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Research article

Economics of social trade-off: Balancing wastewater treatment cost and ecosystem damage

Yu Jiang [a,*], Ariel Dinar [b], Petra Hellegers [c]

[a] Environmental Economics and Natural Resources Group, Wageningen University, P.O. Box 17, 6700 AA, Wageningen, The Netherlands
[b] School of Public Policy, University of California, Riverside, CA 92521, USA
[c] Water Resources Management Group, Wageningen University, P.O. Box 47, 6700 AA, Wageningen, The Netherlands

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ABSTRACT

We have developed a social optimization model that integrates the financial and ecological costs associated with wastewater treatment and ecosystem damage. The social optimal abatement level of water pollution is determined by finding the trade-off between the cost of pollution control and its resulting ecosystem damage. The model is applied to data from the Lake Taihu region in China to demonstrate this trade-off. 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 accuracy of the economic 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. The Act also applies national standards set by the United States Environmental Protection Agency (US EPA) to control water sources in rivers, lakes, reservoirs, springs, and groundwater 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 fit into the eco-environmental character 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 trade-off between ecosystem functions and economic activities.

Aquatic ecosystems (e.g., lake ecosystems) are able to store and absorb waste from human economic activities through dilution, assimilation, and chemical decomposition to a limited extent, acting as "free" water purification plants (De Groot et al., 2002). If the waste amount exceeds the aquatic ecosystem's purification capacity, the ecosystem will be damaged. On one hand, the over-exploitation of the ecosystem capability in attenuating pollution can compromise the long-term functionality of the aquatic ecosystem functionality. On the other hand, not fully using the receiving water system's assimilative capacities creates higher wastewater treatment costs than necessary. 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

* Corresponding author.
E-mail addresses: yu.jiang@wur.nl (Y. Jiang), ariel.dinar@ucr.edu (A. Dinar), petra.hellegers@wur.nl (P. Hellegers).

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studies link the ecosystem response behavior with the level of wastewater treatment to allow the estimation of economic trade-off 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). However, 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). 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 this 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, in addition to 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 the quality of wastewater to be discharged into the lake. The trade-off is between the cost of treatment to reach high-quality discharged wastewater and the damage to the lake's ecosystem. Both of these are components in the social objective function of the region. There are differences in the level of economic development in various regions of China. People's valuation of ecosystem services also varies among regions, due to the level of economic development as well as environmental situations, local traditions, and institutions. Compared to the alternative option provided in our social optimization model, the cost incurred in meeting current unified water quality criteria does not reflect these local economic, traditional, institutional, and environmental situations.

Several simplifying assumptions were used, which took into consideration population levels, economic activity, as well as water volume and quality in the lake. The relationship between the water pollution level and the damage to the lake ecosystem was modeled using a steady-state approach (Hein, 2006; Bostian et al., 2015). This approach does not fully reflect the dynamic behavior of pollution. However, the objective of this study was to reflect the long-term steady state of the system so that scientific insights can be provided to the water quality regulator. This purpose was fully achieved by using the steady-state framework.

The model also assumed that water treatment was performed in one wastewater treatment facility, while in reality the lake water was used for irrigation and for drinking purposes. Since the interest of this study was in the trade-off between pollution control cost and ecological damage, it was assumed for simplicity and without loss of generality that the only use of the lake water was for recharge of the treated wastewater and for recreation. In this respect, our model is considered partial equilibrium. 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 was 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 operation and maintenance (O&M cost) C is represented by $C = C(Q, F, E)$ expressed in million \$, where Q is the designed capacity of the plant expressed in m^3/day, F is the wastewater flow expressed in m^3/day, and E is the pollutant removal efficiency expressed in percentage. Q is used for investment cost function estimation, and F is used for O&M cost function estimation. E is defined as $(q_{in} - q_{out})/q_{in}$, where q_{in} represents pollutant influent concentration measured in mg/L, and q_{out} represents effluent concentration measured in mg/L. 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). 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 type, which is totally different (c) is not continuous. The response line is folded backward, which is known as a “catastrophe fold.” Ecosystems respond to external stress following a curve that is folded backward, as shown in Fig. 1 (c). If the ecosystem state is on the upper line and close to point “A,” small changes in the conditions may lead to a catastrophic switch to the lower line. To switch again to the upper line, the external conditions need to be reversed far enough to reach point “B” (Scheffer et al., 2001; Esteban and Dinar, 2016).

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. That is 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), or turbidity of the lake. The term “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.