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PRICING OF WATER RESOURCES WITH DEPLETABLE EXTERNALITY - THE EFFECTS OF POLLUTION CHARGES -

by

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1. Introduction

In highly industrialized river basins such as the Rhine in Central Europe and the Yodo River in Japan where water is utilized by many and varied entities and "return flows" from upstream users are discharged back into the river, the problem of using river water for the domestic water supply is not at all a question of quantity, but simply one of water quality, that is, of the pollution of the river (Sontheimer, 1976). Figure 1 is taken from Yoshitake and Kajino(1986) and shows a typical water quality problem in the Yodo River, where the Yodo Basin consists of an area of 8453 km^2 with the population of nearly 10.12 million in 1980 and supplies water for over 14 million. The figure shows annual as well as seasonal variation of two water quality parameters of biological oxygen demand (BOD) and ammonia nitrogen (NH_3-N) during the river's low main channel flow at the Kunijima water intake point in the city of Osaka, at the lower end of the Basin. A siginificant improvement in BOD, a general index of organic compounds, has been achieved due to the early implementation of BOD discharge standards on the major industrial and public dischargers and to the development of public sewer systems.

On the other hand, the river's ammonia nitrogen levels show a steady annual increase in Figure 1, where the concentration is greater in the winter than in the summer. This steady increase is thought to be mainly caused by the increase in the ammonia load in land drainage and the limitations of conventional primary and secondary wastewater processes in extracting nitrogen (Clark et al, 1977,p739). The increase in ammonia nitrogen presents a difficult problem for the domestic water supply in industrialized river basins. Although ammonia can be eliminated by

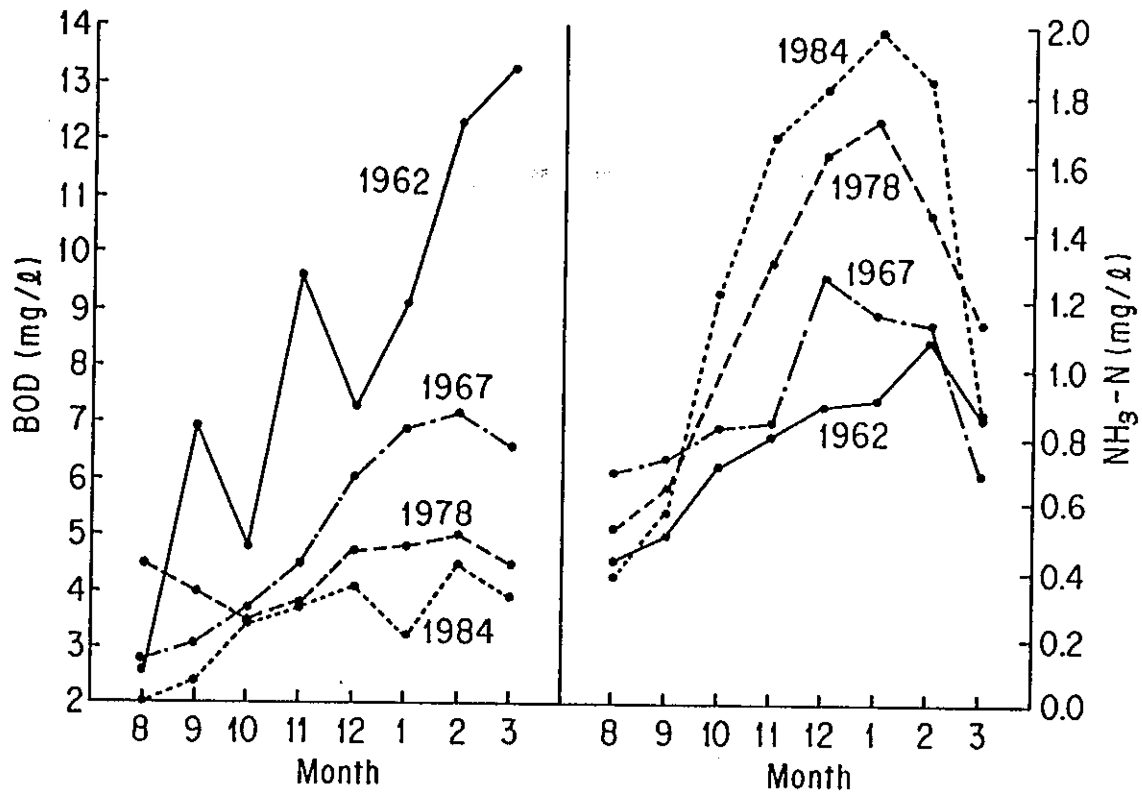

Figure 1 Trend of representative quality parameters during low channel flow in the lower end of the Yodo River (Yoshitake and Kajino 1986, p 485, Figure 2)

the breakpoint chlorination process used in water treatment (Clark et al, 1977,p448), it is known that "as a result of this mixing with chlorine, unwanted organochlorine compounds can arise through secondary reactions, and especially if the water contains high concentrations of organic compounds" (Sontheimer,1976).

In other words, an increase in organics, especially, refractory organics in surface water coupled with the practice of disinfection by chlorination can lead to a higher probability of generating carcinogens such as trihalomethane. The majority of refractory organics is thought to consist of humic substances in natural colored water and in a secondary treatment effluent (Tambo and Kamei, 1985). Thus, under limited financial resources, there is a growing need for advanced wastewater treatment which can remove nitrogen and refractory contaminants. Possible related issues concern the balance to be maintained between the need to treat and discharge effluents from upstream water users into water bodies and the need to conserve water quality for the downstream water supply.

This paper addresses the problems of integrating two main aspects of river water utilization, using river water for the domestic water supply and for the depositary of effluent discharges. In particular, we employ the asset utilization model of externalities, developed by Mohring and Boyd(1971), followed by Peskin(1988), to clarify the effectiveness of a system of charges on water abstraction (withdrawals) and on pollution discharges promoting efficient use of the abstraction and assimilative services provided by the water resources. Though, in this paper, we do not deal with the seasonal variation of the water pollution phenomena shown in Figure 1, the water resource pricing policy to be discussed in the paper may have a beneficial effect on the domestic water supply by shifting the pollution curve downward (see for related discussion in Baumol and Oates, 1975, ch.11).

There are two main reasons for employing the asset utilization framework. Recognizing the often conflicting needs of different water resource services, it is preferable to place pollution control in the more general context of utilizing regenerative water resources. Specifically, we agree with the statement made by Dasgupta(1982, p7) that "conceptually it is useful to bear in mind ... that the emission of pollutants in effect means the reduction in the quality or the size (or both) of the stock of a regenerative resource." Using Haveman's refinement of the economic definition of environment (1975, p102-107), we may view the water resource as a depletable capital asset which over time, yields a stream of services such as water supply and residuals assimilation services. The asset utilization model of externalities is best suited to deal with the asset depletability of water resources. "Depletability" may be seen as the reduction in the quantity of water of a certain minimum quality (such as one specified by the water quality standard) available, as a result of increases in pollution discharge. This constitutes our first reason for using the asset utilization framework.

The second reason is related to the possible conflicts arising between upstream pollution dischargers and downstream water users. Mohring and Boyd(1971) apply the asset utilization model of externalities to a producer-producer externality case within a river basin, where the river provides water quality and waste removal services and the quality of water provided by a downstream firm is dependent on the wastes discharged by upstream firms. They then made clear that, unless the locations and demands of water quality users are fixed, social optimum in terms of the mobility of two factors (abstracted water and capital) and perfect factor price flexibility, the full employment of the two factors and the total amount of pollution discharge is written as follows:

$$b_{L1}X_1 + b_{L2}X_2 = L \qquad (3a)$$

$$b_{K1}X_1 + b_{K2}X_2 = K \qquad (3b)$$

$$b_{Z1}X_1 + b_{Z2}X_2 = Z \qquad (3c)$$

where K, L, and Z are, respectivly, regional resource constraints on capital, surface water abstraction, and discharged pollution load. Under perfect competition and a serious water pollution problem, and assuming nonspecialization in production, the unit cost of each commodity equals its market price. Let r be the rental paid on capital, w the shadow price of the water abstraction constraint, t the governmentally imposed pollution charge, and P_j the price of the jth good. Then the final equation set of the BCY model is written as,

$$b_{Lj}w + b_{Kj}r + b_{Zj}t = P_j \qquad \text{for} \quad j=1,2 \qquad (4)$$

where, with quasi-concave and linearly homogeneous production functions, each input-output coefficient is homogeneous of degree zero in the factor prices:

$$b_{ij} = b_{ij}(w,r,t) \qquad \text{for} \quad i=K,L,Z \text{ and } j=1,2 \qquad (5)$$

This completes the description of the main structure of the BCY model. Before proceeding, one point should be kept in mind. In equation (3), the RHS of (3c) represents the total amount of discharged pollution. Alternatively, we may treat it, as Yohe(1979) does, as the governmentally imposed total pollution constraint. In this latter case, the pollution charge rate becomes the shadow price of the pollution constraint. Since, as we prove later, the incidence of the pricing of pollution discharge (under prevailing condition of the long run equilibrium) is shown to be equivalent to that of pollution control policy constraining the total amount of pollution, two policy instruments of pollution charge and pollution control are used interchangeably in this paper.

2.2 Extension of the BCY model

Now we extend the BCY model to deal with the asset depletability of water resources. Here, we assume that the environmental capability of supplying water for abstraction purposes at a predetermined level of water quality diminishes with an increase in the total amount of pollution discharge, Z. Specifically, L(Z) is defined as being the resource depletion function, where L(0) corresponds to the case of zero pollution discharge. Thus equation (3a) is rewritten as,

$$b_{L1}X_1 + b_{L2}X_2 = L(Z) \qquad (3a')$$

where $L(0)=L_0$ and $\partial L(Z)/\partial Z = L_Z < 0$. In the case where pollution discharge does not affect the environmental capability of supplying water, we have the "no" depletion case, L(Z)=L(0).

Before proceeding further, it is better to give the practical interpretation of this resource depletion function. Although the paper does not deal with the dynamic aspect of water resource utilization processes, Figure 2 illustrates L(Z) in historical perspectives. As time goes by, a general indicator of pollution load, Z(t), increases, with the increase in economic activities, as shown in the lower part of Figure 2. We may specify a certain maximum allowable concentration of Z(t) in relation to available water treatment technology. For example, in 1973 the International Consortium of Waterworks in the Rhine Catchment Area classsified important water quality parameters into two groups (Sontheimer, 1976):

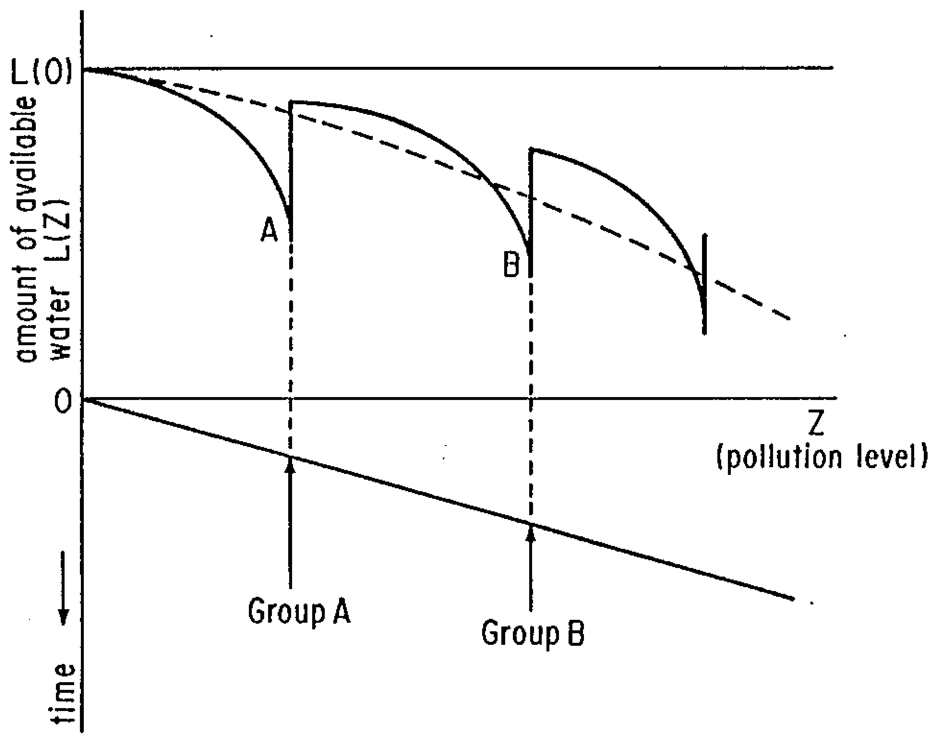

Figure 2 Illustrative example of the water resource depletion function

Group A: maximum allowable concentrations where natural purification processes are used, and

Group B: maximum allowable concentrations where known and tested processes for more thorough-going water treatment are used.

Given certain water treatment technology, we may draw L(Z) in the upper part of Figure 2 as representing the total quantity of available "safe" surface water for the corresponding pollution load Z. Here the adjective "safe" corresponds to the situation where pollution discharge level Z is less than a certain water quality level such as the Group A or Group B value. Under this situation, we assume that it is possible to supply water with "zero" risk or no cancer risk. In other words, if Z value exceeds the maximum allowable pollution load for an employed treatment technology, we consider that the supplied water may contain a risk factor. As a more advanced water treatment process is employed, the value of L(Z) is assumed to increase in Figure 2.

The main reason for employing the assumption of "zero" risk water is to limit our analysis to the producer-producer externality case treated by Mohring and Boyd(1971). We especially deal with a situation in which the product price vector is exogenously given data or determined outside the region. If you allow sector products with some risk factor and the risk factor is caused by the total pollution discharge (Z), then we have to deal with a more complicated externality model such as the modifed version of the Mohring and Boyd's asset utilization model which incorporates the Baumol and Oates (1975)'s direct interaction externalities models or Uzawa(1971,1972)'s social overhead capital model, where the consumer's utility function as well as the product price vector may be affected by Z.

This kind of mixed version model is discussed in Haveman(1973) and recently referred to by Freeman(1988).

Since the paper deals with the long run equilibrium nature of water resource utilization, the resource depletion function L(Z) is assumed to be something like a dashed line in Figure 2. In the author's opinion, this concept of resource depletion function is a natural consequence of the asset utilization model of externalities which interprets the existence of depletable externality as asset depletablility, "the using up of some desirable, but unpriced, asset" (to use Peskin(1988)'s phrase).

2.3 Analysis of the model

For later use, we duplicate, with relevant modifications, some of the equation sets derived by Batra and Casas. First of all, totally differentiating (3a'), (3b) and (3c), we obtain,

$$\lambda_{L1}X_1^* + \lambda_{L2}X_2^* = L(Z)^* - (\lambda_{L1}b_{L1}^* + \lambda_{L2}b_{L2}^*) \tag{6a}$$

$$\lambda_{K1}X_1^* + \lambda_{K2}X_2^* = K^* - (\lambda_{K1}b_{K1}^* + \lambda_{K2}b_{K2}^*) \tag{6b}$$

$$\lambda_{Z1}X_1^* + \lambda_{Z2}X_2^* = Z^* - (\lambda_{Z1}b_{Z1}^* + \lambda_{Z2}b_{Z2}^*) \tag{6c}$$

, where the following notations are used:

starred variables such as $X_i^* = dX_i/X_i$ used in this paper represent the percentage change in variables such as X_i, and

$\lambda_{ij} = b_{ij}X_j/i$ (i=K,L(Z),Z) (j=1,2) are the proportion of the total supply of the i-th factor employed in the j-th sector.

A similar manipulation of (4) leads to,

$$P_j^* = \theta_{Lj}w^* + \theta_{Kj}r^* + \theta_{Zj}t^* \qquad \text{for} \quad j=1,2 \tag{7}$$

where we utilized the cost minimizing constraint on a linearly homogeneous production function, $wdb_{Lj}+rdb_{Kj}+tdb_{Zj}= 0$, and

θ_{ij} = (the i-th factor price multiplied with b_{ij})/P_j

: the cost share allocated to the i-th factor in the j-th sector (i=K,L(Z),Z) (j=1,2)

(8)

The final set of equations is obtained by totally differentiating (5) as follows,

$$b_{Lj}^* = \theta_{Kj}\sigma_{KL}^{j}(r^* - w^*) + \theta_{Zj}\sigma_{LZ}^{j}(t^* - w^*) \quad (9a)$$

$$b_{Kj}^* = \theta_{Lj}\sigma_{KL}^{j}(w^* - r^*) + \theta_{Zj}\sigma_{ZK}^{j}(t^* - r^*) \quad (9b)$$

$$b_{Zj}^* = \theta_{Kj}\sigma_{KZ}^{j}(r^* - t^*) + \theta_{Lj}\sigma_{LZ}^{j}(w^* - t^*) \quad (9c)$$

where σ_{ik}^{j} are the Allen's partial elasticities of substitution. Though the equation set (9) was originally derived by Batra and Casas(1976,p24), Appendix 2 provides its proof.

If we eliminate X_1^* and X_2^* from equation (6a), we obtain

$$(E_1)w^* + (E_2)r^* + (E_3)t^* = (A_1)Z^* - (B_1)K^* - (B_2)L(Z)^* \quad (10)$$

where

$$(A_1) = \lambda_{K2}\lambda_{L1} - \lambda_{K1}\lambda_{L2}$$

$$(B_1) = \lambda_{Z2}\lambda_{L1} - \lambda_{Z1}\lambda_{L2}$$

$$(B_2) = \lambda_{Z1}\lambda_{K2} - \lambda_{Z2}\lambda_{K1}$$

and the exact expressions for (E_1),(E_2), and (E_3) are derived as follows (see Appendix 3 for the derivation of equation (10)):

(E_1) is the sum of the following terms;

$$\left.\begin{array}{l} \sigma_{KL}^{1}((B_2)\lambda_{L1}\theta_{K1} - (B_1)\lambda_{K1}\theta_{L1}) \\ \sigma_{KL}^{2}((B_2)\lambda_{L2}\theta_{K2} - (B_1)\lambda_{K2}\theta_{L2}) \end{array}\right\} \quad (11a)$$

$$\left.\begin{array}{l} \sigma_{ZL}^{1}((B_2)\lambda_{L1}\theta_{Z1} + (A_1)\lambda_{Z1}\theta_{L1}) \\ \sigma_{ZL}^{2}((B_2)\lambda_{L2}\theta_{Z2} + (A_1)\lambda_{Z2}\theta_{L2}) \end{array}\right\} \quad (11b)$$

(E_2) is the sum of the folowing terms;

$$\left.\begin{array}{l} \sigma_{KZ}^{1}(\ (A_1)\lambda_{Z1}\theta_{K1}+(B_1)\lambda_{K1}\theta_{Z1}) \\ \sigma_{KL}^{1}(\ -(B_2)\lambda_{L1}\theta_{K1}\ +\ (B_1)\lambda_{K1}\theta_{L1}) \\ \sigma_{KL}^{2}(\ -(B_2)\lambda_{L2}\theta_{K2}\ +\ (B_1)\lambda_{K2}\theta_{L2}\ ) \end{array}\right\} \quad (12a)$$

$$\sigma_{KZ}^{2}(\ (A_1)\lambda_{Z2}\theta_{K2}+(B_1)\lambda_{K2}\theta_{Z2}) \qquad (12b)$$

(E_3) is the sum of the following terms;

$$\sigma_{ZK}^{1}(\ -(B_1)\lambda_{K1}\theta_{Z1}\ -\ (A_1)\lambda_{Z1}\theta_{K1}\ ) \quad > 0 \qquad (13a)$$

$$\left.\begin{array}{l} \sigma_{ZK}^{2}(\ -(B_1)\lambda_{K2}\theta_{Z2}\ -\ (A_1)\lambda_{Z2}\theta_{K2} \qquad > \ 0 \\ \sigma_{ZL}^{1}(\ -(B_2)\lambda_{L1}\theta_{Z1}\ -\ (A_1)\lambda_{Z1}\theta_{L1}\ ) \\ \sigma_{ZL}^{2}(\ -(B_2)\lambda_{L2}\theta_{Z2}\ -\ (A_1)\lambda_{Z2}\theta_{L2}\ ) \end{array}\right\} \quad (13b)$$

Now we may rewrite eqs. (7) and (10) as follows:

$$\begin{pmatrix} \theta_{L1} & \theta_{K1} & 0 \\ \theta_{L2} & \theta_{K2} & 0 \\ (E_1) & (E_2) & -G \end{pmatrix} \begin{pmatrix} w^* \\ r^* \\ Z^* \end{pmatrix} = \begin{pmatrix} P_1^* - \theta_{Z1}t^* \\ P_2^* - \theta_{Z2}t^* \\ -(E_3)t^* - (B_1)K^* \end{pmatrix} \qquad (14a)$$

where $G = (A_1) - (B_2)L_Z\ Z/L$. Alternatively, we may rewrite eqs. (7) and (10) as follows,

$$\begin{pmatrix} \theta_{L1} & \theta_{K1} & \theta_{Z1} \\ \theta_{L2} & \theta_{K2} & \theta_{Z2} \\ (E_1) & (E_2) & (E_3) \end{pmatrix} \begin{pmatrix} w^* \\ r^* \\ t^* \end{pmatrix} = \begin{pmatrix} P_1^* \\ P_2^* \\ (A_1)Z^*-(B_2)L(Z)^*-\ (B_1)K^* \end{pmatrix} \qquad (14b)$$

where $L(Z)^* = dL(Z)/L(Z)$ represents the previously defined percentage change in $L(Z)$. Eqs.(14a) and (14b) are employed to analyze the incidence of higher pollution charges (t^*) and of stronger pollution control (Z^*), respectively.

We are now ready to prove that the incidence of the pricing of pollution discharge is equivalent to that of a pollution control policy constraining the total amount of pollution. Assuming $P_1^* = P_2^* = K^* = 0$ and employing Cramer's rule, we get that, from eq. (14a),

$$\left.\begin{aligned} w^* &= (D_1)t^*/(D_3) \\ r^* &= (D_2)t^*/(D_3) \\ Z^* &= D\ t^*/G(D_3) \end{aligned}\right\} \qquad (15a)$$

and, from eq. (14b),

$$\left.\begin{aligned} w^* &= G(D_1)Z^*/D \\ r^* &= G(D_2)Z^*/D \\ t^* &= G(D_3)Z^*/D \end{aligned}\right\} \qquad (15b)$$

where

$$\left.\begin{aligned} (D_1) &= \theta_{K1}\theta_{Z2}-\theta_{K2}\theta_{Z1} \\ (D_2) &= \theta_{L2}\theta_{Z1}-\theta_{L1}\theta_{Z2} \\ (D_3) &= \theta_{L1}\theta_{K2}-\theta_{K1}\theta_{L2} \\ D &= (E_1)(D_1) + (E_2)(D_2) + (E_3)(D_3) \end{aligned}\right\} \qquad (16)$$

When we assume the "strong factor intensity condition" introduced by Batra and Casas (1976,p26),

$$b_{K1}/b_{K2} > b_{Z1}/b_{Z2} > b_{L1}/b_{L2} \qquad (17)$$

implying that sector 1 is strongly intensive in the use of capital, and that sector 2 is strongly intensive in water abstraction, we then obtain $(D1)>0$, $(D2)>0$, and $(D3)<0$.

Thus

$$w^*t^* < 0, \qquad t^*r^* < 0 \qquad (18)$$

This is all that can be said, unless two more restrictive assumptions introduced by Yohe(1979) are made. When it is assumed $b_{Z2} = 0$ and

$\sigma_{LZ}{}^{1} = 0$, then the terms in (11b), (12b), and (13b) are zero, and consequently we obtain (C1)>0, (C2)<0, and (C3)>0. Thus we get D<0 from equation (16). Consequently we know that eqs. (15a) and (15b) generate the same sign conditions of $t^*r^* < 0$ and $t^*w^* > 0$, while the sign of t^*Z^* depends on the sign of the term $G = (A_1)-(B_2)L_Z Z/L$, where the signs of (A_1) and (B_2) are negative. For the case of a concave(convex) water resource depletion function, the sign of G is likely to be negative(positive) for large values of Z and positive(negative) for small values of Z. This completes the proof of the equivalence relationship between a higher pollution charge policy and a stronger pollution control policy.

We may now present the modified version of Yohe's Proposition 1.

If $K^*=P_1{}^*=P_2{}^*=0$, then the increase in the pollution charge rate generates a situation in which the real returns to capital (r) and water abstraction (w) move in opposite directions and those of water abstraction (w) and pollution discharge (t) in the same direction.

Yohe's Proposition 3, which imitates Batra and Casas's theorem 6(1976,p34), states that as pollution control becomes more restrictive ($Z^*<0$), at constant commodity price and factor endowments, the polluting sector will contract ($X_1{}^*<0$), and the nonpolluting sector will expand ($X_2{}^* > 0$). In order to see the validity of this proposition, we see that as pollution control becomes more restrictive ($Z^*<0$) or the pollution charge rate increases ($t^*>0$), equations (15) and (9) lead to

$$\left.\begin{aligned} b_{Lj}{}^* &= \theta_{Kj}\sigma_{KL}{}^{j}(r^* - w^*) < 0 \\ b_{K1}{}^* &= \theta_{L1}\sigma_{KL}{}^{1}(w^* - r^*) + \theta_{Z1}\sigma_{ZK}{}^{1}(t^* - r^*) > 0 \\ b_{K2}{}^* &= \theta_{L2}\sigma_{KL}{}^{2}(w^* - r^*) > 0 \end{aligned}\right\} \qquad (19)$$

and, consequently, b_{Lj}/b_{Kj} for j=1 and 2 becomes smaller. In terms of the Edgeworth and Bowley diagrammatic technique modified by Savosnick(1958), we may then prove $Y_1^* < 0$ and $Y_2^* > 0$ (see related discussion in Kitabatake(1989) for proof). Furthermore as $Z^* < 0$ ($t^* > 0$), the available quantity of water abstraction increases ($L^* > 0$). Thus the so-called Rybczynski effect, of favoring the industry sector which uses the water abstraction factor relatively intensively, further guarantees $Y_1^* < 0$ and $Y_2^* > 0$.

The major difference between Yohe's model and the extended version lies in Yohe's Proposition 2 which states that national income falls with stronger pollution control. Let's totally differentiate the identity,

$$Y = wL(Z) + rK + tZ$$

and consider the following identities

$$\left.\begin{aligned}
&\theta_1 + \theta_2 = 1 \\
&\theta_L + \theta_K + \theta_Z = 1 \\
&\theta_L = \theta_1(\theta_{L1} - \theta_{L2}) + \theta_{L2} \\
&\theta_K = \theta_1(\theta_{K1} - \theta_{K2}) + \theta_{K2} \\
&\theta_Z = \theta_1(\theta_{Z1} - \theta_{Z2}) + \theta_{Z2}
\end{aligned}\right\} \qquad (20)$$

where

$$\theta_i = P_i X_i / Y \quad \text{for} \quad i=1,2$$

$$\theta_L = w\,L(Z)/Y$$

$$\theta_K = r\,K/Y$$

$$\theta_Z = t\,Z/Y$$

We then obtain,

$$\begin{aligned}
Y^* &= (\theta_L w^* + \theta_K r^* + \theta_Z t^*) + \theta_L L(Z)^* + \theta_Z Z^* \\
&= (\theta_L L_Z Z/L + \theta_Z) Z^* \\
&= Z^*(t + wL_Z)Z/Y
\end{aligned} \qquad (21)$$

where the relation $\theta_L w^* + \theta_K r^* + \theta_Z t^* = 0$ can be proved in terms of (8), (15b), and (20). Here θ_i is the total i-th factor cost divided by national income. In our model, if the marginal cost of pollution control (t) is less than the marginal benefit of pollution control ($-wL_Z$), then national income increases with stronger pollution control, while in the original Yohe model the marginal benefit of pollution control is zero, and consequently, national income cannot increase.

3. Numerical example

In this section we present a numerical algorithm for solving an illustrative two-sector and three-factor model. Since we are interested in the substitution effects of relative factor price changes on the production side of a regional economy, we employ as equation (1) the following production functions,

$$X_1 = d_{11} K_1{}^{q} ((d_{12} L_1)^{\rho} + (d_{13} Z_1)^{\rho})^{\gamma/\rho} \tag{22}$$

$$X_2 = ((d_{21} K_2)^{\theta} + (d_{22} L_2)^{\theta})^{1/\theta} \tag{23}$$

where

$q + \gamma = 1$ (a homogeneous production function of degree one)

Equation (23) is specified, based on one of the Yohe model's restriction, $b_{Z2}=0$. The elasticity of substitution, σ_{LZ}, of water abstraction service for pollution discharge, is calculated from equation (22) to be $1/(\rho-1)$ and does not satisfy the other Yohe model's restrictions, $\sigma_{LZ}=0$. From the definition of the elasticity of substitution, $\sigma_{LZ}=$ $(\partial(L/Z)/(L/Z))/(\partial(w/t)/(w/t))$, we know that the smaller the value of this elasticity, the more skewed is the isoquant curve, and correspondingly the more difficult it is to substitute L for Z unless the factor price ratio (w/t) increases sharply. Thus we may approximate the restriction of $\sigma_{LZ}=0$ by some large negative value of ρ.

A cost function for sector j is derived by finding a cost-minimizing way to produce a given level of output, X_j,

$$\text{Min} \quad r K_j + w L_j + t Z_j$$
$$\text{s.t.} \quad (22) \text{ for } j=1, \quad (23) \text{ for } j=2$$

The derived cost functions C^j for sector j=1,2 are

$$C^1(r,w,t,X_1) = C_1^{\ 1}(r,w,t)X_1$$
$$C^2(r,w,X_2) = C_1^{\ 2}(r,w)X_2$$

where $C_1^{\ j} = \partial C^j/\partial X_j$ for j=1,2. Especially,

$$C_1^{\ 1}(r,w,t) = ((\rho+q)/(d_{11}\rho^{\gamma}))(r/q)^q((w/d_{12})^{\rho/(\rho-1)}+(t/d_{13})^{\rho/(\rho-1)})^{(\rho-1)\gamma/\rho} \tag{24}$$

$$C_1^{\ 2}(r,w) = ((r/d_{21})^{\theta/(\theta-1)}+(w/d_{22})^{\theta/(\theta-1)})^{(\theta-1)/\theta} \tag{25}$$

The variable coefficients simplex algorithm developed in Diewert and Woodland(1977,p378-382) and Woodland(1982,p60-63) is a numerical algorithm for solving our two-sector and three-factor model. We employed Fortran programs for linear programming and a linear equation system supplied by Yakowitz and Szidarovszky(1986), which proceed as follows.

Algorithm

(a) Specify a value of pollution charge rate, t, and a value of regional income to be some large positive values. Initiate the algorithm by choosing a price vector (r,w) > 0 and computing the input-output coefficients.

$$b_{Kj} = \partial C_1^{\,j}(r,w,t)/\partial r \qquad \text{for} \quad j=1,2$$

$$b_{Lj} = \partial C_1^{\,j}(r,w,t)/\partial w \qquad \text{for} \quad j=1,2$$

$$b_{Z1} = \partial C_1^{\,1}(r,w,t)/\partial t$$

(b) Solve the dual of the maximum gross regional product problem, the minimization of the factor payments problem without depletability

$$\text{Min} \qquad rK + wL(0)$$

s.t.

$$rb_{K1} + wb_{L1} \geq P_1 - tb_{Z1}$$

$$rb_{K2} + wb_{L2} \geq P_2 \qquad (26)$$

and compute the value of gross regional income Y= rK+wL(Z)+tZ in terms of the restricted solution (r,w) and the specified value of t.

(c) If the value of gross regional income is calculated to be smaller than the previous value, then solve the subproblems. That is, using the solution for (r,w) from (b) and the specified value of t compute b_{Kj}, b_{Lj}, and b_{Z1}.

(d) Check for the convergence of the no depletability problem.

(i) If the calculated value of gross regional income does not improve and the computed values of input-output coefficients are the same as in (a), the optimal solution vector $(b_{Kj}, b_{Lj}, b_{Z1}, r\ , w\ )$ for a predetermined price vector (P_1, P_2, t) has been obtained. Then proceed to solve the primal problem in (e). (ii) If the computed values of the input-output coefficients are not the same as in (a), proceed to (b).

(e) Solve the equilibrium output quantities (X_1, X_2) from the following linear equation system

$$b_{K1}X_1 + b_{K2}X_2 = K$$

$$b_{L1}X_1 + b_{L2}X_2 = L(Z)$$

where for no depletable problem $L(Z) = L(0)$. Then compute the value of the total quantity of pollution discharge, $Z = b_{Z1}X_1$, and proceed to (f).

(f) Using the solution for Z from (e), calculate a value of the resource depletable function, $L(Z)$, and proceed to (b').

(b') Solve the dual, or minimization of factor payments, problem with depletability

$$\text{Min} \quad rK + wL(Z)$$

s.t.

$$rb_{K1} + wb_{L1} \geq P_1 - tb_{Z1}$$

$$rb_{K2} + wb_{L2} \geq P_2 \qquad (27)$$

and compute the value of gross regional income $Y = rK+wL(Z)+tZ$ in terms of the restricted solution (r,w) and the specified value of t. Then proceed to (c').

(c') Check for the convergence of the depletable problem.

(i) If the value of gross regional income does not improve, the optimal solution vector $(b_{Kj},b_{Lj},b_{Z1},r,w,X_1,X_2,Z,Y)$ for a predetermined value vector (P_1,P_2,t) has been obtained. (ii) If the value of gross regional income is calculated to be smaller than the previous value, solve the subproblem. That is, for (r,w) from (b') and the specified value of t, compute b_{Kj},b_{Lj}, and b_{Z1}. Then proceed to (e).

For numerical simulation, let us assume the following parameter values:

output price	$P_1 = 1.0$,	$P_2 = 3.0$
initial endowment	$K = 30.$	$L(0) = 16.$
production function	$\rho = -300.$	$\theta = -50.$
	$q = 0.7$,	$r = 0.3$
	$d_{11}=d_{12}=d_{13}=d_{21}=1.0$,	$d_{22}=0.5$

Table 1 then summarizes the computational results for alternative values of the pollution charge rate (t) and for alternative forms of the resource depletable function L(Z), where for computational simplicity the constant term $((\rho+q)/(d_{11}\rho^{\gamma}))$ in (24) is disregarded. The following two forms are employed for L(Z),

concave form $\quad L(Z) = L(0) - Z^{2.0}$ (28a)

convex form $\quad L(Z) = L(0) - Z^{0.5}$ (28b)

In either form, the results in Table 1 conform to the modified version of Yohe's Propositions 1 and 3. As the pollution charge rate (t) becomes larger, the discharged quantity of pollutant (Z) decreases, the real return to capital (r) decreases and that of water abstraction (w) increases. Furthermore the polluting sector contracts ($X_1^* < 0$) and the nonpolluting sector expands ($X_2^* > 0$). The main contribution of this paper is to show that if the marginal benefit of pollution control ($-wL_Z$) isgreater than the pollution charge rate (t), then gross regional income increases. This modifed version of Yohe's Proposition 2 is also verified in Table 1. In the case of the convex depletable water supply function, the net marginal benefit of pollution control ($-t-wL_Z$) is positive for low values of $t < 0.3$, while in the case of the concave depletable function the net marginal benefit remains positive until t takes relatively large values greater than 2.0.

TABLE 1. Computation Results

Pollution Charge Rate	Convex Case						Concave Case					
	Discharged Pollution Load	Rental Rate on Capital	Water Abstraction Price	Output of Sector 1	Output of Sector 2	Gross Regional Income	Discharged Pollution Load	Rental Rate on Capital	Water Abstraction Price	Output of Sector 1	Output of Sector 2	Gross Regional Income
(t)	(Z)	(r)	(w)	(X_1)	(X_2)	(Y)	(Z)	(r)	(w)	(X_1)	(X_2)	(Y)
0.1	5.5	0.63	1.17	23.28	4.08	35.53						
0.3	4.3	0.59	1.19	21.05	4.85	35.61						
0.5	3.4	0.56	1.21	19.43	5.37	35.53	4.11	0.56	1.21	23.37	0.57	25.07
1.0	2.2	0.50	1.24	16.73	6.12	35.09	2.41	0.50	1.24	17.97	4.43	31.26
2.0	1.3	0.42	1.28	13.78	6.79	34.16	1.27	0.42	1.28	13.91	6.59	33.67
3.0	0.8	0.37	1.30	12.08	7.10	33.40	0.84	0.37	1.30	12.02	7.22	33.68
4.0	0.6	0.34	1.32	10.94	7.28	32.79	0.61	0.34	1.32	10.83	7.49	33.30
5.0	0.5	0.32	1.33	10.09	7.40	32.29	0.47	0.32	1.33	9.98	7.63	32.88

Keeping in mind that environmental regulation is usually preceded by a progressively worsening pollution problem, if an employed regulatory instrument enhances economic efficiency so as to increase gross regional product (potential Pareto improvement), then the economic acceptability of such an instrument would be high. In this sense, a pollution control policy such as total pollution control or the imposition of a pollution charge is more economically viable in the case of a concave depletable function than in that of a convex function.

5. Concluding remark

In terms of a general two-sector, three-factor model, we are able to analyze the long run comparative statics of higher pollution charges or of stricter pollution control on sector outputs, gross regional income, and three factors of production, capital and two water resource services of water abstraction and the assimilation of pollution discharge. As in most general equilibrium models, a number of simplifying assumptions have been made. Output prices as well as capital endowment and the regional environment's capability of supplying "safe" water, under the state of zero pollution discharge, are fixed. There also are competitive markets for sector outputs and the first water resource service of water abstraction.

An increase in the pollution charge rate for the second water resource service or a stronger pollution control policy brings about the clear incidence effects, if we assume that only one of the two sectors is polluting, large(small) values of Z for the case of the concave(convex) depletion function, and the elasticity of the substitution of the water abstraction service for pollution discharge is zero, 1) the polluting sector contracts and the nonpolluting sector expands, 2) the total quantity of discharged pollutants (Z) decreases, and 3) the real returns to capital and water abstraction service move in opposite directions. These results are similar to the incidence effects of stronger pollution control without the water resource depletion function analyzed by Yohe(1979).

The major point made in this paper is that gross regional income (product) may increase with an increase in the pollution charge rate or stronger pollution control. Especially when the water resource depletion function, L(Z), is a concave, rather than a convex function of Z, it is more likely that gross regional income increases with a higher pollution charge policy or stronger pollution control policy. This contrasts with Yohe's conclusion that national income, (gross regional income using our terminology), decreases with a stronger pollution control policy. This difference in conclusions is mainly due to the existence of the resource depletion function in our model.

We may interpret our findings in terms of their practical significance. Sector 1 and Sector 2 may be considered, respectively, to be regional economies in upstream and downstream parts of a river basin. If we assume that Sector 2 discharges pollution into the ocean and that we disregard the problem of ocean pollution, the production function of sector 2 does not contain Z variable and, consequently, the resource depletion function L(Z) is only affected by discharge from sector 1. We then know from the above findings that, if L(Z) is a concave (convex) function, then it is likely to be better to expand the downstream (upstream) economy by increasing (decreasing) the pollution charge rate, where the author has been unable to find any empirical evidence concerning the shape of L(Z).

Appendix 1 A general framework for regional evaluation of the water resource pricing policy

In this appendix we explain the links between input-output analysis and the comsumption of water resource services. Although the arguments can be extended to an interregional input-output framework, we will limit them to the regional level for the sake of expositional simplicity. Figure A1 illustrates the analytical structure of a regional input-output model which is augmented to include a water resource service dimension, where

X_I = vector, with n industry components, of industrial gross outputs

X_ℓ = physical output of the public water supply treatment sector (the ℓ-th sector)

X_m = physical output of the public wastewater treatment sector (the m-th sector)

a_{ij}= the value of intermediate product requirements for the products of sector i per unit in sector j (i=1...n, ℓ ,m; j=1...n, ℓ ,m)

b_{ij}= the value of the primary or water resource service input requirements for the i-th input factor per unit in sector j (i=v,K,L,Z; j=1...n, ℓ ,m)

F = final demand vector with n product components

and, V, K, L, Z are, respectively, regional resource constraints on labour, capital, surface water abstraction, and discharged pollution load. In this Figure, not only withdrawal of water from surface water by industry and water treatment sectors, but also return flow from the wastewater treatment sector to surface water are considered. Also considered, is the emission of pollutants by the industrial sectors and the

	Industrial activities		water supply activities	wastewater treatment activities
COMMODITIES				
Industrial	$1-a_{11}$	$-a_{1n}$	$-a_{1\ell}$	$-a_{1m}$
commodities	$-a_{n1}$	$-a_{nn}$	$-a_{n\ell}$	$-a_{nm}$
water supply services	$-a_{\ell 1}$	$-a_{\ell n}$	$1-a_{\ell\ell}$	$-a_{\ell m}$
wastewater treatment services	$-a_{m1}$	$-a_{mn}$	0	$-(1-a_{mm})$
PRIMARY FACTOR AND WATER RESOURCE INPUTS				
labour	$-b_{v1}$	$-b_{vn}$	$-b_{v\ell}$	$-b_{vm}$
capital	$-b_{K1}$	$-b_{Kn}$	$-b_{K\ell}$	$-b_{Km}$
water abstraction	$-b_{L1}$	$-b_{Ln}$	$-b_{L\ell}$	$(1-b_{Lm})$
discharged pollution loads	$-b_{Z1}$	$-b_{Zn}$	0	$(1-b_{Zm})$

X

Industrial outputs (X_I)
Water supply service outputs $(X\ )$
Wastewater treatment service output (X_m)

=

FINAL DEMANDS

F

$\geqq$

RESOURCE CONSTRAINTS

- V
- K
- L
- Z

Figure A1 Link of Water Resource Services with the Interindustry Model wastewater treatment sector, where industrial sectors may treat part of the wastes by temselves.

In the standard input-output analysis, we begin with the given final demand vector F and calculate the level of gross outputs in each sector as follows,

$$(X_I \; X_\ell \; X_m)' = (I-A)^{-1}F \qquad (G1)$$

where $(X_I \; X_\ell \; X_m)'$ is the transpose of the vector $(X_I \; X_\ell \; X_m)$, $A=(a_{ij})$ the input matrix, and $(I-A)^{-1}$ the inverted form of (I-A). If the calculated gross output vector satisfies the regional resource constraints (V K L Z), then the given final demand vector F is called technologically feasible. Furthermore if we denote the corresponding product price vector and the factor price vector as $(P_1 \ldots \; P_n)$ and (v r w t), respectively, and provisionally assume that there are competitive markets for sector products and factor inputs, then in a long-run competitive equilibrium the following equality holds,

$$(P_1 \; \ldots\ldots \; P_n)' = (I-A')^{-1}(-B')(v \;\; r \;\; w \;\; t)' \qquad \text{or}$$

$$(I-A')(P_1 \; \ldots\ldots \; P_n)' = (-B')(v \;\; r \;\; w \;\; t)' \qquad (G2)$$

One of the well known theorem in input-output analysis is a theorem on substitution (see, for example, Dorfman et al(p224,1958)) stating that, even if there are several different processes available for each sector, there is one prefered production process for each sector regardless of the final demand vector, provided that there is only one factor endowment. Since in our model we deal with more than two factor inputs, we can no longer imagine that there are unique (A) and (B) matrices.

In this paper we only deal with the case where (A) matrix as well as the sector product prices are exogenously determined. Especially, we deal with a general equilibrium analysis of the relationship between (B) matrix and factor prices. As to the existence of a competitive factor market, we assume that the water abstraction charge rate (w), wage rate (v), and rental price (r) are determined competitively so as to satisfy the respective supply = demand equality, while the pollution charge rate (t) is imposed by the regional government.

In sum, regional evaluation of pollution charge policy may be analyzed in the following three steps, though a theoretical analysis in the txt does not treat the second or third step: 1) given production technology for each sector, product prices, and the total available labour(V), capital(K), and surface water in the state of zero pollution discharge L(0), execute general equilibrium analysis of governmentally imposed pollution charge rate (t) and get (B) matrix , an equilibrium factor price vector (v r w), an equilibrium production vector (X_I X_ℓ X_m), and an equilibrium quantity of the total pollution discharge (Z), 2) calculate the final demand vector (F) in terms of equation (G1), 3) if the final demand vector calculated in 2) is different from an observed final demand vector, analyze the impact on the product price vector, and return to 1) with a new product price vector. If you allow our region to trade not only outputs but also primary factors of labour and capital with other regions, we have to analyze the impacts of changing factor prices on the factor endowment vector (V K).

These three steps may continue until the excess demand vector becomes zero. If the gross regional product, which is the multiple of the equilibrium product price vector and the equilibrium production vector, increase after the imposition of pollution charge, we may judge that the pricing policy employed here enhances an allocative efficiency in the sense of potential Pareto improvement.

Appendix 2 Derivation of equation (9)

When we express the unit production function for the j-th product as in (2), we may calculate the slope of the level surface of the production function based on the profit maximization conditions:

$$\left.\begin{aligned} P_j \partial f_j/\partial b_{Lj} &= w \\ P_j \partial f_j/\partial b_{Kj} &= r \\ P_j \partial f_j/\partial b_{Zj} &= t \end{aligned}\right\} \tag{S1}$$

Totally differentiating eqs. (2) and (S1) with respect to w, we obtain

$$\begin{pmatrix} 0 & f_1 & f_2 & f_3 \\ f_1 & f_{11} & f_{12} & f_{13} \\ f_2 & f_{21} & f_{22} & f_{23} \\ f_3 & f_{31} & f_{32} & f_{33} \end{pmatrix} \begin{pmatrix} (\partial P_j/\partial w)/P_j \\ \partial b_{Lj}/\partial w \\ \partial b_{Kj}/\partial w \\ \partial b_{Zj}/\partial w \end{pmatrix} = \begin{pmatrix} 0 \\ 1/P_j \\ 0 \\ 0 \end{pmatrix} \tag{S2}$$

where $f_{hk}=\partial^2 f_j/\partial b_h \partial b_k$ for $h,k=L_j,K_j,Z_j$. Then we get from eq. (S2)

$$\partial b_{Lj}/\partial w = \begin{pmatrix} 0 & f_2 & f_3 \\ f_2 & f_{22} & f_{23} \\ f_3 & f_{32} & f_{33} \end{pmatrix} /P_j(F)$$

$$\begin{aligned} &= F_{11}/P_j(F) \\ &= a_{Lj}\theta_{Lj}\sigma^j_{LL}/P_j f_{Lj} \end{aligned} \tag{S3}$$

$$\begin{aligned} \partial b_{Kj}/\partial w &= F_{12}/P_j(F) \\ &= b_{Kj}\theta_{Lj}\sigma^j_{LK}/P_j f_{Lj} \end{aligned} \tag{S4}$$

$$\partial b_{Zj}/\partial w = F_{13}/P_j(F)$$
$$= b_{Zj}\theta_{Lj}\sigma^j_{LZ}/P_j f_{Lj} \qquad (S5)$$

, where (F) is the matrix determinant of eq. (S2). F_{hk} is the minor of the element f_{hk} and the Allen's partial elasticity of substitution, σ^j_{hk} is defined to be

$$F_{hk} = b_h(F)\theta_k\sigma^j_{hk}/f_k$$
$$= b_k(F)\theta_h\sigma^j_{hk}/f_h \qquad (S6)$$

Similarly, totally differentiating eq. (2) and (S1) with respect to r, we obtain

$$\partial b_{Lj}/\partial r = F_{21}/P_j$$
$$= b_{Lj}\theta_{Kj}\sigma^j_{KL}/P_j f_{Kj} \qquad (S7)$$
$$\partial b_{Kj}/\partial r = b_{Kj}\theta_{Kj}\sigma^j_{KK}/P_j f_{Kj} \qquad (S8)$$
$$\partial b_{Zj}/\partial r = b_{Zj}\theta_{Kj}\sigma^j_{KZ}/P_j f_{Kj} \qquad (S9)$$

Finally, totally differentiating eq. (2) and (S1) with respect to t, we get

$$\partial b_{Lj}/\partial t = F_{31}/P_j(F)$$
$$= b_{Lj}\theta_{Zj}\sigma^j_{ZL}/P_j f_{Zj} \qquad (S10)$$
$$\partial b_{Kj}/\partial t = F_{32}/P_j(F)$$
$$= b_{Kj}\theta_{Zj}\sigma^j_{ZK}/P_j f_{Zj} \qquad (S11)$$
$$\partial b_{Zj}/\partial t = F_{33}/P_j(F)$$
$$= b_{Zj}\theta_{Zj}\sigma^j_{ZZ}/P_j f_{Zj} \qquad (S12)$$

Now we are ready to derive equation (9). Since the derivation procedure is the same, we here derive only the first equation of (9).

From equation (5) we derive

$$b^*_{Lj} = (db_{Lj}/d\tau)/b_{Lj}$$
$$= (\partial b_{Lj}/\partial w)(dw/d\tau)(w/w)(1/b_{Lj})$$
$$+ \ (\partial b_{Lj}/\partial r)(dr/d\tau)(r/r)(1/b_{Lj})$$

$$+ \quad (\partial b_{Lj}/\partial t)(dt/d\tau)(t/t)(1/b_{Lj}) \qquad \text{(S13)}$$

, where τ is used to differentiate time from compensation rate t. From equations (S3),(S7), and (S10), we obtain

$$b^*_{Lj} = (w^*w/b_{Lj})(b_{Lj}\theta_{Lj}\sigma^j_{LL}/P_j f_{Lj})$$
$$+ (r^*r/b_{Lj})((b_{Lj}\theta_{Kj}\sigma^j_{KL})/(P_j f_{Kj}))$$
$$+ (t^*t/b_{Lj})((b_{Lj}\theta_{Zj}\sigma^j_{ZL})/(P_j f_{Zj})) \qquad \text{(S14)}$$

Using equation (S1),

$$b^*_{Lj} = w^*(\theta_{Lj}\sigma^j_{LL}) + r^*\theta_{Kj}\sigma^j_{KL}$$
$$+ t^*\theta_{Zj}\sigma^j_{ZL} \qquad \text{(S15)}$$

Since the input-output coefficient funciton is homogeneous of degree zero with respect to w,r,t, we obtain

$$w\ \partial b_{Lj}/\partial w + r\ \partial b_{Lj}/\partial r + t\ \partial b_{Lj}/\partial t = 0$$

which is rewritten by using (S3),(S7) and (S10) as follows

$$(\sigma^j_{LL})\theta_{Lj} + \theta_{Kj}\sigma^j_{KL} + \sigma^j_{ZL}\theta_{Zj} = 0 \qquad \text{(S16)}$$

Now substituting (S16) into (S15), we obtain the first equation of equation set (9).

Appendix 3 Derivation of equation (10) and Proof of D < 0

From equation (6) we get

$$X_1^* = (-\lambda_{L2}(K^*+\beta_k)+\lambda_{K2}(L(Z)^*+\beta_L)/(A1)$$

$$X_2^* = (\lambda_{L1}(K^*+\beta_k)-\lambda_{K1}(L(Z)^*+\beta_L)/(A1) \qquad (Q1)$$

$$(A1)\ Z^* = (A1)\ \lambda_{Z1}X_1^* + (A1)\lambda_{Z2}X_2^* + (A1)\lambda_{Z1}b_{Z1}^* + (A1)\lambda_{Z2}b_{Z2}^* \qquad (Q3)$$

, where

$$(A1) = \lambda_{K2}\lambda_{L1}-\lambda_{K1}\lambda_{L2} \quad < \quad 0$$

$$\beta_L = -(\lambda_{L1}b_{L1}^*+\lambda_{L2}b_{L2}^*)$$

$$\beta_K = -(\lambda_{K1}b_{K1}^*+\lambda_{K2}b_{K2}^*) \qquad (Q3)$$

Substituting (Q1) into (Q2), we obtain

$$(A1)Z^* = (A1)(\lambda_{Z1}b_{Z1}^* + \lambda_{Z2}b_{Z2}^*)$$
$$+ (K^*+\beta_k)(\lambda_{Z2}\lambda_{L1}-\lambda_{Z1}\lambda_{L2})$$
$$+ (\lambda_{Z1}\lambda_{K2}-\lambda_{Z2}\lambda_{K1})(L^*+\beta_L) \qquad (Q4)$$

Substituting (9) and (Q3) into (Q4), we get as follows;

The first term in the RHS of equation (Q4) excluding (A1)

$$= (\lambda_{Z1}\theta_{L1}\sigma_{LZ}^1+\lambda_{Z2}\theta_{L2}\sigma_{LZ}^2)(w^*-t^*)$$
$$+ (\lambda_{Z1}\theta_{K1}\sigma_{KZ}^1+\lambda_{Z2}\theta_{K2}\sigma_{KZ}^2)(r^*-t^*) \qquad (Q5)$$

The second term in the RHS of equation (Q4)

$$= K^*(B1) - ((B1)(\lambda_{K1}\theta_{L1}\sigma_{KL}^1+\lambda_{K2}\theta_{L2}\sigma_{KL}^2))(w^*-r^*)$$
$$+ ((B1)(\lambda_{K1}\theta_{Z1}\sigma_{KZ}^1+\lambda_{K2}\theta_{Z2}\sigma_{KZ}^2))(r^*-t^*) \qquad (Q6)$$

where $(B1) = \lambda_{Z2}(\lambda_{L1})-\lambda_{Z1}(\lambda_{L2}) < 0$

The third term in the RHS of equation (Q4)

$$= L^*(B2) + w^*(B2)(\lambda_{L1}\theta_{K1}\sigma_{KL}^1+\lambda_{L2}\theta_{K2}\sigma_{KL}^2)$$

$$+ w^*(B2)(\lambda_{L1}\theta_{Z1}\sigma^1_{ZL}+\lambda_{L2}\theta_{Z2}\sigma^2_{ZL})$$
$$- r^*(B2)(\lambda_{L1}\theta_{K1}\sigma^1_{KL}+\lambda_{L2}\theta_{K2}\sigma^2_{KL})$$
$$- t^*(B2)(\lambda_{L1}\theta_{Z1}\sigma^1_{ZL}+\lambda_{L2}\theta_{Z2}\sigma^2_{ZL}) \qquad (Q7)$$

where $(B2) = \lambda_{Z1}\lambda_{K2} - \lambda_{Z2}\lambda_{K1} < 0$

Substituting (Q5),(Q6),(Q7) into (Q4), we obtain equation (10):

$$(A1)Z^* = (E1)w^* + (E2)r^* + (E3)t^* + (B2)L(Z)^* + (B1)K^* \qquad (10)$$

where (E1), (E2), and (E3) are defined in (11) through (13).

If we assume $b_{Z2}=0$ and $\sigma^1_{LZ}=0$, then the terms in (11b),(12b), and (13b) are zero, and consequently we obtain (E1)>0, (E2)<0, and (E3)>0. Thus we get D<0 from equation (17).

Notation.

BOD	biological oxygen demand, mg/
NH_3-N	ammonia nitrogen, mg/
X_j	output of sector j per unit time, for j=1,2
K_j	amount of capital stock employed in the j-th sector, for j=1,2.
L_j	amount of water abstraction service employed in the j-th sector, for j=1,2.
Z_j	amount of pollution discharge services employed in the j-th sector, for j=1,2.
L	regional resource constraint on surface water abstraction per unit time.
K	regional resource constraint on capital stock.
Z	total amount of discharged pollution load per unit time.
r	rental rate paid on capital.
w	water abstraction charge rate.
t	pollution charge rate.
P_j	price of the j-th sector output, for j=1,2.
L(Z)	resource depletion function, indicating the environmental capability of supplying water for abstraction purposes at a predetermined level of water quality, as a function of the total discharged pollution load.
Y	gross regional income or gross regional product.
λ_{Lj}	proportion of the total supply of water abstraction service employed in the j-th sector, for j=1,2.
λ_{Kj}	proportion of the total supply of capital employed in the

j-th sector, for j=1,2.

λ_{Zj} proportion of the total supply of pollution discharge services employed in the j-th sector, for j=1,2.

θ_{Kj} share of capital cost in the unit cost of the j-th sector, for j=1,2, $\theta_{Kj} = rb_{Kj}/P_j$.

θ_{Lj} share of water abstraction cost in the unit cost of the j-th sector, for j=1,2, $\theta_{Lj} = wb_{Lj}/P_j$.

θ_{Zj} share of pollution discharge service cost in the unit cost of the j-th sector, for j=1,2, $\theta_{Zj} = tb_{Zj}/P_j$.

$\sigma_{KL}{}^j$ the Allen's partial elasticities of substitution between capital and water abstraction service in the j-th production sector, for j=1,2.

$\sigma_{LZ}{}^j$ the Allen's partial elasticities of substitution between water abstraction service and pollution discharge service in the j-th production sector, for j=1,2.

$\sigma_{KZ}{}^j$ the Allen's partial elasticities of substitution between capital and pollution discharge service in the j-th production sector, for j=1,2.

X^* starred variable representing the percentage change in a variable X, $X^* = dX/X$, where X = X_j, b_{Lj}, b_{Kj}, b_{Zj}, P_j, w, r, t, Z, K, L(Z), Y_j, and Y for j=1,2.

θ_j j-th production sector's share of gross regional product, for j=1,2, $\theta_j = P_jX_j/Y$.

θ_L share of water abstraction cost in gross regional product, $\theta_L = wL(Z)/Y$.

θ_K share of capital cost in gross regional product, $\theta_K = rK/Y$.

θ_Z share of pollution charge payment in gross regional product, $\theta_Z = tZ/Y$.

q, ρ, γ, θ parameters of the production function for the j-th sector, j=1,2.

C^j cost function of the j-th sector, j=1,2.

$C_1^{\,j}$ unit cost function of the j-th sector, $C_1^{\,j} = \partial C^j / \partial X_j$, j=1,2.

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