risk of Tianjin city

The urban anti-risk index was calculated as the ratio of the EYR to the ELR, and measures the ability of a system to anti-risk of urban system [37]. Ulgiata and Brown [37] have noted a system has vitality and potential to develop, while the index is lower than 1, which indicates the system is in high ecological risk and not sustainable. Tianjin city's urban ecological risk index during 1995 and 2009 is shown in Fig. 4, the low values show a weak sustainability and high ecological risk.

4. Conclusions

With a unified ecological measure of emergy, this paper proposed an urban ecologica risk evaluation framework by integrating emergy analysis methods and Pressure-State-Response model. The objective of this study is to measure and evaluate the ecological risk level of Tianjin, which is a coastal city in China. Through a Pressure-State-Response model framework, an indicator system was developed corresponding to three factors of urban ecosystem risk based on emergy, including pressure, state and response. Furthermore, combined with emergy analysis, an emergy-based urban ecological risk index (anti-risk index) was proposed to measure and evaluate the risk levels from 1995 to 2009 in Tianjin, which offers an integrated evaluation tool for urban ecological risk. Urban ecological risk index analysis indicated that there was high ecological risk and low anti-risk ability for sustainable development in Tianjin during 19 years. Consequently, the results revealed that Tianjin was seriously lack of capability for sustaining ecological balance.

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