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Simulation modeling for wetland utilization and protection based on system dynamic model in a coastal city, China

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Abstract

Wetlands are distributed between terrestrial ecosystem and aquatic ecosystem with unique hydrological and biological characteristics. However, increased human activities have caused wetland destroyed at alarming rates. Wetland conservation has become world's focus. Tianjin as one of China's developed cities is drawing the attention of the world. The wetland ecosystems in this area have been recognized for providing various ecological functions. Therefore, study on wetland utilization and conservation for this area is of great significance. This research deals with the dynamic simulation modeling of wetlands utilization and protection, and analysis on potential sustainable management policies. The objective of the study is to find a balance between economic development and wetland protection in this region. To this end, a system dynamic model for wetland management was constructed. The model was based on the analysis of 24 indexes and five subsystems, which are population, ecological, environmental, scientific, economic and social system. The statistical data in Tianjin from 1990 to 2008 have been used to verify the model. We also selected six typical models for scenario simulation in 2010, 2030 and 2050. The results show that: (1) Current wetland management approaches lead to wetland degradation; (2) Different scenario runs reveal that the other five wetland management models have obvious advantages; (3) The major causes for wetland degradation are unreasonable industry structure and environmental pollution. As for the alternative policies tested, 'controlling population', 'improving wetland restoration technology', and 'improving industry structure' are sustainable policies that lead to better conditions. Thus, we suggested that ecological protection, population control and industrial structure adjustment are sustainable approaches to achieve wetland wise utilization and protection in this area.

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1. Introduction

Wetland ecosystem is one the most productive and the most diverse habitats all over the world, which is known as 'kidneys of the earth' and 'ecological supermarkets' to bring attention to the important functions it provide. Wetlands not only provide water resources, aquatic products for human, but also provide ecological function such as improving climate, cleaning water quality, and playing role in maintaining ecological balance. Wetlands have been used as a water source for irrigation, reclaimed for agricultural production, used as fish habitat, and exploited for aquaculture and urban development [1, 2]. However, increased human activities have caused wetland destroyed at alarming rates. During the 20th century, half of the world wetlands have been lost [3]. The speed of wetland loss is striking. The China State Forestry Bureau (http://www.forestry.gov.cn/) reported that China has lost at least 23.0% of its freshwater bogs, 16.1% of its lakes, 5.3% of its rivers, and 51.2% of its coastal wetlands to development in the past 50 years. In addition, 39.5% of the lakes, 27.2% of the coastal wetlands, and 24.5% of the bogs in 323 important Chinese wetland sites are threatened by pollution, and 43.3% of the lakes are threatened by excessive siltation. Cyranoski reported in 'Nature' magazine that some scholar found that nearly 30% of China's natural wetlands vanished between 1990 and 2000 [4]. It is worth noting that wetland management is crucial for wetland conservation. Therefore, sustainable management for wetlands has become an important issue. Wetland sustainable management aims at analyzing the relationship between wetland related components, so that to achieve the goal of sustainability, which means reasonable structure, effective function and harmonious relationships in ecosystem.

As we enter the new century, the research on wetlands is undergoing dramatic growth as an academic discipline and involves important approach, such as system dynamics (SD). SD, which was introduced by Jay Forrester in the 1960s [5], provides effective methodology for better understanding large-scale and complex management problems [6]. SD, which is based on system thinking, is a well-established tool for studying, analyzing and visualizing complex dynamic feedback systems. It requires constructing the 'causal loop diagrams' or 'stock and flow diagram' to form a system dynamics model for applications [7]. SD has been used in many areas including social management systems [8, 9], management decision making systems [10], business systems [11], agricultural systems [12], environmental systems [13-15]. In environmental systems, researchers have extensively used SD methodology to analysis green gas emission [16, 17], global warming [18], solid waste management [19], ecological modeling [20], and sustainable development [21-22]. Within the water resources management regime, SD has also been applied to related studies, such as water resource planning [23], eutrophication management [24-25], watershed planning and management [26], and many other situations.

Tianjin as one of China's developed cities is the center for Bohai Economic Rim, an emerging economic development region. It is becoming one of the Northern economic powerhouses, rivaling the Pearl River Delta in the south and Yangtze River Delta in the east and drawing the attention of the world. Consequently, the impacts of increased urbanization and human disturbance to wetland ecosystem will be greatly increased. The total area of wetlands in Tianjin is 363,086ha, in which natural wetlands and created wetlands account for 11.22% and 3.2% of total area of Tianjin. The wetlands in this area have been valuable as sources and sinks for chemical materials, and have been recognized for providing various habitats for wildlife. If less attention be paid to wetland conservation and protection, wetland ecosystem

will be lost at a high rate. Therefore, study on wetland utilization and protection for this area is of great significance.

This paper focused on a research for concrete policy measures to facilitate the wetland sustainable management in Tianjin. For this purpose, a system dynamics model has been developed to explore the potential long-term ecological, economic, and social interactions of wetland development. The model is used to test the outcomes of development policy scenarios and make forecasts. This study is aimed at providing a simulation platform to investigate the complex relationships between various components related to wetland management. The components in this study include population system, economic system, social system, scientific and technological system, ecological and environmental system. The study will simulate the wetland changes in the medium to long term, and investigate the possible outcomes of different scenarios under alternative government policies. The result may help local authorities better understand the complex relationship, and develop an improved regional environmental management strategy to balance economic growth and wetland conservation. The findings are expected to assist in the process of government's policy decision making concerning wetland management and sustainable development.

2. Study region



Fig.1. Location of Tianjin City in China

Tianjin (38°34'N-40°15'N and 116°43'E-118°194'E) is located in the Northeastern China, and bounded to the east by the Bohai Bay (Fig.1). It is a metropolis with area of approximately 11,760 km² and one of the five national central cities [27]. Climatic conditions are characterized by a temperate, continental monsoon climate, distinct seasons, and contemporary conditions for rain and heat. The average annual air temperature is 12.6°C, and total evaporation is about 1750~1840mm, total precipitation is about 500~600 mm, most of which falls between June and August. It is border Beijing Municipality, and the population of Tianjin ranks sixth in the People's Republic of China. At the end of 2010, the population of the Tianjin Municipality was 12.94 million and Tianjin's gross domestic product (GDP) was 140.9 billion US\$(910.8 billion RMB). Tianjin is known as one of China's developed cities is the center of Northern China and an emerging economic development region with rapid economic growth in recent years.

3. Model description

System dynamics model is based on interaction feedback between subsystems and indexes. The SD model for this study was developed for scenario building and conducting policy experiments for wetland management. A flow diagram, shown in Fig. 2, was established by incorporating the various features

related to the wetland management. The flow diagram was also present the association between each element in the diagram. The model so evolved was run for a period of 19 years starting from the baseline year 1990. The mutual interactions associated with wetland management are qualitatively expressed in the diagram. Dynamics of the model are determined by the feedback loops of the diagram. Each arrow in the diagram indicates the influence of one element on the other. The influence is considered negative (-) if a decrease in one element causes an increase in another or positive (+) in the opposite case. The diagram also shows physical and information flows in the SD model in detail. A single line represents information flow. A cloud symbol is showing for source and sink of the structure. The cloud symbol indicates infinity and marks the boundary of the model. The level variables are shown as rectangular boxes which indicate accumulated flows to that level. A double arrow indicates the physical flows, which is controlled by a flow rate. The rate variables are represented by valves. The information from the level variables to the rate variables is transformed by a third variable called the auxiliary variable, showed on or next to the double arrow. The symbol such as Gnr represents constants, which do not vary over the run period of simulation. Five subsystems corresponding to different scenarios are developed and discussed: population subsystem, ecological and environmental subsystem, social structure subsystem, and science and technology subsystem. The interactions/causal-effective relationships between the five subsystems are visualized as the diagram (Fig. 2). The details of the contents in the five subsystems are described below the diagram.



Bio.w-Productivity of wetland, Bld.r-Ratio of urban construction area, Eco.E-ecological and environmental level, G. Plc-economic policy, Gnr-net birth rate, Live.E-livable environment level, Mgr-net immigration rate, P. Dns-population density, P. Plc-population growth rate, Pop-total population, S.i.GDP-secondary industry output value, S.i.r-proportion of secondary industry, Swg.E-sewage discharge, Swg.tr-sewage treatment rate, Tcn.d- technological development level, Tcn.f- funds of science and technology for wetlands, Tcn.p-number of researchers of scientific and technological for wetlands, Tcn.r- investment ratio of scientific and technological research for wetlands, U. Plc-urbanization rate, Urb- urbanization level, Wat.r-rate of water resources change, Water-water resources, Wet.a-wetland area, Wet.r-proportion of wetland area. Iww-industrial waste water, L.s- domestic wastewater discharge

Fig. 2. Flowchart of wetland management system dynamics

3.1. Regional population subsystem

The total population (Pop.) was taken as level variables. Pop. depends on population growth rate (P. Plc) and livable environment (Live.E). P. Plc which includes net birth rate (Gnr) and net immigration rate (Mgr) had more impact on total population, thus, considered to be the main factors for the population subsystem. Pop. had effect on the urbanization level (Urb.), technological development level (Tcn.d), and ecological and environmental level (Eco.E). It was also influenced by livable environment level (Live.E).

3.2. Regional economic activities subsystem

We selected the gross domestic product (GDP) for the level variable, which mainly depends on economic policy (G. Plc). We focused on secondary industry output value (SiGDP) and funds of science and technology for wetlands (Tcn.f) as auxiliary variables to connect with other subsystems. SiGDP was influenced by the proportion of secondary industry (S.i.r), investment ratio of scientific and technological research for wetlands (Tcn.r). The secondary industry is the most important parts among the three industries. The index was connected with wetland ecological and environmental subsystem by industrial waste water (Iww). This subsystem was connected with the scientific technological subsystem by Tcn.f.

3.3. Ecological and environmental subsystem

This subsystem was reflecting the regional water resources, ecological conditions, environmental pollution, and human disturbance. The regional wetland ecological and environmental level (Eco.E) was taken as level variables in this subsystem. Regional water resources (Water), productivity of wetland (Bio.w), sewage discharge (Swg.E) and technological development level (Tcn.d) were the main factors influencing the Eco.E. Water resource condition in Eco.E was represented by the water resources (Water) and rate of water resources change (Wat.r). The Ecological and environmental subsystem was associated with social structure subsystem by ratio of urban construction area (Bld.r) which was influenced by wetland area (Wet.a) and Bio.w. This subsystem was associated with population subsystem and economic activities subsystem by Swg.E which was influenced by L.s and Iww. This subsystem was associated with other subsystems by auxiliary variables.

3.4. Regional social structure subsystem

Urbanization is one of the important indicators of socialization, which could connect the process of economic, population, and environmental subsystem. Urbanization level (Urb.) was taken as level variables in social structure subsystem. This subsystem was associated with the regional population subsystem by population density (P.Dns), and linked with the ecological and environmental subsystem by affecting the Ratio of urban construction area (Bld.r) to Wet.r.

3.5. Regional scientific and technological subsystem

Technological development level (Tcn.d) was taken as level variables in scientific and technological subsystem. It depends on Tcn.r, Tcn.f, and number of researchers of scientific and technological for wetlands (Tcn.p). It was indirectly affected by Pop and GDP. This subsystem was associated with population subsystem by Live.E and with ecological and environmental subsystem by Iww.

3.6. Data sources and data processing

The statistical data and investigated data were taken as the main data sources for this study. The data of eco-environmental indicators are originally from China Environment Yearbook (1990-2008). The other data are obtained in Tianjin Statistical Yearbook (1990-2008). We used software package Vensim (version 5.9) for system dynamics analysis and software SPSS (Statistical Program for Social Sciences, version 13.0) for data analysis.

4. Model validation

4.1. The parameters for the system dynamics model

According to the structural characteristics of wetland management system dynamics model, the parameters for the model were based on three kinds of methods. First, for the univariate parameters with high stability were determined by arithmetic average method with the historical statistical data, and trend extrapolation processing and by referring to the reference model. Second, for the parameters with obvious relationship between the variables and adequate historical data were calculated by statistical regression analysis. Third, for the parameters without obvious relationship between the variables or adequate historical data were defined by table functions.

4.2. Modeling validation

It is necessary to make sure whether the model dynamically reflects the relationship among the variables, and in what extent the model fits actual situations [7]. Model validation and testing aim at justifying the reliability of the model and providing confidence for the model further application. This step is crucial, because the purpose of a system dynamics model research is to systematically facilitate learning as the essential prerequisite to the evaluation of alternative structures (e.g., strategies, policies) in order to improve the system behavior [28]. Accuracy of the model behaviour is meaningful only if there is sufficient confidence in the structure of the model [21]. The wetland related statistical data from 1990 to 2008 in Tianjin were used to conduct model testing and validation. The results of testing and validation showed that the relative errors between simulation and real values range from -7.6% to 6.8%. Thus, the system dynamics model was reliable and could be applied in wetland sustainable management scenario analysis.

5. Scenario and policy analyses

According to scenario and policy analysis, modifications on the base model were discussed in order to attain a better understanding of the dynamic system and improve the model with policy recommendations. We predicted the wetland changes in future 2years, 20 years and 40 years to reveal that if the wetland management policies are sustainable. The results were used to design recommendations for the management of the wetland region. All policies were introduced in the model in the beginning of the year 2008 and the time horizon is taken to be 2years, 20 years and 40 years.

5.1. Scenario I: current wetland management policies

Scenario I is the current management mode under current wetland management policies. The simulation results show that: ①Wetland area will be reduced in 2030 and 2050. Tianjin wetland area will

be 3.62×10^3 km² and 3.20×10^3 km² in 2030and 2050, reduced by 0.3% and 11.7% compared with 2010, respectively (Fig. 3).⁽²⁾ Wetland production will increase slightly by 0.53% and up to 44.47×10⁴t in 2050 (Fig. 4). ⁽³⁾Human induced environmental pressure for wetland will increase. The sewage discharged into the wetlands in 2030 and 2050 will be 5.5×10^8 t and 6.9×10^8 t, respectively. The average sewage discharged into the wetlands will increase by 2.00% (Fig. 5). ⁽⁴⁾The regional ecological and environmental level for wetland will be 0.054 and 0.049 in 2030 and 2050, respectively. The index will decrease by 12.2% and 20.6% compared with that in 2010, with an average decrease rate of 0.520% (Fig. 6). Thus, current management mode with current policies is not sustainable.



Fig.3. Wetland area (103km2)



Fig.5. Sewage discharged into the wetlands $(10^8 t)$





Fig.6. Ecological and environmental level for wetland

5.2. Scenario II: Population control mode

Population control mode is to adjust and control the population growth as the main management policy. Average annual growth rate of population in Tianjin from 1990 to 2008 was 1.56%, which is higher than the national average growth rate. Therefore, a scenario analysis regarding 'reduction by 2% in average annual growth rate (actual growth rate is 1.53%) of population' was done to find out what wetland will change in that case. The simulation results show that: ①average annual reduction rate of wetland area is decreased by 0.19% during future 40 years. ②The wetland production will increase by 0.73% in average annual rate during future 40 years. The wetland area and wetland production index indicate that scenario II is better than scenario I. ③The population growth rate will increase slightly slow, domestic sewage

discharge will decrease. The sewage discharge will increase by 58.0% in 2050 compared with 2010, with annual increase rate of 1.45%. This index indicates that the human impact on the wetland environment is smaller than scenario I with current management policies. (4) The ecological and wetland environmental level show that the ecological and environmental index will increase by 1.0% and 2.5% in 2030 and 2050, respectively, with an average annual increase rate of 0.063%. The overall wetland environment will be improved than that scenario I under this population control policy. This scenario has potential of wetland sustainable development.

5.3. Scenario III: economic adjustment policies

Tianjin economic had experienced rapid development from 1990 to 2008 with an average annual growth rate of 18.2% in GDP. During 19 years, industrial structure adjustment and optimization have been accelerated in Tianjin. The proportion of secondary industry has declined. Therefore, a scenario analysis regarding 'reduction by10% in the proportion of secondary industry (actual proportion of secondary industry is 50%)' was conducted to investigate what results will emerge. The simulation results show that: ①Average annual reduction rate of wetland area is 0.20%, average annual increase rate of wetland production is 0.77%. The ecological and environmental level of scenario III is better than that of scenario II. ②The sewage discharge to wetlands will increase by 34.7% and 61.8% in 2030 and 2050 with an average annual increase rate of 1.53%. ③The regional ecological and environmental level in scenario III is better than that in scenario I and worse than that in scenario II with an average increase rate of 0.027%. Therefore, scenario III with economic adjustment policies for wetland management has potential of sustainable development.

5.4. Scenario IV: ecological and environmental adjustment and control policies

We divided ecological and environmental adjustment policies into environmental adjustment policies (scenario IV-1) and ecological adjustment policies (scenario IV-2). Scenario IV-1 is to reduce and control human impacts on wetlands, mainly including sewage treatment improvement. Scenario IV-2 is to adjust the ecological policies, mainly including wetland water supplement.

Scenario IV-1: The sewage treatment rate was 56% in Tianjin during last 19 years. Therefore, a scenario analysis regarding 'increase sewage treatment rate by10 % (actual rate is 66 %)' was conduct to ask what would happen in wetland change in that case. The simulation results show that: ①Wetland area will decrease by 0.17% and 8.25% in 2030 and 2050 compared with that in 2010. The average annual reduction rate of wetland area is 0.21%. ②The average annual increase rate for wetland production is 0.91%. ③The average annual increase rate of sewage discharge is 1.58%. ④The ecological and environmental level will increase with an average annual increase rate of 0.082%.

Scenario IV-2: This scenario analysis is to investigate what if 'increase water supplement by 2 %' to happen in wetland change. The simulation results show that: ①The reduction rate of wetland area are 0.15% and 7.89% compared with that in 2010, with an average annual reduction rate of 0.20%. ②The increase rate of wetland production are 15.0% and 29.8% compared with that in 2010, with an average annual increasing rate of 0.74%. ③The average annual increase rate of sewage discharge is1.53%. ④The average annual increase rate of wetland ecological and environmental level is 0.166%.

Overall, scenario IV-1 and scenario IV-2 with environmental and ecological adjustment policies are better than that of scenario I and scenario III for wetland management.

5.5. Scenario V: Scientific and technological promotion policies

Scientific and technological management policies involve increasing investment in research of wetlands and promoting scientific and technological development. The investment of science and technology for Tianjin wetland research was 2.865 billion yuan (0.421billion\$) in 2008, with an increase rate of 28.3% over the previous year. Scenario V is regarding to 'increase proportion of investment of scientific and technological research for wetlands by 50%' to see what result will show in that case. The simulation results show that: ①Wetland area will decrease by 0.12% and 7.50% in 2030 and 2050, with an average annual decrease rate of 0.18%. ②Wetland production will increase by 11.46% and 21.66% in 2030 and 2050, with an average annual increase rate of 0.54%. ③Sewage discharge into wetland will increase by 41.80% and 74.00% in 2030 and 2050, with an average annual increase rate of 1.85%. ④The ecological and environmental level is better than that of scenario I. Human impacts for wetland is less than scenario I, but higher than scenario II, scenario III, and scenario IV. The level of wetland environment will decrease by 0.44% annually, slightly better than scenario I, however, this scenarios is not as good as other scenarios.

5.6. Scenario VI: social adjustment policies

Urbanization adjustment management policy is one of the most important parts in the social management policy. Tianjin had rapid social development with the urbanization index of 55%-60% from 1990 to 2008. Scenario VI is regarding to 'reduction of urbanization by 50% of the original index'. The simulation results show that: ①The average annual reduction rate of wetland area is 0.07%. ②The average annual increase rate of wetland production is 0.27%. ③The average annual increase rate of sewage discharge to wetland is 3.85%, much higher than other scenarios under other policies. It is mainly because a lower level of urbanization is not conducive to sewage centralized treatment. Human factors on the wetland environment could cause greater impacts. The ecological and environmental level of wetland will decrease by 1.43% annually, which has discrepancy with other scenarios. Scenarios VI is not as good as other scenarios in ecological condition of wetland ecosystem, human environmental impact, and overall regional ecological and environmental level for wetlands.

6. Discussions

6.1. Management policies selection

We compared with seven scenarios under different management policies. In view of the simulation results, scenario I is not conducive to wetland sustainable management. Four indexes indicate that scenario II is better than scenario I. The wetland production and sewage treatment capacity in scenario III are much better than scenario I, and wetland area and ecological level in scenario III ranked fourth among

seven scenarios. Scenario IV-1 which has characteristics of wetland sustainable management could be used as auxiliary development mode, but need to be further improved. Scenario IV-2 with ecological adjustment policies is better than that of scenario I for wetland management. Although scenario V and scenario VI have advantages in some indicators, they could not reach the objective of wetland sustainable development overall. Therefore, scenario II, scenario III, and scenario IV-2 are sustainable management for wetlands (Table 1). Population control, industry structure adjustment and environmental adjustment should be worthy strategies to be recommended.

Scenarios	Ι	II	III	IV-1	IV-2	V	VI
Wetland area (Wet.a)		*	☆		☆	**	***
Wetland production (Bio.w)		☆	**	***	*		
Sewage treatment capacity (Swg.E)		***	**	☆	**		
Ecological and environmental condition (Eco.E)	×	*	${\simeq}$	**	***	×	×

Table 1 Selection of sustainable management policy for wetlands

 \star symbol indicates the prior index in seven scenarios, $\star \star \star$ indicates most optimal level, $\star \star$ indicates more optimal level, \star indicates optimal level, \Leftrightarrow indicates the middle level of seven scenarios, \times indicates the scenario that does not meet selection requirements.

6.2. Analysis of the management policies

The sustainable wetland management of urbanization and eco-environment in Tianjin is a dynamic process, rather than a static process. The system is affected by many factors, such as population, social policy, economic structure, ecological and environmental conservation conditions. Therefore, systemic analysis and dynamic modeling of are essential for the future wetland management sustainability. After systemic analysis, modeling simulation and scenario analysis, the prior management policies for wetland sustainable management emerged. Firstly, the population control policies are essential for future wetland sustainability. It is because more population could lead to more pressure for wetland conservation infrastructure and heavy eco-environmental pollution. Secondly, rapid economic growth will also lead to eco-environmental pollution pressure and natural resource pressure. The proportion of secondary industry is one of the most important parts among the economic indicators. Thus, enhancing industrial structure adjustment and optimization is also the sustainable management policy. Thirdly, social adjustment policies especially controlling the speed of urbanization can availably meet the goal of urban sprawl and urban infrastructure improvement, but it not suitable for the sustainable management for wetlands. This is mainly because that urbanization is conducive to research of advanced ecological and environmental related technology and application of the technology. Thus, urbanization contributes to improving regional ecological and environmental levels for wetlands. This result is in agreement with Shen's [29] observation that social urbanization can not only rapidly promotes urban socialization process, but also effectively protects eco-environment condition.

This SD model addresses wetland management problem by integrating the coupling relationship evaluations, forecasting of potential wetland changes, and assessing wetland management sustainability into a general framework. It can reflect midterm and longterm wetland changes in different oriented policies. The SD model is characteristic of systematic, integrated, and dynamic. The dual goals of economic growth and wetland conservation need to be satisfied in the sustainability management process, especially for the cities experiencing rapid development in Tianjin, China. The selection of index of the system is also essential for developing the SD model and assessing relationship of the components in the system. The 24 critical variables in this study are associated with the special goals of wetland sustainability management for eco-environmental and socio-economic requirements. Meanwhile, the systematic and complex characteristics of the SD model make the system analysis be an essential tool for supporting the scenario analysis under different sustainable management policies. The SD model is a basic and useful tool for forecasting the potential wetland changes and evaluating management sustainability.

7. Conclusions

The major objective of this research was to construct a framework to analyze the interactions between the ecological, social and economic factors related to wetlands in Tianjin. To this end, a system dynamics model of wetland management was built. Validation tests were conducted with available data and qualitative tests indicate that the model could be the base for further scenarios analysis. The study found that wetland management system dynamics model is a multi-feedback, multi-interface and nonlinear complex system. Seven scenario analyses with seven different management policies runs were conducted. The scenario analysis found that: (1)the current management mode has obvious defects for the future development. The ecological and environmental condition of wetlands will become worse, environment pollution will increase, and the environment will be significantly deteriorated. Therefore, it does not meet wetland sustainable development requirement under current management, and need to be improved. ⁽²⁾Promoting technological development, and slowing down urbanization process are helpful for certain aspects of wetland development, but they are not essential ways for solving the sustainable related problems. ③Environmental control methods such as enhancing sewage treatment technology could be assistant policy for wetland sustainable management due to some indicators need to be improved. (4) The sustainable management policies are ecological protection, population control and industrial structure adjustment for wetlands. We suggest that these methods could be applied in wetland sustainable management in the future.

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