Assessment and Early Warning of Geo-Environmental Carrying Capacity: A Case Study of Tianjin Binhai New Area, China

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Abstract. The geo-environmental carrying capacity (GCC) is to provide a scientific method for government to make a reasonable strategic decision for the land use planning and distribution of industrial structures. In this paper, the assessment indicators system and the assessment model of geo-environmental carrying capacity (GCC) based on the System dynamics (SD) theory were established for a case study of Tianjin Binhai New Area, China. Then the assessment model was applied to the land use planning of the study area. The results show that about 15 percent over loading sub-areas was eliminated in the Tianjin Binhai New Area by land use re-planning and adjustment of industrial structures. The study proposed a new method for the assessment and early warning of the geo-environmental carrying capacity.

Keywords: Geo-environmental carrying capacity (GCC), System dynamics (SD), Carrying capacity index.

1. Introduction

The theory of carrying capacity was first proposed in the field of mechanics in 1760 [1]. Since this theory was first introduced to the field of ecosystems and forest resources, carrying capacity had also evolved into tourism carrying capacity in the late 1890s [2, 3]. Subsequently, environmental carrying capacity had become an important indicator for environmental planning and management [4, 5].

Carrying capacity has no a universal definition. Some scholars defined the carrying capacity as an ecological concept, which expresses the relationship between population and the natural environment, so it has also been called ecological capacity [6, 7]. It is also estimated by comparing stress on the environment against environmental thresholds.

The concept of carrying capacity has been developed significantly both in form and content since its appearance and it has been extended to the natural world in application. The concept of environmental carrying capacity is defined currently as follows: The environmental carrying capacity is the thresholds expressing the relationship between natural environment and human economical activities under a historical period or a social economical background, which includes two main components, namely, carrying body and carried object [8, 9].
The geo-environment system has a certain ability to carry outside stress and will not deteriorate in the natural structure and function. Fundamentally, the natural attribute of the geo-environment system is the source of the carrying capacity and the inherent properties of the geo-environment system determine the thresholds of the carrying capacity [10]. So the outside stress of human economical activities to the geo-environment system has a limit for the social economic sustainable development.

The concept of geo-environmental carrying capacity (GCC) could be defined as follows: the GCC is the maximum capacity of the population and social economical activities supported by the geo-environment system under the conditions of the geo-environment system without deterioration in it’s structures and functions, in other words, the thresholds of the geo-environment system providing the capability for human economical activities is the GCC [11]. It is an objective quantity reflecting the property of the geo-environment system. The concept of the GCC has a viewpoint as the carrying body is the geo-environment system and the carried object is the human economical activities [12].

The objective of GCC assessment is to provide a scientific method for local government to make a reasonable strategic decision for the land use planning and distribution of industrial structures.

In this paper, the assessment indicators system and the assessment model of GCC based on the System dynamics (SD) theory were established for the Tianjin Binhai New Area, which presents a new method for the assessment and early warning of the GCC.

2. Site Description

2.1. Study area

Tianjin Binhai New Area (TBNA) is located in the downstream of the Haihe River basin (38°40’-39°00’E, 117°20’-118°00’ N), the west coast of Bohai Bay, which is one of the district of Tianjin City, with a population of 2.72 million, covering area of 2,270km² with average altitude of 3.0m above sea level and a coastline of 153km (Fig. 1).

2.2. Geo-environmental conditions

The terrain of Tianjin Binhai New Area (TBNA) is dominated by the plains and low-lying lands. It is located in the north of the Huanghua depression, which is a 3rd tectonic unit still in the state of slow land subsidence by the control of the boundary faults. The faults include Cangdong Faults, Chadian Faults, Dazhangtuo Faults, Huaixi Faults, Haihe Faults and Hangu Faults, which represents that the geological structure of the TBNA (Fig. 2) is very complicated and vulnerable.

The geo-environmental issues of the TBNA are as follows:
(1) Land subsidence is the most serious geo-environmental hazard in the TBNA [13, 14]. As in the central area of TBNA, the cumulative land subsidence of the sub-area of Tanggu was 3.36m during the period of 1960-2016. The mean value of land subsidence was 27mm and the maximum value was 35mm in 2016.

(2) Weak soil is widely distributed in the TBNA. The lithofacies of TBNA coastal region are comprised by the thick weak soil with marine and continental alternative deposition. The thickness of weak soil crust in the TBNA is generally between 5.0m and 15.0m, and the maximum thickness can reach to 25.0m in the eastern coastal region. So the distinct geological characteristics of the TBNA are widespread distribution of deep weak soil.

(3) Sand liquefaction is also a serious geo-environmental issue in the TBNA [15]. The land formation of the TBNA is comparatively later in the geological history and the lithofacies are comprised by the thick weak soil with marine and continental alternative deposition. The ration of liquefaction sand within depth of 20.0m is more than 50 percent according to the standard of “Chinese Code for Seismic Design of Buildings”.

(4) Soil salinization is another serious geo-environmental issue in the TBNA. The region of TBNA is adjacent to the Bohai Sea connecting with the Western Pacific Ocean. The salinity of shallow groundwater is higher comparatively by the seawater intrusion and the total dissolved solid is more than 10g/L. The area of the salted soil is more than 813.56km² accounting for 35.8% of the total area of TBNA.

(5) Corrosion of groundwater and soil is also a serious issue in the TBNA. The concentrations of Mg²⁺, Cl⁻, SO₄²⁻ ions are greater than 6000mg/L in the groundwater and 3500mg/kg in the soil respectively, which has greater corrosion to the steel reinforced concrete of buildings and has greater damage to the building understructure.

(6) Contamination of groundwater and soil is also serious in the TBNA. The area is abundant in oil gas deposits, the faults are fully developed and the crusts are fully fragmentated as well as the oil gas deposit strata are very superficial in depth, and the cementation degree of the cover strata is very weak.
comparatively. It caused the groundwater and soil contamination in the exploitation, transportation and refining of petroleum.

3. Methods and Data

3.1. Indicator system of the GCC

The first step of the assessment of GCC is to establish the assessment indicators system. The assessment indicators system of the GCC should include two aspects: the geo-environmental indicators and the human economical activities, in which the geo-environment system is the carrying body and the human economical activities is the carried object. The assessment indicators system was established according to the geo-environment conditions and states of TBNA, which is shown in Fig. 3.

The geo-environment indicators system includes two grades indicator hierarchical structures. The 1st indicator hierarchical structure include four indicators of the crustal stability, engineering geology, hydrogeology and soil environment and the 2nd indicator hierarchical structures include eleven indicators of seismicity, fracture distribution, sand liquefaction, land subsidence, weak soil, groundwater quality, groundwater level, groundwater corrosiveness, soil contamination, soil salinization and soil corrosiveness respectively, which influence the geo-environment system carrying capacity.

Figure 3. The indicators system of the GCC.
The carried object of the geo-environment system is the human economical activities, which is the study objective of the GCC. In the carried object indicators system, the land use planning is for the land reasonable use of the petrochemical industry, high-tech industry, machinery manufacturing industry, port logistics industry, agriculture, ecotourism.

The goal of the GCC study is to do scientific and reasonable land using plan for the local industries structure distributions and social economic sustainable development.

3.2. System analysis of the GCC

The geo-environmental system and the human social activities system are the two sub-systems of the natural macroscopic system, within which the human social activities system has a pressure to the geo-environmental system and the geo-environmental system has influence to the human social activities system, that is to say, the various interactions are between the two systems [16, 17].

System dynamics (SD) is a methodology and mathematical modeling technique to understanding the nonlinear relationships of complex issues and problems over time using flows, internal feedback loops and time delays [18]. The SD is currently being used throughout the public and private sector for policy analysis and design. It is feasible to use the SD method to study the geo-environment carrying capacity in this paper.

The geo-environment system is the basis for the human beings social and economic activities. The system analysis is to clarify the relationships among the internal systems and subsystems, for every factor in the systems have some influences to the other subsystems and the other factors [19]. The flow chart of the geo-environment carrying capacity SD model is the first step to establish for the system analysis.

The analysis of the GCC of the feedback loop and the interface are as shown in Fig. 4.

![Figure 4. The flow chart of the Geo-environment carrying capacity SD model system.](image)

3.3. The SD equations of the GCC

Generally, the SD equations includes the horizontal equation, the rate equation, the auxiliary equation, the constant equation and the initial value equation, and the horizontal equation is the basic equation.

The main SD equations of geo-environmental carrying capacity of the model are as follows:

1) Geo-environment carrying capacity \( F = f( F_1, F_2, F_3, F_4) = w_1 \text{ (regional crustal stability) } + w_2 \text{ (engineering geology) } + w_3 \text{ (hydrogeology) } + w_4 \text{ (water and soil environment) } \)

2) \( w_1 = 0.25, w_2 = 0.35, w_3 = 0.22, w_4 = 0.18. \)
(3) Crustal stability $F_1 = f_1 (a_1 \text{ fracture distribution} + a_2 \text{ seismicity})$

(4) $a_1 = 0.72, a_2 = 0.28.$

(5) Seismicity $F_2 = f_2 (\text{ frequency of earthquake occurrence, earthquake intensity})$

(6) Engineering geological $F_3 = f_3 (b_1 \text{ land subsidence} + b_2 \text{ land desertification} + b_3 \text{ weak soil distribution})$

(7) $b_1 = 0.40, b_2 = 0.30, b_3 = 0.30$

(8) Hydrogeology $F_4 = f_4 (c_1 \text{ groundwater level} + c_2 \text{ groundwater quality} + c_3 \text{ seawater intrusion})$

(9) $c_1 = 0.35, c_2 = 0.35, c_3 = 0.30$

(10) Water and soil environment $F_5 = f_5 (d_1 \text{ soil pollution} + d_2 \text{ soil salinization} + d_3 \text{ water and soil corrosiveness})$

(11) $d_1 = 0.40, d_2 = 0.35, d_3 = 0.25$

(12) Social and economic pressures on geo-environment $F_7 = f_7 (e_1 \text{ construction land type} + e_2 \text{ social economy})$

(13) $e_1 = 0.45, e_2 = 0.55$

(14) Land use planning $F_8 = f_8 (g_1 \text{ petrochemical industry}, g_2 \text{ machine manufacturing industry}, g_3 \text{ port logistics industry}, g_4 \text{ Business industry}, g_5 \text{ Ecotourism industry}, g_6 \text{ Agriculture}, g_7 \text{ high-tech industry})$

(15) $g_1 = 0.30, g_2 = 0.20, g_3 = 0.15, g_4 = 0.15, g_5 = 0.10, g_6 = 0.10, g_7 = 0.05$

(16) Influencing factors of industrial land use planning $F_4 = f_4 (\text{ crustal stability, land subsidence, soil corrosion, sand liquefaction})$

(17) Cumulative number of land subsidence = INTEG (land subsidence increment, 1.6m)

(18) Land subsidence increment = Cumulative number of land subsidence $\times$ land subsidence rate

(19) Land subsidence rate = $((2012, 30)-(2020, 40), (2012, 32), (2016, 34), (2020, 36)) \text{ mm/a}$

(20) Impacting factor of geo-environment carrying capacity = a fun (geo-environment carrying capacity)

3.4. Calibration and validation of the SD models

It is necessary to calibrate and validate the parameters and equations of the geo-environment carrying capacity SD models repeatedly to ensure the objectivity and accuracy of the simulation results. The historical validation method was used to test the geo-environment carrying capacity SD models in this paper.

The data of the land subsidence historically monitored were used to validate the accuracy of the geo-environment carrying capacity SD models. The simulation land subsidence data were drawn out by the Vensim software for the SD models [20]. The cumulative land subsidence of the study area during the period of 2001 and 2010 were taken as an example to verify the SD models. The results are shown in Table 1.

| Time   | Cumulative land subsidence values | Errors (%) |
|--------|----------------------------------|------------|
|        | Historical values (mm) | Simulation values (mm) |          |
| 2001   | 1377                             | 1369       | -0.584   |
| 2002   | 1399                             | 1415       | 1.131    |
| 2003   | 1420                             | 1405       | -1.068   |
| 2004   | 1440                             | 1450       | 0.690    |
| 2005   | 1459                             | 1463       | 0.273    |
| 2006   | 1478                             | 1487       | 0.605    |
| 2007   | 1496                             | 1512       | 1.058    |
| 2008   | 1516                             | 1532       | 1.044    |
| 2009   | 1535                             | 1549       | 0.904    |
| 2010   | 1556                             | 1573       | 1.081    |
The errors between the historical monitored data and the simulation data during the period of 2001 to 2010 are less than 2%, which show that the accuracy of the geo-environment carry capacity SD models are accurate comparatively.

3.5. Assessment methods
The GCC is measured by the carrying capacity index, which is a ratio of the pressure state index of the human being social activity on the geo-environment carrying capacity index (Table2). The carrying capacity index equation is as follows:

$$S_i = \frac{P_i}{B_i}$$

Where $S_i$ is the carrying capacity index, $P_i$ is the pressure index of the human being social activity on the geo-environment system and $B_i$ is geo-environment carrying capacity index.

| Carrying state | Non over loading | Over loading |
|----------------|------------------|--------------|
| Non overloading | Abundance        | Overloading  |
|                 | Equilibrium      | Moderate overloading |
|                 |                  | Severe overloading |
| Standard        | $S_i < 0.7$      | $1.0 < S_i < 1.2$ |
| Warning state   | Green            | Yellow       |
|                 | Blue             | Orange       |
|                 | Yellow           | Red          |

3.6. Assessment and early warning of the GCC
The purpose of GCC assessment is to propose land use planning for social economic sustainable development without causing serious geo-environment issues. The industrial structures in the TBNA includes six industrial function areas of petrochemical industry area, high-tech industry area, machinery manufacturing industry area, port logistics industry area, agriculture area and ecotourism area.

The two different land use planning schemes are proposed for the six industrial function areas according to the TBNA development planning, which are as the current steady tendency, the industrial land use planning adjustment.

The geo-environment carrying capacity SD models were established for different land use planning schemes. The geo-environment carrying capacity index would be put out if the different industrial parameters and geo-environment monitoring data are put into the SD models.

(1) The GCC early warning for the current steady tendency
The meaning of the current steady tendency refers to that all the parameters of the social economic activities including industrial structures and scales and populations unchanged and maintained at the current development states.

The GCC index can be simulated by the geo-environment carrying capacity SD model under the current steady tendency. The prediction results are shown in Table 3 and Fig.5.

| Industrial areas      | $B_i$ | $P_i$ | $S_i$ | Warning status |
|-----------------------|-------|-------|-------|----------------|
| High-technology area  | 7.2   | 5.2   | 0.72  | Blue           |
| Advanced manufacturing area | 7.3   | 6.5   | 0.89  | Blue           |
| Business area         | 7.2   | 5.8   | 0.81  | Blue           |
| Ecotourism area       | 7.2   | 2.7   | 0.38  | Green          |
| Port logistics area   | 6.4   | 7.3   | 1.14  | Yellow         |
| Petrochemical area    | 5.8   | 7.2   | 1.24  | Orange         |
| Agriculture area      | 7.4   | 4.8   | 0.65  | Green          |
The petrochemical industries have greater influence to the geo-environment system and need more stable geo-environment to develop. The prediction showed that the GCC index of the petrochemical area reached to 1.24, which shows that the geo-environment of the petrochemical industries sub-area is too vulnerable to develop the petrochemical industries.

The industrial economic scales of the port logistics industries are comparatively larger and the geo-environment of the sub-area is vulnerable, as well as the issues of the land subsidence and the weak soil distribution are serious comparatively, so the GCC index reached to 1.14, which shows that the GCC of the port logistics industries sub-area is overloaded.

2) The GCC early warning of the industrial land use planning and industrial structures adjustment

Different industrial structures or social economic activities would bring different influence and cause different geo-environment pressure to the geo-environment system, and the GCCs are also different conversely in the different sub-areas. The strategy of the industrial land use planning adjustment refers to that the industrial land use planning is adjusted according to the GCC, and the distribution of the industrial land use are fitted to the GCC so as to optimize the reasonable distribution of industrial structures and improve the GCC with the rapid social economical development.

The prediction results show that the GCC index is relatively lower in the coastal zone of the TBNA where it is the new land reclamation area near the Bohai sea. On the other hand, the geo-environmental pressure of the ecotourism industry is relatively lower, so the coastal zone of the TBNA and the new land reclamation area are suitable for the development of coastal ecotourism.

The petrochemical industries have relatively great environment potential hazards and safety danger, and cause relatively great pressure on the geo-environment system. The GCC index of the south sub-area Dagang in the TBNA is relatively higher and would be developed as the petrochemical industrial zone where the geological structure is relatively stable and have no serious geo-environment issues such as land subsidence and weak soil distribution.

The GCC of the petrochemical industries sub-areas and the port logistics industries sub-areas are at overloaded states before adjustment, and the GCC of the sub-areas are greater enough to develop the petrochemical industries and the port logistics industries by the measures of land use planning adjustment and industrial structures scales adjustment. The prediction results are shown in Table 4 and Fig. 6.

| Industrial areas          | Bi | Pi  | Si  | Warning status |
|---------------------------|----|-----|-----|----------------|
| High-technology area      | 7.2| 5.2 | 0.72| Blue           |
| Advanced manufacturing area| 7.3| 6.5 | 0.89| Blue           |
| Business area             | 7.2| 5.8 | 0.81| Blue           |
| Ecotourism area           | 5.8| 2.7 | 0.46| Green          |
| Port logistics area       | 6.4| 6.3 | 0.98| Blue           |
| Petrochemical area        | 7.2| 7.2 | 1.00| Blue           |
| Agriculture area          | 7.4| 4.8 | 0.65| Green          |
Figure 5. Geo-environment carrying capacity prediction for the current steady tendency. (1-High-technology area, 2-Advanced manufacturing area, 3-Business area, 4-Ecotourism area, 5-Port logistics area, 6-Petrochemical area, 7-Agriculture area)

Figure 6. Geo-environment carrying capacity prediction of the industrial land use planning adjustment. (1-High-technology area, 2-Advanced manufacturing area, 3-Business area, 4-Ecotourism area, 5-Port logistics area, 6-Petrochemical area, 7-Agriculture area)
4. Conclusions
Firstly, the concept of the GCC was defined and the assessment indicators system was established for a case study of the TBNA.
Secondly, the assessment model of GCC based on the System dynamics (SD) theory was established and the concept of the carrying capacity index was proposed to measure the GCC in the assessment methods.
Finally, the different land use planning schemes vs. industrial structures adjustment and distribution of the TBNA were studied by the SD model and assessment methods of the GCC. The results show that about 15 percent over loading sub-areas was eliminated in the Tianjin Binhai New Area by land use re-planning and adjustment of industrial structures. The study proposed a new method for the assessment and early warning of the geo-environmental carrying capacity.

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