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Empirical Research on Carrying Capacity of Human Settlement System in Dalian City, Liaoning Province, China

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Abstract: Using the theories of population carrying capacity and ecological elasticity in other fields for reference, the connotation of regional human settlement system was defined from the viewpoint of the complex relationship among the factors such as regional population, resources, environment and economic and social development in the context of China′s rapid urbanization. Then the concept and characterization methods of the regional human settlement carrying capacity were proposed by means of population scale. Furthermore, a model of carrying capacity-pressure-state-response (CPSR) on regional human settlement system was established by referencing pressure-state-response (PSR) model, and the Catastrophe Theory was introduced to determine the corresponding standards of multi-criteria programming and evaluation. Taking Dalian City, Liaoning Province, China as an example, an empirical analysis on evaluation of human settlement system from 2000 to 2012 was carried out. The results showed that the carrying capacity of human settlement system in Dalian was fluctuating between 9.6×10^6 to 10×10^6 persons with a quantitative stage of the dynamic regulation. During the research period the load index of human settlement system in Dalian dropped from 0.96 to 0.84 with a lower pressure of human settlement system than the national average level. And the emergency response grades of human settlement system in Dalian were kept in grade Ⅱ (orange warning) or grade Ⅲ (yellow warning). Human settlement system of Dalian was in slight security state as a whole, but the load had a tendency of increase in recent years. The related departments should pay close attention to regional human settlement system and take active measures to improve human settlement by both intensity control and total quantity control. By comparison, analysis and discussion, it was considered that the results were basically accordded with the current situations of human settlement in Dalian, and the evaluation results were more reliable, visualized and easily applied in practice. Therefore, the above-mentioned concepts, characterization and evaluation methods of the regional human settlement system and carrying capacity could provide a new thought and method for quantitative evaluation of human settlement.

Keywords: human settlement; capacity-pressure-state-response (CPSR) model; carrying capacity; multi-objective decision making; Dalian City; China

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1 Introduction

With the fast development of global urbanization, the continuous increase of human activities intensity and range, the problems of urban human settlement in the global especially in developing countries are increasingly becoming one of the focused issues of relevant subjects and fields (Carvalho *et al*., 1997; Elnazir and

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Feng, 2004; UN-HABITAT, 2011). The traditional evaluations of human settlement put emphasis on the applying of willingness investigation method, the alternative price method, the hypothetical market method, and expense payment method. Although above-mentioned methods could reflect the residents′ overall awareness towards their settlement environment to some degree, the assessment results might be a little subjective. In recent years, with the development of Quantitative Ecology and Quantitative Geography, the changing process of land use and vegetation types in different spatial-temporal scales could be simulated by various mathematic models. The spatial-temporal evolution tendency of human settlement could be visually forecasted by discussing the interaction among different environmental elements. The measurement indexes on sustainable development could be obtained from the compound system comprising population, resources, environment, economy, culture and society. The objectives and programs of human settlement on different levels could be quantitatively assessed by several specific indexes such as the quality of human settlement and the pressure index. So the methods and means of human settlement have been increasingly diverse. Amanatidis *et al.* (1993), Banta *et al.* (1998), and Arnfield (2003) had respectively discussed the influencing mechanism and evolution tendency of human activities on state and structure of surrounding environment from the viewpoint of Aerodynamics, energy balance and regional microclimate change. Small Christopher and Robert (2003), McGranahan *et al.* (2007) and Gary (2011) had respectively carried out some empirical researches on the impact of natural elements such as greenhouse gas emission, global climate change, disasters and environmental change on human settlement. Rohe *et al.* (2002), Reinout (2004), Talen (2006) and Clos (2011) had respectively studied to determine fair, democratic and stable schemes of human settlement on the basis of the humanity and society factors as isolation, differentiation and democracy of community.

Although it is later than western countries to start these studies on human settlement in China, we have got a series of outstanding achievements by steady efforts of many scholars during the past 20 years. Wu (1997) firstly proposed to establish the science of human settlement in China, and he studied the system framework of human settlement from the viewpoint of system science. He indicated that the human settlement was composed of five subsystems that were human, natural, social, residential and support systems, and expected the development tendency of the science of human settlement in China (Wu and Li, 2010). Li *et al*. (1999) and Li *et al*. (2000) had respectively defined the concept of human settlement combined with a certain empirical study. Then some scholars classified the patterns of human settlement based on different subject. Ning (1999) sorted the human settlement into soft environment and hard environment, and Zhang *et al*. (2006) classified it into human factors and natural factors according to geography. Wu and Wei (2004), Zhang and Wang (2007) researched the evaluation index system of human settlement from the perspective of sustainable development. Chen and Chen (2000), Feng *et al*. (2008), Hao and Ren (2009), Long *et al*. (2012) evaluated the conditions of human settlement in different areas using the data gathered from survey statistics, GPS, RS and GIS. Li and Li (2007), Du *et al*. (2009) and Tan *et al*. (2009) respectively studied the human settlement quality in different urban in China through energy synthesis, Principal Component Analysis (PCA) and Genetic Algorithm (GA). Furthermore, some other Chinese scholars (Zhang *et al*., 2004; Li and Jin, 2012) did the relevant researches on human settlements in watersheds, rural areas, plains, coastal areas, mountainous areas and undeveloped areas based on different spatial-temporal scales. These researches positively deepened the development of human settlement science in China.

As a physical concept, Carrying Capacity firstly refers to the maximum pressure that an object could bear within the specified pressure deformation extent. With the persistent study of sustainable development, the concept of carrying capacity was applied widely in many fields including Humanities and Social and Earth System Science. Population carrying capacity was put forward after Malthus′s theory of resources limitation and population increase. Then Pearl and Reed (1920) measured the restriction of resources and environment to population growth with the concept of capacity using Logistic Equation, which became the beginning of quantitative researches on Malthus′s Theory. Generally, population carrying capacity was defined as the population quantity that all kinds of resources can stably support in long-term period without damage to biosphere or without exhaustion of available non-renewable re-

sources (Ehrlich and Holdrens, 1971; Irmi and Clem, 1999). Park and Burgess (1921) introduced the concept of carrying capacity to Ecology and defined Ecological Carrying Capacity as the maximum quantity of the individual existence under the certain specific environment conditions as sunshine, nutrients, living space or their combination. Hadwen and Palmer (1922) added sustainable development connotation into concept of resources carrying capacity on the basis of former concept of carrying capacity that emphasized maximum limited quantity, which made concept of carrying capacity get large breakthrough. UNESCO and FAO (1985) defined resources carrying capacity as maximum population quantity that the national or regional resources could continuously support under the material living standard that meet the social and cultural criterion with local energy, natural resources, human intelligence and technology in a predictable period. The concept of environment carrying capacity was presented later, and it originally referred to maximum pollutant load capacity of natural environment in terms of environmental quality standards. Because the above concept indirectly expressed a negative meaning that human development was based on the expense of the damage to the environment, and it neglected the other support functions of environment system to human production and living to a certain extent. So this concept evolved into a threshold of human activity that regional environment could bear in a certain period or condition. As a whole, scholars usually did some researches using environment load, environment carrying capacity or pollutant carrying capacity on the basis of different background (Fujiwara *et al*., 1986; Carey, 1993; Wang *et al*., 2005). At present, there is no consensus of the definition of environment carrying capacity.

With the rapid promotion of China′s urbanization, Urban Disease and problem of population, resources, environment and economic-social development (PRED) have become more and more obvious in individual regions. These problems of economic development disequilibrium and the resulting resources exhaustion and environment pollution have been increasingly serious. The traditional urbanization patterns only pursuing development speed and scale is urgently transforming to the new urbanization pattern including overall urban-rural development, industrial interaction, high efficiency and intension, ecological livability and harmonious development. Referenced the above-mentioned research achievements on human settlement science, human settlement composed of population, resources, environment and economy, social development was defined as regional human settlement system based on PRED in this paper. Then the concepts of regional carrying capacity and load index on human settlement were advanced on the basis of the theories of population carrying capacity and ecological elasticity. Moreover, CPSR evaluation index system of regional human settlement system was established referencing PSR model. Combined with Catastrophe Theory, the multi-objective programming and decision methods were introduced to comprehensively evaluate the load of regional human settlement system in Dalian of China from 2000 to 2012. Analysis of the results could provide a new idea and method for the quantitative evaluation of human settlement in the context of new-type urbanization.

2 Methods

2.1 Carrying capacity and load index of regional human settlement system

2.1.1 Carrying capacity of regional human settlement system

With the increasing interaction between human economy, social activities and earth ecosystem, the concept of carrying capacity has been widely applied in Earth System Science. However, the concept of carrying capacity still has no unified characterization and measurements because of the differences or exclusiveness existing in different subjects or different evaluation subjects. Based on the above-mentioned ideas and concepts of population carrying capacity, combined with the characteristics of human settlement science, regional human settlement carrying capacity was defined as the maximum population quantity that the regional human settlement elements or system could support under the condition of the lowest standard satisfying human basic living during a certain stage of social development. It can be expressed by the following formula.

$$C = S / P \tag{1}$$

where C is regional human settlement carrying capacity which can characterize the natural attribute of human settlement. The higher value indicates theoretically higher regional human settlement carrying capacity and

more population the region can support. S is the current characterization amount of regional human settlement (total quantity); P is the lowest standard of living quality satisfying human survival, because we do not agree on the standard in China or the standard is still imperfect at present stage, so national per capita availability was used to replace the standard and to characterize the dynamic quality standards of changing environment, hereinafter referred to reference standard.

As previously mentioned, human settlement is a complicated system composed by various environmental elements. We defined regional human settlement system as a unity comprising many subsystems and a number of factors of each subsystem. These subsystems include population, resources, environment, economic development and social development. In order to exactly express human settlement carrying capacity of a certain factor or all the factors, the corresponding formulas of carrying capacity on single-factor and total-factor were proposed and expressed as follows:

$$C_{ij} = S_{ij} / P_{ij} (i = 1, 2, ..., m; \quad j = 1, 2, ..., n) \tag{2}$$

$$C_i = \text{AVERAGE}\ (C_{ij}) (i = 1, 2, ..., m; \quad j = 1, 2, ..., n) \tag{3}$$

where C_{ij}, S_{ij} and P_{ij} are respectively signal-factor carrying capacity, the characteristic values of consumption or production amounts, and per capita characterization amount of reference standard for factor j in subsystem i (i =1–4 orderly presents resource, environment, economic and social subsystem); C_i is total-factor carrying capacity of subsystem i constructed by n factors. According to ecological elasticity theory (Wang and Lu, 2011), the value of total-factor carrying capacity dynamically fluctuated between maximum and minimum of single-factor (subsystem) carrying capacity within the elastic deformation. Therefore, it was expressed by the average value of concerned single-factor (subsystem) carrying capacity of human settlement.

2.1.2 Load index of regional human settlement system

Regional human settlement system not only provides positive supports of economic benefit and social services for human survival, but also causes carrying capacity decline by resource exhaustion and environmental stress. Therefore, human settlement system is a complex system coupled mutually by positive and negative indexes. There exists an unspecific relation of supply and demand between people and human settlement system factors in the condition of different time and space. In order to horizontally compare the human settlement system pressures in different regions or to different factors in the same region, referencing the concept of environmental load (Fujiwara *et al*., 1986), single-factor and total-factor load indexes of regional human settlement system were respectively defined and the corresponding formulas are just as follows:

$$L_{ij} = \begin{cases} C_{ij}^{+} / p & (i = 1, 2, \ldots, m; \ j = 1, 2, ..., n) \\ p / C_{ij}^{-} & (i = 1, 2, \ldots, m; \ j = 1, 2, ..., n) \end{cases} \tag{4}$$

$$L_i = \text{AVERAGE}\ (c_{ij}) \ \ (i = 1, 2, ..., m; \ j = 1, 2, ..., n) \tag{5}$$

where L_{ij} is single-factor load index of factor S_{ij} in regional human settlement system (zero dimension) which can characterize the relative pressure supported by single factor of regional human settlement system: L_{ij} = 1 presents factor S_{ij} is same as the referenced value of load level; L_{ij} > 1 shows factor S_{ij} is higher than the referenced value (overload); while L_{ij} < 1 means it is lower than the referenced value (underload). C_{ij}^{+} and C_{ij}^{-} express respectively single-factor carrying capacity (factor j in subsystem i) for the positive indexes and negative indexes; p is regional population; L_i is total-factor load index (correspond with C_i) which was expressed by average value of single-factor load indexes.

2.2 Criterion of evolution stage, secure state and emergency response grade of regional human settlement system

2.2.1 Division criterion of evolution stage and secure state

The spatial-temporal change of geographic elements including various factors of human settlement system is full of stage and mutability (Yao *et al*., 2013). According to the above-mentioned concepts, the evolution of regional human settlement system was divided into quantitative change (gradual change) stage and qualitative change (sudden change) stage. Simultaneously, system state was divided into four types: security, slight security, slight insecurity, insecurity according to criticality from low to high. Details are showed in Table 1.

As shown in Table 1, total-factor carrying capacity is the threshold of quantitative change and qualitative change on the system evolution. When regional population scale was less than total-factor carrying capacity,

Table 1 Division criterions of evolution stage and secure state of regional human settlement system

	Regional population scale		Regional population scale	
	$p < \text{MIN}(C_{ij})$	$\text{MIN}(C_{ij}) < p \le C_i$	$C_i < p \le \text{MAX}(C_{ij})$	$\text{MAX}(C_{ij}) < p$
Evolution stage of system	Quantitative change	Quantitative change	Qualitative change	Qualitative change
Secure state of system	Security	Slight security	Slight insecurity	Insecurity

Notes: C_{ij} is signal-factor carrying capacity for factor j in subsystem i; C_i is total-factor carrying capacity of subsystem i; p is the numbers of people

the system was in the stage of quantitative change with elastic adjustment, and the system was the state of security or slight security which the minimum of signal-factor carrying capacity was set as the critical point. Otherwise when regional population scale was more than total-factor carrying capacity, the system was in the stage of qualitative change and the state of slight insecurity or insecurity which the maximum of signal-factor carrying capacity was taken as the critical point.

2.2.2 Division criterion of emergency response grades

Load index is a zero dimension indicator to measure the differences between regional human settlement system (subsystem or one of the factors) and reference standard from the point of the relativity. For regional human settlement system is a nonlinear and multi-criteria giant system composed of 5 subsystems including population, resources, environment and economy, society, which causes a certain fuzziness and uncertainty. Therefore, the cognition or evaluation of load conditions of system could not be expressed in simple superposition of load indexes of all subsystems or factors. To fully reflect the complexity of human settlement system, the responsivity model of regional human settlement system was proposed by using the concept of membership in fuzzy mathematics for reference. The formula is as follows:

$$R = \sum_{i=1}^{m} \sum_{j=1}^{n} w_{ij} \times U(L_{ij}) \tag{6}$$

where R is responsivity of regional human settlement system (zero dimension) which can characterize the overall cognition of regional people towards load conditions of human settlement system; w_{ij} is the weight of factor j in subsystem i; $U(L_{ij})$ is the fuzzy membership of signal-factor load index L_{ij}.

Considering the limitation of development level of human productivity at present, human are still confronted with these problems such as resource exhaustion and environment contamination to some extent, even if the goal is confirmed as the lowest living quality standard that satisfied the basic mankind survival. If people can constantly deepen the crisis consciousness to these negatives that influence economic and social development benefits, they would have to make a positive response to these negative factors. So the correct judgment to current conditions of human settlement is the premise and key to decide what kinds of measures should be taken and what time and place to perform the countermeasures. In this paper, we referenced the evaluation results of human settlement with different methods (Li and Jin, 2012) or in different regions of China (Zhang *et al*., 2006) and the researches of disaster warning in meteorology and catastrophology, the division criterions of emergency response grades (emergency degree decreasing from Grade Ⅰ to Ⅴ) and warning signal colors of regional human settlement system were proposed as a secondary standard to judge the system state (Table 2).

2.3 Evaluation index system and method of regional human settlement system

2.3.1 Evaluation index system

In the process of transformation from the traditional urbanization to the new-type urbanization, the development would mostly go though a terrible period of unsustainable development which could cause agricultural land decrease, ecological environment deterioration, inharmonious economy development and social public service loss. And then the problem of balance between economic-social development and resource consumption

Table 2 Division criterions of emergency response grades of regional human settlement system

	System responsivity				
	$0 < R \le 0.2$	$0.2 < R \le 0.4$	$0.4 < R \le 0.6$	$0.6 < R \le 0.8$	$0.8 < R \le 1.0$
Emergency response grade	Grade Ⅴ	Grade Ⅳ	Grade Ⅲ	Grade Ⅱ	Grade Ⅰ
Warning signal color	Green	Blue	Yellow	Orange	Red

Notes: R is responsivity of regional human settlement system.

and environment protection will be followed. To improve evaluation comprehensiveness, based on the pressure-state-response (PSR) model, carrying capacity-pressure-state-response (CPSR) model was established as the evaluation index system of regional human settlement system as shown in Table 3.

2.3.2 Multi-objective evaluation method

Compared with the objectivity of C_{ij} or C_i, the concept of L_{ij} and L_j is relatively subjective for adding population as a factor. So it could characterize the social attribute of human settlement factors or system. Combining with Formula (6), it would be known that the responsivity of regional human settlement system was both objective and subjective, which could show the natural attribute and social attribute of system. That is to say the evaluation on load of regional human settlement system is a

Table 3 Evaluation index system of regional human settlement system based on carrying capacity-pressure-state-response (CPSR) model

Objective	Criterion	Index	Explanation of indexes
S	*P*	S_{11}: Residents′ domestic water consumption (t)	Larger value lead to greater carrying capacity, greater load to meet living supply
		S_{12}: Residents′ domestic electricity consumption (kWh)	Larger value lead to greater carrying capacity, greater load to meet living supply
		S_{13}: Residents′ domestic gas consumption (m^3)	Larger value lead to greater carrying capacity, greater load to meet living supply
		S_{14}: Agricultural land area (ha)	Larger value lead to greater carrying capacity, greater load to meet living supply
		S_{15}: Agricultural products (t)	Larger value lead to greater carrying capacity, greater load to meet resource supply
		S_{21}: Standard wastewater discharge (m^3)	Larger value lead to greater carrying capacity, greater load of governance input
		S_{22}: Standard exhaust gas (t)	Larger value lead to greater carrying capacity, greater load of governance input
		S_{23}: Harmless solid waste (t)	Larger value lead to greater carrying capacity, greater load of governance input
		S_{24}: Environmental protection investment (yuan)	Larger value lead to greater carrying capacity, fund occupation increases overall system load
		S_{25}: Disaster prevention investment (yuan)	Larger value lead to greater carrying capacity, fund occupation increases overall system load
	C	S_{31}: Regional GDP (yuan)	Larger value lead to greater carrying capacity, economic security decreases overall system load
		S_{32}: Per capita disposable income (yuan)	Larger value lead to greater carrying capacity, people's livelihood security decreases overall system load
		S_{33}: Outstanding household deposits (yuan)	Larger value lead to greater carrying capacity, people's livelihood security decreases overall system load
		S_{34}: Estate investment (yuan)	Larger value lead to greater carrying capacity, housing security decreases overall system load
		S_{35}: Social retail sales of consumer goods (yuan)	Larger value lead to greater carrying capacity, people's livelihood security decreases overall system load
		S_{41}: Hospital beds	Larger value lead to greater carrying capacity, medical security decreases overall system load
		S_{42}: Public traffic vehicles	Larger value lead to greater carrying capacity, traffic security decreases overall system load
		S_{43}: Science and education investment (yuan)	Larger value lead to greater carrying capacity, educational security decreases overall system load
		S_{44}: Road traffic facilities (km^2)	Larger value lead to greater carrying capacity, traffic security decreases overall system load
		S_{45}: Collected books in public libraries	Larger value lead to greater carrying capacity, cultural security decreases overall system load
	R	S_{51}: Evolution stage	Evolution was divided into 2 stages of quantitative change and qualitative change by using total-factor carrying capacity of system as the threshold
		S_{52}: Secure state of system	State was classified by total-factor carrying capacity, the maximum and minimum of signal-factor carrying capacity
		S_{53}: Responsivity of system	Comprehensively presents the theoretical load value of regional human settlement system
		S_{54}: Emergency response grade of system	Presents the facing risk grade of regional human settlement system
		S_{55}: Warning signal color of system	Presents the facing risk grade of regional human settlement system

Notes: *S*, *R*, *C* and *P* represent respectively state, response, carrying capacity and pressure of human settlement system

multi-objective and multi-criterion process of solution.

Catastrophe Theory was a mathematical theory established on the basis of Singularity Theory and Stability Theory to research the discontinuous movement and was widely applied in multi-criteria and multi-objective system decision and evaluation (Sun *et al*., 2013). The evaluation objective was disintegrated into multiple layers using the Catastrophe Progression Method. Then fuzzy membership function was produced by catastrophe model. Finally, the total membership function can be obtained by quantitative calculation of the normalization (Zheng *et al*., 2014).

The weights of under-layer indexes to subsystem and subsystems to upper-layer system must be determined in the process of using catastrophe progression method. The Delphi method was usually used to calculate the weights. In this paper, we introduced Analytic Hierarchy Process (AHP) and Entropy method to determine the subjective and objective weight to make the evaluation results more scientific. Then the relative importance of evaluated indexes in the subsystem (or the subsystems in the system) was determined by weighted average.

3 Empirical analysis

Dalian (39°01′–39°04′N, 121°44′–121°49′E) is located in the southern of Northeast China and has relatively scarce resources and fragile regional ecosystem; meanwhile as one of the most economically developed cities in Northeast China, Dalian absorbs a large number of surrounding surplus labor so that it has large scale of floating population and becomes one of cities having high proportion of urban population in China. Dalian has ever won Dubai International Award for Best Practices to Improve the Living Environment by the United Nations Human Settlements Programme in 2000. It was also one of the five cities that have won China Habitat Environment Award by Ministry of Construction in 2001. In the different urbanization periods of China, Dalian has experienced the different development stages from macrocosm urbanization, rapid urbanization to new-type urbanization for the past more than ten years. Therefore, it would be very significant to evaluate comprehensively the development evolution, current situation and growing tendency of human settlement system. Therefore, human settlement system in Dalian was evaluated based on the CPSR evaluation index system in Table 3 and taking the human settlement background values of China (not including Hong Kong, Macao and Taiwan) at the same period as the reference standards since 2000. The results would provide a reference to make scientific decisions for the concerned departments.

The data sources and treatments were explained as follows: the data on the population (floating population not included for accurate data missing. According to conservative estimate of government, the total population in 2012 was 6×10^6–7.2×10^6) and the economic development indexes came from *Statistical Bulletin for National Economic and Social Development* (Dalian Bureau of Statistics, 2001–2013); the standard wastewater discharge, standard exhaust gas, harmless solid waste and residents′ domestic water consumption originated from *Environmental Bulletin* (Environmental Protection Bureau of Dalian, 2001–2013) and *Water Resources Bulletin* (Water Authority of Dalian, 2001–2013); the social development indexes and residents′ domestic electricity consumption, residents′ domestic gas consumption and agricultural land area (including cultivated land, forest land, garden plot, grassland and other farmland) came from *Dalian Statistical Yearbook* (Dalian Bureau of Statistics, 2001–2013); China′s population and the background values of the related factors on human settlement were calculated according to the data in *China Statistical Yearbook* (National Bureau of Statistics of China, 2001–2013). Some related data were preprocessed by spatial interpolation or calculation because they can not be found directly in any books. For the length limitation, this paper only presented the data of 2012 (Table 4).

3.1 Analysis of human settlement system carrying capacity

According to formulas (2) and (3) and above-mentioned data, signal-factor and total-factor carrying capacities of all subsystems in human settlement system from 2000 to 2012 in Dalian were respectively calculated and shown in Figs. 1a–1d and Fig. 1e.

Figure 1a showed the change trend of each signal-factor carrying capacity for resource subsystem (S_1) of Dalian in 2000–2012. The carrying capacity of residents′ domestic water consumption was the highest and more than 6×10^6 persons all the years, and there were two raising stages in 2000–2005 and 2006–2012. The carrying capacities of residents′ domestic electricity

Table 4 Data of evaluation indexes on human settlement system of Dalian and China (not including Hong Kong, Macao and Taiwan) in 2012

	S_{11} (10^9 t)	S_{12} (10^9 kWh)	S_{13} (10^9 m^3)	S_{14} (10^6 ha)	S_{15} (10^6 t)	S_{21} (10^9 m^3)	S_{22} (10^6 t)	S_{23} (10^9 t)	S_{24} (10^9 yuan)	S_{25} (10^9 yuan)
Dalian	0.405	19.210	0.271	0.968	0.142	0.617	0.366	7.067	0.020	0.167
China	46.500	4940.000	107.220	6593.980	339.854	68.460	514.000	32900.000	3.747	44.547
	S_{31} (10^9 yuan)	S_{32} (10^6 yuan)	S_{33} (10^9 yuan)	S_{34} (10^9 yuan)	S_{35} (10^9 yuan)	S_{41} (10^6)	S_{42} (10^6)	S_{43} (10^9 yuan)	S_{44} (10^6 km^2)	S_{45} (10^6)
Dalian	700.280	0.027	423.720	139.650	222.400	0.031	0.011	2.080	0.008	9.890
China	51930.000	0.025	41020.000	9230.000	21030.000	5.090	1.422	467.900	1.518	600.000

Notes: The meaning of index is same with Table 3; yuan represents yuan (RMB)

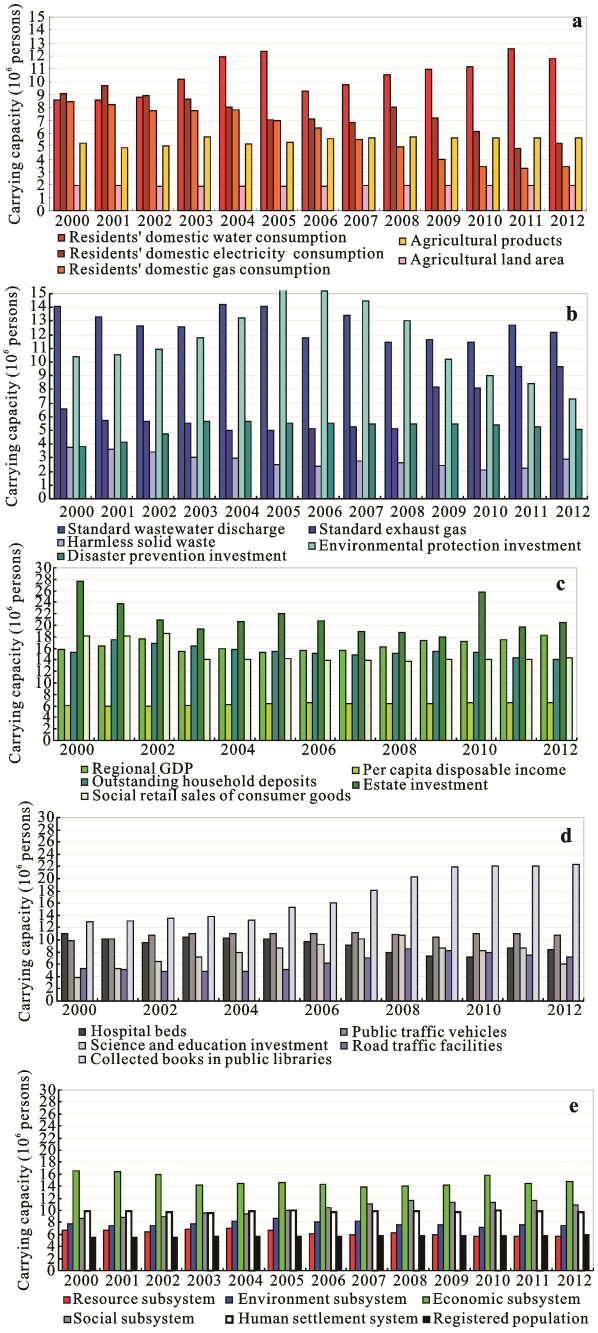

Fig. 1 Changing trend of human settlement system carrying capacity in Dalian from 2000 to 2012

consumption and gas consumption were continuously decreasing and the fall extent was particularly obvious in recent years. The carrying capacities of agricultural land area and agricultural products have kept stable, but the former was in a lower level (no more than 2×10^6 persons over the years) which conformed to the objective conditions that the agricultural land in Dalian was relatively less and the agricultural products depended on the import from outside over a long period.

Figure 1b indicated the change trend of each signal-factor carrying capacity for environment subsystem (S_2) of Dalian in 2000–2012. The carrying capacities of standard wastewater discharge and environmental protection investment were higher, which showed that the government has made a larger effort on wastewater standard treatment and environmental protection. The carrying capacities of harmless solid waste and disaster prevention investment were lower than 6×10^6 persons all the time and kept relatively stable. The carrying capacity of standard exhaust gas had a tendency of rising after the first dropping, and was rising faster after 2009, which attributed to the increase of vehicles and exhaust emissions and also showed the effect of exhaust gas treatment.

Figure 1c figured out the change trend of each signal-factor carrying capacity for economic subsystem (S_3) of Dalian in 2000–2012. The carrying capacity of estate investment was higher, which showed that the government has continued to enhance the construction of commercial housing and security housing. The carrying capacity of per capita disposable income always maintained about 7×10^6 persons close to actual population in Dalian. The carrying capacities of regional GDP, outstanding household deposits and social retail sales of consumer goods were over 12×10^6 persons coming near twice of regional population, which coincided with Dalian′s economic strength and status.

Figure 1d revealed the change trend of each sig-

nal-factor carrying capacity for social subsystem (S_4) of Dalian in 2000–2012. The carrying capacities of hospital beds, public traffic vehicles, and collected books in public libraries were all above 6×10^6 persons. The carrying capacities of science and education investment and road traffic facilities have broken 6×10^6 persons with a rising trend as a whole. Especially the quick increase of road traffic carrying capacity denoted that the growth of vehicle number has promoted the construction of road traffic at an accelerating pace.

In general, Figure 1e showed the total-factor carrying capacities for the state of human settlement system (S) of Dalian in 2000–2012. The total-factor carrying capacities of economic subsystem and social subsystem were higher. Benefiting from the influences of these two aspects especially economic contribution, the annual total-factor carrying capacity of human settlement system in Dalian was kept in 9.6×10^6 to 10×10^6 persons, which was higher than annual summation of the registered population and floating population (Commission of Population and Family Planning of Dalian City, 2013). Suffering from the 4 aspects factors including scarcity of agricultural lands, undersupply of agricultural products, low disaster prevention investment and inefficiency of solid waste harmless disposal (Fig. 1a–Fig. 1b), the total-factor carrying capacities of resource subsystem and environment subsystem were fluctuating around 7×10^6 persons, and the former was less than the registered population even in 2010 to 2012. In view of floating population and the above analysis results, we can draw a final conclusion that Dalian was in a quantitative change stage and slight security state of human settlement system.

3.2 Analysis of human settlement system load index in Dalian

Using formulas (4) and (5) and the corresponding data, signal-factor and total-factor load indexes of all subsystems in human settlement system from 2000 to 2012 in Dalian were respectively computed and shown in Fig. 2a–Fig. 2d and Fig. 2e.

Figure 2a and 2b showed that the loads of residents′ domestic water consumption, standard wastewater discharge and environmental protection investment were higher than the national averages that is the line with load index equal to 1(the same as below), while those of agricultural land area, agricultural products, harmless

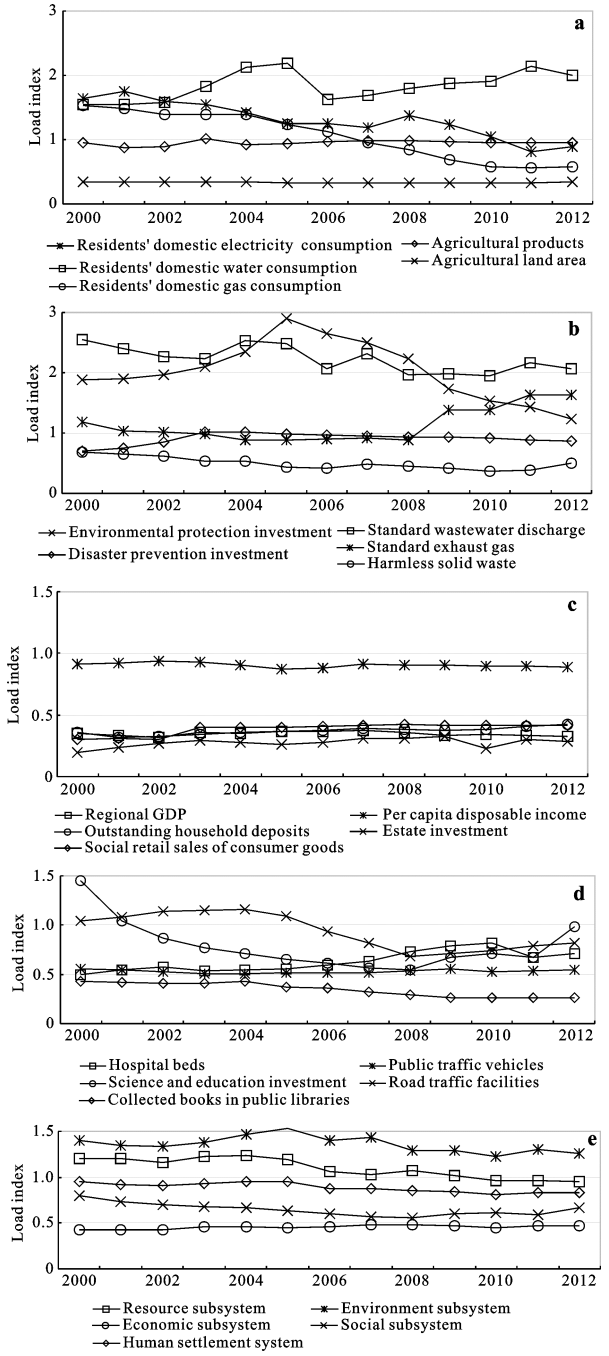

Fig. 2 Changing trend of human settlement system load indexes in Dalian from 2000 to 2012

solid waste and disaster prevention investment were lower than the reference standard in Dalian from 2000 to 2012. Meanwhile, the loads of residents′ domestic electricity consumption and gas consumption have gradually fallen under the national averages, and emissions intensity of exhaust gas has risen above the national averages from 2009. From Fig. 2c to Fig. 2d, it was observed that the loads of regional GDP, per capita

disposable income, outstanding household deposits, estate investment, social retail sales of consumer goods, hospital beds, public traffic vehicles and collected books in public libraries were lower than the national averages in Dalian during 2000–2012. In addition to individual years, the loads of road traffic facilities and science and education investment were lower than the national averages as well. As a whole, total-factor load index of human settlement system was less than 1 in Dalian from 2000 to 2012, which showed that the pressure of human settlement in Dalian was relatively lower than China′s overall situation. This is consistent with the achievements of Dalian on human settlement construction in recent years (China Habitat Award Office, 2013).

From formulas (4) and (5) and the above-mentioned definitions, we can conclude that load index of regional human settlement is actually the ratio of regional per capita availability to corresponding reference standard of single-factor (resources consumption, environmental stress, economic development and social development) or total-factor (human settlement system) for positive indexes, whereas it is the reciprocal for negative indexes. Owing to adding the ′population′ factor, human settlement load index is manageable. The load of regional human settlement system can be relieved to a certain extent by a series of measures such as strengthening environmental protection, optimizing the ecological planning, controlling regional population increase and so on. Therefore, the relevant departments should adjust actively the traditional strategy that emphasized on ′intensity management′, and take the measure of ′total quantity control′ on resources consumption, environmental protection and population scale. With the cooperation of the two aspects, regional human settlement quality would be improved constantly.

3.3 Analysis of evaluation results on human settlement system

Analytic Hierarchy Process and entropy method were used to calculate the subjective weight and objective weight, and then the weighted average was set as the normalized combination weight of each index showed in Table 5. Using the cottage catastrophe model or the butterfly catastrophe model (Zheng *et al*., 2014) and Formula (6), the responsivity, emergency response grades and warning signal color of human settlement system in Dalian from 2000 to 2012 were obtained and showed in Fig. 3.

From Fig. 3 we could find that the responsivity of human settlement system in Dalian from 2000 to 2012 fluctuated from 0.5 to 0.8. Taking the year of 2004 as a break point (0.758), there were two kinds of changing trends of rising after the first dropping. The first stage was gradual state of rising after the first dropping from 2000 to 2004, which agreed with government′s strategy of macrocosm urbanization during that period. The second stage was also the state of rising after the first dropping from 2004 to 2012 except for two catastrophic

Table 5 Weights of all evaluation indexes of human settlement system in Dalian

	Evaluation indexes			
	S_{11}–S_{15}	S_{21}–S_{25}	S_{31}–S_{35}	S_{41}–S_{45}
Subjective weight	[0.128,0.066,0.032,0.016,0.008]	[0.128,0.066,0.032,0.016,0.008]	[0.128,0.066,0.032,0.016,0.008]	[0.128,0.066,0.032,0.016,0.008]
Objective weight	[0.025,0.079,0.211,0.007,0.003]	[0.015,0.097,0.067,0.093,0.019]	[0.004,0.001,0.011,0.029,0.026]	[0.043,0.002,0.143,0.061,0.065]
Combination weight	[0.077,0.072,0.122,0.012,0.005]	[0.072,0.081,0.049,0.055,0.013]	[0.066,0.033,0.021,0.023,0.017]	[0.085,0.034,0.088,0.039,0.036]

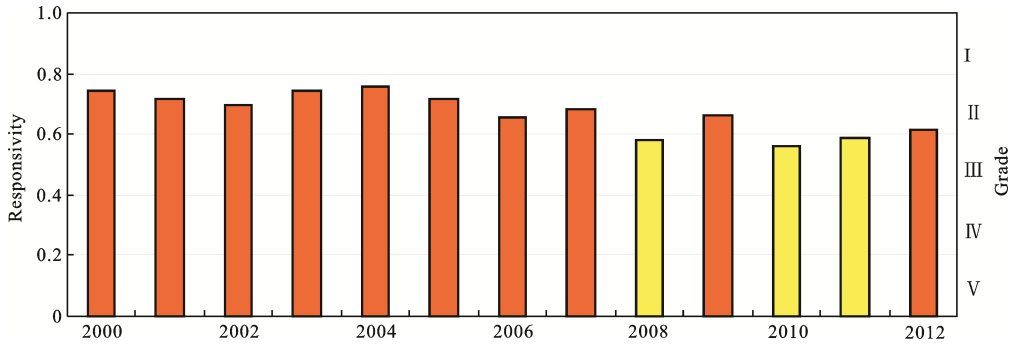

Fig. 3 Comprehensive evaluation results of human settlement system in Dalian from 2000 to 2012, orange means in grade Ⅱ, yellow means in grade Ⅲ

points (in 2007 and 2009), which reflected the hard choice between rapid urbanization and new-type urbanization. In general, the warning signal color of human settlement system in Dalian were orange warning during the research period except for the years of 2008, 2010 and 2011 that were yellow warning. Emergency response grades of human settlement system were between grade Ⅲ and grade Ⅱ, which agrees with the former judgment that regional human settlement system was in the condition of slight security. It should be pointed out that emergency responsivity of human settlement system in Dalian was rising and resource subsystem turned to overload state during the later period (2010–2012) from Fig. 3. According to above theory and the empirical analysis, we considered the evaluation results were caused by the interactive development of local resources, environmental restriction, and economic and social support. Besides, another important reason was that China′s urban human settlement has been constantly improved, and the lowest living standard that satisfied basic survival was also improved under the background of new-type urbanization promotion in China.

4 Discussion

Using the theory of carrying capacity and the concept of population carrying capacity in some subjects and fields for reference, the connotation of regional human settlement system was defined based on PRED system, and then the concept and characterization methods of human settlement carrying capacity were put forward in this study. Compared with the human settlement evaluations based on coordination degree, suitability, and security, the evaluation process of human settlement carrying capacity using population as unit and measuring standard had a higher visibility, and evaluation results were more visualized and the methods were easier to practice.

Compared with the evaluation methods of human settlement quality based on index system and exponential model, we took the ratio of current characterization values in study area to background values of human settlement factors (per capita availability or capacity) as load index of regional human settlement in this paper. This definition of load index can incarnate the difference of social attributes on human settlement in different regions from the point of relative quantity, and make up for the defect of results absoluteness.

Referencing the PSR model, a CPSR evaluation index system of regional human settlement system was established. These multi-objective programming and decision methods as catastrophe theory, Analytic Hierarchy Process and entropy method were introduced to determine the comprehensive evaluation standards of regional human settlement system. Compared with the former studies on the basis of the questionnaire survey and the concept of the satisfaction degree, the evaluation process based on the combination weights not only reflected the intrinsic characteristics and the natural attributes of human settlement, but also incarnated the residents′ subjective cognition towards their human settlements. The scientificity and reliability of evaluation results were enhanced.

Owing to the difficulty in getting some data about the floating population, agricultural products supply by outside region and the social public service indexes in Dalian, the load index of regional human settlement based on the registered population and regional agriculture products might be a little different from reality. In addition, it should be improved to choose and explain some two-side indexes (for instance wastewater, exhaust gas and solid waste), and to fully establish the evaluation index system in the future. We just took the evaluation of Dalian human settlement system in 2000–2012 as an example to testify the concept, evaluation methods, stage division and state judgment of human settlement carrying capacity. The discussion of related evaluation results was not wide enough. It is necessary to further research the evolution mechanism of regional human settlement system by combining more empirical studies of micro-spatial scale, describing the catastrophe point of regional human settlement system and identifying the major driving forces in the future.

5 Conclusions

Based on our study results, the reality of human settlement in Dalian and the effective work that the local government has done to improve regional human settlement quality, we drew the conclusions as follows:

During 2000 and 2012, the carrying capacity of human settlement system in Dalian was kept between 9.6×10^6 and 10×10^6 persons with slight security state (considering floating population). The carrying capacities of resource subsystem and environment subsystem were

lower while those of economic subsystem and social subsystem were higher. Each subsystem and regional human settlement system were in a stage of quantitative change with the elastic adjustment as a whole. Meanwhile, the pressure of human settlement system in Dalian was always lower than the national average, and emergency response grades of system were kept in grade Ⅱ (orange warning) or grade Ⅲ (yellow warning).

Although human settlement system of Dalian was in slight security state, the system load was trending to increase in recent years. For the related departments, it is necessary to strengthen the consciousness of suffering and tension, pay close attention to the dynamic change of regional human settlement quality and make a positive response. On the one hand, the departments should accelerate greatly the controlling and supervising on the intensity of resources consumption and pollutant discharge, and improve regional economic-social development quality; on the other hand, they should carry out the strategy of ′total quantity control′ to resources, environment and population, and promote the regional human settlement construction to move towards sustainable development.

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