Economics of Social Trade-off: Abatement Level vs. Ecosystem Damage

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Abstract

We have developed a social optimization model that integrates wastewater treatment cost function and ecosystem damage cost function. The social optimal abatement level of water pollution is determined by finding the tradeoff between pollution control cost and ecosystem damage. The model is applied to data from the Lake Taihu region in China to demonstrate this tradeoff. A wastewater treatment cost function is estimated with a sizable sample from China, and an ecological damage cost function is estimated following an ecosystem service valuation framework. Results show that the wastewater treatment cost function has economies of scale in facility capacity, and diseconomies in pollutant removal efficiency. Results also show that a low value of the ecosystem service will lead to serious ecological damage. One important policy implication is that the assimilative capacity of the lake should be enhanced by forbidding over extraction of water from the lake. It is also suggested that more work should be done to improve the economic valuation accuracy.

Keywords: social optimization; trade-off; ecosystem response; treatment cost; ecosystem valuation.

1. Introduction

Water quality standards are frequently used as the scientific basis for environmental water management policies. Environmental regulations in many countries are based on national quality standards. For example, the Safe Drinking Water Act (enacted in the United States in 1974 and amended in 1986 and 1996) was established to protect public health by regulating the nation's public drinking water supply and to apply national standards set by the United States Environmental Protection Agency (US EPA) to control water sources in rivers, lakes, reservoirs, springs, and ground water wells (Tiemann 2010). Similarly, the water quality standards in China are nationally unified, including water quality, pollutant discharge, monitoring methods, and environmental sample standards, which were derived from, or based on, environmental quality standards of developed countries (Wu et al. 2010). This means that current water quality standards may not fit regional environmental conditions and demands. These standards may not apply to the environmental and economic situation in all regions and, thus, may over or under regulate the water quality in some bodies of water. A more location-specific approach that incorporates both the abatement cost and the ecological damage may perform better in meeting the specific social objectives of protecting both human health and ecosystem health. Furthermore
such an approach would provide a policy tool for evaluating the tradeoff between ecosystem functions and economic activities.

Aquatic ecosystems (i.e., lake ecosystems) are able to store and absorb wastes from human economic activities through dilution, assimilation and chemical decomposition to a limited extent (De Groot et al. 2002). If the waste amount exceeds the aquatic ecosystem’s purification capacity, the ecosystem will be damaged. Wastewater treatment facilities are now the most commonly used abatement measures to resolve point-source water pollution. Many studies have focused on the analysis of wastewater treatment cost structures (Tsagarakis et al. 2003, Hernandez-Sancho et al. 2011). However, very few studies, if any, link the ecosystem response behavior with the level of wastewater treatment to allow the estimation of economic tradeoff associated with setting optimal water quality levels. Some studies analyze the effects of wastewater discharge on lake ecosystems’ functioning (Newcombe and MacDonald 1991, Camargo and Alonso 2006, Gücker et al. 2006, Machado and Imberger 2012). But the literature considers the issue from an ecological perspective only, with no reference to the economic value of ecosystem or water pollution control costs. Very few studies have managed to combine the pollution abatement cost with the economic value of ecosystems under different states of nature to provide information on the cost-effectiveness of different control policy options (Hein 2006, Laukkanen and Huhtala 2008). However, none of these studies provide information on the optimal water pollution control level based on control costs and the valuation of ecosystem.

In this paper, we aim to fill the gap in the literature by applying a social optimization model, including wastewater treatment and ecological damage costs, to allow a socially optimal solution for pollutant control levels. Considering both wastewater treatment costs and valuation of ecosystem damage, this paper provides more options for decision-makers to choose from, based on their regional economic and environmental situations, instead of existing rigid standards and regulations.

The paper proceeds as follows: The social optimization model is developed, and the relationship between key variables in the optimal solution are derived in section 2. Section 3 introduces the case of Lake Taihu in detail. In section 4, the wastewater treatment cost function and the ecological damage cost function are estimated, based on secondary data collected from existing publications. The theoretical model is empirically specified and applied in section 5 to the case of Lake Taihu, providing the empirical results. Section 6 concludes and discusses policy implications.

2. Social optimization model of wastewater treatment and discharge

The model is developed for a regional setup in which several municipalities treat sewage and discharge it into a lake. The lake is used for recreation, benefitting the citizens of the municipalities. The dilemma of the region is to minimize the social cost of discharging wastewater by deciding on quantity and quality of the wastewater to be discharged into the lake. The tradeoff is between the cost of treatment to reach a high quality of discharged wastewater
and ecological damage to the lake’s ecosystem. Both of these are components in the social objective function of the region.

Several simplifying assumptions are used. It is assumed that the model is static. As such, it considers population levels, economic activity, as well as water quantity and quality in the lake as given. It is also assumed that water treatment is performed in one wastewater treatment facility. While in reality the lake water is also used for irrigation and for drinking purposes, it is assumed for simplicity that the only use of the lake water is for recharge of the treated wastewater and for recreation. In this respect, our model is considered partial equilibrium, but since the interest of this study is in the tradeoff between treatment cost and ecological damage, the simplification we introduce is legitimate. We also consider the lake as one homogeneous ecological ecosystem rather than a compartmental system. Finally, we assume that the only factor affecting social preferences is the total social cost – either as treatment expenses or as loss of benefits from recreation.

Based on recent literature (Hernandez-Sancho et al. 2011, Fraas and Munley 1984, Goldar et al. 2001, Friedler and Pisanty 2006), the wastewater treatment cost model in this paper incorporates both quantity and quality variables of wastewater treatment processes. The wastewater quality variable is the control variable of the social optimization model.

The wastewater treatment cost (both investment cost and O&M cost) \( C \) is represented by \( C = C(Q, F, E) \), where \( Q \) is the designed capacity of the plant, \( F \) is the wastewater flow, and \( E \) is the pollutant removal efficiency. \( Q \) is used for investment cost function estimation, and \( F \) is used for operation and maintenance (O&M) cost function estimation. \( E \) is defined as \( (q_{in} - q_{out})/q_{in} \), where \( q_{in} \) represents pollutant influent concentration, and \( q_{out} \) represents effluent concentration. \( C \) is twice differentiable with \( \partial C/\partial Q \geq 0; \partial C/\partial F \geq 0; \partial C/\partial E \geq 0 \) and \( \partial^2 C/\partial Q^2 \leq 0; \partial^2 C/\partial F^2 \leq 0; \partial^2 C/\partial E^2 \geq 0 \). For simplicity, \( q_{in} \) and \( q_{out} \) are measured with one quality parameter \( E \) only.

The other aspect of the social optimization model is ecological damage cost. Several studies analyze a wide class of ecosystems’ behaviors under human activities’ stress (Holling 1973; Carpenter and Pace 1997; Ludwig et al. 1997; Scheffer et al. 2001). These studies indicate that ecosystems tend to respond nonlinearly to stress increases resulting from human intervention. Scheffer et al. (2001) identified three main ecosystem response types (see Fig. 1). The first type (a) shows that the state of some ecosystems may respond in a continuous way to increasing stress. The second type (b) shows that the system state remains relatively stable over certain ranges of stress and then responds dramatically when the stress approaches a critical level. The third one, which is a totally different type (c) is not continuous, instead the response line is folded backward, which is known as a “catastrophe fold” (Scheffer et al. 2001).

Fig. 1 illustrates the possible relationships between ecosystem state and human-induced stress. As indicated by Scheffer et al. (2000), much of the essence of ecosystem state can often be captured by a single key variable, because many aspects of the system’s state tend to shift in
concert with a few important key variables in a given type of ecosystem. For instance, possible key state variables can be total plant biomass (ecosystem population) per unit area, or turbidity of the lake. The term of “stress” is used to describe the effect of human use. Human use of the ecosystem can be through harvesting or destroying biomass or stressing the system by affecting its abiotic conditions (Scheffer et al. 2000). The intensity of stress can be reflected by variables such as eutrophication level, groundwater reduction level, or water pollution level.

Keeler et al. (2012) introduced a comprehensive and generalizable framework for linking human-induced stress to values for water quality related ecosystem services. The framework is illustrated in Fig. 2.

Linking human-induced ecosystem stress (e.g., water quality impairment) and change of ecosystem state can be achieved through biophysical models. The ecosystem state function is written as $S = S(F, E)$. $F$ and $E$ were defined earlier. The illustration of function $S(F, E)$ can be one of the three types in Fig. 1. From Fig. 1, we can infer that $\partial S / \partial E \geq 0$.

Economic value of ecosystem is usually obtained from valuating the service it can provide by eliciting citizens’ willingness to pay for the service (Wilson and Carpenter 1999; Loomis et al. 2000; Pan et al. 2002; Xiao et al. 2003; Xie et al. 2008; Huang and Ma 2013). The valuation not only depends on the ecosystem state, but also on socio-demographic factors such as people’s income, education, and so on. The ecosystem damage cost is difficult to measure directly, instead it can be measured as a reflection of the citizens’ utility loss from not being able to use the ecosystem service. In other words, the ecosystem damage cost is the difference between economic value of a reference ecosystem state and the current ecosystem state. $\xi$ is used to represent the unit economic value of the ecosystem service. It is typically assumed that people are willing to pay more for one unit of improvement at a lower level of ecosystem state than at the higher level of state. Therefore, $\xi$ may change along with the ecosystem state. $S_0$ is used to represent the reference ecosystem state. When the ecosystem state is worse than $S_0$, the ecosystem is damaged. $D$ is used to represent the ecosystem damage cost, $D(\xi, F, E) = \xi \cdot [S_0 - S(F, E)]$, which is also interpreted as the citizens’ utility loss of using ecosystem service. And $\partial D / \partial E \leq 0$.

It is easier for decision-makers to make decisions on the pollution control level when the ecosystem damage is taken into consideration in a same currency with the wastewater treatment cost. After translating the ecological damage into monetary terms, it can be well integrated into the social optimization model together with the wastewater treatment cost. The social optimization model aims at minimizing the social cost, including both wastewater treatment costs and ecological damage costs. An increase of wastewater treatment cost leads to a decrease of ecological damage cost, and vice versa. The tradeoff of reducing cost of either side is illustrated in Fig. 3. The illustration was inspired by the graphic theory in Scheffer et al. (2000), in which they used similar graphs to show how a theoretical society of “enjoyers” and “affectors” may obtain optimal social welfare from the use of an ecosystem. As indicated in Fig. 3, if there is no restriction, the minimum social cost can be obtained by a combination of the best
ecosystem state (no ecological damage cost) and the highest level of stress (no wastewater treatment cost) (point A). However, the ecosystem state is a function of stress $S(F,E)$, the ecosystem response will limit the possible combination of wastewater treatment and ecological damage costs to points on the stable equilibrium lines (e.g., the dash line in Fig.3).

Mathematically, the social optimization problem is written as:

$$\min_{E} f = C(Q,F,E) + D(\xi,F,E)$$

subject to

$$0 \leq E \leq 1$$

Write the Lagrangian multiplier equation as

$$L = C(Q,F,E) + D(\xi,F,E) - \alpha \cdot (-E) - \beta \cdot (E - 1)$$

The Karush-Kuhn-Tucker conditions are given as below:

$$\frac{\partial L}{\partial E} = \frac{\partial c}{\partial E} + \frac{\partial d}{\partial E} + \alpha - \beta = 0$$

$$\alpha \cdot (-E) = 0$$

$$\beta \cdot (E - 1) = 0$$

$$0 \leq E \leq 1, \alpha \geq 0, \beta \geq 0$$

Combine conditions (4) - (7), it can be derived that

when $E = 1, -\frac{\partial d}{\partial E} \leq \frac{\partial c}{\partial E}$

when $E = 0, -\frac{\partial d}{\partial E} \geq \frac{\partial c}{\partial E}$

when $0 < E < 1, -\frac{\partial d}{\partial E} = \frac{\partial c}{\partial E}$

As indicated earlier, $\frac{\partial d}{\partial E} \leq 0, \frac{\partial c}{\partial E} \geq 0$. Therefore, the results under Karush-Kuhn-Tucker conditions can be interpreted as follows:

When the removal efficiency is at its maximum (100 percent), the marginal ecosystem damage cost of decreasing the removal efficiency by one unit is smaller than the marginal treatment cost of decreasing the removal efficiency by one unit. There is incentive for reducing the removal efficiency. When the removal efficiency is minimal (0 percent), the avoided marginal ecosystem damage cost of increasing the removal efficiency by one unit is larger than the marginal treatment cost of increasing the removal efficiency by one unit. There is also incentive for increasing the removal efficiency. When the removal efficiency is between 0 and 100 percent, the avoided marginal ecosystem damage cost of increasing the removal efficiency by one unit is equal to the marginal treatment cost of increasing the removal efficiency by one unit.
The theoretical model will be empirically applied in section 5, to the case of Lake Taihu in China. Prior to embarking on the empirical application, Lake Taihu and its economy will be introduced in the next section.

3. Basic facts on Lake Taihu

Lake Taihu is located in the Yangtze delta. It is the third largest freshwater lake in China. It is located within the jurisdiction of Suzhou, Wuxi, and Changzhou municipalities in Jiangsu Province, which are among the most industrial and developed regions in China. Water pollution is very serious because of the industrial and agricultural development. The investment in wastewater treatment in Lake Taihu region is very significant. For instance, Jiangsu Province invests almost $325 million ($1=6.15 CNY) every year for wastewater treatment facilities in Lake Taihu (National Bureau of Statistics of China 1978-2006). Water pollution in Lake Taihu produces eutrophication and causes serious damage to the lake ecosystem.

The area of Lake Taihu is 2,338 km². Lake Taihu basin accounts for 0.4 percent of China’s land area, but the gross domestic product (GDP) in this region accounts for 11 percent of the Chinese economy (Qin et al. 2007). Approximately 40 million people live in the Taihu basin. The lake is an important source of drinking water supply in the basin area, a valuable tourism resource, and supports fishery and extraction of water for irrigated agriculture. Furthermore, it is also a repository of waste from urban, agricultural, and industrial sectors.

The mean depth of the lake is 1.9 m, and maximum depth is 2.6 m corresponding to an elevation of 3.0 m above sea level. The shallow-water area with mean depth below 1.5 m is about 452 km², mostly in East Taihu, accounting for 19.3 percent of the total surface area. The deepest areas over 2.5 m are in the north and west, occupying 197 km² (8.4 percent of the total lake area) (Qin et al. 2007). The water volume is 44.33×10⁸ m³. The annual precipitation and the annual average evaporation in the area are 1,000-1,400, and 941 mm, respectively (Hu et al. 2006). The annual runoff into the lake is about 57×10⁸ m³. The retention time of water in the lake is 284 days. There are 172 rivers or channels connected to the lake.

Lake Taihu has a rich set of ecosystem service, as was indicated earlier. Xu et al. (2010) estimated the economic value of the ecosystem services of Lake Taihu wetland at $1.83 billion (see Annex-Table 1 for details). However, due to economic development in past decades, serious water pollution from industry, agricultural, and urban sectors caused degradation of the lake ecosystem and deterioration of its water quality and service. For example, algal bloom has degraded the economic potential of the region and damaged the tourism industry. The total economic loss incurred from the 1998 algal bloom in the catchment area was estimated at nearly $6.5 billion (Le et al. 2010). The algal bloom events that occurred during the summer of 2007 led to a crisis of water supplies for approximately two million residents in Wuxi city (Qin et al. 2010). According to Guo (2007), the root cause of severe eutrophication in Lake Taihu is an accumulation of nutrient-rich sewage and agricultural runoff in the shallow lake.
The wastewater treatment plants have to follow specific standards. Municipal wastewater treatment plants in Lake Taihu basin need to follow the Discharge Standard of Pollutants for Municipal Wastewater Treatment Plant (GB 18918-2002). The emission standard is categorized into four classes (see Annex-Table 2). According to Yu et al. (2011), Class IA corresponds to tertiary treatment level, Class IB and Class II correspond to secondary treatment level (Class IB requires advanced secondary treatment level), and Class III corresponds to primary treatment level.

Besides the current regulations implemented in Lake Taihu basin, there are also some other measures used to deal with the serious water pollution. For example, a water transfer project from the Yangtze River to Lake Taihu was initiated in 2002 to dilute polluted water and to accelerate flushing pollutants and algae out of the lake, and this transfer is still ongoing.

4. Estimation of the wastewater treatment cost function and the ecological damage cost function

4.1. Wastewater treatment cost function

Following the literature (Tsagarakis et al. 2003, Fraas and Munley 1984, Uluatam 1991, Balmér and Mattsson 1994, Vanrolleghem et al. 1996) an exponential functional form is used to represent wastewater treatment cost function (either investment, or O&M cost function), as is presented below:

\[ C = \alpha \cdot Q^\beta \]  

(11)

where \( C \) is the wastewater treatment cost, \( Q \) is the wastewater treatment plant capacity, \( \alpha, \beta \) are coefficients.

Some other studies (Hernandez-Sancho et al. 2011, Goldar et al. 2001, Dasgupta et al. 2001) include quality variables including effluent/influent concentration ratio and other variables such as the input vector and character of the treatment plant (age, ownership, etc.), as is shown in Eq. 12:

\[ C = \alpha' \cdot Q^{\beta'} \cdot P^{\gamma'} \cdot X^{\theta'} \]  

(12)

where \( C \) is the wastewater treatment cost, \( Q \) is the designed capacity, \( P \) is the quality variable (i.e., effluent/influent concentration ratio), and \( X \) is the vector of input prices (labor, energy, and materials, etc.) in the location of the plants. \( \alpha', \beta', \gamma', \theta' \) are the coefficients to be estimated.

Since the quality aspect of wastewater effluent is very important for our analysis, we also include a quality variable. Some adjustments are introduced. First, pollutant removal efficiency is used as the quality variable instead of effluent to influent ratio, which is used in literature (Goldar et al., 2001, Dasgupta et al., 2001). The higher the pollutant removal efficiency, the lower the effluent to influent ratio; second, it is assumed that the vector of input prices (labor, energy and materials, etc.) is stable over space and is the same in different regions in China. Therefore, the vector of input prices variable in Eq. 12 is not included in this study; third, we use
wastewater flow instead of treatment capacity to estimate the O&M cost function because the O&M cost is determined by the actual wastewater quantity treated instead of the designed treatment capacity.

The investment cost function specification is presented below as:

\[ INV = e^a \cdot Q^b \cdot E^c \]  \hspace{1cm} (13)

where \( INV \) is the capital investment costs, \( Q \) is the treatment capacity, and \( E \) is the pollutant removal efficiency. \( a, b \) and \( c \) are parameters to be estimated.

The O&M cost function specification is presented below as:

\[ VC = e^{a'} \cdot F^{b'} \cdot E^{c'} \]  \hspace{1cm} (14)

where \( VC \) is the O&M costs, \( F \) is the wastewater flow, and \( E \) is the pollutant removal efficiency. \( a', b' \) and \( c' \) are parameters to be estimated.

4.2. Wastewater treatment data

The data used in this paper for the estimation of wastewater treatment cost functions include information of wastewater treatment plants’ designed capacity, wastewater flow, investment cost, O&M cost, pollutant (BOD, COD, and SS) influent concentration and effluent concentration. Most of the data was taken from China’s Urban Sewage Treatment Plant Assembly (Yang 2006), which includes 501 wastewater treatment plants from all over the nation. Of all the 501 wastewater treatment plants’ data, 275 plants’ data were abandoned (remaining with 226 observations) for two reasons: first, some of the data are not complete in terms of investment cost, O&M cost, and pollutant influent and effluent concentration data; second, some of the observations are outliers. The outlying could be due to either mistakes in data recording or special cases (i.e., plants in special geographic locations, such as in mountainous locations, cost more than plants in plateaus). To inflate and deflate the monetary values to 2006 levels, the consumer price index data were used (National Bureau of Statistics of China 1978-2006). The wastewater flow data was taken from China Urban Wastewater Treatment Facilities List (Ministry of Environmental Protection of China 2012), for only 166 plants of the 226 of the entire sample we used from China’s Urban Sewage Treatment Plant Assembly. There are two reasons for this difference: first, some of the plants are listed in the assembly but not in China Urban Wastewater Treatment Facilities List (2012); second, the facilities’ information in China Urban Wastewater Treatment Facilities List (2012) is relatively new, which shows that some plants have been updated in terms of capacity and wastewater flow in the past seven years (2006-2012), therefore these wastewater flow data cannot be used to match the other data in the Assembly. All the statistical analyses are conducted using IBM SPSS 20 software.

Of all the 226 plants, for primary treatment, about 44 percent and 37 percent perform over and under the standard (See Annex Table 2), respectively; for the secondary treatment level plants, about 84 percent and about 3 percent perform over and under the standard, respectively; for the tertiary treatment level plants, about 93 percent perform over the required standard.
Initial scrutiny of the data suggests that there is a group of wastewater treatment plants with high pollutant removal efficiency but with relatively low investment and O&M costs (Fig. 4 and 5, right panels). For Fig. 4 (investment cost), the main explanation is that these treatment plants are state owned, and may have cost advantages (i.e., treatment plant land price subsidized by the government) over the private-owned treatment plants. According to the study of Tsagarakis et al. (2003) and Wang et al. (2009), the energy costs account for a large proportion of the total O&M costs. In the Tsagarakis et al. (2003) study, the energy cost accounts for 28 percent to 45 percent of the annual O&M costs in Greece. The manpower costs account for a larger proportion than the energy costs. In the Wang et al. (2009) study in China, the energy costs account for 40 percent to 60 percent of the annual O&M costs. Therefore, the energy costs are an important factor determining the annual O&M costs. We can explain the phenomenon in Fig. 5 (O&M cost) by suggesting that this group of treatment plants get electricity subsidies from the government. However, since we lack enough data to prove it, these two explanations are just speculations.

4.2.1. Estimation of the capital investment cost function

We use only one quality parameter – suspended solids (SS) – removal efficiency as the quality variable, because we want the wastewater treatment cost function and the ecological damage function to use the same quality variable. SS is used in the literature (Newcombe and MacDonald 1991) to represent stress level in ecosystems. The SS concentration alone shows relatively poor indication of stress. The combination of concentration and duration will be a better indicator of stress level. However, because the social optimization model in this paper is a static one, only SS concentration is used to represent the stress level. The relationships between capital investment cost and designed capacity, and SS removal efficiency are presented in Fig. 4 (left panel and right panel, respectively).

The dummy variable is defined as: $\text{Dummy}_E S S = 1$, if $0.9 < E < 1$, and if $0 < \text{INV} < 20$ million $; \text{otherwise } \text{Dummy}_E S S = 0$. Modifying Eq. 13, the capital investment cost function is written as

$$\text{INV} = \alpha_1 + \alpha_2 \cdot \text{Dummy}_E S S \cdot Q^b \cdot E^c$$

(15)

where INV is capital investment cost in million $/year, Q is designed capacity (10⁴ m³/day), E is the pollutant removal efficiency, $\text{Dummy}_E S S$, as defined earlier, is the dummy variable, $\alpha_1, \alpha_2, b$ and $c$ are coefficients to be estimated.

A general linear regression model (GLM) in natural logarithm is used to estimate the capital investment cost function. The regression result is shown in Table 2. Each parameter reaches significance at 0.1 percent level. The parameter of designed capacity is less than one (0.484), therefore, the capital investment cost function shows strong economies of scale.

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¹ Dynamic relationships will be developed in the future work.
4.2.2. Estimation of the O&M cost function

The relationships between O&M cost and wastewater quantity, and SS removal efficiency are presented in Fig. 5 (left and right panel, respectively).

The dummy variable is defined as: $\text{Dummy}_{\text{ESS}} = 1$ if $0.9 < E < 1$, and if $0 < VC < 1 \text{ million } \$, otherwise $\text{Dummy}_{\text{ESS}} = 0$. Modifying Eq. 14, the O&M cost function is written as:

$$VC = e^{a_1' + a_2' \cdot \text{Dummy}_{\text{ESS}}'} \cdot F^{b'} \cdot E^{c'}$$

(16)

where $VC$ is operation and maintenance costs in million $/year, F$ is wastewater flow (10$^4$ m$^3$/day), $E$ is pollutant removal efficiency, $\text{Dummy}_{\text{ESS}}'$ is the dummy variable for O&M cost function, $a_1', a_2', b'$ and $c'$ are coefficients to be estimated.

The regression result is presented in Table 3. The intercept is not significantly different from 0, which means that the O&M cost is zero when there is no wastewater flow.

4.2.3. Calculating annual total wastewater treatment cost function

To calculate the total annual costs, the capital investment cost is annuitized by using the capital recovery factor (CRF) (Tsagarakis et al. 2003). The CRF is calculated as

$$\text{CRF} = \frac{r(1+r)^t}{(1+r)^t-1}$$

(17)

where $r$ is the discount rate, and $t$ is the designed life time of the treatment plant.

Considering the circumstances in China, a discount rate of 4 percent and lifetime of 20 years are set in this paper based on Wang et al. (1992), Niu et al. (2011) and Yu et al. (2011). Thus, CRF is calculated as 0.0736.

The annual total wastewater cost function is therefore written as:

$$C = 0.0736 \cdot e^{2.647-0.782 \cdot \text{Dummy}_{\text{ESS}}} \cdot Q^{0.484} \cdot E^{3.104} + e^{0.119-0.907 \cdot \text{Dummy}_{\text{ESS}}} \cdot F^{0.413} \cdot E^{2.575}$$

(18)

where $C$ is the annual wastewater treatment cost (million $).

4.3. Estimation of the ecological damage cost function

Ecological damage function in Lake Taihu is estimated following the framework introduced earlier (see Fig. 2) introduced by Keeler et al. (2012).

Step 1: Link human activities (wastewater discharge) and changes in water quality

The association is estimated based on the assumption that our model is a static one, and the suspended solids (SS) from wastewater treatment facility is diluted by the water in the lake after being discharged. The SS concentration in the lake after wastewater discharge is:

$$S = \frac{Q_{\text{out}}F}{F+Q_L} + S_o$$

(19)
where $S$ is the final suspended solids concentration in Lake Taihu ($mg/L$), $S_0$ is the original concentration in the lake before wastewater discharge $mg/L$, and $Q_L$ is the water quantity in Lake Taihu ($m^3$).

**Step 2: Link changes in water quality to changes in ecosystem services**

As assumed in the beginning of this paper, the recreation and waste disposal are considered to be the only functions of the lake. Waste disposal service is not associated with water quality, while the recreation service (e.g., swimming, angling, and viewing) depends on water quality, especially on water clarity. Thus, changes in water clarity will lead to changes in the recreation service. Water clarity is usually measured in Secchi Transparency. Although Secchi Transparency is often used as a water quality indicator, it can also be used as an ecosystem state indicator due to its close association with algal biomass. For example, in the ecosystem health assessment study of Xu et al. (1999), Secchi Transparency was used as one of the ecological indicators of ecosystem state. As indicated in section 2, Scheffer et al. (2000) argued that much of the essence of ecosystem state can often be captured by a single key variable. Therefore, we adopt the Secchi Transparency as the indicator of ecosystem state of Lake Taihu ecosystem.

The empirical relationship between Secchi Transparency and suspended solids in Lake Taihu is adopted from the study of Qin et al. (2007), as shown in Eq. 20

$$ ST = e^{1.39 - 1.17SS^{0.25}} \tag{20} $$

where $ST$ is the Secchi Transparency ($m$), and $SS$ is the suspended solids concentration ($mg/L$) in Lake Taihu.

Eq. 20 is plotted in Fig. 6, which is similar to type (a) in Fig. 1. It shows that the ecosystem state (indicated by Secchi Transparency) worsens dramatically at the beginning when the human-induced stress (indicated by suspended solids’ concentration) increases. After reaching a certain level of stress, the deterioration rate slows down.

**Step 3: Link changes in ecosystem services to changes in values**

Zhang (2011) measured the economic value of water quality improvement in Lake Taihu by eliciting local citizens’ willingness to pay for a hypothetical water quality improvement project. The target of the hypothetical project is to improve the water quality to Grade IV and partly to Grade III, based on National Surface Water Quality Standard (GB 3838-2002). As presented in Zhang (2011), water quality in most areas of the survey cities (69.1 percent) surrounding Lake Taihu is worse than Grade V. Therefore, it is acceptable to equal the economic value measured by Zhang (2011) to the economic value of improving the water clarity from values worse than Grade V to values within Grade IV.

The standard for Secchi Transparency was deleted in the recent version of the Water Quality Standard (GB 3838-2002). The difference between GB 3838-2002 and GB 3838-88 is mainly about adding or deleting a few indicator items, the values of each indicator under
different grades, and the description for each grade are exactly the same. In the previous version of the National Surface Water Quality Standard (GB 3838-88), the values of Secchi Transparency of Grade IV, Grade V, and worse than Grade V, are 2.5 m, 1.5 m, and 0.5 m, respectively. Therefore, improving the water clarity from values worse than Grade V to values within Grade IV is also assumed to be equal to increase the water clarity from 0.5 m to 2.5. Since the willingness to pay for water quality improvement measured by Zhang (2011) may include other aspects of water quality improvement besides water clarity, therefore, the economic value we take from Zhang (2011) may exceed the actual economic value of increasing water clarity by 2 meters. There is a very high uncertainty level associated with this economic value, therefore, the sensitivity analyses will be applied.

As defined earlier, $\xi$ represents the unit economic value of ecosystem service. It was assumed in the theoretical part of section 2 that citizens are willing to pay more for one unit of improvement at lower levels of the ecosystem state than at the higher levels of the ecosystem state, which means $\xi$ will change as the ecosystem state changes. However, the data in the literature does not allow us to differentiate $\xi$. In the numerical application, we can only assume that the marginal recreation utility of increasing Secchi Transparency by one meter is the same under various water clarity levels. Ideally, in the future when the data is more complete, we can relax this assumption. The economic value from Zhang (2011) is $27.8$ million/meter (deflated to the 2006 level). Therefore, $\xi = 27.8$ million/meter.

As introduced earlier, the ecological damage cost is defined as the difference between economic values of the current and reference ecosystem states. In this numerical application, we select the highest Secchi Transparency as the reference ecosystem state. Based on the fact that Lake Taihu is a shallow lake with a maximum depth of 2.6 m, the reference ecosystem state without any damage is defined as 2.6 meter water clarity as measured by Secchi Transparency. The corresponding suspended solid concentration to the maximum transparency is 0.02 mg/L. This implies that ecological damage will occur once SS concentration in the lake is higher than 0.02 mg/L.

The change in Lake Taihu ecosystem state is indicated by the change in water clarity, measured by Secchi Transparency. The reference ecosystem state is $S_0 = 2.6$ m, as introduced earlier. Combined with Eq. 20, the change of water clarity is measured by Eq. 21,

$$S_0 - ST = 2.6 - e^{1.39 - 1.17 \cdot S^{0.25}} \quad (21)$$

where $S_0$ is the reference ecosystem state measured by Secchi Transparency (m).

Hence, the ecological damage cost is the product of unit economic value of ecosystem service ($\xi$) and change of ecosystem state (Eq. 21),

$$D = \xi \cdot (2.6 - e^{1.39 - 1.17 \cdot S^{0.25}}) = 72.28 - 27.8 \cdot e^{1.39 - 1.17 \cdot S^{0.25}} \quad (22)$$

where $D$ is the ecological damage cost (million $)$. Eq. 22 is plotted in Fig. 7.
5. Numerical application of social optimization model to Lake Taihu in China

Based on the results in section 4, the numerical social optimization model is written as Eq. 23:

\[ \begin{align*}
\min_{E} & \quad C_1(Q, E, F) + \xi \cdot D(S) \\
& = 0.0736 \cdot e^{2.647 \cdot 0.782 \cdot \text{Dummy}_{ESS}} \cdot Q^{0.484} \cdot E^{3.104} + e^{0.119 \cdot 0.907 \cdot \text{Dummy}_{ESS}'} \cdot F^{0.413} \cdot E^{2.575} + 72.28 - 27.8 \cdot e^{1.39 \cdot 1.17 \cdot SS^{0.25}} 
\end{align*} \tag{23} \]

The empirical constraints of this model are as below:

\[ E \cdot q_{in} = q_{in} - q_{out} \tag{24} \]

\[ SS = \frac{q_{out} \cdot F}{F+Q_L} + 0.02 \tag{25} \]

\[ 0 \leq E \leq 1 \tag{26} \]

\[ SS \geq 0.02 \tag{27} \]

The total wastewater discharged to Lake Taihu is \(2.92 \times 10^9\) m\(^3\) in 2006 (Taihu Basin Authority 2006), hence the wastewater flow per day is \(8 \times 10^6\) m\(^3/\)day. The discharged wastewater quantity is taken as exogenous.

\[ F = Q = 8 \times 10^6\text{ m}^3/\text{day} \tag{28} \]

\[ \text{Dummy}_{ESS} = 1, if \ 0 < e^{2.647 \cdot 0.782 \cdot \text{Dummy}_{ESS}} \cdot Q^{0.484} \cdot E^{3.104} < 20 \text{ and } 0.9 < E < 1; \ otherwise, \text{Dummy}_{ESS} = 0 \tag{29} \]

\[ \text{Dummy}_{ESS}’ = 1, if \ 0 < e^{0.119 \cdot 0.907 \cdot \text{Dummy}_{ESS}’} \cdot F^{0.413} \cdot E^{2.575} < 1 \text{ and } 0.9 < E < 1; \ otherwise, \text{Dummy}_{ESS}’ = 0 \tag{30} \]

As described in section 3, the water volume of Lake Taihu is \(44.33 \times 10^8\) m\(^3\). We use the average value of SS as the influent concentration in the model (see Table 1), which is 243.83 mg/L. All the coefficients of parameters used for the numerical application are listed in Table 4. The non-linear programming optimization is conducted in LINGO 14.0.

The optimal solution of the model is based on the coefficients in Table 4 and presented in Table 5.

Because the coefficients (Table 4) used for the base run are assumed, high uncertainty is associated with their values. Sensitivity analyses are therefore applied by changing the coefficients of Lake Taihu’s water quantity and the economic value of its ecosystem service. The sensitivity analyses results are shown in Annex 3.
The sensitivity analyses results presented in the following paragraphs explore how the water quantity in Lake Taihu and the economic value of its ecosystem service can affect the treatment level and social cost in the optimal solutions.

Fig. 8 shows that treatment level and social optimal costs are sensitive to the change of water quantity coefficients’ values. When the water quantity in Lake Taihu increases, the optimal wastewater treatment level decreases, and the corresponding social optimal cost also decreases. It is reasonable because the assimilative capacity and dilution ability of the lake increases when the water quantity in the lake increases. When the assimilative capacity and dilution ability increases, the lake ecosystem is not vulnerable to the damage from pollution under a certain level, therefore the requirement for the pollution treatment level is reduced, and the social optimal cost is also reduced due to less treatment cost and unchanged or less ecological damage cost. An empirical example was already mentioned in section 3: water transfer from the Yangtze River to Lake Taihu (increasing the water quantity) was initiated in 2002 to dilute polluted water and to accelerate flushing pollutants and algae out of Lake Taihu. This process is still ongoing.

Fig. 9 suggests that the optimal treatment level and social optimal costs are sensitive to the changes of economic value of ecosystem service. As shown in Table 5 and Annex-Table 4, when the value of the ecosystem service is $27.8 million /meter measured by Zhang (2011), the optimal treatment already reaches the highest level and there is no ecosystem damage. This implies that the $27.8 million /meter valuation level is high enough to convince society to prioritize ecosystem health rather than damaging it. A higher level of ecosystem service will not change both the optimal treatment level and overall social optimal cost (see Annex-Table 4). When the valuation level is lower than the base case, as shown in Fig. 9, the optimal treatment level and social optimal cost decrease, which implies that the decision-maker may decrease the treatment level when the valuation of the ecosystem is low in order to achieve the minimal social cost. However, as presented in Annex-Table 4, the corresponding ecosystem damage increases to a very high level. This implies that the economic valuation of ecosystem service will affect decision-making. An accurate valuation, which is close to the “real” value of the ecosystem service is very important in the decision-making process with respect to ecosystem protection.

6. Conclusions and policy implications

In this paper wastewater treatment level decisions are combined with ecological damage to a receiving body of the treated water. A social optimization model, specifically, social cost minimization model, was developed in order to economically assess the tradeoff between human-based pollution abatement and the damage to the ecosystem of the receiving body (lake). To integrate the biophysical model of ecosystem response to human-induced stress into the social optimization model, a valuation framework, proposed recently in literature, is used. By integrating treatment cost decision and ecological damage in one model, policy-makers are better equipped to identify tradeoff for socially optimal solutions under various conditions, such as
initial quantity of the water in the receiving body and the value of the services that can be obtained from the lake ecosystem.

The empirical wastewater treatment cost function estimated for China shows strong economies of scale in terms of capacity and diseconomies in terms of pollutant removal efficiency (treatment level). The ecosystem damage cost function was estimated by integrating existing biophysical model and economic valuation model in the literature. Although there is a very high uncertainty level associated with the use of ecosystem damage cost function, the application of such a damage cost function provides insights on the tradeoff between the abatement level and ecosystem damage much better than without such a function.

The theoretical model was applied to the well-known case of Lake Taihu in China, using existing secondary data from the literature, and additional simplifications necessary to demonstrate the concept of endogenous considerations of the ecological damage. Sensitivity analyses were conducted to key variables (water quantity in the lake and economic value of ecosystem service) to assess the robustness of the model results.

The base run of our model suggests that a full treatment of pollution is required in the region to minimize social cost. Results also show that the larger the lake water volume, the lower the requirement for the treatment level, and the lower the social optimal cost. This can be explained by the lake’s assimilative capacity and dilution ability. Furthermore, it is found that a low economic valuation of the ecosystem will lead to serious ecosystem damage. When the valuation reaches certain level, it will not affect both treatment level and social optimal cost because the treatment level is high enough to prevent the ecological damage (the ecological damage is zero under high valuation).

One important policy implication is that the assimilative capacity of the lake should be enhanced by forbidding over-extraction of water from the lake. In this way, the lake’s water helps to dilute the pollution, and the requirement for treatment will be reduced as well as the social cost. The other policy implication is that more work needs to be done on the economic valuation of ecosystem service in order to guarantee reliable information for decision-making involving ecosystem protection.

In a future study, the partial equilibrium model will be upgraded to a general equilibrium model by including more sectors that benefit from the lake ecosystem. The ecological damage cost function will be further developed to include more complex ecosystem health indicators. A dynamic model will also be applied. Furthermore, for Lake Taihu specifically, it can be divided into several sub-zones in order to take spatial heterogeneity of vulnerability into consideration.

7. Acknowledgements

The authors would like to thank Francesc Hernandez Sancho (University of Valencia), Konstantinos P. Tsagarakis (Democritus University of Thrace), and Hans-Peter Weikard (Wageningen University) for their helpful comments on the manuscript. The authors are also
indebted to Marten Scheffer and Lars Hein (Wageningen University) for their help with the ecosystem knowledge.

8. References


Taihu Basin Authority (2006) Taihu basin and southeast rivers water resources bulletin.


Figures

Figure 1. Three main shift types of ecosystem states with increases of stress. Note: stress increases from left to right; ecosystem state worsens from top to bottom. Source: Adapted with modification from Scheffer et al. (2001)

Figure 2. Framework for linking human-induced stress to ecosystem service values Note: Illustration is based on the framework proposed by (Keeler et al. 2012)
Figure 3. Graphic illustration of social cost minimization model.

Note: The figure is based and inspired by the theory of Scheffer et al. (2000:458). The dashed line is an example of the equilibrium state, which corresponds to type “b” in Fig. 1. The equilibrium state can also be type “a” or type “c” in Fig. 1 depending on specific context.

Figure 4: Relationship between investment cost and wastewater treatment capacity (left panel), and SS removal efficiency (right panel).
Figure 5: Relationship between O&M costs and wastewater flow (left panel), and SS removal efficiency (right panel).

Figure 6. Empirical relationship between Secchi Transparency and SS concentration in Lake Taihu.
Figure 7. Ecological damage cost function plot.
Note: The range of this horizontal axis is supported Qin et al. (2007) (Fig. 4 in their paper)

Figure 8. Sensitivity analysis by changing the coefficients of water quantity value in Lake Taihu.
Figure 9. Sensitivity analysis by changing the coefficients of economic value of ecosystem service in Lake Taihu.
### Table 1. Descriptive statistics of wastewater treatment plants data in China in our sample.

<table>
<thead>
<tr>
<th>Treatment plant type</th>
<th>Observations</th>
<th>Capacity (Wastewater Flow) (10^4 \text{ m}^3/\text{day})</th>
<th>BOD influent (mg/L)</th>
<th>BOD effluent (mg/L)</th>
<th>COD influent (mg/L)</th>
<th>COD effluent (mg/L)</th>
<th>SS influent (mg/L)</th>
<th>SS effluent (mg/L)</th>
<th>Investment cost (million $)</th>
<th>O&amp;M Cost (million $)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary</td>
<td>27 (18)</td>
<td>4.04 (4.37)</td>
<td>269.67 (230.11)</td>
<td>25.02 (23.27)</td>
<td>562.09 (472.13)</td>
<td>97.73 (94.60)</td>
<td>415.18 (366.13)</td>
<td>46.72 (36.02)</td>
<td>16.44 (18.66)</td>
<td>1.42 (1.33)</td>
</tr>
<tr>
<td>Secondary</td>
<td>184 (135)</td>
<td>7.23 (7.59)</td>
<td>164.83 (164.55)</td>
<td>13.46 (12.89)</td>
<td>371.00 (363.67)</td>
<td>49.8 (49.08)</td>
<td>221.17 (216.78)</td>
<td>16.43 (15.96)</td>
<td>26.53 (28.60)</td>
<td>1.89 (2.00)</td>
</tr>
<tr>
<td>Tertiary</td>
<td>13 (13)</td>
<td>9.80 (10.43)</td>
<td>94.5 (138.05)</td>
<td>6.28 (6.00)</td>
<td>290.86 (278.51)</td>
<td>28.09 (27.67)</td>
<td>213.25 (205.74)</td>
<td>7.13 (7.25)</td>
<td>45.78 (39.78)</td>
<td>1.95 (2.08)</td>
</tr>
<tr>
<td>Total</td>
<td>226 (166)</td>
<td>7.02 (7.46)</td>
<td>176.02 (169.58)</td>
<td>14.36 (13.47)</td>
<td>388.52 (368.77)</td>
<td>54.09 (52.34)</td>
<td>243.83 (232.11)</td>
<td>19.43 (17.46)</td>
<td>26.60 (28.39)</td>
<td>1.84 (1.94)</td>
</tr>
</tbody>
</table>

Note: All the numbers are mean values of the corresponding sample. In parenthesis are the descriptive statistics (mean value) of O&M cost sample (N=166).

### Table 2. Regression Results of Investment Cost Model (Adjusted R Square=0.596, F=111.632, p<0.001***)^2

<table>
<thead>
<tr>
<th></th>
<th>B</th>
<th>Standard error</th>
<th>t</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>2.647</td>
<td>0.145</td>
<td>18.261</td>
<td>&lt;0.001***</td>
</tr>
<tr>
<td>Dummy_ESS</td>
<td>-0.782</td>
<td>0.097</td>
<td>-8.078</td>
<td>&lt;0.001***</td>
</tr>
<tr>
<td>Capacity</td>
<td>0.484</td>
<td>0.049</td>
<td>9.804</td>
<td>&lt;0.001***</td>
</tr>
<tr>
<td>Efficiency</td>
<td>3.629</td>
<td>0.855</td>
<td>4.243</td>
<td>&lt;0.001***</td>
</tr>
</tbody>
</table>

Note: *** indicates significance at 0.1% level.

^2 We also estimated the investment cost function with designed capacity with the same sample (N=166), which is used to estimate O&M costs (Results can be obtained from the authors upon request). We find that the coefficients, t test, significance level, adjusted R square, F test and model significance level are all very close to the one we estimated with the larger sample (N=226). Therefore, it is acceptable for us to use the regression results, which are estimated based on 226 samples (Table 4) to estimate the investment cost function and then use it in the social optimization model.
Table 3. Regression results of O&M costs model (adjusted $R^2=0.585$, $F=78.423$, $p=0.000^{***}$)

<table>
<thead>
<tr>
<th></th>
<th>B</th>
<th>Standard error</th>
<th>T</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>0.119</td>
<td>0.138</td>
<td>0.863</td>
<td>0.389</td>
</tr>
<tr>
<td>Dummy_ESS’</td>
<td>-0.907</td>
<td>0.120</td>
<td>-7.577</td>
<td>&lt;0.001***</td>
</tr>
<tr>
<td>Flow</td>
<td>0.413</td>
<td>0.050</td>
<td>8.211</td>
<td>&lt;0.001***</td>
</tr>
<tr>
<td>Efficiency</td>
<td>2.575</td>
<td>0.758</td>
<td>3.396</td>
<td>&lt;0.001***</td>
</tr>
</tbody>
</table>

Note: *** indicate significance at 0.1% level.

Table 4. Coefficients of parameters used for the social optimization model of Lake Taihu.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Description</th>
<th>Units</th>
<th>Value</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>$q_{in}$</td>
<td>SS influent concentration</td>
<td>mg/L</td>
<td>243.83</td>
<td>Yang (2006)</td>
</tr>
<tr>
<td>$Q_L$</td>
<td>Water volume of the lake before discharging the wastewater</td>
<td>m$^3$</td>
<td>$44.33 \times 10^8$</td>
<td>Hu et al. (2006)</td>
</tr>
<tr>
<td>$\xi$</td>
<td>Unit economic value of ecosystem</td>
<td>million $/m$</td>
<td>27.8</td>
<td>Zhang (2011)</td>
</tr>
</tbody>
</table>

Table 5. The solutions of the social optimization model based on coefficients in Table 4 (base run).

<table>
<thead>
<tr>
<th>$q_{in}$ (mg/L)</th>
<th>$Q_L$ m$^3$</th>
<th>$\xi$ (million $$/m)</th>
<th>$E$</th>
<th>Ecosystem damage (m)</th>
<th>$q_{out}$ (mg/L)</th>
<th>Optimal Solution (million $)</th>
</tr>
</thead>
<tbody>
<tr>
<td>243.83</td>
<td>$44.33 \times 10^8$</td>
<td>27.8</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>44.21</td>
</tr>
</tbody>
</table>
Annexes

Annex 1
Annex-Table 1. Valuation of Lake Taihu wetland ecosystem service (Adapted from Xu et al. 2010).

<table>
<thead>
<tr>
<th>Ecosystem Service Type</th>
<th>Value (million $)</th>
<th>Share in Total Value (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material Production and Supply</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aquatic Production</td>
<td>81.46</td>
<td>4.46</td>
</tr>
<tr>
<td>Vegetation Resource Production</td>
<td>1.63</td>
<td>0.09</td>
</tr>
<tr>
<td>Water Supply</td>
<td>448.78</td>
<td>24.56</td>
</tr>
<tr>
<td>Subtotal</td>
<td>531.87</td>
<td>29.10</td>
</tr>
<tr>
<td>Environmental Regulation and Adjustment</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Climate Regulation</td>
<td>333.17</td>
<td>18.23</td>
</tr>
<tr>
<td>Water Purification</td>
<td>43.41</td>
<td>2.38</td>
</tr>
<tr>
<td>Flood Control</td>
<td>479.35</td>
<td>26.23</td>
</tr>
<tr>
<td>Water Conservation</td>
<td>31.71</td>
<td>1.74</td>
</tr>
<tr>
<td>Biodiversity Protection</td>
<td>7.48</td>
<td>0.41</td>
</tr>
<tr>
<td>Subtotal</td>
<td>895.12</td>
<td>48.98</td>
</tr>
<tr>
<td>Cultural Services</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Recreation and Tourism</td>
<td>160.00</td>
<td>8.76</td>
</tr>
<tr>
<td>Research and Education</td>
<td>240.49</td>
<td>13.16</td>
</tr>
<tr>
<td>Subtotal</td>
<td>398.86</td>
<td>21.91</td>
</tr>
<tr>
<td>Total Value</td>
<td>1827.48</td>
<td>100.00</td>
</tr>
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</table>
Annex 2
Annex-Table 2 Discharge standards of pollutant effluent concentration for municipal wastewater treatment plant (GB 18918-2002), (mg/L)

<table>
<thead>
<tr>
<th></th>
<th>Class IA</th>
<th>Class IB</th>
<th>Class II</th>
<th>Class III</th>
</tr>
</thead>
<tbody>
<tr>
<td>COD</td>
<td>50</td>
<td>60</td>
<td>100</td>
<td>120 (a)</td>
</tr>
<tr>
<td>BOD5</td>
<td>10</td>
<td>20</td>
<td>30</td>
<td>60 (b)</td>
</tr>
<tr>
<td>SS</td>
<td>10</td>
<td>20</td>
<td>30</td>
<td>50</td>
</tr>
<tr>
<td>NH3-N</td>
<td>5</td>
<td>8</td>
<td>25</td>
<td></td>
</tr>
<tr>
<td>P (c)</td>
<td>1</td>
<td>1.5</td>
<td>3</td>
<td>5</td>
</tr>
</tbody>
</table>

Notes:  

(a) when COD influent>350 g/m³, the removal efficiency should be larger than 60%;  
(b) when BOD influent>160 g/m³, the removal efficiency should be larger than 50%;  
(c) the phosphorus emission standards presented here are for plants constructed before December 31, 2005, because the wastewater treatment plant data we used are before 2006.
Annex 3
Annex-Table 3. Sensitivity analyses result by changing coefficient water quantity of Lake Taihu.

<table>
<thead>
<tr>
<th>Sensitivity analysis</th>
<th>$q_{in}$ (mg/L)</th>
<th>$Q_L$ m$^3$</th>
<th>$\xi$ (million $$/ m$$)</th>
<th>E</th>
<th>Ecosystem damage (m)</th>
<th>$q_{out}$ (mg/L)</th>
<th>Optimal Solution (million $)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>243.83</td>
<td>1.00 $\times 10^4$</td>
<td>27.8</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>44.21</td>
</tr>
<tr>
<td>2</td>
<td>243.83</td>
<td>1.00 $\times 10^6$</td>
<td>27.8</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>44.21</td>
</tr>
<tr>
<td>3</td>
<td>243.83</td>
<td>44.33 $\times 10^8$</td>
<td>27.8</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>44.21</td>
</tr>
<tr>
<td>4</td>
<td>243.83</td>
<td>1.00 $\times 10^{10}$</td>
<td>27.8</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>44.21</td>
</tr>
<tr>
<td>5</td>
<td>243.83</td>
<td>1.00 $\times 10^{12}$</td>
<td>27.8</td>
<td>0.31</td>
<td>0</td>
<td>167.89</td>
<td>32.30</td>
</tr>
<tr>
<td>6</td>
<td>243.83</td>
<td>1.00 $\times 10^{14}$</td>
<td>27.8</td>
<td>0.11</td>
<td>0</td>
<td>216.40</td>
<td>2.39</td>
</tr>
<tr>
<td>7</td>
<td>243.83</td>
<td>1.00 $\times 10^{16}$</td>
<td>27.8</td>
<td>0.01</td>
<td>0</td>
<td>241.73</td>
<td>0.03</td>
</tr>
</tbody>
</table>

*The row with dark background means the solution of run with base values.*
Annex 4
Annex-Table 4. Sensitivity analyses result by change coefficients ecosystem service values

<table>
<thead>
<tr>
<th>Sensitivity analysis</th>
<th>$q_{in}$ (mg/L)</th>
<th>$Q_L$ m$^3$</th>
<th>$\xi$ (million $$/m$$)</th>
<th>$E$</th>
<th>Ecosystem damage (m)</th>
<th>$q_{out}$ (mg/L)</th>
<th>Optimal Solution (million $)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>243.8 x $10^8$</td>
<td>0.00</td>
<td>0.0</td>
<td>0</td>
<td>2.50</td>
<td>243.8 x $10^8$</td>
<td>0.00</td>
</tr>
<tr>
<td>2</td>
<td>243.8 x $10^8$</td>
<td>0.278</td>
<td>0.0</td>
<td>1</td>
<td>2.50</td>
<td>241.8 x $10^8$</td>
<td>0.69</td>
</tr>
<tr>
<td>3</td>
<td>243.8 x $10^8$</td>
<td>2.78</td>
<td>0.0</td>
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<td>2.50</td>
<td>235.7 x $10^8$</td>
<td>6.94</td>
</tr>
<tr>
<td>4</td>
<td>243.8 x $10^8$</td>
<td>13.9</td>
<td>0.0</td>
<td>9</td>
<td>2.49</td>
<td>222.1 x $10^8$</td>
<td>34.64</td>
</tr>
<tr>
<td>5</td>
<td>243.8 x $10^8$</td>
<td>27.8</td>
<td>1</td>
<td>0.00</td>
<td>0</td>
<td>44.21</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>243.8 x $10^8$</td>
<td>278</td>
<td>1</td>
<td>0.00</td>
<td>0</td>
<td>44.21</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>243.8 x $10^8$</td>
<td>2780</td>
<td>1</td>
<td>0.00</td>
<td>0</td>
<td>44.21</td>
<td></td>
</tr>
</tbody>
</table>

*The row with dark background means the solution of run with base values.
Annex 5

Code of the Social Optimization Model in LINGO 14.0 Software.

MODEL:

[1] MIN = 0.0736 * INV + VC + 27.8 * DAMAGE;
[2] INV = @EXP( 2.647 - 0.782 * D) * 1466 ^ 0.484 * ( E ^ 3.104);
[3] VC = @EXP( 0.119 - 0.907 * B) * F ^ 0.413 * ( E ^ 2.575);
[4] DAMAGE = 2.6 - @EXP( 1.39 - 1.17 * S ^ 0.25);
[5] S = ( 243.83 * F * 3650000 - 243.83 * E * F * 3650000) / ( 4433000000 + F * 3650000) + 0.01901822219;
[7] E <= 1;
[8] F = 800;
[9] D = @IF( ( INV #GT# 0) #AND# ( INV #LT# 20) #AND# ( E #GT# 0.9) #AND# ( E #LT# 1), 1, 0); 
[10] B = @IF( ( VC #GT# 0) #AND# ( VC #LT# 1) #AND# ( E #GT# 0.9) #AND# ( E #LT# 1), 1, 0);