Bi-Level Programming-Based Regional Ecological Management Model in Xiamen

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Abstract: The shortage of land resources, ecological damage and pollutant discharge pose great challenges to the sustainable development of Xiamen. In this study, a bi-level programming (BP) is developed to manage the regional ecosystem of reclamation (REM). BP can balance the trade-off between the two decision makers, including maximizing the system benefit as the upper level goal, maximizing the ecological service value as the lower level goal, and constructing the regional ecosystem management system model in Xiamen. The main research results are: (i) Carbon fixation, oxygen release and water conservation are the main ecological service value of ecosystem; (ii) The system benefits would reduce by 15.3%, while the ecological service value would increase by 17.6%; (iii) Compared with single level model, COD, NH₃-N, SO₂, solid waste emissions could reduce by 32.8%, 9.0%, 16.1%, 24.7% and 31.5% respectively.

Keywords: bi-level, ecological service value, ecosystem, emission

1. Introduction

China has a long mainland coastline, and coastal areas raise 40% of the population with 15% of the territory, creating more than half of the GDP. With China's economic development and increasing land demand, large-scale reclamation projects are a common way to develop into Marine space in the process of urbanization. Although a large amount of land resources and economic benefits have been obtained in the short term, reclamation projects from the long-term sustainable development perspective have caused a permanent break to the coastal belt ecology and Marine ecosystem.

Chaikaew et al. [1] assessed the preference of climate regulation, water purification, material productivity in ecosystem service functions, providing effective theoretical reference for the management and protection of regional ecosystems. Guimaraes et al. [2] developed forest ecological service indicators through questionnaire and index selection, and finally obtained 25 ecological service indicators of Atlantic Forest area, providing an effective reference for regional ecosystem planning and management. Cooper et al. [3] used geographic information technology in Northern Ireland to actually investigate the coastal defense structure and analyzed the impact of defense structure on coastal ecosystems. The bi-level programming was first proposed by Stackelberg to effectively solve the multi-layer decision problem. Both upper and lower models have respective objective functions and decision variables, which both are interconnected [4][5]. Ma et al. developed a bi-level programming for water allocation system. Upper planning pursues maximizing the benefits of the
system, and the lower level seeks minimum overall water distribution to ensure the water resource demand of Amu River basin [6]. Jin et al. used bi-level programming to manage air quality. This results analysis can help different decision makers adjust tolerance to achieve overall satisfactory degree with studying energy system programming [7]. However, few people currently use bi-level programming for ecosystem management.

The purpose of this study is to develop a regional ecological management of reclamation (REM) model based on a bi-level programming (BP). The REM model will be applied to Xiamen reclamation project. These results will advise decision makers on the best regional ecosystem management and analyze the trade-offs between system benefits and ecological value and decision maker satisfaction in-depth.

2. Methodology

Bi-level programming is a multi-objective optimization that involves two decision makers, the upper decider and the lower decider [8]. It can be defined as follows [9]:

\[
\begin{align*}
\text{Max } & f_1(x_1, x_2) \\
\text{Max } & f_2(x_1, x_2) \\
G = & \{ (x_1, x_2) | g_1(x_1, x_2) \leq 0, i = 1, 2, ..., m, x_1, x_2 \geq 0 \}
\end{align*}
\]

First, we solve the upper decision problem, assuming that the result of the upper model is \( (x_1^u, x_2^u, f_1^u) \), then solving the lower decision problem, assuming the result of the lower model is \( (x_1^l, x_2^l, f_2^l) \). The decision variable \( x_i \) should be within the range of \( x_i^u \), with a maximum tolerance value of \( p_i \). The membership function of the decision \( x_i \) can be stated as [10]:

\[
\mu_{i} \left( x_i \right) = \begin{cases} 
\frac{x_i - (x_i^u - p_i)}{p_i}, & \text{if } x_i^u - p_i < x_i \leq x_i^u \\
\frac{(x_i^u + p_i) - x_i}{p_i}, & \text{if } x_i^u < x_i \leq x_i^u + p_i \\
0, & \text{if otherwise}
\end{cases}
\]

\( x_i^u \) is the most satisfactory decision. \( x_i^u + p_i \) and \( x_i^u - p_i \) are the worst acceptable decision. The deciders' preference would continually increase within \([x_i^u - p_i, x_i^u]\), while preference would continually decrease within \([x_i^u, x_i^u + p_i]\). Since the upper level model pursues the maximum target value, so all \( f_i \geq f_i^u \) being fully acceptable. The lower level model can obtain the optimum at \((x_1^l, x_2^l)\), whose value in the upper level objective function is \( f_i \), leading to any \( f_i \leq f_i = f_i \left( x_1^l, x_2^l \right) \) fully unacceptable. The following membership function can be stated as:

\[
\mu_{i} \left( f_i \left( x \right) \right) = \begin{cases} 
1, & \text{if } f_i \left( x \right) > f_i^u \\
\frac{f_i \left( x \right) - f_i^u}{f_i^u - f_i}, & \text{if } f_i^u \leq f_i \left( x \right) \leq f_i^u \\
0, & \text{if } f_i \left( x \right) < f_i^u
\end{cases}
\]

Similarly, the lower level decision obtains a membership function:
$$\mu_i \left( f_z (x) \right) = \begin{cases} 
1, & \text{if } f_z (x) > f^L_z \\
f_z (x) - f^L_z \over f^L_z - f^L_z, & \text{if } f^L_z \leq f_z (x) \leq f^L_z \\
0, & \text{if } f_z (x) < f^L_z 
\end{cases} \quad (4)$$

where $f_z = f_z \left( x^L, x^U \right)$. The lower level will fully accept all $f_z (x) > f^L_z$ and not accept any $f_z (x) < f^L_z$ due to the same reason. Thus, the optimal solution for the overall satisfaction degree of the upper and lower levels can be expressed as [11]:

$$\max \lambda \quad (5a)$$

Subject to: $x \in G, \mu_i \left( x_i \right) \geq \lambda \theta$, $\mu_i \left[ f_z (x) \right] \geq \lambda$, $x_i, x_2 \geq 0$, $\lambda \in [0,1]$ \quad (5b)

where $\lambda$ is the overall satisfactory degree, and $I$ is a column vector and its all elements are equal to 1.

3. Case Study

Xiamen is located on the southeast of Fujian Province, China, and covers a land area of 1700 square kilometers, including a coastline of 234 kilometers and a sea area of 390 square kilometers. The study area is located in the Tongan Bay area of Xiamen City, and covers an area of about 89.9 square kilometers. At present, the research field has become a new industrial manufacturing and trade center in Xiamen City. Here, electronic information, automobile manufacturing, container terminal, real estate development and other industries are booming. In response to rapid economic development, population growth, and urbanization, a reclamation scheme of about 20km$^2$ has been proposed, accounting for 16.33% of Tongan Bay area [12].

4. Modeling Formulation

The upper level target is to maximize the system benefits, including the benefits for human productive activity and the benefit for ecological benefit. The lower level target is to maximize the ecological service value while satisfying certain human activity land.

Objective function:

Upper level: $\max f = PROIND + PROECO$

Lower level: $\max f = PROECO$

(1) Economic benefits of industrial land:

$$PROIND = \sum_{i=1}^{4} \sum_{t=1}^{2} L_i \times PI_{i,j} \times IEB_{i,j}$$

(2) Ecosystem service values:

$$PROECO = \sum_{i=1}^{4} \sum_{t=1}^{2} L_i \times PE_{i,j} \times HYE_{i,j} \times HP_t + \sum_{i=1}^{4} \sum_{t=1}^{2} L_i \times PE_{i,j} \times CAC_{i,j} \times CT_i$$

$$+ \sum_{i=1}^{4} \sum_{t=1}^{2} L_i \times PE_{i,j} \times CAC_{i,j} \times OP + \sum_{i=1}^{4} \sum_{t=1}^{2} L_i \times PE_{i,j} \times \left( CAS_{i,j} \times CSR + CAN_{i,j} \times CRN + ADE_{i,j} \times CDA \right)$$

$$+ \sum_{i=1}^{4} \sum_{t=1}^{2} L_i \times PE_{i,j} \times SWE_{i,j} \times CWT_t + \sum_{i=1}^{4} \sum_{t=1}^{2} L_i \times PE_{i,j} \times 10 \times LP_t \times SRE_{i,j} \times RC_t + \sum_{i=1}^{4} \sum_{t=1}^{2} L_i \times PE_{i,j} \times CWE_{i,j} \times CST_t$$

$$+ \sum_{i=1}^{4} \sum_{t=1}^{2} L_i \times PE_{i,j} \times CES_t + \sum_{i=1}^{4} \sum_{t=1}^{2} L_i \times PE_{i,j} \times VBE_{i,j} + \sum_{i=1}^{4} \sum_{t=1}^{2} L_i \times PE_{i,j} \times ETV_{i,j}$$

Constraints:

(1) Reallocated land constraints: $\sum_{i=1}^{4} \sum_{k=1}^{4} PE_{i,j} + \sum_{k=1}^{4} PI_{i,j} \leq S_t, \forall t$

(2) COD discharging constraint: $\sum_{k=1}^{4} PI_{i,j} \times CPI_{i,j} \times (1 - CRI_{i,j}) - \sum_{i=1}^{4} PE_{i,j} \times CAE_{i,j} \leq ACD_t, \forall t$
(3) NH$_3$-N discharging constraint: $\sum_{k,t}^4 PI_{k,t} \times NPI_{k,t} \times (1 - NRI_{k,t}) - \sum_{i,t}^4 PE_{i,t} \times NAE_{i,t} \leq AND_t, \forall t$

(4) Carbon emission constraint: $\sum_{k,t}^4 PI_{k,t} \times CEI_{k,t} - \sum_{i,t}^4 PE_{i,t} \times CAC_{i,t} \leq ACE_t, \forall t$

(5) Solid waste discharging constraint: $\sum_{k,t}^4 PI_{k,t} \times SWI_{k,t} \times (1 - RI_{k,t}) - \sum_{i,t}^4 PE_{i,t} \times SWE_{i,t} \leq ASW_t, \forall t$

(6) Forestry and grass coverage constraint: $\sum_{k,t}^4 PI_{k,t} \times VAE_{i,t} + \sum_{k,t}^4 PI_{k,t} \times VAI_{i,t}) / S_i \geq PFG_t, \forall t$

(7) Ecological water demand constraint: $\sum_{i,t}^4 (1 - MOE_{i,t}) \times CCE_{i,t} \times SRE_{i,t} \times PE_{i,t} \leq AEQ_t, \forall t$

(8) Sewage purification constraint: $\sum_{k,t}^4 PI_{k,t} \times SDI_{k,t} \times (1 - TRW_{k,t}) - \sum_{i,t}^4 PE_{i,t} \times CWE_{i,t} \leq AWD_t, \forall t$

(9) SO$_2$ discharge constraint: $\sum_{k,t}^4 PI_{k,t} \times DDI_{k,t} \times (1 - DRW_{k,t}) - \sum_{i,t}^4 PE_{i,t} \times CAS_{i,t} \leq ASD_t, \forall t$

(10) Area scale constraint: $\sum_{i,t}^4 PE_{i,t} / \sum_{k,t}^4 PI_{k,t} \leq 2, \ PE_{i,t} \geq MINE_{i,t}, \ PI_{k,t} \geq MINI_{k,t}, \forall i, \forall k, \forall t$

5. Result and Discussion

Figure 1 presents ecosystem service value from BP model. CO, WC, RP, PA, SW, SP, SF, BY and LE means carbon fixation and oxygen release, water conservation, raw material provision, air purification, solid waste purification, sewage purification, soil conservation, biodiversity, and leisure entertainment respectively. According to the estimation results, the value of carbon fixation and oxygen release and water conservation occupy the main position, which indicates that the urban ecosystem plays an important role in promoting carbon emission reduction and water resources protection. During the second period, various ecological service value would all increase. This is mainly because the model would allocate more ecological land area to purify the pollutants as allowable amount of pollutant emission decreases in the second period. With more attention to carbon emission reduction and the growth of carbon tax, carbon fixation and oxygen release value of urban ecosystem is far more than other ecological services value. Therefore, government departments should vigorously strengthen ecological construction and protection, give full play to various ecological service functions, and achieve the effect of sustainable utilization of ecological resources.

Figure 1. Ecosystem service value from BP model

Figure 2 presents the planning area of each type of land. The human activity land area would decrease from 931.4 ha to 749.0 ha in the first period, and the area from 887.9 ha to 720.8 ha in the second period. Instead, the ecological land area would rise, and during the first period, the area would
increase from 992.7 ha to 1175.1 ha, in the second period, and the area would increase from 1036.1 ha to 1203.2 ha. Although system benefits would decrease from 376.5×10^9 RMB¥ to 318.9×10^9 RMB¥, the ecological service value would increase from 2.03×10^9 RMB¥ to 2.39×10^9 RMB¥. This is mainly because the economic benefit of industrial land is higher compared with the ecosystem, and when the target function of the model is economically maximized, the model will be allocated to the less land area of the ecosystem to meet the maximization of the system benefits. When the ecological optimum is considered, the economic benefits of industrial land will no longer play a dominant role.

The overall satisfactory degree of this bi-level model is 0.544, indicating that the BP-REM model also obtains an eco-friendly planning scheme while pursuing economic benefits, mainly because the decision makers of traditional single models mainly focus on the overall system benefits, while the ecological value accounts for a relatively small system income, often ignoring the long-term value of the ecological environment. BP decision maker can consider the balance of system benefits and ecological service value and obtain appropriate solutions from an economic and ecological perspective.

Figure 2. The planning area of each type of land

Figure 3 presents the results of pollutant emissions. Compared to the traditional single level model, the emission of the bi-level model would reduce. During the two planning periods, COD emissions would reduce from 7375.0 ton to 4955.5 ton, by 32.8%; The NH₃-N emissions would reduce from 3900.0 ton to 3548.5 ton, by 9.0%; The SO₂ emissions would reduce from 4680.0 ton to 3927.5 ton, by 16.1%; Solid waste emissions would reduce from 238.3×10^3 ton to 179.5×10^3 ton, by 24.7%; Sewage discharge would reduce from 14.3×10^6 ton to 9.8×10^6 ton, by 31.5%. The results show that the bi-level model has a reduction effect on pollutant emissions. In addition to the artificial degradation of pollutants, the purification capacity of the ecosystem also plays an important role in the pollutant emission reduction. When decision makers more prefer ecological construction, the more significantly the ecosystem purify pollutants. Then the decision makers would weigh the pollutant emission of economic benefits and the intensity of pollutant reduction. This not only reduces human degradation costs, but also promotes urban sustainability.

Figure 3. The results of pollutant emissions
6. Conclusion
In this study, a bi-level programming (BP) based Xiamen regional ecosystem management model (BP-REM) is developed. The developed model represents a decision strategy for system benefits as a leader and ecological service value as a follower, with optimization solutions such as land planning, ecological value and pollutant emissions. Furthermore, trade-offs between different decision makers are obtained effectively solved and quantified, and the results from the single and bi-level model are compared. Based on the result analysis and discussion, the following conclusions can obtain: Carbon fixation and oxygen release and water conservation are the main ecological service value of the regional ecosystem in Xiamen; The system benefits of bi-level programming would reduce by 15.3%, but ecological service value would increase by 17.6%, the land planning would be more friendly to the ecological environment, and some human activity land would be converted into ecological land; Bi-level programming would promote pollutant reduction.

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Appendix
\( f \): system benefit (RMB\¥)
\( i \): ecological land; \( i=1, 2, 3, 4 \) (for urban green area, tidal flats, mangrove, artificial wetland)
\( k \): human activity land; \( j=1, 2, 3, 4 \) (for residential and commercial land, container terminal, electronic
information industry, automotive industry)

$t$: period; $t = 1, 2$ (for years of 2021-2025, years of 2026-2030);

$PROIND$: economic benefits (RMB¥)

$PROECO$: ecosystem service values (RMB¥)

$PIk,t$: planning area of human activity land $k$ (ha)

$PEl,t$: planning area of ecological land $l$ (ha)

$S_i$: planning area of land reclamation (ha)

$IEBk,t$: economic benefit of human activity land $k$ (RMB¥/ha)

$HYE_i,t$: hay yield (ton/ha)

$HP_t$: hay prices (RMB¥/ton)

$CACi,t$: capacity to absorb $CO_2$ (ton/ha)

$CT,t$: carbon tax (RMB¥/ton)

$OP_t$: oxygen production price (RMB¥/ton)

$CAS_i,t$: capacity to absorb $SO_2$ (ton/ha)

$CSR_t$: cost of $SO_2$ removal (RMB¥/ton)

$CAN_i,t$: capacity to absorb $NO_x$ (ton/ha)

$CNR,t$: cost of $NO_x$ removal (RMB¥/ton)

$ADE_i,t$: absorbing dust ability (ton/ha)

$CDA_t$: cost of dust absorption (RMB¥/ton)

$LP_t$: local precipitation (mm)

$SRE_i,t$: surface runoff coefficient (%) 

$RC_t$: cost of the water (RMB¥/m³)

$CWE_i,t$: capacity to purify water quality (ton/ha)

$CST_t$: cost of sewage treatment (RMB¥/ton)

$SEE_i,t$: soil erosion index (ton/(ha·a))

$CES_t$: costs of excavation and transportation of soil (RMB¥/ton)

$VBE_i,t$: the value of the biodiversity (RMB¥/ha)

$ETV_i,t$: entertainment and tourism value (RMB¥/ha)

$SDl,t$: sewage discharge of human activity land $k$ (ton/ha)

$SWl,t$: solid waste produced from human activity land $k$ (ton/ha)

$CWT_t$: cost of solid waste treatment (RMB¥/ton)

$TRWk,t$: treatment rate of sewage (%) 

$AWD_i$: allowable amount of sewage discharge (ton)

$CPIk,t$: COD produced from human activity land $k$ (ton/ha)

$CRIk,t$: COD removal rate (%) 

$NAEi,t$: COD absorption ability (ton/ha)

$AND_t$: maximum allowable discharge of COD (ton/ha)

$NPIk,t$: $NH_3$-N produced from human activity land $k$ (ton/ha)

$NRIk,t$: $NH_3$-N removal rate (%) 

$NAXi,t$: $NH_3$-N absorption ability (ton/ha)

$ACE_t$: maximum allowable emission of carbon (ton)

$RIk,t$: solid waste recovery rate (%) 

$SWEXi,t$: solid waste absorption ability (ton/ha)

$ASW_t$: maximum allowable discharge of solid waste (ton)

$VAEil,t$: vegetation coverage of ecological land $l$ (%) 

$VALk,t$: vegetation coverage of human activity land $k$ (%) 

$PFG_t$: the forestry and grass coverage (%) 

$DDIk,t$: $SO_2$ produced from human activity land $k$ (ton/ha)

$DRIk,t$: $SO_2$ removal rate (%)
ASD: maximum allowable discharge of SO₂ (ton/ha)
AEQ: available ecological water demand (m³)
AWD: maximum allowable discharge of sewage (ton/ha)
MOE: moisturizing coefficient (%)
CCE: water conservation volume (m³/ha)
MINE: minimum area of ecological land i (ha)
MINI: minimum area of human activity land k (ha)