Comprehensive Watershed Management Policies in the Dian Chi Lake
China with a Focus on Non-point Source Pollution

Hong Li*, Feng Xu**, Takeshi Mizunoya***, Jianchao Luo****, Helmut Yabar***** and Yoshiro Higano******

Abstract
Nitrogen and phosphorus mainly from non-point source pollution are the major nutrients that cause eutrophication and degrade water quality. The most serious environmental problem of Dian Chi Lake is eutrophication. Continuing deterioration of the water quality of the lake threatens the drinking water of Kun Ming City and greatly affects local economic development and people’s lives. Therefore, in this study, we chose Dian Chi Lake as a case study to consider all factors that influence water quality by focusing on non-point source pollution. The interrelationships between environmental and socio-economic indicators and variables were described and integrated into a dynamic linear mathematical model. The computer simulation approach was used to make comprehensive environmental policies and to evaluate the most cost effective measures to effectively improve water quality. The simulations were run with the computer-based programming software called LINGO.

JEL Classification : C61, Q01, Q53
Keywords : Environmental Quality, Non-point Source Pollution, Simulation, Watershed Management

1. Introduction
Dian Chi Lake (Fig. 1) is one of the most polluted lakes in China. Improvement of the environment in the lake and its watershed has been listed as one of the Chinese national key targets, “three rivers and three lakes.” The water of Dian Chi Lake has shown serious eutrophication, which also becomes a serious threat to the sustainable development of Kun Ming City. Therefore, environmental policies must be implemented promptly. However, since 80% of the gross national product of Kun Ming City is produced in the watershed, a comprehensive watershed management must be introduced in order to minimize negative impacts of the implementation on the socio-economic development of Kun Ming City.

There are many studies that have been done in dealing with water pollution problems. Mizunoya et al.
analyzed synthetic environmental policy by including biomass recycle plant in the policy options. The watershed of Dian Chi Lake locates in the undeveloped area of China (developing country) that is different from Japan (developed country). Yan et al. [9] analyzed that protection of water environment is of the greatest priority in Miyun reservoir and objective function was constructed to minimize the total load of water pollutant T-N. The watershed area of Dian Chi Lake is also different from Miyun reservoir. The government gives the priority to the development of local economy. Therefore, the objective function was constructed to maximize GRP.

In this study, the computer simulation with the socio-economic and ecological model of the watershed profiled the best watershed management in the sense that it maximizes reduction in the water pollutants that flow into the Lake while it minimizes the negative impacts on the socio-economic activities in the watershed area. The watershed of the Lake is the region in which chemical fertilizer used by agricultural production per acre is most in China. So, in this study we especially focus on control of the pollutants from land use. The policy that gives motivation to farmers to use low–elution fertilizer, which is a kind of coated fertilizer to control elution of nutrient into soil, is included in the policy options. Hopefully, we can provide useful ideas and information for the municipal leaders who are responsible for managing the water quality of Dian Chi Lake.

2. Methods

In order to improve water quality in the Lake, first of all, the amount of pollutants that are generated in the watershed and flow into the Lake must be reduced. With the above reason a comprehensive watershed management must be implemented for the reduction. In order to reduce the generation of water pollutants, new technologies must be introduced in the watershed management since the policies so far implemented have not improved the situation drastically. The computer simulation with the socio-economic and ecological model of the watershed will profile the best watershed management; it identifies the best combination of technologies in the choice set, which is composed of new technologies as well as those of the current policies, for implementing the best comprehensive watershed management; it identifies the scale of the total budget necessary for implementing the best profiled watershed management; it identifies the best assignment of the budget for investment into selected technologies and related policies in the dynamic and spatial context, etc.

Non-point source of pollution, unlike point source of pollution composed of farm, household, sewage treatment plant, etc., is the source of pollution whose discharge of pollution cannot be easily corresponded to the related activities at the individual level. Typical example of the pollution is due to the usage of the chemical fertilizer by the agricultural production in the watershed. We assume generation of water pollutants by the agricultural production is dependent on the area of land that is devoted for the production. Therefore, in
this study we classify the pollution generation sources into three types: industry, household, and land use. Each is further classified into several categories depending on the adopted treatment technologies, industrial sectors, minutes of land use, etc.

The simulation models are composed of the following two sub models and one objective function: the socio-economic model and the material flow balance model. The socio-economic model describes the social and economic activities in the watershed and the relationship between the activities and the emission of pollutants. The material flow balance model describes change in the amount of generation and flow of pollutants in the lakes. The simulation is made with maximization of the gross regional product (GRP), being subject to the structural equations of the combined sub models. The simulation running period was from 2008-2017 (total 10 years) and the pollutants measured in this study were total nitrogen (T-N), total phosphorus (T-P) and chemical oxygen demand (COD), which strongly affect water quality (Table 1). The target area was classified into seven zones (Table 2). The water pollutant generation source of household is divided into two categories depending on wastewater disposal. The land use is further divided into 5 categories. The industry is into 6 (Table 3). The water pollutants flowing into Dian Chi Lake were to reduce 0%, 10%, 20%, 30%, 36% and 37% the tenth year, designated as Case 0, Case 10, Case 20, Case 30, Case 36 and Case 37 respec-

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Measures for treatment of water pollutants are shown in Table 5.

### 3. Model structure

The dynamic simulation model consists of more than forty mathematical formulas. We only list the most important model equations in this paper.

#### 3-1 Objective Function

We considered the gross regional product of the basin as an index to reflect the level of socio-economic activities. It is also the objective function maximized in this research over the target term.

\[
\max \sum_{t=1}^{t} \frac{1}{(1+\rho)^{t-1}} GRP(t) \quad (1)
\]

\[
GRP(t) = nx(t) \quad (2)
\]

\(GRP(t)\): Gross Regional Product at time t (endogenous);
\(\rho\): social interest rate = 0.05, t = 1: 2008, ..., t = 10: 2017;
\(nx\): row vector of m-th element is rate of added value in the m-th industry (exogenous).

**3-2 Material flow balance model**

The net water pollutants flowing in the lake are defined as the sum discharged by socio-economic activities, sewage plants, fisheries, and rainfall in the watershed of the lake.

(1) Water pollutant load of Dian Chi Lake
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\[ Q^p(t) = \sum_i r^p_i(t) + QF^p(t) + \sum_d QD^p_d(t) + QR^p \]  (3)

- \( Q^p(t) \): total net load of water pollutant \( p \) of the lake at time \( t \) (endogenous);
- \( r^p_i(t) \): load of water pollutant \( p \) by socio-economic activities in region \( i \) at time \( t \) (endogenous);
- \( QF^p(t) \): load of water pollutant \( p \) by fisheries at time \( t \) (endogenous);
- \( QD^p_d(t) \): load of water pollutant \( p \) by sewage plants \( d \) at time \( t \) (endogenous);
- \( QR^p \): load of water pollutant \( p \) by rainfall at time \( t \) (exogenous).

(2) Water pollutant emitted by socio-economic activities

The total pollutants emitted by socio-economic activities in the sub-basin are composed of pollutants from households, land use and industries.

\[ r^p_i(t) = QZ^p_i(t) + QL^p_i(t) + QX^p_i(t) \]  (4)

- \( QZ^p_i(t) \): water pollutant \( p \) emitted by households in region \( i \) at time \( t \) (endogenous);
- \( QL^p_i(t) \): water pollutant \( p \) emitted by land use in region \( i \) at time \( t \) (endogenous);
- \( QX^p_i(t) \): water pollutant \( p \) emitted by industries (excluding those by fisheries) in region \( i \) at time \( t \) (endogenous).

(3) Load of water pollutants by fisheries

\[ QF^p(t) = P^{x^p} \cdot x^p(t) \]  (5)

- \( P^{x^p} \): coefficient of water pollutant \( p \) emitted by fisheries (exogenous);
- \( x^p(t) \): production of fisheries at time \( t \) (endogenous).

(4) Load of water pollutants from rainfall

\[ QR^p(t) = \phi^p \cdot L \]  (6)

- \( \phi^p \): coefficient of water pollutant \( p \) emitted by rainfall (exogenous);
- \( L \): area of the watershed (endogenous).

3-3 The socio-economic model

(1) Treatment measures for household wastewater generation sources

Treatment for household wastewater is provided by sewage plants. These treatments are mainly implemented by the governments.

(1-1) Increasing population that uses the sewage pants is dependent on the construction investment:

\[ \Delta Z^i(t) \leq \Gamma_i \cdot i^i(t) \]  (7)

- \( \Delta Z^i(t) \): increase of population that uses sewage plant in region \( i \) at time \( t \) (endogenous);
- \( \Gamma_i \): reciprocal of the necessary construction investment per person that uses the sewage plants in region \( i \) (exogenous);
- \( i^i(t) \): construction investment in region \( i \) for sewage plants at time \( t \) (endogenous).

(1-2) Sewage plant

The construction investment for sewage plant is determined by the construction allotment of the government and the subsidy that is provided by the government:

\[ i^i(t) = \left( \frac{1}{1 - M_i} \right) CC^i(t) \]  (8)

- \( M_i \): rate of subsidization by the prefectural and central governments in region \( i \) (exogenous);
- \( CC^i(t) \): construction allotment for the sewage plant in region \( i \) at time \( t \) (endogenous).

(2) Treatment measures for land use pollutant sources

Conversion from dry farmland and paddy field to other land use, categorized as land use for other purposes, is subsidized by the prefectural government:

(2-1) Use of the land

\[ L_t = \sum_{i=1}^3 L^i_t(t) \]  (9)

- \( L_t \): area of the land under use at time \( t \) (endogenous).
\( L_i \): total area of watershed in region i (exogenous); 
\( L_i(t) \): area of land use l in region i at time t (endogenous). 

(2-2) Change in land use

\[
L_i(t+1) = L_i(t) + \Delta L_i(t)
\]

\[
\Delta L_i(t) = \sum_{l=1}^{L} L_i^l(t) - \sum_{l=1}^{L} L_i^l(t)
\]

\( \Delta L_i^l(t) \): change of land use \( l \) in region i at time t (endogenous); 
\( L_i^l(t) \): conversion of land use from \( l \) to \( L \) in region i at time t (endogenous); 
\( L_i^L(t) \): conversion of land use from \( L \) to \( l \) in region i at time t (endogenous).

(2-3) Conversion from dry farmland and paddy field to other land use is dependent on the amount of subsidization by the prefectural government:

\[
L_i^l(t) \geq \lambda S_i(t)
\]

\( \lambda \): reciprocal of the subsidy for one unit conversion of land use \( l \) to land use for other purposes (index=5) (exogenous); 
\( S_i(t) \): subsidy given by the prefectural government for conversion of land use \( l \) (\( l=1 \) : dry farmland and \( l=2 \) : paddy field) into land use for other purposes in region i at time t (endogenous).

(2-4) City area and other land use

\[
L_i^l(t) \geq \xi \Delta a_i(t) + \psi^l \Delta i^l_i(t) + \psi^5 \Delta i^5_i(t)
\]

\( \xi \): coefficient of land use for housing demand by population growth (exogenous); 
\( \psi^l \): coefficient of land use for manufacturing industries and other industries (exogenous); 
\( \psi^5 \): coefficient of land use for manufacturing industries and other industries in region i at time t (endogenous).

(2-5) Environmental preserved agriculture

\[
L_i^{1,2}(t) = LN_i^{1,2}(t) + LU_i^{1,2}(t)
\]

\[
LU_i^{1,2}(t+1) = LU_i^{1,2}(t) + \Delta LU_i^{1,2}(t)
\]

\[
LU_i^{1,2}(t) = SU_i^{1,2}(t) \cdot TPU_i^{1,2}(t)
\]

\( LN_i^{1,2}(t) \): area of paddy fields and dry farmlands in region i at time t (endogenous); 
1=dry farmland, 2=paddy field; 
\( LU_i^{1,2}(t) \): area of paddy fields and dry farmland that use low-elution fertilizer in region i at time t (endogenous); 
\( \Delta LU_i^{1,2}(t) \): increasing area of paddy fields and dry farmlands that use low-elution fertilizer in region i at time t (endogenous); 
\( SU_i^{1,2}(t) \): subsidization for use of low-elution fertilizer from the municipality in region i at time t (endogenous); 
\( TPU_i^{1,2}(t) \): increasing area of paddy fields and dry farmlands that use low-elution fertilizer with subsidization by the prefectural government in region i at time t (exogenous).

(3) Treatment measures for production generation sources

(3-1) Production function and curtailment

Production is dependent on the capital accumulated. The prefectural government restricts production of dry farmlands (\( m=1 \)) and paddy fields (\( m=2 \)) by the other land use policy. The production of other industries (\( m=3...6 \)) is restricted by leaving capital idle and subsidizing losses due to idle capital. The production of dry farmlands and paddy fields is also dependent on the area of cultivated land.

\[
X_i^m(t) = a^m k_i^m(t) \quad \text{for } m = 1 \text{ and } 2
\]

\[
X_i^m(t) = a^m k_i^m(t) - s_i^m(t) \quad \text{for } m = 3, ..., 6
\]

\( a^m \): ratio of capital to output in industry m (exogenous); 
\( s_i^m(t) \): subsidy for industry m wastewater measures by prefectural government in region i at time t (endogenous).
Total budget from the prefectural government for the counter measures

\[ y(t) \geq \sum_i S_i(t) + \sum_i S_{it}^m(t) + \sum_i S_{lt}^m(t) + \sum_i SU_{i,12}^m \]  

(19)

\( S_i \): budget for household wastewater treatment measures by prefectural government in region \( i \) (endogenous);

\( S_{it}^m \): budget for industry wastewater treatment measures by prefectural government in region \( i \) at time \( t \) (endogenous);

\( S_{lt}^m \): budget for land use wastes treatment measures by prefectural government in region \( i \) at time \( t \) (endogenous);

\( SU_{i,12}^m \): budget for promoting the use of low-elution fertilizer by prefectural government in region \( i \) (endogenous);

\( y(t) \): total budget spent by the prefectural government for implementing the counter measures at time \( t \) (exogenous).

3-4 Flow balance in the commodity market

(1) Balance of supply and demand decides the total products of each industry.

\[ X(t) = A \cdot X(t) + C(t) + I^m(t) + B^t \cdot i(t) + \epsilon(t) \]  

(20)

\( X(t) = \sum_i X(t)_i \): column vector of the \( m \)-th element is the total product of industry \( m \) in region \( i \) at time \( t \) (endogenous);

\( I^m(t) = \sum_i I^m_i(t) \): column vector of the \( m \)-th element is the total investment in industry \( m \) in region \( i \) at time \( t \) (endogenous);

\( i(t) = \sum_i i(t)_i \): total investment for construction of sewage system in region \( i \) at time \( t \) (endogenous);

\( A \): input-output coefficient matrix (exogenous);

\( C(t) \): column vector of consumption (endogenous);

\( B^t \): column vector of the \( m \)-th coefficient is induced production in industry \( m \) by construction sewage systems (exogenous);

\( \epsilon(t) \): column vector of net export (endogenous).

(2) Constraints on net export

\[ e_{\min} \leq \epsilon(t) \leq e_{\max} \]  

(21)

3-5 Constraints on the pollutants

\[ \sum_i Q^t_i(t) \leq \sum_i Q^t_i(t-1) \]  

(22)

\[ \sum_i Q^t_i(t) \leq Q^t(t) \]  

(23)

\( Q^t(t) \): the restriction of the pollutants that flow into Dian Chi Lake (endogenous)

4. Results of the simulation

In this study, feasible solutions were achieved from Case 0 to Case 37. If we set the pollutant decrease greater than 37% in the tenth year, no feasible solutions can be achieved.

4-1 Objective function

The results show the total GRP in ten years (Fig. 2). GRP rapidly decreases in Case 36 while it is almost kept at the initial level from Case 0 till Case 30. The average annual increase in the rate of GRP for ten years in Case 36 is 1.1%, but only 0.4% in Case 37. This is because of sudden and critical brakes on the growth of GRP due to stricter restriction on the emission of water pollutants beyond the critical level, which
is characterized by the socio-economic and geographical structure of the watershed. The production from agriculture, fisheries, pig farming industry and other livestock farming industry did not increase, but decreased in Case 36 and Case 37. This is a great loss of development of the local economy. Therefore, as a policy target reduction rate of 36% and 37% in the emitted water pollutants that flow into the Lake are not acceptable for stakeholders in the watershed since the economy in China everywhere must grow with annual growth rate at least 6% following the national economic plan. Decreases of 30% (Case 30) are the most acceptable reduction rate.

4-2 Budget expenditure for each policy

In recent years, the prefectural government has spent more than 4 billion RMB (Currency of China) to treat the pollution of Dian Chi Lake with no obvious effect. If the simulation of Case 30 is adopted, only half of the budget the government has so far assigned to deal with Dian Chi pollution problems (Fig. 3). It shows that the policy plan is more cost effective than plans so far adopted. The budget assigned for promoting the use of low-elution fertilizer in Case 36 and Case 37 is less than in Case 10, Case 20 and Case 30. That is because areas of dry farmland and paddy fields have been changed to other land uses. The budget needed in Case 37 is 3,585 million RMB more than the amount needed in Case 30. That is because 67% of the budget has been subsidized for treating the pollutants from industry, especially pig farming industry which has the largest water pollutants emission coefficient. Therefore it is essential and necessary to introduce new advanced technologies when pollutants restriction becomes strict.
4-3 Allocation of the budget in Case 30

From the allocation of the budget in Case 30 we know that subsidization assigned in 2009 is the minimum amount necessary for the following growth of the local economy and subsidization assigned in 2017 is the minimum necessary amount to meet the pollutants constraints at the final stage (Fig. 4). In order to reduce the pollutants that flow into Dian Chi Lake while maximizing GRP, this research has also made it clear that Kun Ming government should distribute a budget for policies following the priorities of household, low-elution fertilizer, industry and change of land use. When the pollutants constraints become stricter, change of land use policy has to be taken, even though it is costly.

4-4 Effectiveness of low-elution fertilizer policy

We can find that low-elution fertilizer is an effective policy to decrease the pollutants from land use. All the land is subsidized to use low-elution fertilizer in the tenth year (Fig. 5). The planting land is the largest in Zone 7 (Song Ming County) in the seven zones. While the increasing acreage that use low-elution fertilizer is slow. That is because local financial scale is small in Zone 7 where low-elution fertilizer policy is much harder to implement. Large amount of budget and subsidization from Kun Ming government needs to be assigned in Zone 7. We could also find that as a result of including low-elution fertilizer in the policy option, 572 tons of T-N, 65 tons of T-P, and 819 tons of COD can be decreased compared with the reduction rate when low-elution fertilizer is not included in the policy option.
5. Conclusion

In this study, comprehensive environmental policies are proposed, with which we could maximize the gross regional products in the watershed of Dian Chi Lake while minimizing the water pollutants that flow into the Lake. The proposals specify the timing when each policy shall be implemented, the amount of budget assigned for each policy measure and the cost in terms of change in GPR, with exogenous reduction rate in water pollutant. First, pollutants decreased by 30% are the highest acceptable case. Compare to the case in which pollutants decreased by 0% in the tenth year, the objective value GPR is 568 million RMB less but more of the pollutants, 5,811 tons of T-N, 629 tons of T-P and 24,807 tons of COD can be decreased when the reduction rate is 30%. This means that it pays to introduce and implement policy measures proposed here as far as the total cost of those measures is less than 568 million RMB. Second, the results show that in order to reduce water pollutants beyond 30%, new advanced technologies which is more cost effective than those assumed in the paper must be introduced, like biomass recycle plant to deal with wastes from pig farming industries. Finally, the comprehensive environmental management model was verified as an effective method to improve water quality effectively and minimize the negative impacts on the socio-economic activities as small as possible in the basin of Dian Chi Lake.

References