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A Rating Tax Control Model to Mitigate China's Transboundary Water Pollution Problems

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ABSTRACT

In this paper, we introduce a rating tax control model (RTCM) based on generalized Nash equilibrium theory to deal with transboundary water pollution problem. Under RTCM, the more transfer of pollution, the high should be paid in the presence of rating tax. We prove that the RTCM is equivalent to a nonlinear program. With the help of generalized Clarke's gradient, we give the optimality condition of RTCM. Finally, we use a simple example to illustrate the validity of our results.

INTRODUCTION

Transboundary pollution is the pollution that originates in one region (or country) but is able to cause damage in another region's environment, by crossing borders through pathways like water, for which pollution can be transported across hundreds and even thousands of kilometres. This is why it is called 'transboundary pollution'. One of the problems with transboundary pollution is that it can carry pollution away from a heavy emitter and deposit it onto a nation whose emissions are relatively low. Due to the fact that 'all things connect', the heavy pollution that is evident in the developed world also becomes evident in remote areas.

The amount and the deleterious effects of the transboundary water pollution discharged from region crossing borders is now well-documented (Bernauer & Kuhn 2010, Kulmatov et al. 2013). The need to prevent further environmental damage due to increasing transboundary pollution has led to various governmental legislation such as the Helsinki Convention proposed in 1974, which is the most widely known convention on the protection and use of transboundary rivers and lakes, and the UN Watercourses Convention introduced in 1997. The legislations are stimulating the development of analytical frameworks for both pollution control and of purification facilities improvement.

Recently, pollution tax as a pollution reduction instrument has received far more attention than wastewater purification facilities control in both theory and practice. By studying the tax competition problem in the presence of transboundary pollution, Cremer & Gahvari (2004) concluded that a harmonized emission tax at a level above the unrestricted Nash equilibrium value would lead firms to adopt less-polluting technology, and would also decrease aggregate emission. Barcena-ruiz (2006) analysed a game between two governments on whether to set environmental tax sequentially or simultaneously depending on transboundary pollution spillovers. Researchers mentioned above focus on the economic analysis of transboundary pollution between two regions only without considering the geographical structure of the basin, the boundaries that surround the basin and individual regions, or the nature of the game between the central government and individual regions. Yuzbasi et al. (2012) investigated the pollution problem of three lakes with interconnecting channels using a collocation approach. In particular, government can use revenues from pollution taxes to decrease other, distortionary taxes. In this way, environmental taxes may yield a "double dividend"- not only a cleaner environment, but also a less distortionary tax system (Endres 2011). However, none of these papers take the structure of the lake basin into full consideration (Zhao et al. 2012).

Through auctioning or purchasing their pollution permit while not breaking the total pollution limit in the region, issuing pollution permit would satisfy the demands of national standard and further resulted effectively in an overall pollution reduction (Chung et al. 2012). However, this would only happen in a state of equilibrium market and there is a unique price for every commodity in question. But, in a practical developing country, which is imperfect by nature, permit trading is never at equilibrium and very volatile depending upon the vagaries of the market forces (Goulder 2013).

Many economists have argued that pollution levies are an efficient instrument for achieving environmental objectives (Engel et al. 2008). Some have gone even further to suggest that environmental taxes may yield benefit over and above a cleaner environment (Peretto 2009). Therefore, the focus is now turning to compulsory measure such as obliged levying pollution tax (or charge) or forcing upgrade waste water treatment facilities as a tool to address water pollution. Based on a bilevel programming problems, Zhao et al. (2012, 2013) proposed models of uniform transfer tax which incorporates a typical Stackelberg game between the administrator and individual regions. Their models guaranteed that the imposed environmental quality standard was met through the uniform transfer tax. However, under the uniform tax, no matter how serious the environment damaged by the transfer pollution, the marginal transfer cost is uniform. It implies that this approach would weaken regions' initiative to mitigate their individual pollution. For example, if the uniform transfer tax is too low compared with some region's marginal reduction cost, then this region would like to transfer this pollution and ask other regions to reduce it. Although the whole region's pollution control objective is obtained by their model, the environment has been unfortunately damaged due to the over polluted by that region's transfer of pollution.

Located in the east of Asia, China has 1580 large rivers and each river basin covers more than 1000 km^2. Large rivers usually spanning several regions inevitably results in transboundary water pollution problems. Chinese government has been aware of this issue for more than ten years. Up to the present, a basic legal system has been established to deal with the problem. However, its effect is not notable and the water pollution is still worsening day by day. One reason for the failure is that water pollution like Zhanghe river and Taihu lake usually crossing several administrative region boundary in nature, but controlled separately by each administrative region.

In this paper, we develop a rating tax control model (RTCM) to mitigate China's transboundary water pollution problem, and prove that the RTCM is equivalent to a nonlinear program. The RTCM can ensure that the environmental quality standard is arrived. Under RTCM, the more transfer pollution, the high it should be paid. Moreover, from a management (as well as a computational) perspective an optimality condition of RTCM is proposed. Finally, we use a simple example to illustrate the validity of our results.

TRANSBOUNDARY WATER POLLUTION UNDER RANKING TRANSFER TAX CONTROL

We consider China's transboundary water pollution control problem based on an underlying complete directed graph $G(I,T)$, where I (i.e., the number of regions) that denotes the set of nodes, and T, of cardinality $\frac{|I|\cdot(|I|-1)}{2}$, that denotes the set of arcs. A node represents a region that can potentially transfer pollutants or pollutant credits or the end of an arc along which pollutants or credits are transferred. The arc set T denotes the pollutant quantity transferred between each pair of regions. Some other basic variables used in the RTCM are described in Table 1.

In this paper, we make the following assumptions on reduction function, and the bounds of reduction variables are described as follows:

(a) For any $i \in I$, $RC_i : R^1_+ \to R^1$ is strictly increasing and strictly convex.

(b) $\sum_{i\in I} l_i \le P_{0t} - P_{t\max} \le \sum_{i\in I} u_i$

Transboundary water pollution problem under rating tax control: For region $i\in I$, its environmental cost function π_i contains two parts: pollution reduction cost and transfer cost, i.e.,

$$\pi_i = RC_i(P_i) + \mathrm{TC}(\sum_{m\neq i,m=1}^{|I|} T_{im}) \quad ...(1)$$

The sign of denotes the transferable pollution, T_{ij} is transferred from region i to region j or from region j to region i. From the pollution quantity conservation, we have:

$$\sum_{i=1}^{|I|}\sum_{j\neq i,j=1}^{|I|} T_{ij} = 0 \quad ...(2)$$

Let $y_i = \sum_{j\neq i,j=1}^{|I|} T_{ij}$ for short. Then

$$\sum_{i\in I} y_i = 0. \quad ...(3)$$

From the definition of transfer cost function TC in Table 1, it is a piecewise linear function regarding to transferable pollution quantity and its compact form is as follows:

$$\mathrm{TC}(y_i) = \begin{cases} k_1 y_i, & b_0 \le y_i \le b_1 \\ k_1 b_1 + \sum_{l=2}^{j} k_l(b_l - b_{l-1}) + k_{j+1}(y_i - b_j), & b_j \le y_i \le b_{j+1}, j \ge 2 \end{cases} \quad ...(4)$$

Table 1: Notations.

Variable	Explanation
P_{0i}	The annual initial air pollutant quantity produced by region $i \in I$.
P_{0t}	The total annual air pollutant industry quantity produced by all regions in the transboundary water pollution problem, where $P_{0t} = \sum_{i \in I} P_{0i}$.
P_i	The annual water pollutant quantity produced by region $i \in I$.
$P_{i\max}$	The maximum quantity of water pollutant emissions for region $i \in I$ based on the national pollutant quality standard.
$P_{t\max}$	The total maximum quantity of air pollutant emissions for all regions in the transboundary water pollution problem, where $P_{t\max} = \sum_{i \in I} P_{i\max}$.
P_i	The annual water pollutant reduction by region $i \in I$.
l_i	the lower limit of the annual pollution reduction ability for region $i \in I$.
u_i	The upper limit of the annual pollution reduction ability for region $i \in I$.
T_{im}	The pollutant quantity transferred between region i and region m during one year. The sign of T_{im} depends on the tradeoff between the actual pollutant concentration and the national quality standard at the transboundary section, and it reveals the pollutant transferred from region i to region m or from region m to region i.
b_j	The breakpoint of transfer pollution. There are $N+1$ grades of transfer pollution $\{b_j\}_0^N$,which is a strictly increasing sequence.
k_j	The jth grade of rating tax, which means that a payment will be levied on the region if the pollution quantity between b_{j-1} and b_j that it transfers through the transboundary section exceeds the national standard. The more the pollution transferred to other regions, the more is paid, i.e., the N grades of rating tax $\{k_j\}_1^N$ is a strictly increasing sequence.
RC_i	The annual water pollutant reduction cost function for region $i \in I$.
TC	The transfer cost function regarding with the transfer pollution quantity and the grade of rating tax.
π_i	the annual total environmental cost for region $i \in I$.

Where $b_j, j = 0,1,2,\cdots,N$ is the breakpoints of transfer pollution and satisfy the following condition:

$$b_0 \le 0 < b_1 < b_2 < \cdots < b_N \qquad ...(5)$$

Combining the above discussion, the rating tax control model (RTCM) for the transboundary water pollution can be described as the follows: For each region $i \in I$,

$$\text{RTCM} \qquad \min_{P_i, y_i} \quad \pi_i = RC_i(P_i) + \mathrm{TC}(y_i) \qquad ...(6)$$

$$\text{s.t.} \quad l_i \le P_i \le u_i, \qquad ...(7)$$

$$P_i + y_i \ge P_{0i} - P_{i\max}, \qquad ...(8)$$

$$\sum_{i \in I} y_i = 0. \qquad ...(9)$$

Under RTCM, each region aims to optimize its own objective function (π_i) with respect to variables P_i and , constraint (7) means the ability of each region's wastewater treatment facilities, constraint (8) represents that the aim of pollution reduction is to control the level of the pollutant in region $i \in I$ below the national standard, and constraint (9) represents the pollution quantity conservation.

The RTCM is actually a generalized Nash game, in which each region's strategy set depends on the other players' strategies due to the coupled constraint (9). This kind of game is known to admit a large number, and in some cases, a manifold of generalized Nash games (Facchinei & Kanzow 2007, Pang & Fukushima 2005). In general, obtaining generalized Nash games requires a solution of an ill-posed system which leads to a quasi-variational inequality in the primal-space and a non-square complementary problem in the primal-dual space (Kulkarni & Shanbhag 2012). Fortunately, RTCM is a special generalized Nash game, whose objective function is separate. The next proposition shows that the RTCM is equivalent to a common nonlinear program.

Proposition 1: $(\overline{P}_i)_{i \in I}$ is the optimal solution to the following nonlinear programming problem (NP) if there exists $(\overline{y}_i)_{i \in I}$ such that $(\overline{P}_i, \overline{y}_i)$ solves RTCM. Here

$$\text{NP} \quad \min_{P_i \ge 0} \ \pi_t = \sum_{i \in I} RC_i(P_i) + \sum_{i \in I} \mathrm{TC}(P_{0i} - P_{i\max} - P_i) \qquad ...(10)$$

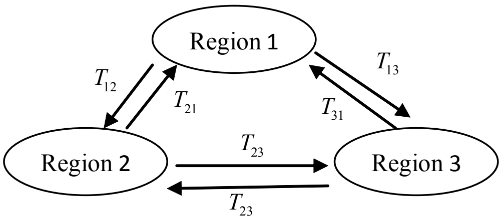

Fig. 1: The lake surounded by three regions.

$$\text{s.t.} \quad l_i \le P_i \le u_i, i \in I. \qquad ...(11)$$

$$\sum_{i\in I} P_i = P_{0t} - P_{t\max}, \qquad ...(12)$$

Proof: We first claim that constraint (8) in RTCM is actually an equality constraint. If not, let $(\tilde{P}_i, \tilde{y}_i)_{i\in I}$ be any optimal solution of RTCM. Then there exists at least a $j \in I$ such that $\tilde{P}_j - \tilde{y}_j > P_{0j} - P_{j\max}$. Therefore, we can choose $\hat{P}_j$ satisfying $\hat{P}_j < \tilde{P}_j$ and $\hat{P}_j - \tilde{y}_j = P_{0j} - P_{j\max}$.

Recalling assumption (a), the reduction function $RC_j(\cdot)$ is strictly increasing. Then, we have:

$RC_i(\hat{P}_i) + \mathrm{TC}(\tilde{y}_i) < RC_i(\tilde{P}_i) + \mathrm{TC}(\tilde{y}_i)$, which contradicts with the optimality of $(\tilde{P}_i, \tilde{y}_i)_{i\in I}$. Therefore,

$$\tilde{P}_i - \tilde{y}_i = P_{0i} - P_{i\max}.$$

This implies that RTCM is equivalent to the following problem: for any region $i \in I$,

$$\text{P1:} \quad \min_{P_i, y_i} \quad \pi_i = RC_i(P_i) + \mathrm{TC}(y_i) \qquad ...(13)$$

$$\text{s.t.} \quad l_i \le P_i \le u_i, \qquad ...(14)$$

$$P_i + y_i = P_{0i} - P_{i\max}, \qquad ...(15)$$

$$\sum_{i\in I} y_i = 0. \qquad ...(16)$$

Considering constraints (15) and (16), in which transfer volume y_i can be considered as relaxed variable, then we reformulate the above optimization program as follows: For any region $i \in I$,

$$\text{P2:} \quad \min_{P_i} \quad \pi_i = RC_i(P_i) + \mathrm{TC}(P_{0i} - P_{i\max} - P_i)$$

$$\text{s.t.} \quad l_i \le P_i \le u_i, i \in I, \qquad ...(17)$$

$$\sum_{i\in I} P_i = P_{0t} - P_{t\max}. \qquad ...(18)$$

Then, in order to complete the proof, we only need to prove the equivalence of P2 and NP.

Suppose that $(\bar{P}_i)_{i\in I}$ is the optimal solution of P2. Then for any P_i satisfying constraints (6) and (7), we have,

$$RC_i(\bar{P}_i) + \mathrm{TC}(P_{0i} - P_{i\max} - \bar{P}_i) \le RC_i(P_i) + \mathrm{TC}(P_{0i} - P_{i\max} - P_i)$$

Summing the above up, we have,

$$\sum_{i\in I} RC_i(\bar{P}_i) + \sum_{i\in I} \mathrm{TC}(P_{0i} - P_{i\max} - \bar{P}_i) \le$$

$$\sum_{i\in I} RC_i(P_i) + \sum_{i\in I} \mathrm{TC}(P_{0i} - P_{i\max} - P_i)$$

Therefore, combining the feasibility of $(\bar{P}_i)_{i\in I}$, $(\bar{P}_i)_{i\in I}$ is the optimal solution of NP. For any $_{i\in I}$, since reduction function $RC_i(.)$ and transfer cost TC(.) are strictly convex, NP has a unique minima. It implies that the converse is true. Then we complete our proof.

Optimality conditions of RTCM: Form the definition of transfer cost function, we can see that it is non-differentiable in the common sense. Here, we use the Clarke's generalized gradient to solve optimization problem NP.

Let $\varphi: R^n \to R$ be a convex function, then the Clarke generalized gradient (Ye & Zhu 2010) at $\bar{x}$ is a convex and compact subset of R^n defined by,

$$\partial\varphi(\bar{x}) = \{\xi \in R^n : \xi' d \le \varphi^0(\bar{x}; d) \quad \forall d \in R^n\},$$

$$\text{where, } \varphi^0(\bar{x}; d) = \limsup_{\substack{x\to\bar{x} \\ t\downarrow 0}} \frac{\varphi(\bar{x} + td) - \varphi(\bar{x})}{t}$$

Proposition 2: If $(\tilde{P}_i, \tilde{y}_i)_{i\in I}$ is the optimal solution to RTCM, then there exists $\tilde{\gamma}_i, i = 1, 2, \cdots, |I|$ and $\tilde{\lambda} \ge 0$ such that for any $i = 1, 2, \cdots, |I|$,

$$\tilde{P}_i = \begin{cases} l_i, & \tilde{\lambda} \le RC_i'(l_i) - \tilde{\gamma}_i \\ RC_i'(\tilde{\gamma}_i + \tilde{\lambda})^{-1}, & RC_i'(l_i) - \tilde{\gamma}_i < \tilde{\lambda} < RC_i'(u_i) - \tilde{\gamma}_i \\ u_i, & \tilde{\lambda} \ge RC_i'(u_i) - \tilde{\gamma}_i \end{cases},$$

Where, $RC_i'(\cdot)$ is the derivative of $RC_i(\cdot)$, and $RC_i(\cdot)^{-1}$ is the inverse function of $RC_i'(\cdot)$.

Proof: Recalling the results of Proposition 1, we only need to prove the proposition holds for NP. Consider the non-differentiable optimization problem NP. From the convexity of $RC_i(.)$ and TC(.), there exist $\tilde{\gamma}_i \in \partial\mathrm{TC}(P_{0i} - P_{i\max} - \tilde{P}_i), i = 1, 2, \cdots, |I|$ and $\tilde{\lambda} \ge 0$ such that

$$\begin{cases} RC_i'(l_i) - \tilde{\gamma}_i - \tilde{\lambda} \ge 0, & \tilde{P}_i = l_i \\ RC_i'(\tilde{P}_i) - \tilde{\gamma}_i - \tilde{\lambda} = 0, & l_i < \tilde{P}_i < u_i \\ RC_i'(u_i) - \tilde{\gamma}_i - \tilde{\lambda} \le 0, & \tilde{P}_i = u_i \end{cases},$$

Where,

$$\partial\ \mathrm{TC}(P_{0i} - P_{i\max} - \tilde{P}_i) =$$

$$\begin{cases} \{k_1\}, & P_{0i} - P_{i\max} - b_1 \le \tilde{P}_i \le P_{0i} - P_{i\max} - b_0 \\ [k_l, k_{l+1}], & \tilde{P}_i = P_{0i} - P_{i\max} - b_l, \text{ where } l > 1 \\ k_{l+1}, & P_{0i} - P_{i\max} - b_{l+1} \le \tilde{P}_i \le P_{0i} - P_{i\max} - b_l, \text{ where } l > 1 \end{cases}$$

Since $RC_i(\cdot)$ is strictly increasing, $RC_i(\cdot)^{-1}$ is well defined.

Table 2: Data for the example.

	Lower bound of reduction (10^4 t)	Upper bound of reduction (10^4 t)	Reduction cost function (10^4 RMB)	Current reduction (10^4 t)
Region 1	46.0110	85.4490	$484.756\ P_1^{1.096}$	63.3780
Region 2	44.9890	83.5510	$371.8\ P_2^{1.154}$	53.6460
Region 3	39.6133	73.5677	$48.91\ P_3^{2.277}$	23.7799

Therefore,

$$\tilde{P}_i = \begin{cases} l_i, & \tilde{\lambda} \le RC_i^{'}(l_i) - \tilde{\gamma}_i \\ RC_i^{'}(\tilde{\gamma}_i + \tilde{\lambda})^{-1}, & RC_i^{'}(l_i) - \tilde{\gamma}_i < \tilde{\lambda} < RC_i^{'}(u_i) - \tilde{\gamma}_i \\ u_i, & \tilde{\lambda} \ge RC_i^{'}(u_i) - \tilde{\gamma}_i \end{cases} \quad ...(19)$$

Then, we complete our proof.

In view of Proposition 1 and equation (17), we can see the optimal reduction of RTCM is a function with variable of λ, i.e., $\tilde{P}_i = P_i(\tilde{\lambda})$. In order to find the optimal reduction of RTCM, we only need to find a $\tilde{\lambda}$ such that,

$$\sum_{i \in I} P_i(\tilde{\lambda}) = P_{0t} - P_{t\max} \quad ...(20)$$

In view of assumption (b), $\sum_{i \in I} l_i \le P_{0t} - P_{t\max} \le \sum_{i \in I} u_i$. From the mean value theorem and the strictly increasing property of $RC_i^{'}(\cdot)^{-1}$, we can see that equation (20) has one and only one solution.

An illustrate example: Let us consider a lake surrounded by 3 regions. The structure is shown in Fig. 1 and all used data for this example are given in Table 2.

Choose, $b_0 = -10,\ b_1 = 10, b_2 = 20,\ k_0 = 1,\ k_1 = 300, k_2 = 350,$ if we do not use the generalized Clarke's gradient, we can directly compute the reaction function 1, 2 and 3, and plot them in Fig. 2.

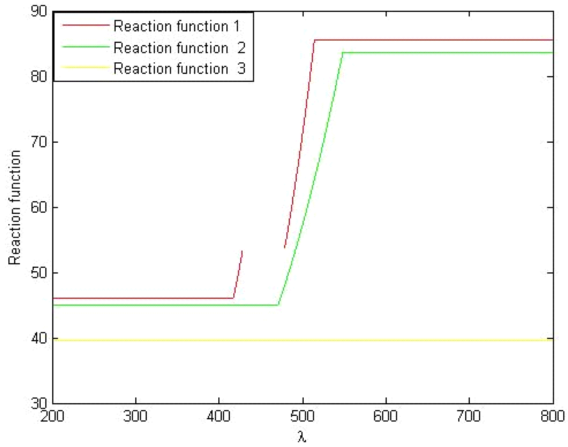

Fig. 2: Reaction functions.

Due to the discontinuity of reaction function 1, the summation of the three reaction functions is also discontinuous. If we use the Clarke's gradient, the reaction function 1 and summation of three reaction functions are all become continuous. The modified picture for the reaction functions is shown in Fig. 3.

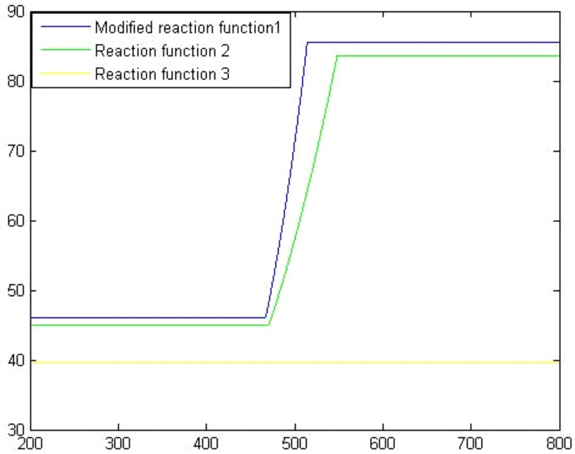

Fig. 3: Modified reaction functions.

According to (19-20), we can test that the optimal results are $\gamma^* = 300$ and $\lambda^* = 478.332$ with optimal reductions for the three regions P_1^*=533.783 thousand tons, $P_2^* = 47.8123$ thousand tons and $P_3^* = 39.6133$ thousand tons, respectively.

CONCLUSION

In this paper, we have introduced, analysed and implemented an efficient RTCM over China's transboundary water pollution control. One of the main features of the model being its non-differentiable cost function, this raises the issue of alternative existence theory and new pollution control approaches. Prime suspects in that class would be models based on taking water or air transport function as the transfer cost. Another natural extension is introducing physical structure into the model, features that have been mainly considered in the framework of uniform tax policy. Both will be the topic of forthcoming works.

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