

An economic analysis on the externality of ground water exploitation in fish farms

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Abstract

The rapid development of the aquaculture industry in coastal areas has created high demand for water, threatening the environment and attracting public concern due to its negative effects on the environment. We attempt to design an economic incentive mechanism to encourage fish farms to reduce their externalities of ground water exploitation in a sustainable way through the imposition of an environmental tax. Most of the literature on environmental tax basically focus on the environmental externalities of immediate impacts and neglects the potential impacts of an ecological value loss. We present three models to determine the private optima, social optima, and the gap between private optima and social optima, and analyze the effects of fish price, ground water price, and discount rate on the optimal water consumption. A ground water exploitation rate is employed as a decision variable for the farmer and the policy planner by maximizing private profits and social benefits respectively. In this paper we compare the farmer's optima and social optima and suggest that two types of an environmental tax must be imposed on the fish farm in

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order to reduce pollution emissions and improve the ecological values of water storage. The results of our analysis may provide some insight regarding the quantitative relevance between production revenues of fish farms and externalities of ground water exploitation.

Keywords: carrying capacity, stocking rate, feeding rate, fish farm, water exploitation.

1. Introduction

The rapid growth in industrial output accompanied with population increases has accelerated the need for food and environmental resources in developing countries. As a consequence, a great amount of water is consumed and becomes exhaustible since water is an essential resource for human beings' production and daily use. Thus, accessible water for personal, industrial, and agricultural purposes is limited. About 1.5-2 billion people globally are unable to get enough water for personal use² (Postel et al., 1996; Ehrlich, et al., 1999).

According to a Taiwan governmental report, current annual water consumption amounts to $181 \times 10^8 \text{ m}^3$, of which 75% is used for agricultural production. About 35% of the total water consumption amounting to $63 \times 10^8 \text{ m}^3$ is extracted from groundwater storage which is more than the ground water infiltration into water storage of $40 \times 10^8 \text{ m}^3$. Thus, the over-exploitation of ground water in Taiwan is about $23 \times 10^8 \text{ m}^3/\text{year}$ (Taiwan Water Resource Agency, 2003). Many fish farms in Taiwan's coastal areas are believed to be the major cause for the over-exploitation of groundwater. As a consequence, the accumulated land subsidence depth in some coastal areas has been up to 2.5-3.2m (Chang Hwa country and Pingtung Country) over the past 30 years. Moreover, land subsidence is going on at the rate of 10-17.6 cm annually (Taiwan Water Resource Agency, 2003). Under such a circumstance,

² A rough estimate points out that total human consumption for water each day is about 50 liters (Gleick, 1996). The minimum water requirement for survival must be 2.5-4 liters per day and for personal use, including cooking, bathing, etc. in a modern society, it must be 50 liters per day (Gleick, 1996).

efforts to develop an optimal water policy have become very critical. Rosegrant and Ringler (1997) suggest using a variety of policy reforms, including economic incentives for water conservation, privatization of management functions, and effluent charges, to improve the sustainable use of water resources.

Many researchers analyze the optimal water exploitation through econometric approaches or on mathematical programming models parameterized with agronomic yield relationships (e.g. Kim et al., 1989; Knapp and Olson, 1995). The maintenance of water resource and the introduction of environmental programs ensure that economic efficiency is achieved (Janssen et al., 1994; Pearce and Turner 1990). These studies in the literature focus on the conservation of water resources and express a loose link with fishery production. A fishery policy traditionally focuses on the conservation of fishery stocks for sustainable exploitation and neglects the environmental impacts of fishery production. For example, Clark (1979, 1990), Hartman (1976) and Choudary and Johnson (1990) study the optimal harvesting schedule with harvesting taxes for renewable resources, while Barrett (1991) and Krautkraemer (1994) link the growth of renewable resource with shifting cultivation to determine the optimality.

In this paper we first present a model to describe a management problem, which contains several management variables for a fish farm to determine when seeking private profits. This model focuses on the management of a fish farm for a single species of fish with the optimal stocking rate, feeding rate, water exploitation rate, and harvesting period by neglecting the environmental impacts of groundwater exploitation.

The negative effects of fish farms' groundwater exploitation on the environment include two categories: the immediate environmental impacts (such as nutrient emissions of water pollution from fish farms) and the potential impacts (such as land subsidence of ecological value loss). We present another two models for the policy planner when considering the immediate impacts and the potential impacts of ground water exploitation in order to determine the social optima and compare the social optima difference. In this paper, environmental tax mechanisms are shown to mitigate the externalities of immediate and potential impacts separately.

2. Assumptions and notations

A farmer rents a fish of farm size F for fish farming. At time $t = 0$, he needs to recharge a biomass R of juvenile fish to sustain the growth and exploitation of the fishery stock and at time $t = T$, all the biomass of the fishery stock should be harvested, and the new restocking of juvenile fish R is administered. During the cycle of the harvesting period, nutrients and feeds for fish are implemented so as to speed up the growth of fish stock and water circulation in order to clean fishponds and aeration to prevent fish dying.

The function of fish growth rates³ is assumed to be

$$\frac{dx}{dt} = \alpha g(x), \quad (2.1)$$

with properties of $g'(x) < 0$, where α is the growth coefficient and x represents

³ Many researchers employ a logistic function expressed as $\frac{dx}{dt} = \alpha x (1 - \frac{x}{F})$ for the fish growth function, where F is the carrying capacity of the fish farm. This equation implies that when the population of the fishery stock is beyond the carrying capacity, it will lead to higher mortality and reduce the growth rate. Fisheries' yield is directly related to the carrying capacity of the farm. In general, the carrying capacity is positively proportional to the size of the fish farm and defined as an inherent maximum number of fish that can be supported by the given area of the ecological system or as the maximum size of fishery stock that can sustain the growth and survival of fishes without degrading the ecosystem and suitability for that use (Odum, 1997) or the upper limit of the biomass of the fishery stock that can be supported by a set of primary productions and food web structures (Christensen and Pauly, 1998). Therefore, we assume that the carrying capacity in this paper represents the farm size. It can affect fishery yield and harvest rate, and is seen as an external parameters.

the biomass of the fishery stock. Through experimental analysis, many researchers conclude that the growth is affected by many factors such as the feeding rate and feeding schedule (Sugiura and Hardy, 2000; McGoogan and Gatlin, 2000; De Silva and Anderson, 1995; Gershanovich and Taufik, 1992; Tacon and Cowey, 1985; Talbot, 1985), moisture content of diet (Higgs et al., 1985), and some abiotic factors such as water circulation, water quality, water temperature, and water management (Jobling, 1994; Kestemont, 1995; Tacon et al., 1995; Phillips, 1997; Beveridge et al., 1998; Black, 2001; Tacon, 2001).

We categorized these factors into two groups: the feeding factor f and the watering factor (water exploitation rate) w , where f represents the feeding rate per unit of fishery biomass per unit time and w denotes the water exploitation per unit time per unit of farm size. Assuming the growth coefficient is affected by the two factors, i.e. $\alpha = \alpha(f, w)$, the growth function of the fishery stock of Equation (2.1) is thus modified as:

$$\frac{dx}{dt} = \alpha(f, w) g(x). \quad (2.2)$$

The harvest period (stocking time) is an important factor to affect survival rate (McKinnell and Lundqvist, 2000) and eventually the harvest rate of the fishery stock. At time $t = 0$, the biomass of the fishery stock is equivalent to the stocking rate R , i.e.

$$x(0) = R. \quad \text{The harvest rate at time } t = T \text{ will be } x(R, f, w, T) = \int_0^T \alpha(f, w) g(x) dt.$$

The harvesting cost is assumed to be independent of the harvesting rate and the fish market is completely competitive, so that fish price p is also given and fixed and will not be affected by the output level. The unit price of juvenile fish c_1 is assumed to be given and fixed and thus the farm needs to pay for stocking with costs $c_1 R$. The feeding rate per each biomass f is instantaneously implemented to speed up the growth of the fishery stock and thus the total cost of feeding activities during the cycle is $\int_0^T c_2 f x(R, f, w, t) e^{-rt} dt$, where c_2 is the unit cost of feed, the constant flow of water per each farm size is circulated through the fish pond and total cost during a cycle is $\int_0^T c_3 w F e^{-rt} dt$, where c_3 is the unit cost of ground water including the operation cost of pumping, and rent cost is $\int_0^T c_4 F e^{-rt} dt$, where c_4 is the rent per

unit of farm size per unit of time.

3. The farmer's model

In this paper the farmer is assumed to be seeking for the maximization of the discounted current values of fish harvesting minus the cost to support the farm operating over time. In other words, a farmer will determine the optimal stocking rate, feeding rate, water exploitation rate, and harvesting period by maximizing the private profit. Thus, the farmer's objective function is expressed as follows:

$$\begin{aligned}
 & \underset{R, f, w, T}{Max} \quad \pi = \\
 & px(R, f, w, T) e^{-rT} - c_1 R - \int_0^T c_2 fx(R, f, w, t) e^{-rt} dt - \int_0^T c_3 w F e^{-rt} dt - \int_0^T c_4 F e^{-rt} dt \\
 & = px(R, f, w, T) e^{-rT} - c_1 R - \int_0^T c_2 fx(R, f, w, t) e^{-rt} dt - \frac{c_3 w F}{r} (1 - e^{-rT}) - \frac{c_4 F}{r} (1 - e^{-rT}).
 \end{aligned}$$

(P1)

Model (P1) is viewed as an optimization problem in which the fish price, the juvenile fish price, feed price, and water price are all treated as exogenous variables, because individual farmers cannot affect these parameters in a competitive market.

Solving the problem yields the first-order conditions⁴:

$$0 = \frac{\partial \pi}{\partial R} = p x_R(\cdot) e^{-rT} - c_1 \quad (3.1)$$

$$0 = \frac{\partial \pi}{\partial f} = p x_f(\cdot) e^{-rT} - \int_0^T c_2 f x_f(\cdot) e^{-rt} dt \quad (3.2)$$

$$0 = \frac{\partial \pi}{\partial w} = x_w(\cdot) e^{-rT} - \frac{c_3 F}{r} (1 - e^{-rT}) \quad (3.3)$$

$$0 = \frac{\partial \pi}{\partial T} = p(x_T(\cdot) e^{-rT} - x(\cdot) r) e^{-rT} - c_2 f x(\cdot) T e^{-rT} - c_3 w F e^{-rT} - c_4 F e^{-rT}. \quad (3.4)$$

Equation (3.1) requires that the marginal benefit of the stocking rate should equal its marginal cost, (3.2) requires that the marginal benefit of the feeding rate should be equal to its marginal cost, (3.3) indicates that the marginal benefit of water use must be equal to its marginal costs, and (3.4) asks that the marginal revenue arising from an

⁴ The subscript of $x(\cdot)$ denotes the partial derivative.

increase of the harvesting period must be equal to its extra costs of extending the harvesting period. The first term of Equation (3.1) describes the current value of marginal revenues of the stocking rate with the property of a negative slope (i.e. $p x_{RR}(\cdot) e^{-rT} < 0$) in Figure 1. It clearly demonstrates that a decrease in the cost of juvenile fish from c_1^H to c_1^L will lead to a lower stocking rate from R^* to $R^\#$, and similarly an increase in the fish price will encourage the farmer to increase the stocking rate, and an increase in the discount rate will reduce the stocking rate.

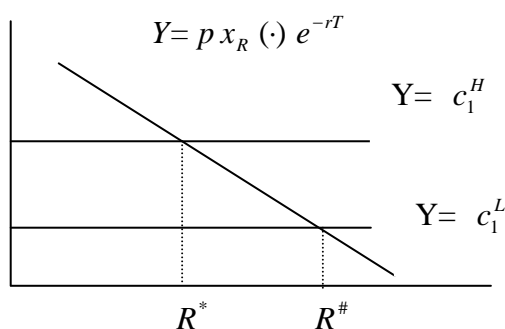


Figure 1. The determination of the optimal stocking rate

In a similar way, we can show that an increase in feed price will reduce the feeding rate, while an increase in fish price will provide incentives to use more feed by Equation (3.2). The decided optimality by a single farmer to exploit the required water for his fishpond is concluded based on the situation where the marginal benefit of water use (indicated as $p x_w(\cdot) e^{-rT}$) as the demand curve should be equal to the marginal cost $\frac{c_3^F}{r}(1 - e^{-rT})$ in Equation (3.3). If water price is reduced or fish price is increased, the farmer will exploit more ground water for fish production so as to increase his profit. Larger farms will exploit less groundwater per unit of farm size. The first term on the right side of Equation (3.4) describes the economic effects of an increase in harvesting period and the remaining items describe extra cost of an increase in the harvesting period paying for feeds, water, and facility rents. It is clearly indicated by Equation (3.4) that an increase in rent charge, farm size, and water costs will reduce the harvesting period.

By solving the simultaneous equations of (3.1)-(3.4), the private fish farm can attain the optimality to achieve a maximization of profit by optimizing resources used (the stocking rate, the feeding rate, the ground water exploitation rate, and the

harvesting period (time expense)). Thus, it does not warrant that the optimal growth of fish stocks (output per unit time) as the stocking rates, feeding rates, watering rate, and harvest periods may interact to affect profitability.

4. The policy planner's model

A farmer in general will neglect the negative impacts of an over-consumption of underground water on the environment while the policy planner needs to consider reducing the environmental impacts (the external costs of farmers' water exploitation) and internalizing the external costs through an appropriate measure. In this paper we classify the environmental impacts into two categories: immediate impacts and potential impacts. The former affects a human's life immediately, such as public health, production reduction etc. Many researchers have identified the immediate environmental impacts caused by different types of nutrient emissions from fish farms to lakes or rivers (e.g. Gowen et al., 1990, Silvert, 1992). The negative effects of nutrient emissions include increased water turbidity, a changed composition of the algae flora, disturbed fish reproduction, and possibly more algal blooms. In contrast, the potential environmental impacts of the latter will emerge after a period of time. As in a practical world, the consumption of ground water in fish farms may lead to land subsidence and destroy environmental resources for aquatic habitat (Dunne and Leopold, 1978; Strahle, 1981), because the water storage may collapse and cannot return back to its original state due to limited assimilative capacity (or resilience). We will discuss the policy setting of the former impacts in Section 4.1 and that of the latter in Section 4.2.

4.1 The policy planner's model in the presence of immediate environmental impacts

The immediate impacts of wastewater pollutions from fish farms on the environment depend upon the species cultured, farming system (Boyd and Queiroz, 2001), water management, and the assimilative capacity of the fish farm (farm size) (Tacon et al., 1995; Phillips, 1997; Black 2001, Tacon, 2001). Thus, we assume that the immediate environmental impacts of waste water pollution emitted from a fish pond⁵ is assumed to be a function of the total consumption of ground water during

⁵ Many researchers have presented models to estimate the environmental impact in coastal waters on the environment (e.g. Silvert, 1992, Gowen, 1994, Ervik et al., 1997, and Dudley et al., 2000).

the harvest period T , i.e. $D = D(\int_0^T wFe^{-rt} dt)$. We assume that there is a representative fish farm to produce fish for the market and the social objective is defined as the total revenue of the representative fish farm minus the cost and environmental damage of environmental pollution which can be expressed as

$$\begin{aligned} & \text{Max}_{R, f, w, T} \quad S = px(R, f, w, T) e^{-rT} - c_1 R - \int_0^T c_2 fx(R, f, w, t) e^{-rt} dt - \\ & \int_0^T c_3 wFe^{-rt} dt - \int_0^T c_4 Fe^{-rt} dt - D(\int_0^T wFe^{-rt} dt) \\ & = px(R, f, w, T) e^{-rT} - c_1 R - \int_0^T c_2 fx(R, f, w, t) e^{-rt} dt - \frac{c_3 wF}{r} (1 - e^{-rT}) \\ & - \frac{c_4 F}{r} (1 - e^{-rT}) - D(\frac{wF}{r} (1 - e^{-rT})). \end{aligned} \quad (P2)$$

The necessary conditions of the policy planner's model with respect to the four variables are:

$$0 = \frac{\partial S}{\partial R} = p x_R(\cdot) e^{-rT} - c_1 \quad (4.1)$$

$$0 = \frac{\partial S}{\partial f} = p x_f(\cdot) e^{-rT} - \int_0^T c_2 f x_f(\cdot) e^{-rt} dt \quad (4.2)$$

$$0 = \frac{\partial S}{\partial w} = \frac{p}{rT} x_F(\cdot) e^{-rT} - \frac{c_3 F}{r} (1 - e^{-rT}) - D'(\frac{wF}{r} (1 - e^{-rT})) \frac{F}{r} (1 - e^{-rT}) \quad (4.3)$$

$$0 = \frac{\partial S}{\partial T} = p(x_T(\cdot) e^{-rT} - x(\cdot) r) e^{-rT} - c_2 x(\cdot) f T e^{-rT} - c_3 wF e^{-rT} - c_4 F e^{-rT} - D'(\cdot) wF e^{-rT}. \quad (4.4)$$

Compared to the farmer's model, a new item $D(\cdot)$ appears in (P2) that describes the immediate environmental impacts of water pollution. After comparing the necessary conditions of (P2) to (P1), we find a new item that appears in Equations (4.3) and (4.4), which represents the immediate environmental impacts of water exploitation and the harvesting period. The signs of this new item in Equations (4.3) and (4.4) are positive and thus it is shown that a gap between farmers' optima and socially optimal solutions does exist. In the two models, the private discount rate is

assumed to be the same as the social discount rate. This simplifies our analysis.

4.2 The policy planner's model in presence of potential environmental impacts

As the environmental damage function in Model (P2) is assumed to be given and fixed, it implies that the ground water storage is not affected by activities of fish farms and the continual exploitation of ground water will not universally lead to physical exhaustion or affect the forms and patterns of environmental damages. In practice, the over-consumption of groundwater will bring about negative impacts on ecological circumstances. Because a fishing farm relies on water supplies, produces environmental impacts, and competes with other activities like agriculture, resulting in conflicts over the use of environmental resources as a common resource (Barg, 1992), the reserve of groundwater may bring more benefits to society under the case of removing fish production (Lewis and Schmalensee, 1977; Loomis et al., 1990).

The policy planner will set up a policy or make a decision on whether to preserve the ground water storage based on the social objective, including the environmental damage arising from the over-exploitation of ground water and the private farms' net values of production. In other words, the policy planner needs to obtain information about the working of the ecological systems and the utility derived from the public who enjoy the services provided by the environmental resources of water storage. The ecological values E of water resources is a function of water storage and defined as $E = E(W)$ with properties of $E'(W) > 0$. The dynamical state of water storage could be expressed as

$$\frac{dW}{dt} = \beta g(W) - F w, \quad (4.5)$$

where W is water storage, $g(W)$ is the natural replenishment function of ground water with properties $g'(W) < 0$, and β is the natural replenishment rate ($\beta > 0$). The growth rate of water storage is increasing if the water exploitation is less than the natural replenishment; Otherwise, it is decreasing.

To achieve the sustainable use of groundwater, the policy planner regulates that the rate of water consumption cannot exceed the natural rate of groundwater replenishment, i.e. $\frac{dW}{dt} = 0$. Thus, we get $\beta g(W) = F w$ (4.6)

as a constraint to the social planner's objective function. In this case, the social

planner is seeking to

$$\begin{aligned}
 \underset{R, f, w, T}{Max} \quad W &= px(R, f, w, T) e^{-rT} - c_1 R - \int_0^T c_2 fx(R, f, w, t) e^{-rt} dt - \\
 &\int_0^T c_3 wF e^{-rt} dt - \int_0^T c_4 F e^{-rt} dt - D\left(\int_0^T wF e^{-rt} dt\right) + E(W) \\
 &= px(R, f, w, T) e^{-rT} - c_1 R - \int_0^T c_2 fx(R, f, w, t) e^{-rt} dt - \frac{c_3 wF}{r} (1 - e^{-rT}) - \frac{c_4 F}{r} (1 - e^{-rT}) \\
 &- D\left(\frac{wF}{r} (1 - e^{-rT})\right) + E(W), \tag{P3}
 \end{aligned}$$

under the constraint of (4.6). Here, the Lagrangian function of (P3) becomes

$$\begin{aligned}
 L &= px(R, f, w, T) e^{-rT} - c_1 R - \int_0^T c_2 fx(R, f, w, t) e^{-rt} dt - \frac{c_3 wF}{r} (1 - e^{-rT}) \\
 &- \frac{c_4 F}{r} (1 - e^{-rT}) - D\left(\frac{wF}{r} (1 - e^{-rT})\right) + E(W) - \lambda (\beta g(W) - Fw),
 \end{aligned}$$

where λ is the shadow price of the resource constraint of Equation (4.6). The necessary conditions for (P3) include

$$0 = \frac{\partial L}{\partial R} = p x_R(\cdot) e^{-rT} - c_1 \tag{4.7}$$

$$0 = \frac{\partial L}{\partial f} = p x_f(\cdot) e^{-rT} - \int_0^T c_2 f x_f(\cdot) e^{-rt} dt \tag{4.8}$$

$$0 = \frac{\partial L}{\partial w} = \frac{p}{rT} x_F(\cdot) e^{-rT} - \frac{c_3 F}{r} (1 - e^{-rT}) - D'\left(\frac{wF}{r} (1 - e^{-rT})\right) \frac{F}{r} (1 - e^{-rT}) + \lambda F \tag{4.9}$$

$$0 = \frac{\partial L}{\partial T} = p(x_T(\cdot) e^{-rT} - x(\cdot) r e^{-rT} - c_2 x_f T e^{-rT} - c_3 wF e^{-rT} - c_4 F e^{-rT} - D(\cdot) wF e^{-rT} \tag{4.10}$$

$$0 = \frac{\partial L}{\partial W} = E'(W) - \lambda \beta g'(W) \tag{4.11}$$

and the constraint of (4.6).

By solving the simultaneously equations of (4.6)-(4.11), one can yield the optimal solutions of the socially optimal stocking rate, feeding rate, ground water exploitation rate, and harvesting period. Comparing between (4.3) and (4.9), a new item in Equation (4.9) is find. It is clear that the social optimum of Model (P3)

deviates from Model (P2).

5. Policy implications

Based on Equations (4.9), (4.3), and (3.3), we can find that an objective conflict exists for the policy planner to decide between generating revenues of fish production from fish farms and encouraging water conservation through an imposition of a surcharge on ground water exploitation. The necessary conditions of (P1) and (P2) suggest that there is an optimality gap between the two models since (3.3) and (4.3) are different. The difference in the first-order conditions for the two models explains why a gap in the optimal points between the private farm and the policy planner exists. If governmental intervention is excluded, the farmer will consume more water to maximize its fish yields without any limitation and does not care about the negative impacts of environmental damage due to water consumption. Farmers do not have an incentive to consider the external effects of water consumption leading to ground sinking. In addition, a farm will consume more water than the social optimum without regulating water consumption or imposing an extra tax on water consumption.

To mitigate environmental impacts caused from environmental pollution, governmental intervention is required. Equations (3.3) and (4.3) suggest that the water prices should be revised as

$$c_3^* = c_3 + D'(\cdot),$$

where c_3^* represent the optimal water price to encourage a fish farmer's water exploitation to comply with socially optimal conditions. If the current price c_3 is replaced by the optimal water price c_3^* , then the fish farmers will be motivated to determine their watering rate in compliance with the social optima. To achieve the social optimum, the government needs to impose an environmental tax directly related to the environmental damage (or marginal user cost) of water that is derived from (4.1)-(4.4). The tax rate per unit of water is

$$\tau = D' \left(\frac{wF}{r} (1 - e^{-rT}) \right). \quad (5.1)$$

As $D'(\cdot) > 0$, we achieve $c_3^* > c_3$. Equation demonstrates that the tax rate on ground water exploitation τ depends on the specified function of environmental impacts arising from nutrient emissions, the farm size F , and the discount rate. It is easy to prove that the tax rate is progressive with farm size as $\frac{d\tau}{dF} = D''(\cdot) \frac{F}{r} (1 - e^{-rT}) > 0$. This tax system can motivate the large fish farms to develop new technology or new processes to reduce water exploitation.

Model (P2) neglects the rate of natural groundwater replenishment and the sustainable use of ground water. A policy reform is required by pricing water according to the social optimum when considering the ecological values of ground water to prevent the potential impacts on the environment. Model (P3) shows fundamental changes to improve the efficiency of water consumption and achieve the objectives of sustainable use. Comparing (4.3) and (4.9), we find that the surcharge for water consumption in Model (P2) is insufficient to compensate for the loss of land subsidence arising from water over-exploitation. The optimal water price of Model (P3) must be

$$c_3^\# = c_3^* - \frac{\lambda r}{1 - e^{-rT}} = c_3 + D'(\cdot) - \frac{\lambda r}{1 - e^{-rT}},$$

where $c_3^\#$ represents the optimal water price to encourage fish farmers' water exploitation to comply with social optimality for sustainable use of ground water based on Model (P3). Rearranging (4.11) yields

$$\lambda = \frac{E'(W)}{\beta g'(W)}. \quad (4.11')$$

As $E'(W) > 0$, $\beta > 0$, and $g'(W) < 0$, we get $\lambda < 0$. In this case, we arrive at

the conclusion that the water price decided by the social planner in considering both ecological values and environmental damages will be higher than the single consideration of immediate environmental impacts, i.e. $c_3^{\#} > c_3^*$. The environmental tax rate on water for the remedy of all the environmental impacts, including immediate impacts and potential impacts, should be

$$t = D' \left(\frac{wF}{r} (1 - e^{-rT}) \right) - \frac{\lambda r}{1 - e^{-rT}}. \quad (5.2)$$

It is clear that a new item is found in Equation (5.2) as compared to (5.1). The first item of the right-hand side in Equation (5.2) represents the tax for immediate environmental impacts, and the second item is for potential impacts. Substituting (4.11') into (5.2) yields

$$t = D' \left(\frac{wF}{r} (1 - e^{-rT}) \right) - \frac{r}{1 - e^{-rT}} \frac{E'(W)}{\beta g'(W)}. \quad (5.3)$$

By Equation (5.3) we can conclude that the environmental tax for potential impacts is affected by the ecological value function $E(W)$, replenishment rate β , and infiltration function $g(W)$.

The specified function of ecological value $E(W)$ represents local residents' ecological values determined by their environmental concerns or preferences on natural resources and the restoration costs of environmental damage such as land subsidence (Chen, 2003). It, in general, varies across regions. Higher environmental concerns and higher restoration costs lead to higher ecological values and thus a higher environmental tax for groundwater exploitation should be imposed on fish farmers. Replenishment rate β and infiltration function $g(W)$ describe the different physical characteristics of ecological systems in each region. A higher replenishment will reduce the environmental tax for the ecological value loss. Thus,

we suggest an environmental tax should be varied across the country and adjusted continuously over time, based on various local factors such as economic base, ecological values of natural resources, population characteristics, ecological status, etc. Fish farms may pay a different environmental tax based on regional characteristics and hydrology dynamics of the ecological system and social systems.

5. Discussions and conclusions

The externalities of groundwater consumption in Taiwan have not been discussed much in the literature, nor have appropriate water policies been taken up by policy planners. Farmers can easily have access to ground water due to loose regulations with low costs of underground water, as low water costs encourage many small and marginal farmers to increase their agricultural production by exploiting ground water without any limit. Thus, this has led to an acceleration of groundwater exploitation and consequently land subsidence in Taiwan's coastal areas. The environmental trends of water resource scarcity will continuously mark up the water price and pollution on the environment from fish farms that aggravate the status of water scarcity.

If the environmental tax on water exploitation is not implemented, then it will lead to more serious problems in land subsidence and crowd out the use of valuable water in other industries, since water resources are also important and essential in other sectors of the economy (Clark, 1977; Johnston, 1992). The implementation of an environmental tax on water exploitation can shift the scarce and valuable resources from the fishing industry to more profitable sectors and lose the environmental impacts. Models (P2) and (P3) may be treated as an effective tool to remedy the current problem through a water pricing system suggested in this paper in order to reflect the environmental damages and opportunity costs in facing the over-exploitation of underground water by mitigating the gap between privately-competitive and socially-optimal exploitation rules.

In this paper we integrate the conservation of water resources, reduction of waste water pollution arising from fisheries, and fishery harvesting problems so as to form a fishery policy, and thus suggest that policy reforms must include at least economic

incentives for a reinforcement on the ecological values of water conservation and prevention of land subsidence (a surcharge of an environmental tax on potential impacts) and the reduction of wastewater pollution caused by nutrient emissions (a surcharge of an environmental tax on immediate impacts). The implementation of this incentive system may regulate groundwater exploitation by motivating fish farmers to improve their water management by recycling or reusing drainage water. This model provides some highlights on the economic incentive system to prevent environmental damage caused by waste water pollution and the loss of ecological values arising from a collapse of the ecological system. We treat the environmental impacts in two distinctive features: the immediate impacts and the potential impacts. It is sufficiently flexible for the policy planner to determine the social optima and the environmental tax based on regional characteristics.

We suggest to find a case for empirical study by applying these models suggested in this paper to decide: (1) optimality for private farmers, (2) social optima, and (3) environmental tax rate on water exploitation. The empirical study requires informational support, including (1) the status of water storage, (2) the impacts of water storage on the ecological system, and (3) the scale of environmental impacts of nutrient emissions. As the assessment of carrying capacity on groundwater storage is scientific and requires an effective indicator to assess the impact of aquacultural waste under a variety of topographic conditions to support policy decisions, this indicator should be simple and effective to evaluate the assimilative capacity and siting of fish farms. The results of the empirical study can help the policy planner to determine the relative potentials of groundwater supply in each region for sustainable use of ground water and provide a highlight on the importance of stability in groundwater supply across the spatial allocation of resources. The location of a fish farm in suitable points within an assimilative capacity should be assessed and regulated through a varied environmental tax determined by the models suggested in this paper in each region in order to ensure sustainable production.

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