TWO ESSAYS OF POLICIES IN WATER RESOURCE MANAGEMENT

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CHAPTER ONE

INTRODUCTION

More water is devoted to uses. That means less water is available in the natural state and less water resource can be used by other users. And the ability of the environment to restore the water resource is limited. Therefore, the key element of the problem is scarcity. In order to solve the water scarcity problem, this dissertation will focus on the following questions: How to find the least cost by a given level of water quality? How can we get more tax revenue when the water quality is trade-off with tax revenue? Are there any alternative solutions (which are different from an optimal solution) due to non-economics problems to help decision makers? Can we find a most efficient technique due to economies of scale? Can the most efficient technique (e.g. chain model) be implemented in the real world due to equity problems (e.g. fair cost allocation)? How can the fair cost allocation technique (e.g. cooperative game) help in implementing the most efficient technique?

Two river basins will be used in this dissertation. The first one, which is used in the first essay, is the simplified sample of the Willamette River in Oregon (Revelle et al. 1968). BOD (biochemical oxygen demand) has been used for a standard measure of the amount of waste pollutants. The water quality standard (BOD) has been set on each reach by an environmental authority. The second study area, which is used in the second essay, is the simplified sample of the Delaware estuary (Zhu and ReVelle 1988; Whitlatch

1973). One of three optimal regional plants, which are found by the Chain model(the most efficient technique), is used to be the empirical study. Three dischargers share the optimal regional plant. The cost allocation (equity) between these three dischargers is present in the essay.

The dissertation consists of two essays in water quality management. The first essay is "the taxation of environmental pollution: a model for tax revenue-environmental quality tradeoffs." Economists have begun to examine the possibility of using taxes on environmental pollution as a mechanism to raise tax revenues. The purpose of the first essay is to show a model (combining the least cost model and the constraint method of multi-objective programming model) that can be used to determine the tax rate on environmental externalities that incorporates both revenue and environmental quality objectives. The discussions in this essay thus focus on the detailed development of the combined model structure and find the efficient solution set for decision makers. Then, in order to allow decision makers to embody important objectives that are difficult to include in a mathematical model, the HSJ (Hop, Skip, and Jump) method (Jeffrey, et al. 1992) has been used to find the near optimal solution (alternative solutions) for decision makers to fit in the real world.

The second essay is "cost allocation and water quality control: the case of a cooperative game in a chain model." Since arrangements of several sets of pipes can provide for efficiency in water quality control in certain situations because of economies of scales, the purpose of the second essay is to show a method (*N*-cooperative game-MCRS approach) that can be used in the chain model (Zhu and ReVelle 1988) to solve the efficiency and equity (cost allocation) problem.

The organizational structure of this study is as follows. First, the introduction of this dissertation is presented. Second, the first essay about the taxation in water quality is shown. Third, the second essay about the cost allocation is presented in this section. The last section is the conclusion and future extension.

CHAPTER TWO

THE TAXATION OF ENVIRONMENTAL POLLUTION: A MODEL FOR TAX REVENUE-ENVIRONMENTAL QUALITY TRADEOFFS

2.1 Introduction

Historically, economists have advocated environmental policies, which are based on economic incentives. These policies can take many different forms, but perhaps the most widely discussed variant is based on the use of taxes (Baumol and Oates, 1988). In contrast, there seemed to be very little enthusiasm and support in the policy-making arena for the use of taxes as the basic foundation for an environmental policy.

The perspective on the use of taxes in an environmental policy has begun to change in recent years. It now seems that there is a belief that environmental taxes, or "green taxes," offer a "double dividend." First, as economists have long argued, appropriately defined taxes can efficiently restrain the levels of polluting activities. Second, these taxes also generate revenues, thus allowing a reduction of tax rates on other forms of taxation throughout an economy that distort the functioning of the economy. The latter point means there will be an increase in the efficiency of the overall tax system. The efficiency aspects of the double dividend argument for "green taxes" have been extensively reviewed and discussed by Oates (1993, 1995). These issues are beyond the scope of this paper. Instead, this paper focuses more directly on the role of tax revenue objectives and environmental quality objectives in the taxation of pollution.

Burke (1997) and Barde and Smith (1997) present a selective country-by-country review of environmental policies that have included “green taxes.” Burke (1997) argues that European countries seem to have taken the lead in implementing environmental taxes. In some cases, these taxes were designed to provide economic incentives (i.e., reduce emissions in order to comply with environmental objectives). In other situations, environmental taxes have been designed to provide resources to finance specific pollution-abatement programs. Barde and Smith (1997) note, for example, that water-effluent charges play an important role in financing pollution-control facilities in France. Environmental taxes have also been levied in some situations to cover the costs of regulating emissions. In yet other cases, environmental taxes have been used as incentives to move toward the achievement of environmental quality objectives. Examples here include a CO_2 tax in Sweden and Norway (Burke, 1997).

The problem of determining environmental tax rates is a complicated issue in a realistic policy setting where the basic problem is one of trying to use a single instrument to regulate pollution and raise revenues. These appear to be conflicting objectives, which means that there are tradeoffs in the sense that sacrificing the requirements of one goal will produce greater returns on the other. This clearly requires a protocol that addresses the tradeoffs between environmental quality objectives and tax revenue objectives. Such a protocol must recognize that decision makers are faced with different objectives that may be of equal or differing importance. In some situations, the goals may not be commensurate; they may not be directly compared or combined. The goals may also conflict, which means there are tradeoffs in the sense that sacrificing the requirements of one goal will produce greater returns on the others.

The decision problem facing decision makers in the context of these discussions is a multiple-objective or multi-criteria decision problem. A common practice is to solve these problems with a multi-objective programming (MOP) or vector optimization technique (Romero and Rehman, 1989). This technique is designed to seek simultaneous optimization of several objectives subject to a constraint set that is usually linear. An optimal solution can not be defined for several simultaneous objectives, so a solution strategy is designed to obtain the set containing efficient solutions instead of locating a single optimal solution. The set of efficient solutions is said to be non-dominated or Pareto efficient. Cohon and Marks (1973) applied multi-objective theory and the constraint method to a water resource development and allocation problem. Detailed descriptions of multi-objective optimization and the generation of Pareto optimum can be found in sources such as Cohon (1978), Cohon and Marks (1973), and Romero and Rehman (1989).

Multi-objective or multi-criteria decision making problems can also be formulated and solved as either "compromise programming" or "goal programming" problems. Problem formulation and solution strategies are given extensive coverage in Romero and Rehman (1989). The range of applications of weighted goal programming to the analysis of tradeoffs in public policy problems include Barnett et al. (1982), Spronk and Veeneklass (1983) , as well as Wheeler and Russell (1977).

A tax is the same as an effluent charge. After solving a least cost model, we can use the tax to implement a least cost solution. The tax rate can be set to equal to marginal treatment cost. In order to implement the above approach, we need to know the set of cost functions (total cost or marginal cost) of all dischargers, which can be found by the model written by Revelle, Loucks, and Lynn (1968).

Brill (1997, p 672) writes that:

> "It would be possible in theory to implement a least cost solution using effluent charges after solving a least cost model. Such an approach, however would require that the set of TC curves (or MC curves) for all dischargers would be used to calculated the set of individual unit charges needed to produce the required set of waste reduction levels."

A case study for a water quality examination is developed and analyzed to illustrate how the model works. The uniqueness of this paper lies with the manner in which the multiple objectives of tax revenues and environmental quality are portrayed. The tax rate used in this paper on emissions is determined by the result of the least cost model (Brill 1997, p. 672). Roskamp (1972) developed a mathematical programming-based policy decision model approach to optimal budgets. Chrisman et al. (1989) provided another example of a multi-objective programming model that has been developed for public sector tax planning. The tax rates are assumed to be known and fixed by Chrisman et al. (1989).

The purpose of this essay is to show a model (combing the least cost model and the constraint method of multi-objective programming model) that can be used to determine the most efficient tradeoffs between a tax rate on environmental externalities that incorporates both revenue and environmental quality objectives. The discussions in this essay thus focus on the detailed development of the combined model structure (the least cost model and the constraint method of multi-objective programming model) and find the efficient solution set for a decision maker.

The organizational structure of this essay is as follows. First, a short discussion is presented of how the tax rate could be set given the two different objectives. Second, a simplified version of a water quality model is presented and then extended to a constraint method of multi-objective programming model. This section will also address some of the issues relevant to the determination of the constraint from the least cost model for the objective function. Then, modeling to generate alternative by HSJ method is presented. Third, this section presents an expanded version of a model that will be implemented along with potential data sources. Finally, solutions and results are presented.

2.2 Modeling Structure

This section provides some relevant information, which is concerned with the modeling structure. In the first subsection, tax revenue is shown. The discussion in this subsection includes the selection of tax rate and tax base. The second subsection explains the water quality model and cost-minimization problem. The third subsection presents the multiple-objective model by using a constraint method. The fourth subsection is multi-objective programming applied in water quality management. Finally, modeling to generate alternative by HSJ method is presented.

2.2.1 Tax Revenue

The first important concern is the tax base. It is an accepted proposition that taxes on externalities should be placed directly on the activity that generates the external cost. Thus, the tax should be levied on emissions (i.e., the tax base is emissions). (For example, see Baumol and Oates [1988] or Tietenberg [1985]).

Recall from earlier discussions that two different objectives were identified for setting the tax rate on emissions. Consider first the problem of setting the tax rate to achieve a target level of revenues. Clearly, there is a wide range of issues pertaining to how the target level of revenues could be determined. Brill (1997) argues that by theory the tax rate, which is equal to marginal treatment cost, can be used to implement a least cost solution. Therefore, the target level of the tax revenue can be found by choosing the appropriate least treatment cost, which decides the amount of emission and the marginal treatment cost.

The second criterion is concerned with environmental management objectives. It is assumed in this case that the tax rate is determined on the basis of the "standards and charges" approach advocated by Baumol and Oates (1988). This proposition states that a tax rate set at a level that achieves the desired reduction in total emission of pollutants satisfies the necessary conditions for the minimization of the program's total costs to society. (A detailed account of the tax rate derivation is not presented in these discussions. The reader is referred to Baumol and Oates [1988].)

The major shortcoming of the methods outlined above lies with their failure to directly address the tradeoffs between the revenue objectives and environmental objectives in the selection of a tax rate. These tradeoffs are ultimately addressed within the context of a constraint method of the multi-objective programming framework. The statement of the constraint method of the multi-objective programming framework is developed in a series of stages. Consider first the nature of the pollutant to be addressed in this study. The relevant type of pollutant is called a "non-uniformly mixed fund pollutant" (Tietenberg, 1985). The distinguishing feature of this type of pollutant is that the environment has some amount of assimilative capacity for them. (That is, the environment can absorb them to some extent.) If the assimilative capacity is high enough relative to the rate of release to the environment, they are not likely to accumulate.

2.2.2 Water Quality Model

A type of fund water pollutant is called "biodegradable" because it degrades or breaks into its component parts within the water. An easy way to measure and state the concentration of biodegradable or organic wastes that reveals the concentration of organics as well as the amount of oxygen that all organic wastes, acting together, will eventually remove from the water is called biochemical oxygen demand (BOD). BOD is the amount of oxygen, determined by testing, that would be consumed if all the organics in one liter of polluted water were oxidized in the presence of air by bacteria and protozoa. This is reported in number of milligrams of oxygen per liter. The discussions in this paper are focused on BOD and its fixed point sources.

The pollutant BOD is a measure of organic waste load that indicates the amount of oxygen drawn up (demanded) in the process of waste decomposition. The rate at which a given quantity and type of organic waste exerts oxygen demand is a function of a set of factors, including chemical characteristics, the temperature of the receiving water, and the type of waste. The rate at which BOD is exerted combined with the rate at which oxygen is restored determines the dissolved oxygen level. The critical measure of environmental quality is dissolved oxygen.

A set of mathematical relationships summarizing these conditions can be developed as follows. A river that is modeled is divided into sections called "reaches." A new reach is defined when one of the following occurs: the flow of the river is altered by effluent entering the river, incremental flow entering the river (groundwater or tributary flow), or the flow in the main channel being augmented to diverted; or when a change occurs in parameters describing the river's response to effluent. The critical point for measuring environmental quality in a reach is where DO is at its lowest level. This is called the "sag point" and occurs at the end of the reach. This sag point is referred to as the "monitoring point" for environmental quality in the remaining discussions. It is also assumed that each fixed point discharger in a reach can have an impact on the level of water quality in the reaches that are located downstream.

These relationships can be formally presented as follows. Let the index i ($i = 1, \ldots, I$) denote a fixed-point discharge source, k ($k = 1, \ldots, K$) the reach number where the fixed-point discharger is located, and j ($j = 1, \ldots, J$) the reach number where water quality is being measured. In addition, define the following notation:

D_j ≡ dissolved oxygen deficit at monitoring point j (mg/l),

B_j ≡ background dissolved oxygen deficit at point j (mg/l),

E_{ik} ≡ BOD emissions from source i in reach k,

a_{kij} ≡ transfer coefficient to translate BOD emissions from source i in reach k to their effect on the dissolved oxygen deficit at the receptor point in each j,

S_j ≡ dissolved oxygen concentration at location j (mg/l),

X_{ik} ≡ percent of BOD removed by source i in reach k,

T_j ≡ dissolved oxygen saturation at location j (mg/l).

The relationship between BOD releases from the fixed-point sources in a reach and the level of water quality at each impacted monitoring point downstream is summarized by the following relationship:

$$D_j = B_j + \sum_{k=1}^{J} \sum_{i=1}^{I} a_{kij} E_{ki} \tag{1}$$

$$(j = 1, \ldots, J).$$

An example of the situation presented by equation (1) is shown in Figure 1. There are several important points of which to be aware regarding equation (1). First, discharge points downstream from each monitoring point have no impact at the point in question. Second, it is not possible to reduce the dissolved oxygen deficit level D_j to zero unless the BOD discharge levels from all point sources along with the background levels of BOD are all equal to zero. Third, the transfer coefficients are generally smaller the further upstream a point source is from the monitoring point. Finally, the transfer coefficient a_{kij} is assumed to be constant in the remaining discussion and indicates the amount that the concentration level of dissolved oxygen will change at the receptor point j as a result of a one-unit change in BOD release at point-source location i in reach k. A more complex and realistic presentation of the water quality modeling system is presented in a later section.

Water quality policy is normally stated as ambient standards and measured in terms of dissolved oxygen concentration rather than a dissolved oxygen deficit. The relationship between the dissolved oxygen level at monitoring location j and the dissolved oxygen concentration level at this location is stated as

$$S_j = T_j - D_j \qquad (2)$$

$$(j = 1, \ldots, J).$$

In summary, equations (1) and (2) provide a representation of the physical conditions of each section of the river and the corresponding impacts of emissions to that section of the river. The information for these equations is often derived from an environmental quality simulation model.

The next task is to develop a cost-minimizing model. First, several modifications must be made to equations (1) and (2) to reflect the presence of pollution abatement activities as well as the water quality objective. Recall that the standard or water quality target is set in terms of DO at the receptor point in each reach. Let the minimum DO level be denoted as $\overline{S}_j$. Then equation (2) is restated as

$$T_j - D_j \geq \overline{S}_j \qquad (3)$$

$$(j = 1, \ldots, J).$$

But if T_j is viewed as fixed and given, then equation (3) can be restated as

$$D_j \leq T_j - \overline{S}_j \qquad (4)$$

$$(j = 1, \ldots, J).$$

Equation (1) must also be modified to represent the percentage of BOD removal in each reach, which is the decision variable for each pollution source. If X_{ik} represents the percentage of BOD removed by source i in reach k, then $(1 - X_{ik})E_{ik}$ represents the amount of BOD remaining. Taking this into account in equation (1) leads to the following statement.

$$B_j + \sum_{k=1}^{j} \sum_{i=1}^{I} a_{kij} \left(1 - X_{ik}\right) E_{ik} = D_j \qquad (5)$$

$$(j = 1, \ldots, J)$$

The next item that must be specified is the cost of pollution abatement. This is initially represented in a very general manner as $C_{ik}(X_{ik})$. Furthermore, it is assumed that

$$\frac{dC_{ik}}{dX_{ik}}(X_{ik}) > 0 \text{ and } \frac{d^2C_{ik}}{dX_{ik}^2}(X_{ik}) > 0.$$

Graphically, this means that the pollution control cost function is as shown in Figure 2. This general form is consistent with most empirically observed situations. Notice that as the percentage of BOD removal increases, the marginal cost of BOD removal increases significantly. How this relationship actually appears depends on each particular situation.

The perspective for the environmental policy makers is assumed to cover all fixed-point discharges over a well-defined number of reaches along a river. Thus the environmental policy makers are concerned with I fixed-point discharges over J reaches along the river. The environmental policy maker's cost-minimization problem is stated as

$$\min_{X_{ik}} \sum_{k=1}^{J} \sum_{i=1}^{I} C_{ik}\left(X_{ik}\right) \tag{6}$$

subject to

$$\sum_{k=1}^{j} \sum_{i=1}^{I} a_{kij}\left(1 - X_{ik}\right)E_{ik} \leq \overline{R}_j \tag{7}$$

$$(j = 1, \ldots, J)$$

where $\overline{R}_j \equiv T_j - \overline{S}_j - B_j$ for $j = 1, \ldots, J$. Recall that T_j and B_j are constants while $\overline{S}_j$ is the ambient water quality objective.

The solution to the cost minimization model given by equations (6) and (7) represents the environmental quality objective problem perspective. This solution also provides the theoretical foundation for the "standards and charges" approach advocated by Baumol and Oates(1988). This proposition states that a tax rate set at a level that achieves the desired reduction in the total emissions of pollutants satisfies the necessary conditions for the cost minimization problem.

2.2.3 Multi-objective Mathematical Model by Using Constraint Method

The following is the general mathematical formula given a multi-objective problem with p objectives (Cohn 1978, p116):

$$\text{Max } Z(X_1, X_2, \ldots, X_n)$$

$$=[Z_1(X_1, X_2, \ldots, X_n), Z_2(X_1, X_2, \ldots, Xn), \ldots Zn(X_1, X_2, \ldots, X_n), Z_p(X_1, X_2, \ldots, X_n)] \quad (8)$$

$$\text{St. } (X_1, X_2, \ldots, X_n) \in F_d \quad (9)$$

where $Z_1, Z_2, \ldots Z_p$ are objective functions.

$X_1, X_2, \ldots, X_n$ are decision variable.

F_d is the feasible resource.

The constraint method of multi-objective programming is:

$$\text{Maximize } Z_h(X_1, X_2, \ldots, X_n) \quad (10)$$

$$\text{St. } (X_1, X_2, \ldots, X_n) \in F_d \quad (11)$$

$$Z_k(X_1, X_2, \ldots, X_n) \geq L_k \quad (12)$$

$$K = 1, 2, \ldots, h-1, h+1, \ldots, p$$

where $Z_1, Z_2, \ldots Z_p$ are objective functions.

$X_1, X_2, \ldots, X_n$ are decision variable.

F_d is the feasible resource.

L_k is the lower bond of Kth objective.

hth objective is arbitrarily chosen for maximization.

"This formulation is a single-objection problem, so it can be solved by conventional methods, e.g., the simplex method for linear problems. The optimal solution to this problem is a non-inferior solution to the original multi-objective problem …." (Cohn

1978, p117). In order to find the non-inferior solution, it has to obey two conditions. One is $Z_k \geq L'$, where L' is the lower bound of objective Z_k. The result will be feasible solutions. Another condition is the choice of the right hand side value, L, which should be binding. Cohn (1978, p117) writes that:

> "Another condition that relates to our choice of the L_k is that all of the constrains on objectives should be binding at the optimal solution to the constrained problem. If this is not the case and if there are alternative optima to the constrained problem, then some of these optima solutions may be inferior alternatives for the original multi-objective problem."

The right hand side value of this constraint, L_k, is set at zero or at some predetermined value. We can increase this value incrementally until the solution becomes infeasible. A point in the non-inferior set is found by the value of the right hand side value.

Shadow price is very important for policy decision. Cohn(1978, p 117) wrote that "…..the change in the objective function that would be observe if one more unit of the resource represented by the constrain were available. This reduced cost was called a dual variable or a shadow price for the constraint with which the slack variable is associated."

2.2.4 Multi-objective Programming Applied in Water Quality Management

Water quality management in a river basin is kind of multi-objective programming. Wen and Lee (1998) wrote that:

> " The problem of water quality management plays an important role in water pollution control and river basin planning. Water quality management in a river basin, which is also a problem of multi-objective programming, seeks feasible alternatives to attain the following goals; (1) to find a reasonable allocation of waste loading for each pollution source to discharge in a river; (2) to achieve standards of water quality for fish and to improve environmental quality, especially water quality; and (3) to determine a basis for the total elimination of mass loading in a deteriorating river."

One model applied in this essay is the least cost model written by Revelle, Loucks, and Lynn (1968). They apply the linear programming to the management of water quality in a river basin. They wrote:

> "The charge is to select the efficiencies of the treatment plants on the river that will achieve the dissolved oxygen standards at a minimum cost. The objective function is structured in terms of the costs of the treatment plants. The principal constraints prevent violation of the dissolved oxygen standards." (p 1).

This essay shows two models, a least cost model and a constraint method of multi-objective programming, which can be combined to determine the optimal tax rate on environmental externalities that incorporates both revenue and environmental quality objectives.

Since water quality objectives and tax revenue objectives may have a tradeoff relationship, we need to find the relationship and to decide the optimal solution for the tax rate. Then the objectives of water quality and tax revenue can be decided. The tax revenue is dependent on the least treatment cost, which is found by least cost model. Therefore, we may find the relationship between water quality and least treatment cost first. Then, by the set of least treatment costs, we can find the relationship between water quality and tax revenue. In order to find the relationship between water quality and least treatment cost, we use the constrained method model of multi-objective programming. In the above approach, we use the following four Steps to find the trade-off relationship between water quality and tax revenue (See Figure3):

Step 1:

Find the least treatment cost from the least cost model (Revelle et al. 1968). Then, the least treatment cost, the solution in this least cost model, is used to be the right side value of "the least cost constraint," which is in Step 2.

Step 2:

Set two objectives, maximizing water quality (minimizing the emission) and minimizing the least cost objectives, in the constrained method model. Then, put the least cost objective as a constraint of this problem. The right hand side value of this constraint is set at the predetermined value, which is the least treatment cost found from Step 1. Now, increase this value incrementally until the solution becomes infeasible. A point in the non-inferior set is found by the every value of the right hand side value in "the least cost constraint".

Step 3:

A value of tax revenue (tax rate multiplied by emission) is found by every point in the non-inferior set solved by Step 2. That is because we use the theory, which is to implement a least cost solution using the tax after solving a least cost model. The reason is explain in Section 2.2.1.

Step 4:

Find the relationship of tax revenue and water quality (negative emission) by drawing these points of result from above. It becomes the non-inferior set; any point in this non-inferior set is efficient.

2.2.5 Modeling to Generate Alternative by HSJ Method

Linear programming has long been applied to solve the water quality management problem. When linear programming is used to solve a complex water quality management problem, it may find the 'optimal' solution, which is not the 'best' solution for the planning problem. Brill (1979) and Chang et al. (1982) argue that even though a multi-objective framework could solve the best solution, it likely lies in the inferior region of the feasible objective space (decided by the model) because of at least one important objective (un-included in this model).

In order to solve the complex water quality management problem, we can apply a mathematical programming method to generate alternative solutions, 'nearly optimal' solutions. The method, called Hop, Skip, and Jump (HSJ)(Brill, 1979; Chang et al. 1982; Brill et al. 1982; Jeffrey et al. 1992), is used in this essay.

Brill et al. (1982, p.222) explain the procedure (HSJ method) very clearly. The following is what they wrote:

> Step 1. Obtain an initial solution by any method. For illustrative purpose, consider a multi-objective mathematical programming model with several objective functions to be minimized, and assume that one solution has been selected by examining non-inferior solutions.
> Step 2. Obtain an alternative solution by solving:
>
> $$\text{Minimize } p = \sum_{k \in K} x_k \quad \text{s.t. } f_j(\bar{x}) \le T_j \ \forall_j, \quad \bar{x} \in X, \qquad (1)$$
>
> where
> K = set of indices of the decision variables that are nonzero in the initial solution,
> $f_j(\bar{x})$ = jth objective function,
> T_j = target specified for the *jth* modeled objective,
> X = set of feasible solutions based on the "technical" constraints of the model,
> The formulation is designed to produce an alternative solution that is *different* from the first one by minimizing the sum of the decision variables that are nonzero in the first plan. The targets specified ensure that the alternative solution will be "good' with respect to modeled objectives. Note that the targets would generally be relaxed somewhat in comparison to the respective values of the objective functions in the solution of Step 1.

Step 3. Attempt to generate a third alternative that is different from each of the first two. The solution can be obtained by using a formulation analogous to that given in (1); the objective function would be to minimize the sum of all variables that are nonzero in either (or both) of the first two solutions.

Step 4. Generate a series of additional alternative solutions by continuing the process. The original feasible space of the mathematical model is restricted by targets on objectives, and the HSJ optimization model is used to find alternative solutions that are "as different as possible" from all previous solutions.

There is an alternative use of the HSJ technique. It is to optimize with respect to specific objectives. Jeffrey et al. (1992, p.15) write that "this variation of the HSJ technique may be useful in identifying nearly optimal solutions that are of particular interest to decision makers."

2.3 Empirical Application

The empirical application of the concepts developed in this research is based on a version of the model used by Revelle, Loucks, and Lynn (1968). Begin by defining the following notation:

t_{ij} ≡ the time of flow from the top of the ith reach to the jth point in the reach, days;

m_i ≡ number of points in the ith reach;

k_i ≡ bio-oxidation constant in the ith reach, $days^{-1}$;

r_i ≡ reaeration coefficient in reach i, $days^{-1}$;

D_i ≡ oxygen deficit at the top of reach i, mg. /liter;

E_i ≡ oxygen deficit at the last point of reach i, mg./liter;

T ≡ oxygen deficit of the waste water discharged by each plant, mg./liter;

D_A ≡ allowable oxygen deficit in the system, mg./liter;

L_i ≡ BOD concentration at the top of reach i, mg./liter;

F_i ≡ BOD concentration at the last point in reach i, mg./liter;

M_i ≡ BOD concentration in the effluent from treatment plant i, mg./liter;

P_i ≡ BOD concentration in the waste flow entering the ith treatment plant, mg./liter;

Q ≡ flow rate in river, million gallons/day;

Q_i ≡ flow rate being withdrawn by community i for its water supply and being discharged as effluent from its waste treatment plant.

In addition, define the following:

$$f_{ij} = \left[\frac{k_i}{r_i - k_i}\right]\left(e^{-k_i t_{ij}} - e^{-r_i t_{ij}}\right)$$

$$g_{ij} = e^{-r_i t_{ij}}.$$

The base case optimization model is a cost minimization model and is as follows.

$$\min \sum_{i=1}^{n} a_i \varepsilon_i \tag{13}$$

subject to

$$\varepsilon_i + \left(\frac{1}{p_i}\right) M_i = 1 \tag{14}$$

$$i = 1, \ldots, n$$

$$\left(Q - Q_i\right) F_{i-1} + Q_i M_i - Q L_i = 0 \tag{15}$$

$$i = 1, \ldots, n$$

$$-\left(Q - Q_i\right) E_{i-1} + Q D_i = T Q_i \tag{16}$$

$$i = 1, \ldots, n$$

$$E_i - f_{ij} L_i - g_{ij} D_i = 0 \tag{17}$$

$$i = 1, \ldots, n-1$$

$$j = m_i$$

$$F_i - h_{ij} L_i = 0 \tag{18}$$

$$i = 1, \ldots, n - 1$$

$$j = m_i$$

$$f_{ij} L_i + g_{ij} D_i \leq D_A \quad (19)$$

$$i = 1, \ldots, n$$

$$j = 1, 2, \ldots, m_i$$

$$D_i \leq D_A \quad (20)$$

$$i = 1, \ldots, n$$

$$\varepsilon_i \geq 0.35 \quad (21a)$$

$$\varepsilon_i \leq 0.90 \quad (21b)$$

$$i = 1, \ldots, n.$$

In the statement of this model, the objective function equation (13) is defined as treatment costs while equation (14) is a definition of treatment efficiency. Equation (15) is an inventory balance equation for BOD while equation (16) is an inventory balance equation for the oxygen deficit. Equation (17) defines E_i while equation (18) defines F_i. Constraints (19) and (20) are the water quality constraints while constraints (21) are treatment efficiency constraints. A more detailed discussion of this model is given in Revelle, et al. (1968).

The empirical application for this research is based on the model structure shown above. A base case data given in Revelle, et al. (1968) has been used to derive a numerical solution for equations (13) - (21). The discharger 1 has been assumed to treat its waste at 67% (Liebman and Lynn 1966). The model structure will then be extended to the constraint method of multi-objective programming model framework such as the one given by equations (22) - (24). This model will be solved by four steps shown in Section 2.2.4 (See also Figure 3).

Set two objectives, maximizing the water quality and minimizing the treatment cost. Put the objective of minimizing the treatment cost in constraint. The other constrains [same as equations (14) – (21)] are from the least cost model (Revelle, et al. 1968). The following is the constraint method of multi-objective programming model in water quality management:

$$\text{Minimize } Z_1(X_1, X_2, \ldots, X_n) \quad (22)$$

$$St.\ (X_1, X_2, \ldots, X_n) \in F_d \quad (23)$$

$$Z_2(X_1, X_2, \ldots, X_n) \geq L_2 \quad (24)$$

where

Z_1 is water quality objective function, $Z_1 = M_1 + M_2 + \ldots + M_{11}$.

Mi is the emission discharged by reach i, $i = 1, 2, \ldots 11$.

Z_2 is the least treatment cost function, which is the same as equation (13).

X_n is the decision variables, $n = 1, 2, \ldots 11$

L_2 is the lower bound of Z_2, which is set at the value from the solution of the least cost model, from equation (13) to equation (21).

Equation (23) is assigned as these equations from equation (14) to equation (21). Then L_2 is increased incrementally until the solution become infeasible. When the problem is solved at every value of L_2, it yields a point in the non-inferior set. The point in the non-inferior set decides the total emission, the least treatment cost, and the tax revenue. That is because the level of the least treatment cost decides not only the set of tax rates (shown in Table 2) but also the emission (shown in Table 3) in each discharger.

2.4 Solutions and Results

There are three assumptions: (1) the original water quality standard (e.g. point A) is not set high enough (2) the damage function is unknown (3) the social indifferent curve is unknown. The solution of the non-inferior set for point A to H is shown on Table 1, Figure 4, and Figure 5. For example, in order to get point *A,* lower bound (L_2) is set as 1.076 (the least treatment cost) million dollars, which is solved from the least cost model. This value is used to solve the problem in constrained method of a multi-objective programming model. It gets the total emission 2054 mg/liter. At the same time, the level of the least treatment cost (1.076 million dollars) also decides the set of tax rate and the set of emission of each discharger, which is shown in Table 2 and Table 3. The relationship between the total least treatment cost and total emission is shown in Figure 4. The relationship between the water quality (negative total emission) and tax revenue is shown in Figure 5. Point A has the total emission 2054 mg/liter, and total revenue 1.63 million dollars. The relationship between the total least treatment cost and total emission has some degree of trade-off relationship. The relationship between water quality (negative total emission) and total tax revenue can be found by connecting these points, from point A to point H, shown in Figure 5. We found that they have a trade-off relationship except

with any point between G and H, which have a positive relationship. After point H, it is infeasible. Therefore, we stop at point H.

It is important to use the multi-objective programming in water quality management. For example, if we use the traditional single objective, the solution will be in point A (tax revenue objective only) or in point H (water quality objective only). The advantage of this model is using multi-objective programming to find the efficient set of solutions. Any points in the non-inferior set are efficient. These points offer the information for policy makers or decision makers to make a decision by political process or their favor.

In general, if we only have the optimal alternative without the preference information, the optimal point is hard to choose. Two approaches, the geometrical argument approach and trade off analysis approach (Cohon and Marks 1973, p.835), could be used to help a decision maker find an optimal point. In this case, the decision-making process may decide the optimal plan by the information that is given in Figure 5 and Table 1. We may expect the decision maker will choose point B by using a geometrical argument approach. That is because point B is very similar to the optimum for a typical IC (indifferent curve) in Figure 6. Trade off analysis approach is also a good method to decide the optimal point for a decision maker. In this case, the decision maker may not choose any points between point A and point B in Figure 5, because relatively large amount of water quality is sacrificed in order to gain some tax revenue when moving from B to A. In the same theory, any points between point B and H are not a good choice, because a relative large amount of tax revenue is sacrificed in order to gain some water quality when moving from B to H. Therefore, point B is a good choice for optimal point by both geometrical argument approach and trade off analysis approach.

Since all of the decision variables in the river model are "non-zero"(the emission has been cleaned between 35 percent to 90 percent), the "alternative use of the HSJ technique"(See Section 2.25) is applied in the essay. For example, the policy maker wants to have a recreation purpose plan in only one area or two areas in this river basin. But the policy maker also wants to keep the same tax revenue. Therefore, he chooses one of the optimal points (e.g. point B) in a non-inferior set and allows the 5 percent of tolerance from the total minimum emission discharged and found the nearly optimal solutions (HSJ1 to HSJ3), which are shown in Table 4. Assume Discharge 1, 2, and 3 are in Area 1, and Discharge 7 and 8 are in Area 2. HSJ1 is obtained by minimizing the emission of the dischargers 1, 2, and 3, when the policy maker have a recreation purpose plan in this area (Area1). The result shows that there is a lot of emission decrease in Discharger 2, but a lot of emission increases in Discharger 8, if we compare HSJ1 to the Optimal Point B. HSJ2 is obtained by minimizing the dischargers 7, and 8, when the decision maker has a recreation purpose plan in this area (Area 2). The result shows that there is a very significant emission decrease in Discharger 7 and 8, but a lot of emission increase in Discharger 2, if we compare the HSJ2 to HSJ1. HSJ3 is obtained by minimizing the dischargers 1, 2, 3, 7, and 8, when the policy maker may have a recreation purpose plan in both of these two areas.

The results in Table 4 shows that there is a significant degree of substitutability between Area 1 (Discharger 1 to 3) and Area 2 (Discharger 7 and 8), and a very significant degree of substitutability between Discharger 2 and Discharger 8. HSJ method provides useful information to policy makers, who are interested in the potential impacts among dischargers, when they are making the policies about the tax revenue, water quality, and other objectives (e.g. recreation purpose).

CHAPTER THREE

COST ALLOCATION AND WATER QUALITY CONTROL: THE CASE OF A COOPERATIVE GAME IN A CHAIN MODEL

3.1 Introduction

Arrangements of several sets of pipes can provide for efficient water quality control in certain situations because of economies of scale. Such a framework is efficient and provides significant savings, but may not work in the real world. This is so because there may not be a regional authority that could help facilitate its evolution. In this case, a bargaining process may provide the necessary impetus to motivate prospective groups to bring about the necessary conditions for efficient regional water quality control. The appropriate bargaining process should be concerned with both efficiency and equity issues.

The purpose of this paper is to show a method for solving the water quality problem that combines efficiency and equity features into a single method. Zhu and ReVelle (1988) use a siting model to solve the water quality control problem for regional wastewater treatment systems when the wastewater sources and treatment plants are arranged in a chain or linear situation. They found the efficient way to treat wastewater, but they did not address the problem of cost allocation among these dischargers. If any of the dischargers who would be likely to have a connection to the regional treatment plant would be unwilling to pay the appropriate treatment cost, they could choose to build their own treatment plant. This could result in a big loss in efficiency.

The purpose of this paper is to show how this problem can be solved using an *n*-cooperative game theoretic approach. The *n*-cooperative game formulation used in this paper is the minimum-cost, remaining-savings (MCRS) approach.

3.2 SELECTED LITERATURE REVIEW

This section provides a selected review of papers from several related areas. First, pricing and cost allocation systems are reviewed. A number of important shortcomings are highlighted in these discussions. The discussion in this section includes and overview of different mechanisms for allocating costs across firms. The second subsection review regional water quality modeling systems. The first part of this subsection looks at cost minimization models, while the second portion examines models constructed on cooperative game theory methods. Finally, the notion of a chain model is presented.

3.2.1 Pricing and Cost Allocation Schemes

Most pricing cost allocation schemes have three shortcomings in common. The first one is the effects of an externality. If one person or one firm affects another person's utility or another firm's production function, then it violates the Pareto optimal resource allocation. Therefore, externality exists (Hanley, Shogren, and White, 1997; Varian, 1996). For example, the upper-stream factory pollutes the river and affects the fish production of the fisherman downstream. The factory sets the price and cost, which should involve consideration of the externality.

The second shortcoming is the failure of some pricing systems to be based on the most efficient (least-cost) combination of treatment methods. Certainly, however, some systems do use least-cost treatment methods in water quality control (Taha, 1976; Loucks, ReVelle, and Lynn, 1967; ReVelle, Loucks, and Lynn, 1968). They focus on maintaining a dissolved oxygen level in the stream. The objective is to seek the least total cost over all dischargers. The least-cost solution is therefore efficient, if the marginal treatment cost is not decreasing. But if the marginal treatment cost is decreasing, we have a condition of economies of scale. In the water quality control case, we may use a pipeline to connect some dischargers and treat the waste in one or several more big treatment plant(s). Zhu and ReVelle (1988) design a model of regional systems for the treatment and collection of wastewater. The model is used to connect each discharger, like a chain. The model exhibits cost savings due to economies of scale in regional plants. Loehman, Pingr, and Whinston (1974) used a mathematical programming model in a river basin. Having institutional and physical constraints for standard water quality, they find the minimum cost that is efficient. They also find that the regional treatment, with a pipeline, has a lot of cost savings (Loehman et al., 1974, p. 229).

The third shortcoming is failure of pricing schemes to satisfy acceptable equity criteria. Heaney and Shikh (1975) used the network model of a river basin to prove that coordinated wastewater treatment strategies are more efficient than individual treatment plants. But there has been little success in enacting such proposals because real-world regional authority to implement them does not exist. In this situation, we need to have a bargaining process among these groups. It tells us that any workable regional program needs efficiency as well as equity for every one of the members (Lejanos and Davos, 1995; Heaney, 1983). Faulhaver (1975, p. 966) argues that one reason to let a member join a coalition is that the joint cost (cost of the combined firms' pollution control) is less than the cost of action independently. If the joint cost (cost of the combined firms' pollution control) is higher than the cost of acting independently, they will choose to forego group cooperation and act by themselves. This implies a significant loss in efficiency. Therefore, if the marginal treatment cost is decreasing and every member has cost savings, the members will join a coalition. That produces both equity and efficiency.

There is a growing literature on different mechanisms for allocating costs across firms. But the actual applications in the real world have been limited in nature for at least two reasons (Biddle and Steinberg, 1984). The first one is that "cost allocation proposals have not always captured essential aspects of the settings in which demands for allocation arise." The second reason is that "the varied and sometime conflicting assumptions, definitions, and methodologies that the alternative approaches employ have made comparisons difficult for managers and researchers alike." In order to overcome the criticisms, Biddle and Steinberg (1984) argue that the cost allocation needs to involve consideration of the nature of the cost being allocated, the allocation method selected, and the decisions to be based on the allocated costs. This implies that whenever the total cost to be allocated has been decided, we need to select the cost allocation method that reflects the nature of the cost being allocated.

On the cost allocation problem, there are some widely used methods from cooperative game theory. They are the Shapley value (Littlechild and Owen, 1973; Loehman et al., 1979), the nucleolus (Littlechild, 1974; Suzuki and Nakayama, 1976), variants of the nucleolus (Young , Okada, and Hashimoto, 1982; Lejano and Davos, 1995), and the core and variants of the core (Young et al., 1982; Heaney and Dickinson, 1982).

Hamlen, Hamlen, and Tshirhart (1977) compare four cost allocation schemes in cooperative game theory. These four cost methods are the activity level allocation scheme, the Shapley value, the nucleolus scheme, and the Moriarity joint cost allocation scheme. In the particular numerical example used, Hamlen et al. (1977, p. 624) found that:

> *For the particular numerical example used, two schemes, the Shapley value and the nucleolus scheme, tend to divide the total value of cooperation evenly among the divisions. This is not necessarily a virtue since in the joint cost problem, the larger division is contributing a proportionately larger part of the joint cost savings. Thus the larger divisions may resist Shapley value and nucleolus scheme allocations. The activity level charges favor the smaller division to an even greater extent. On the other hand, the Moriarity scheme favors the large division to such an extent that it yields a payoff that is not in the core. This result seems more likely to occur when there are a number of small divisions combined with a few large divisions.*

The cooperative game is used as the theoretical basis for the allocation methods based on separable and non-separable costs. In the cooperative game, the separable costs are defined as the difference in cost between the player who joins the coalition and who does not join the coalition (Federal Interagency River Basin Committee, 1950). If every player has been assigned its own separable cost, then those remaining costs, which are not separable costs, are called the "non-separable costs."

Some cost allocation methods are based on separable and non-separable costs. They are the egalitarian non-separable cost (ENSC) method, the separable costs remaining benefits (SCRB) method, the minimum costs remaining savings method (MCRS), and the non-separable cost gap (NSCG) method. Driessen and Tijs (1985) compared these four different cost allocation methods based on joint costs of water resources projects. They argue that:

> *All these methods, except the ENSC method, can be described with the aid of lower and upper bounds for the core of the involved cost game. For convex cost game, these three methods use the same bounds for the core and hence coincide, but their cost allocation does not necessarily belong to the core. For a second class of cost games, the so-called one-convex cost games, all methods except the SCRB method, coincide and their cost allocation turns out to be the center of gravity of the core of the involved cost game.*

The separable costs remaining benefits (SCRB) method is used in multipurpose water reservoir projects in the U.S. (Interagency Committee on Water Resources, 1958). The method was widely used in multipurpose water development projects in the 1980s. The disadvantage of the SCRB method is that it only analyzes coalitions of size 1, $N-1$, and N. All other information is ignored. The bounds, upper and lower, for the core are made by simple formulas.

The minimum costs remaining savings method (MCRS) is proposed by Heaney and Dickinson (1982). It is a generalization of SCRB. The bounds for the core are obtained by solving several linear programs. Therefore, in the MCRS method, those bounds are as sharp as possible (Driessen and Tijs, 1985). The egalitarian non-separable cost (ENSC) method is a naive method. That is because ENSC simply equally assigns the non-separable cost, which should be "proportioned" equally. The non-separable cost gap method (NSCG) is derived by the τ value, which is introduced by Tijs (1981). The method gets the bounds of the core by simple formulas and argues that the allocation of the non-separable cost is not only based on the remaining alternate costs of the one-person coalitions, but also needs to be based on the remaining alternate costs of other coalitions.

If we compare these four methods by bounds for the core, the MCRS method is the best. That is because the method's bounds for the core are as sharp as possible. If we compare these four methods by subclass (convex and one-convex) cost games, MCRS shares with other methods their positive characteristics and becomes one of the best methods. Therefore, if MCRS method's computation cost is not too high, we should choose the MCRS method (Driessen and Tijs, 1985).

3.2.2 Regional Water Quality Modeling Systems

There are some ways to analyze the regional water quality control system in a river basin. One method is to focus on finding the optimal solution for basin-wide cost for a given pollution standard. This can be done with a mathematical programming model. It involves minimizing the total cost, which includes operation, construction, and maintenance costs of all treatment structures in a river basin. The model also needs to be subjected to constraints that include given institutional and physical constraints to achieve the standard water quality. After running through the model, we can find the lowest cost for a given water quality standard (Taha, 1976; Loucks et al, 1967; Revelle et al., 1968).

Taha (1976) used the case of water quality control for three cities in a river basin. Each of these three cities has its own treatment plant. BOD (biochemical oxygen demand) has been used for a standard measure of the amount of waste pollutants. In Taha's model, he sets three reaches that are the portion of the stream between two successive plants. The water quality standard (BOD) has been set on each reach. Several factors affect the waste reduction: the treatment efficiency at each plant, BOD discharge rate from each city, BOD discharge rate from each plant to the stream, fraction of BOD removed in one reach to another reach due to biochemical activity, maximum allowable BOD loading in one reach to the next reach, stream flow in one reach to the next reach, and the cost of BOD removal at the treatment plant (Taha, 1976, p. 22). Then the objective function is set by minimizing the total cost of each treatment plant. Three constraints related to the levels of stream quality are also set. The result is shown to be the least-cost (efficient) solution.

Loucks et al. (1967) used concepts similar to those of Taha (1976). They determine the minimum cost to achieve the water quality required in a river basin. This paper uses steam dissolved oxygen standards and has a more detailed discussion about the fraction of BOD removed in the movement from reach to reach. The models used in the paper not only find the least-cost (efficiency) solution but are also in sensitivity analysis. Loucks et al. (1967) argue that "they can be used not only in determining system costs for various quality standards but also for measuring the cost sensitivity to changes in the design stream and wastewater flows and treatment facility location."

Revelle et al (1968) used the linear programming model, in concept similar to that of Loucks et al. (1967) and Taha (1976) to analyze water quality management. They used the model to compare with dynamic programming (which is used by Liebman and Lynn [1966] in the Willamette River in Oregon.) They found that both techniques, linear programming and dynamic programming, yielded essentially the same results (Revelle et al., 1968, p. 7).

Regional water quality modeling systems have also been constructed on the basis of cooperative game theory methods. Loehman et al. (1974) used a mathematical programming model in a river basin. Having institutional and physical constraints for standard water quality, they find the minimum cost that is efficient. They also find that regional treatment, with a pipeline, yields large cost savings (Loehman et al., 1974, p. 229). Since the regional treatment has the economies of scale, the cooperative game theory can be applied in cost allocation. Cost allocation (with game theory) of regional treatment plants has been used in several case studies (Giglio and Wrightington, 1972; Loehman et al., 1979; Young et al., 1982; Heaney and Dickinson, 1982; Heaney, 1983).

Loehman et al. (1979, p.193) argue that "There are economies of scale in the construction of regional wastewater treatment systems." They used cooperative game theory techniques in the cost allocation method to analyze the Meramec River Basin in Missouri. They compared the cost allocation by the following three methods: (1) generalized Shapley value, (2) minimize disruption, and (3) average cost. Loehman et al. (1979, p. 201) found that "The generalized Shapley value is an efficient solution in that it is based on incremental costs only; and it is an equitable solution in that all dischargers are treated the same in the computations. Nevertheless, there are problems in compliance." Heaney (1983, p. 115) compared the results of Loehman et al (1979) with core bounds and the MCRS (the minimum costs, remaining savings). He argues that "The results indicate that the generalized Shapley value method and the minimize disruption are unacceptable because some of the assigned costs fall outside of the core. The simple average cost method passes the core test. By its nature, the MCRS solution is in the core" (Heaney, 1983, p. 115). In the analysis of the Meramec River Basin case, the MCRS solution is better so far.

Heaney and Dickinson (1982) argue that ". . . if the problem of regionalization of sewage treatment facilities among *N* cities is being examined, the optimal solution may call for one large plant. In order to realize these savings, the *N* communities must somehow apportion the cost of this regional facility among themselves in a fair manner" (p.476). That tells us the importance of cost allocation. In this paper, they also compare several criteria of cost allocation: (1) the Shapley value; (2) the nucleolus; (3) the separable costs, remaining benefits (SCRB); and (4) the minimum cost, remaining savings (MCRS) solution. The Shapley value may fall outside of the corse (which is a very undesirable property) when the game is non-convex. A disadvantage of the nucleolus is that solving $N-1$ linear programs to get the nucleolus value is rather tedious. For the SCRB method, only coalitions of size 1, $N-1$, and N are analyzed (other information is ignored). By contrast, all other intermediate coalition information is used in the MCRS method (Heaney and Dickinson, 1982). Therefore, Heaney and Dickinson (1982) argue that "The MCRS method is preferable to the SCRB method because it uses bounds which are feasible" (p. 481). Furthermore, this model is concerned not only with efficiency but also with equity.

When economies of scale are present, cooperative game theory is a good method to handle the cost allocations in regional water quality modeling systems. However, the cooperative game theory has a disadvantage: in the real world, there is often not enough detailed information on costs to apply the theory, especially when the region is big and the dischargers are many (Young et al, 1982; Giglio and Wrightington, 1972).

In order to apportion the costs of construction in a regional waste treatment system among dischargers, Giglio and Wrightington (1972) used the following five methods to compare the allocation costs: (1) cost sharing based on the measure of pollution; (2) cost sharing based on single plant costs with a rebate proportional to the measure of pollution; (3) cost sharing based on the SCRB method; (4) cost sharing based on free market bargaining; and (5) cost sharing based on bargaining, including the regional authority as a participant. They argue that no one method is universally preferred. However, methods 2 and 3 above (cost sharing based on single plant cost with a rebate proportional to the measure of pollution and cost sharing based on the SCRB method) seem to have the most advantages in most cases. But when the region is huge and the polluters are many, method 5 (cost sharing based on bargaining, including the regional authority as a participant) is better.

In a case study of the Swedish example, Young et al. (1982) argue that when detailed information on cost is not available, just simply taking the proportion of population to allocate costs is better than the game theory technique of cost allocation. If detailed cost information is not available and we consider the arguments of Young et al. (1982) to water quality control in a river basin, methods 1 above (cost sharing based on the measure of pollution) and 2 (cost sharing based on single plant costs with a rebate proportional to the measure of pollution) may be better. Therefore, in choosing the cost allocation method, we need to be concerned with whether detailed cost information is available.

3.2.3 Chain Model

Zhu and ReVelle (1988) design a model of regional systems for the treatment and collection of wastewater. The model has savings due to economies of scale as regional plants. The model is used to connect each discharger like a chain. The model is used to solve the optimal siting problem of regional wastewater treatment plants. The weakness of this model is that it does not provide an explanation for allocating costs across dischargers. To fully understand this issue, consider the following. Suppose that the chain model solution leads to a relatively high cost being imposed on a discharger. It may be possible that the discharger could build its own plant for a lower cost or join a cooperative of other dischargers and build their own treatment plant. But this outcome may not yield an optimal siting of a treatment plant, leading to a suboptimal outcome.

3.3 MODEL, THEORY, AND PROCEDURE

This section shows a number of ways cooperative game theory can be used to find how to set a cost allocation and also get an efficient wastewater treatment system.

3.3.1 Theory of *N*-Person Cooperative Game

Faulhaber (1975, p. 966) argues that one reason to let a member join a coalition is that the joint cost is less than the cost of acting independently. If the joined cost is higher than the cost of acting independently, they will choose not to join the group cooperation and act alone. Cooperative game theory can be applied systematically to make cooperative decisions (Lejano and Davos, 1995, p. 1387). Therefore, fairness must exist between the project members. Cooperative game theory operates as an *N*-person game; they have three choices: (1) act independently, (2) joining the grand coalition of all *N* players, or (3) form a coalition with only a subset (*s*) of the *N* players (Lejano and Davos, 1995, p. 1387; Readnour, 1996, p. 52).

If one game is seeking the minimum cost, we call this game a cost game. Heaney (1982, p. 477) wrote:

> *An N-person game (N, c) in characteristic function form consists of a set N = 1, 2, ..., n of players along with the characteristic function c, which assigns the real number c(S) to each nonempty subset S of players. Cost games are sub-additive, i.e.,*
>
> $c(s) + c(T) \geq c(S \cup T)$ *for* $S \cap T = \phi\ S, T \subset N.$
>
> *Where* ϕ *is the empty set, S and T are any two subsets of N.*

We have assumed that the case is looking for an economic optimization, which is to find the least-cost solution in each coalition. If it is correct, the sub-additivity condition will be satisfied automatically. Then, voluntary cooperation will occur (Heaney, 1982, p. 477). If it is not satisfied, it shows some other information. Heaney (1982, p. 478) wrote:

> *If it is not satisfied, then at least one coalition exists for which costs would be lower if the members did not form the coalition. But this is impossible if the least cost solution has been found for each coalition. At worst, no lower costs would result when the coalition formed in which as the coalition is said to be inessential, i.e.,*
>
> $c(s) + c(T) = c(S \cup T)$ *for* $S \cap T = \phi \quad S, T \subset N$

There are three general axioms in a cost game to set the fair solution (Heaney, 1982, p. 478). In the first, the costs assigned to the *i*th group, $x(i)$, must be no more than their costs when they acted independently, i.e.,

$$x(i) \leq c(i) \qquad \forall i \in N.$$

In the second, the total cost $c(N)$ must be apportioned among the n groups, i.e.,

$$\sum_{i \in N} x(i) = c(N)$$

If the above two equations are satisfied, we call these solution "imputations." In the third, the criterion is extended from the first equation. That means that the cost to each member must less or equal to the costs they would receive in any coalition S contained in N, i.e.,

$$\sum_{i \in s} x(i) \leq c(s) \quad \forall s \in N$$

All solutions satisfied these above three equations. It makes the core of the game.

Heaney (1982, p. 478) argues that:

> *For sub-additive games the set of imputations is nonempty, but the core may be empty. A cost game has a convex core if*
>
> $$c(s) + c(T) \geq c(S \cup T) + c(S \cap T) \text{ for } S \cap T = \phi \quad S, T \subset N$$
>
> *In general, the more attractive (lower cost) the game is, the greater the chance that the core is convex. Conversely, the less attractive the game is, the greater the chance that the core is empty.*

If the games have a core, we can find the upper and lower bounds on each $x(i)$ by solving the following linear programs (Heaney, 1983, p. 101).

$$\text{Maximize or minimize } x(i)$$

subject to:

$$x(i) \leq c(\text{i}) \qquad \forall i \in N$$

$$\sum_{i \in s} x(i) \leq c(s) \quad \forall s \in N$$

$$\sum_{i \in N} x(i) = c(N) \tag{25}$$

$$x(i) \geq 0 \qquad \forall i \in N.$$

If the games have no core, we cannot find the upper and lower bounds on each $x(i)$. We need to relax the values of the characteristic functions in the subgroup coalitions until we find a core. The solution can be found by solving the following linear program (Heaney, 1983, p. 103).

$$\text{Minimize } \theta$$

subject to:

$$\begin{aligned} x(i) &\leq c(i) \qquad \forall i \in N \\ \sum_{i \in s} x(i) - \theta c(s) &\leq c(s) \quad \forall s \in N \\ \sum_{i \in N} x(i) &= c(N) \\ x(i) &\geq 0 \qquad \forall i \in N. \end{aligned} \tag{26}$$

The following is the procedure of the minimum-costs, remaining savings (MCRS) method (Heaney, 1983, p. 103).

Step 1: Find the minimum [$x(i)$ min] and maximum [$x(i)$ max] costs that satisfy the core conditions graphically or by solving linear programs, equation 25 (core exists) or equation 26 (no core exists).

Step 2: Prorate the non-separable cost (NSC) using:

$$\beta(i) = \frac{x(i)\max - x(i)\min}{\sum_{i \in N} [x(i)\max - x(i)\min]}$$

and

$$\text{NSC} = c(N) - \sum_{i \in N} x(i)\min. \tag{27}$$

Step 3: Find the fair solution for each group using:

$$x(i) = x(i)\text{min} + \beta(i)\ (\text{NSC}) \tag{28}$$

3.4 DATA AND Empirical Example

Let us use the numbers that are in one of the optimal and efficient region plants in Zhu and ReVelle (1988, p. 141-142). The data in their paper are from Whitlatch (1973). Zhu and ReVelle (1988) wrote that "The data are adapted from Whitlatch (1973) without change except that the identification numbers of sources and plants have been rearranged for convenience in computation" (p. 141). In the Zhu and ReVelle's (1988) article, the identification numbers, which are 3, 4, and 5 are in the same optimal regional treatment plant, as used in this paper. In Table 5, there are three waste sources (the dischargers 3, 4, and 5) and one optimal regional treatment (R), which was found by the siting model (Zhu and ReVelle, 1988). The data is the same as their paper in Table 4 and is only used for one of three optimal regional treatment plants. The reason for using only one of three optimal regional treatment plants is for ease in explaining the cost allocation.

Table 6 presents the cooperative treatment costs and the at-source treatment cost (no cooperation). For example, the at-source treatment cost of discharger 3 is \$2,916,336. And the cooperative treatment cost of discharger 3, and 4 is \$7,477,245. These costs presented in Table 6 will be used for computing the maximum and minimum costs for each coalition structure.

In order to follow the three general axioms (See Section 3.3.1) in a cost game to set the fair solution, the costs assigned to the dischargers 3, 4, and 5 need to have the following:

In the first, the costs assigned to the ith ($i = 3, 4, 5$) group, $X(i)$, must be no more than their costs when they acted independently. It is shown below.

$$X(3) \leq 2{,}916{,}336$$

$$X(4) \leq 3{,}400{,}115$$

$$X(5) \leq 12{,}719{,}512$$

In the second, the total cost, $c(N,)$ must be apportioned among the N groups, i.e.,

$$X(3) + X(4) + X(5) = 18{,}307{,}871$$

In the third, the criterion is extended from the first equation. That means that the cost to each group must less or equal to the costs they would receive in any coalition S contained in N. It is shown below.

$$X(3) + X(4) \leq 7{,}477{,}245$$

$$X(3) + X(5) \leq 16{,}522{,}087$$

$$X(4) + X(5) \leq 15{,}487{,}793$$

The upper bounds on $X(3)$, $X(4)$ and $X(5)$ have been set by the first three equations. The lower bounds on $X(3)$, $X(4)$, and $X(5)$ have been set by the last four equations. For example, in order to find the lower bound of $X(3)$, we can use the equations $X(4) + X(5) \leq 15{,}487{,}793$ and $X(3) + X(4) + X(5) = 18{,}307{,}871$. By subtracting 15,487,793 from 18,307,871, we can find the lower bound of $X(3)$ is 2,820,078. The following are all the lower and upper bounds situations.

$$2{,}820{,}078 \leq X(3) \leq 2{,}916{,}336$$

$$1{,}785{,}784 \leq X(4) \leq 3{,}400{,}115$$

$$10{,}830{,}626 \leq X(5) \leq 12{,}719{,}512$$

$$X(3) + X(4) + X(5) = 18{,}307{,}871$$

These bounds can also be solved by linear programming represented in equation (25)[or (26), if it is not in the core]. Table 7 presents these lower and upper bounds on costs for three-dischargers cost game.

In order to explain the MCRS method, we use the example for discharger 4 for the coalition (4, 5). Because of this cost game with a core, the upper and lower bound for the discharger 4 can be generated by solving the following linear program shown in equation (25).

$$\text{Maximize or minimize } X(4)$$

subject to:

$$X(4) \le 3{,}400{,}115$$

$$X(5) \le 12{,}719{,}512$$

$$X(4) + X(5) = 15{,}487{,}793$$

The result for maximum and minimum (lower and upper bound) treatment costs assigned to discharger 4 can be found in Table 7. These maximum and minimum values are essential to performing the MCRS solution procedure. The following is the procedure of the minimum-costs, remaining savings (MCRS) method (Heaney, 1983, p. 103) to find the cost allocation of discharger 4 and discharger 5.

Step 1: Find the minimum [$x(4)$ min] and maximum [$x(4)$ max] costs that satisfy the core conditions graphically or by solving linear programs, equation (25) (core exists) or equation (26) (if no core exists).

Step 2: Prorate the non-separable cost (NSC) using equation (27):

$$\beta(4) = \frac{3,400,115 - 2,768,281}{(3,400,115 - 2,768,281) + (12,719,512 - 12,087,678)}$$
$$= 0.5$$

and

$$NSC = 15,487,793 - (2,768,281 + 12,087,678)$$
$$= 631834$$

Step 3: Find the fair solution for each group using equation (28):

$x(4) = 2,768,281 + 0.5 * 631,834 = 3,084,198$

This procedure is also used by discharger 5 and the individual members of each coalition. Table 6 is used to compute the maximum and minimum costs for each coalition structure. Table 7 is found by using linear programming presented in equation (25) [or (26), if the cost game is without a core]. These bounds (maximum and minimum cost) in table 7 are used to calculate the MCRS solution for each coalition structure. Table 8 shows the total treatment cost for each coalition structure, and the cost allocation in each discharger. Table 9 represents the cost saving in various coalition sizes.

3.5 Results and Discussion:

The results in these coalitions, (4, 5) and (3, 4, 5), are consistent with the three general axioms (See Section 3.3.1) in a cost game to set the fair solution (Heaney, 1982, p. 478): (1) the treatment cost assigned to each discharger is not more than their treatment costs when they acted independently, (2) the total treatment cost is apportioned among the discharges, (3) the treatment cost assigned to each member (dischargers) is less or equal to the treatment cost that they would receive in the coalition, *S,* contained in grand coalition, *N.* These two coalitions are feasible coalitions and fall within the core of the cost game. Table 8 shows that no participant pays more than its cost of acting independently.

Cost savings shown in Table 9 are significant when we compare with the cost of acting independently. Because of both individual saving and coalition structure saving shown in Table 8 and 9, it presents the chain model which has an economies of scale situation. Unfortunately, the results show that the saving increases at a decreasing rate as the coalition size grows, which is of a concave shape. Table 9 shows that the cost saving is 3.3 percent as the coalition size is two and the cost saving is only 4 percent as the coalition size is three, when we compare them with the total treatment cost of each dischargers acting independently.

One disadvantage of the chain model is that it ignores the transaction cost. Heaney (1983, p. 103) argues that "As the size of the groups grow, transactions costs would be expected to increase at the margin due to multiple political jurisdictions, growing administrative costs, shifting environmental impacts, etc." He uses Figure 7, the savings-transactions costs for a hypothetical regional problem, as an example to explain the general benefit-cost relationship. Figure 7 shows that the hypothetical saving and transaction cost curve are the function of the size of the largest coalition. The saving increases at a decreasing rate as the coalition size grows, which is of a concave curve. On the other hand, the transaction cost increases at an increasing rate as the coalition size grows. Figure 7 also shows that the optimal size of the largest coalition is three or four. Therefore, if the chain model finds an optimal regional treatment plant, which includes many dischargers, we might consider finding an alternative potential treatment plant, which includes less dischargers. That is because of the relationship between saving and transaction cost.

When the chain model is applied in a big group of dischargers and the model finds the optimal regional plant, which includes many dischargers, the chain model needs to be considered to change to an alternative model (nearly optimal model by HSJ method). There are two main reasons. One is the transaction cost, which is getting higher. The other one is that the information for cost sharing is hard to get. If the dischargers do not pay the fair cost, that may build their own treatment plant. Then, that is a big loss in efficiency.

CHAPTER FOUR

CONCLUSION, DISCUSSION, AND FUTURE STUDY

When we use linear programming to find the least cost of the given level of water quality, which is given by authority, we may find that we still need some other objective(s), for example, the tax revenue. By the multi-objective programming model, we find that, in general, there is a trade off relationship between the tax revenue and water quality. The dissertation finds the efficient set of solutions between these two objectives. When we think about some other non-economics problem (e.g. recreation purpose), the multi-objective programming model is hard to design. Therefore, the nearly optimal solution model (HSJ method) has been suggested to find the alternative and find the good solutions. On the other hand, if the income transfer can be done well, this efficient solution is very useful. For example, the water quality management may have the economies of scale function. The efficient tax revenue can fund the building of a bigger regional treatment plant.

The result in the first essay shows the trade-off relationship between tax revenue and water quality. It also offers the efficient value of these two objectives. That means it offers the weight (trade-off relationship) and the target value (efficient value) for goal programming. Therefore, in the future study, the weight and the target value can be used in goal programming to find the potential for a wide range of applications for tax policy evaluation and selection.

In water quality control cases, analysts are looking for the most efficient technique. The efficient solution usually involves economies of scale, for example, the siting location of the optimal regional wastewater treatment plant. The chain model finds the numbers and the location of the regional facilities at the least total cost (transfer cost and treatment cost). Unfortunately, the chain model ignores the cost allocation problem. In addition, if the dischargers do not pay the fair cost, they may decide to build their own treatment plants. Then, a big loss in efficiency will take place. The chain model also ignores the transaction cost, which increases at an "increasing rate" as the coalition size grows.

Therefore, the dissertation finds a solution, which applies the cooperative game (the equity) to the chain model (the efficiency). In a future study, if there is a big group of dischargers in the same optimal regional treatment plant, the chain model (the optimal and the most efficient technique) may be changed to a "good" model (nearly optimal model by HSJ method), which has less dischargers than the optimal model (solved in chain model) has, because the transaction cost is getting higher and the information is hard to get.

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APPENDIX A

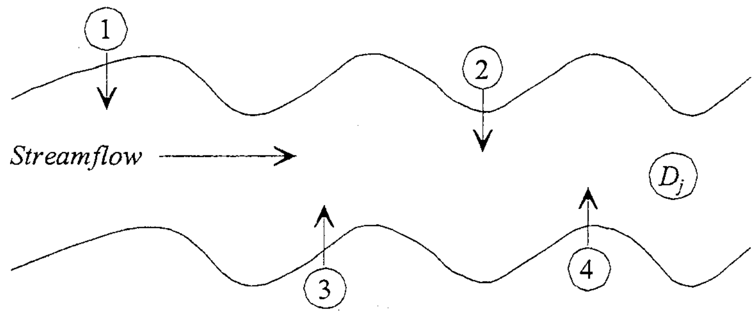


Figure 1. Effect of Location on Local Pollution Concentration

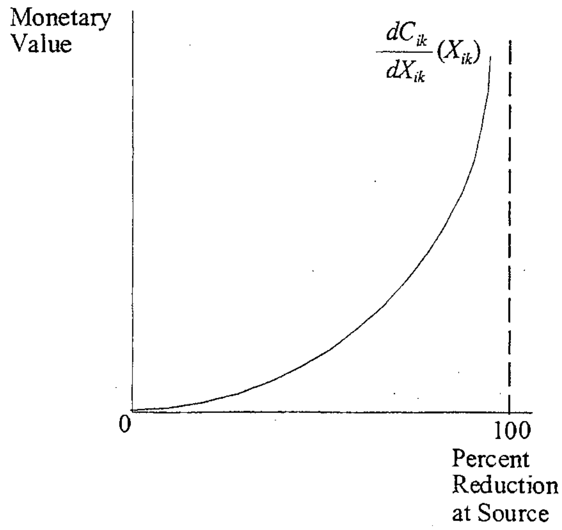
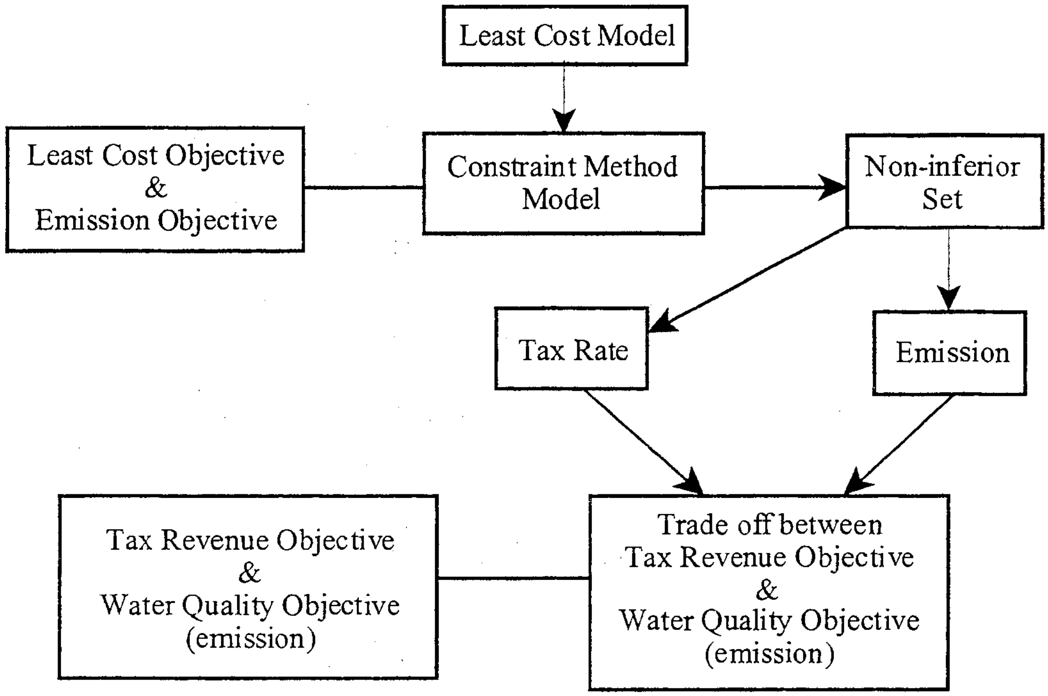


Figure 2. Pollution Control Cost Function for Source *ik*

Figure 3. Procedure for Finding the Trade-off Relationship Between Water Quality and Tax Revenue.



· **Figure 4. Trade-off between Treatment Cost and Total Emission**

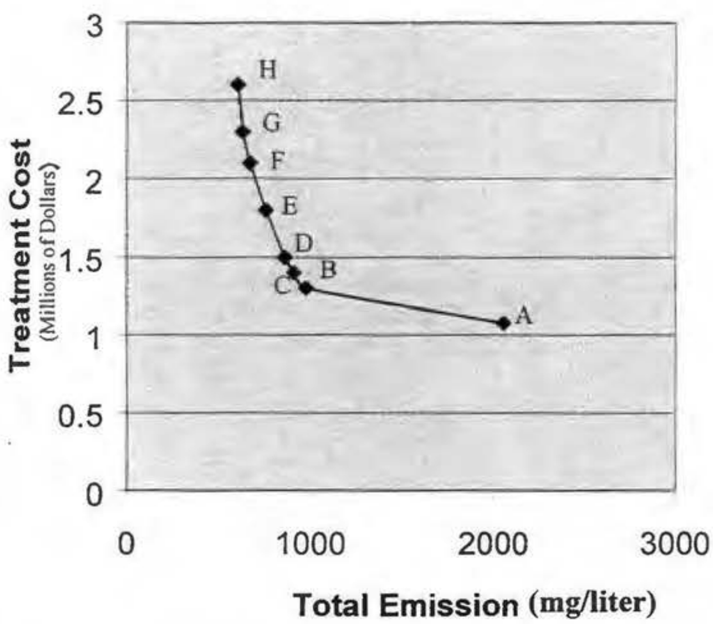


Figure 5. Transformation Curve between Tax Revenue and Water quality (emission)

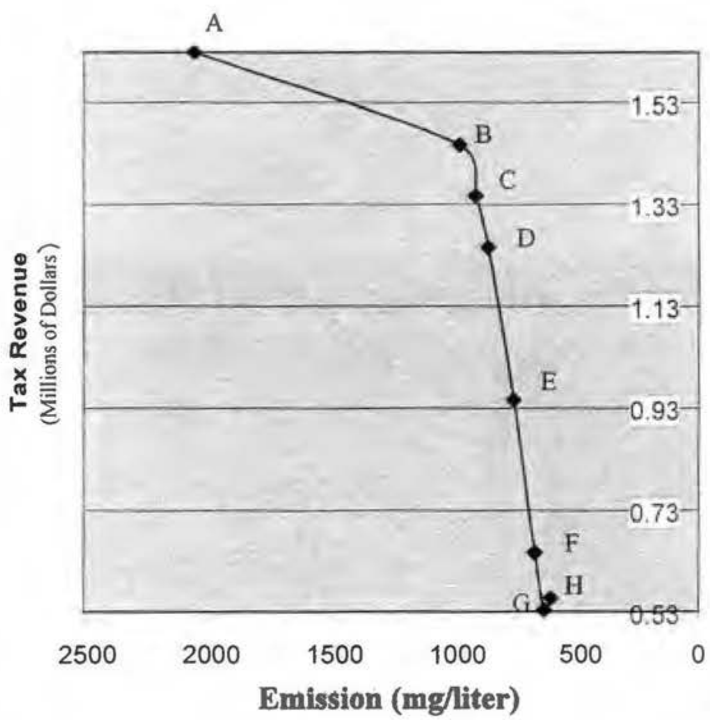


Figure 6. Multi-objective Analysis by Graph

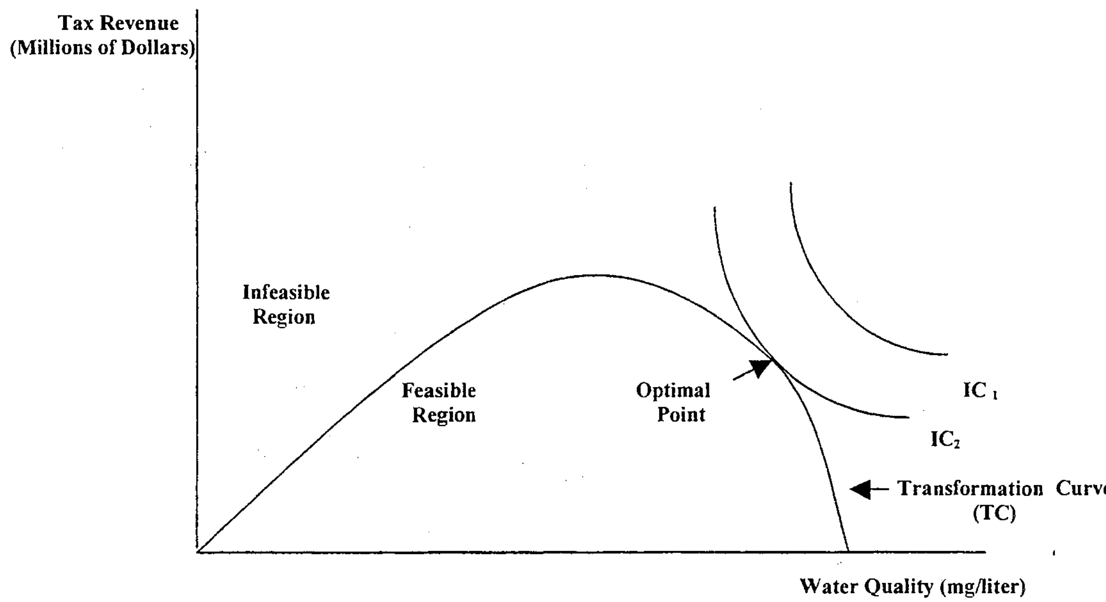
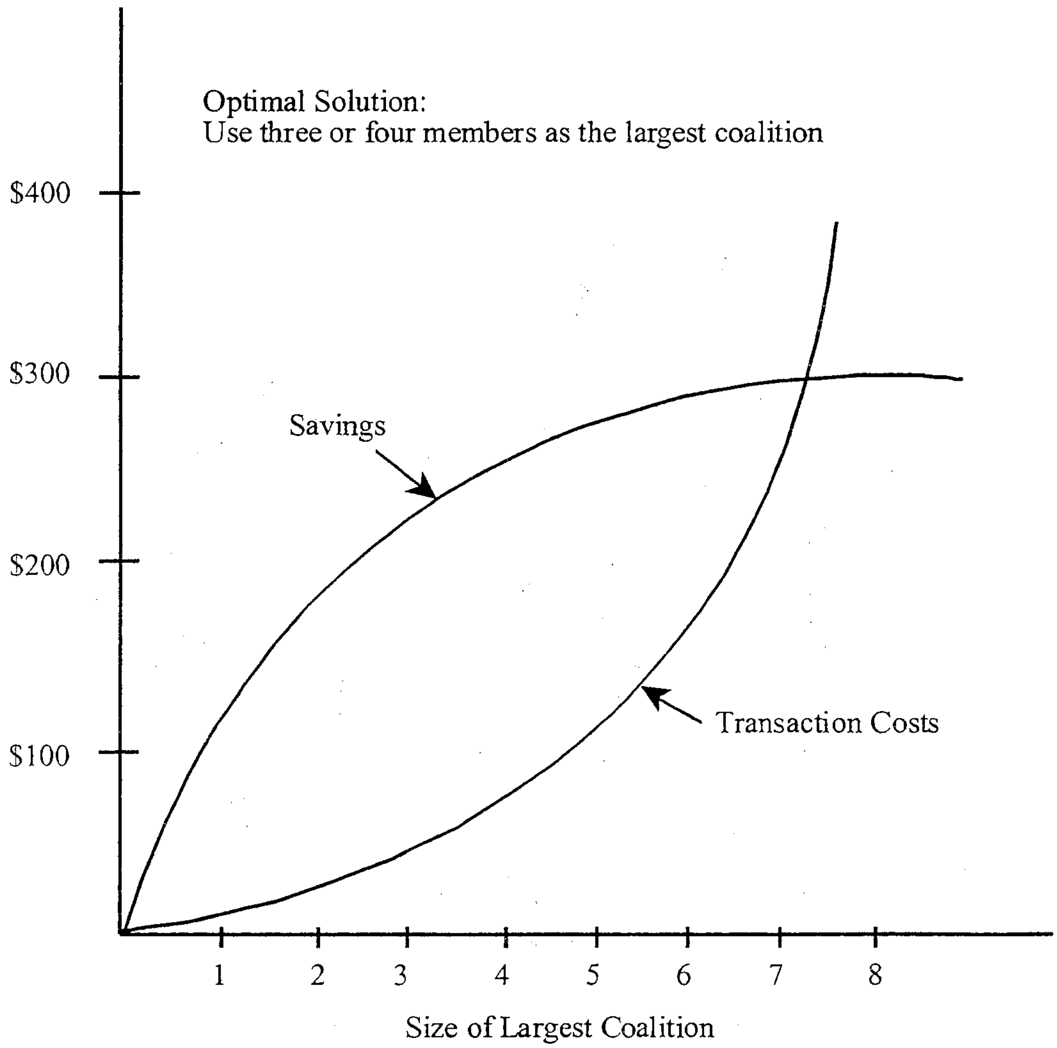


Figure 7. Saving-Transactions Costs for Hypothetical Regional Problem



(Heaney, 1983)

APPENDIX B

Table 1

Total Emission and Tax Revenue Corresponding to Points on the Transformation Curve

	Points on the Transformation Curve							
	A	B	C	D	E	F	G	H
Total Emission	2054	975	908	859	755	668	630	602
Tax Revenue	1.63	1.45	1.35	1.25	0.95	0.65	0.53	0.56
Variable Treatment Cost	1.076	1.3	1.4	1.5	1.8	2.1	2.3	2.6
Total Treatment Cost	2.968	3.192	3.292	3.392	3.692	3.992	4.192	4.492

Tax revenue and Treatment Cost is Millions of Dollars
Fix Treatment Cost = 1.892
Emission is mg/liter

Table 2

Tax Revenue and Tax Rate Corresponding to Points on the Transformation Curve

	Discharger	Points on the Transformation Curve							
		A	B	C	D	E	F	G	H
Tax Rate	2	0.001496	0.001496	0.001496	0.001496	0.001496	0.001496	0.001496	0.001496
	3	0.000126	0.000126	0.000126	0.000126	0.000126	0.000126	0.004237	0.004237
	4	0.003727	0.003727	0.003727	0.003727	0.003727	0.003727	0.003727	0.003727
	5	0.000656	0.000656	0.000656	0.000656	0.000656	0.000656	0.000656	0.014046
	6	0.000475	0.000475	0.000475	0.000475	0.000475	0.000475	0.000475	0.000475
	7	0.006631	0.006631	0.006631	0.006631	0.006631	0.006631	0.006631	0.006631
	8	0.000863	0.000863	0.000863	0.000863	0.000863	0.000863	0.000863	0.000863
	9	3.02E-05	0.000118	0.000118	0.000118	0.000118	0.000118	0.000118	0.000118
	10	4.08E-06	2.75E-05	2.75E-05	2.75E-05	2.75E-05	2.75E-05	2.75E-05	2.75E-05
	11	0.002889	0.002889	0.002889	0.002889	0.002889	0.002889	0.002889	0.002889
Tax Revenue		1.63	1.44659	1.34659	1.24659	0.94659	0.646588	0.533911	0.557692

Tax Rate and Revenue in Millions of Dollars

Table 3

Emission Corresponding to Points on the Transformation Curve

	Discharger	Points on the Transformation Curve							
		A	B	C	D	E	F	G	H
Emission	2	184.6	139.3	72.5	42.6	42.60	42.60	42.6	42.6
	3	46.29	21.24	21.24	21.2	21.24	21.24	11.8	11.8
	4	78.65	78.65	78.65	78.7	78.65	21.77	12.1	12.1
	5	60.45	24.18	24.18	24.2	24.18	24.18	24.18	9.34
	6	156	24	24	24.0	24.00	24.00	24	24
	7	42.25	42.25	42.25	42.3	42.25	42.25	23.56	9.75
	8	143.86	102	102	102.0	102.00	102.00	102	102
	9	360	144	144	144.0	144.00	144.00	144	144
	10	800.29	218	218	218.0	218.00	218.00	218	218
	11	181.35	181.35	181.35	162.2	58.36	27.90	27.9	27.9
Variable Treatment Cost		1.076	1.3	1.4	1.5	1.8	2.1	2.3	2.6
Total Emission		2054	975	908	859	755	668	630	602

Table 4

**Alternative Solutions for the Optimal Point B
In the Non-inferior Set – by HSJ Approach**

	Discharger	Optimal Point B	HSJ1	HSJ2	HSJ3
Emission	2	139	73	185	110
	3	21	21	21	21
	4	79	79	79	79
	5	24	24	39	60
	6	24	24	24	66
	7	42	42	31	42
	8	102	217	102	102
	9	144	144	144	144
	10	218	218	218	218
	11	181	181	181	181
Total Emission		975	1024	1024	1024
Tax Revenue		1.45	1.45	1.45	1.45

Since the Discharge 1 has pre-treated the waste for 67%, it is assumed a fixed variable. Therefore, it is not included in this table (Liebman and Lynn 1966, p. 587).

Table 5

The Optimal Treatment Plant Location and Data

ID #	Flow (mgd)	Distance
3	3	
		15
4	4	
		5
5	29.4	
		2
R	0	

The data is the same as Table 4 in Zhu and ReVelle (1988) and is modified. Since "14R", which is a potential treatment plant in their paper, is not an optimal treatment plant by their sitting model result, "14R" is erased in the paper. Where R, which is "15R" in their paper, is the optimal regional treatment plant.

Table 6

Cost of the Various Coalition Sizes

Number of Coalition	Discharger 3	Discharger 4	Discharger 5	Cost Dollars
I	x			2916336
I		x		3400115
I			x	12719512
II	x	x		7477245
II	x		x	16522087
II		x	x	15487793
III	x	x	x	18307871

Table 7

Lower and Upper Bounds on Costs for Three Discharger Cost Game

Coalition	Discharger Bounds: L = Lower, U = Upper ($)		
	Discharger 3	Discharger 4	Discharger 5
	L-U	L-U	L-U
(3), (4, 5)	None	2768281 – 3400115	12087678 – 12719512
(3, 4), (5)	*----	*----	None
(4), (3, 5)	*----	None	*----
(3, 4, 5)	2820078 – 2916336	1785784 – 3400115	10830626 – 12719512

*The coalitions in (3, 4), 5, and (4), (3, 5) are inessential, because they have less cost if they work individually.

Table 8

Cost Allocation for Optimal Solution and Intermediate Solution

Coalition Structure for Least-Cost Solution	Total Treatment Cost	MCRS Cost Allocation($)		
		Discharger 3	Discharger 4	Discharger 5
(3), (4), (5)	19035963	2916336	3400115	12719512
(3), (4, 5)	18404129	2916336	3084198	12403595
(3, 4, 5)	18307871	2871191	3058641	12378038

Table 9

Cost Saving in Various Coalition Sizes

Size of Largest Coalition	Optimal Coalitions	Total Treatment Cost	Percent Saving
1	(3), (4), (5)	19035963	0.000
2	(3), (4, 5)	18404129	0.033
3	(3, 4, 5)	18307871	0.040

APPENDIX C

GAMS Program
Least Cost Model

```
option limcol=0,limrow=0;
*The least cost model, see Revelle, Loucks, and Lynn (1968)
*The allowable deficit,Da,depends on both the DO standard and on C(S),
* where C(S) is Sat Do in top of reach. That is Da = C(S) - DO Standard.
SCALARS
 Da1   /1.20/
 Da2   /1.31/
 Da3   /1.00/
 Da4   /1.12/
 Da5   /1.00/
 Da6   /1.20/
 Da7   /1.00/
 Da8   /2.54/
 Da9   /2.35/
 Da10  /2.24/
 Da11  /4.17/;
Parameters
* whereQ_1 is the total flow rate in the 1st reach
Q_1      /1360/
Q_2      /2681/
Q_3      /2717/
Q_4      /2730/
Q_5      /2776 /
Q_6      /3430/
Q_7      /3606/
Q_8      /3643/
Q_9      /3841/
Q_10     /3938/
Q_11     /4495/
*where Q_Q1 is the total flow rate minus the flow rate being withdraw by
*community i
Q_Q1       /1355.17 /
Q_Q2       /2649.7/
Q_Q3       /2712.84/
Q_Q4       /2717.1/
Q_Q5       /2762 /
Q_Q6       / 3421.6 /
Q_Q7       / 3591.8 /
Q_Q8       /3606.2/
Q_Q9       / 3837 /
Q_Q10      /3937.67/
Q_Q11      /4454.3/
T1      /9.15/
```

```
T2      /8.95/
T3      /8.64/
T4      /8.66/
T5      /8.54/
T6      /8.74/
T7      /8.54/
T8      /8.54/
T9      /8.35/
T10     /8.24/
T11     /8.17/;

VARIABLES Z;
POSITIVE VARIABLES
X1, X2, X31, X32, X3, X4, X51, X52, X5, X6, X7, X8, X91, X92, X9, X101,
 X102, X10, X11,
M1, M2, M3, M4, M5, M6, M7, M8, M9, M10, M11, L1, L2, L3, L4, L5, L6, L7,
L8, L9, L10, L11,
D1, D2, D3, D4, D5, D6, D7, D8, D9, D10, D11,
E1, E2, E3, E4, E5, E6, E7, E8, E9, E10, E11,
F1, F2, F3, F4, F5, F6, F7, F8, F9, F10, F11;

EQUATIONS

OBJ,
EFFICIEN1, EFFICIEN2, EFFICIEN3, EFFICIEN4, EFFICIEN5,
EFFICIEN6, EFFICIEN7, EFFICIEN8, EFFICIEN9, EFFICIEN10, EFFICIEN11,
InvenBOD1, InvenBOD2, InvenBOD3, InvenBOD4, InvenBOD5,
InvenBOD6, InvenBOD7, InvenBOD8,
InvenBOD9, InvenBOD10, InvenBOD11,
InvenDef1, InvenDef2, InvenDef3, InvenDef4, InvenDef5, InvenDef6,
InvenDef7, InvenDef8, InvenDef9, InvenDef10, InvenDef11,
DefineE1, DefineE2, DefineE3, DefineE4, DefineE5, DefineE6,
DefineE7, DefineE8, DefineE9, DefineE10,
DefineF1, DefineF2, DefineF3, DefineF4, DefineF5, DefineF6,
DefineF7, DefineF8, DefineF9, DefineF10,
QualCons1, QualCons2, QualCons3, QualCons4, QualCons5, QualCons6,
QualCons7, QualCons8, QualCons9, QualCons10, QualCons11,
Quality1, Quality2, Quality3, Quality4, Quality5, Quality6, Quality7,
Quality8, Quality9, Quality10, Quality11,
EffCons1, EffCons2, EffCons31, EffCons32, EffCons4, EffCons51,
EffCons52, EffCons6, EffCons7, EffCons8, EffCons91, EffCons92,
EffCons101, EffCons102, EffCons11,
EffCont2, EffCont31, EffCont32,
EffCont4, EffCont51, EffCont52, EffCont6,
EffCont7, EffCont8, EffCont91, EffCont92,
EffCont101, EffCont102 , EffCont11,
```

```
CostCont3, CostCont5, CostCont9, CostCont10;
* Since the firm has cleaned 67%,reach 1 has no treatment cost (fixed  variable).
*Tax = marginal cost, e.g.T2 = 0.425

OBJ.. Z =E=
     0*X1 + .425*X2 + .0149*X31 +.5*X32 +.451*X4 +.061*X51 +
     1.3063*X52 +.114*X6 + .431*X7 +.352*X8 + .0435*X91 +.17*X92
     +.0089*X101+.06*X102 +.806*X11;

EFFICIEN1.. X1 + (1/248)*M1 =E= 1;
EFFICIEN2.. X2 + (1/284)*M2 =E= 1;
EFFICIEN3.. X3 + (1/118)*M3 =E= 1;
EFFICIEN4.. X4 + (1/121)*M4 =E= 1;
EFFICIEN5.. X5 + (1/93)*M5 =E= 1;
EFFICIEN6.. X6 + (1/240)*M6 =E= 1;
EFFICIEN7.. X7 + (1/65)*M7 =E= 1;
EFFICIEN8.. X8 + (1/408)*M8 =E= 1;
EFFICIEN9.. X9 + (1/1440)*M9 =E= 1;
EFFICIEN10.. X10 + (1/2180)*M10 =E= 1;
EFFICIEN11.. X11 + (1/279)*M11 =E= 1;

InvenBOD1.. Q_Q1*0 + 4.83*M1 - Q_1*L1 =E= 0;
InvenBOD2.. Q_Q2*F1 + 31.3*M2 - Q_2*L2 =E= 0;
InvenBOD3.. Q_Q3*F2 + 4.16*M3 - Q_3*L3 =E= 0;
InvenBOD4.. Q_Q4*F3 + 12.9*M4 - Q_4*L4 =E= 0;
InvenBOD5.. Q_Q5*F4 + 14.0*M5 - Q_5*L5 =E= 0;
InvenBOD6.. Q_Q6*F5 + 8.4*M6 - Q_6*L6 =E= 0;
InvenBOD7.. Q_Q7*F6 + 14.2*M7 - Q_7*L7 =E= 0;
InvenBOD8.. Q_Q8*F7 + 36.8*M8 - Q_8*L8 =E= 0;
InvenBOD9.. Q_Q9*F8 + 4.0*M9 - Q_9*L9 =E= 0;
InvenBOD10.. Q_Q10*F9 + 0.33*M10 - Q_10*L10 =E= 0;
InvenBOD11.. Q_Q11*F10 + 40.7*M11- Q_11*L11 =E= 0;

InvenDef1.. -1*Q_Q1*0 + Q_1*D1=E=T1*4.83;
InvenDef2.. -1*Q_Q2*E1 + Q_2*D2=E=T2*31.3;
InvenDef3.. -1*Q_Q3*E2 + Q_3*D3=E=T3*4.16;
InvenDef4.. -1*Q_Q4*E3 + Q_4*D4=E=T4*12.9;
InvenDef5.. -1*Q_Q5*E4 + Q_5*D5=E=T5*14.0;
InvenDef6.. -1*Q_Q6*E5 + Q_6*D6=E=T6*8.4;
InvenDef7.. -1*Q_Q7*E6 + Q_7*D7=E=T7*14.2;
InvenDef8.. -1*Q_Q8*E7 + Q_8*D8=E=T8*36.8;
InvenDef9.. -1*Q_Q9*E8 + Q_9*D9=E=T9*4.0;
InvenDef10.. -1*Q_Q10*E9 + Q_10*D10=E=T10*0.33;
InvenDef11.. -1*Q_Q11*E10 + Q_11*D11=E=T11*40.4;

DefineE1.. E1 - 0.063*L1 - 0.787*D1 =E= 0;
```

```
DefineE2.. E2 - 0.204*L2 - 0.478*D2 =E= 0;
DefineE3.. E3 - 0.034*L3 - 0.927*D3 =E= 0;
DefineE4.. E4 - 0.089*L4 - 0.802*D4 =E= 0;
DefineE5.. E5 - 0.012*L5 - 0.978*D5 =E= 0;
DefineE6.. E6 - 0.228*L6 - 0.504*D6 =E= 0;
DefineE7.. E7 - 0.031*L7 - 0.953*D7 =E= 0;
DefineE8.. E8 - 0.277*L8 - 0.450*D8 =E= 0;
DefineE9.. E9 - 0.466*L9 - 0.830*D9 =E= 0;
DefineE10.. E10 - 0.286*L10 - 0.863*D10 =E= 0;

DefineF1.. F1 - 0.929*L1 =E= 0;
DefineF2.. F2 - 0.706*L2 =E= 0;
DefineF3.. F3 - 0.965*L3 =E= 0;
DefineF4.. F4 - 0.901*L4 =E= 0;
DefineF5.. F5 - 0.988*L5 =E= 0;
DefineF6.. F6 - 0.678*L6 =E= 0;
DefineF7.. F7 - 0.968*L7 =E= 0;
DefineF8.. F8 - 0.584*L8 =E= 0;
DefineF9.. F9 - 0.483*L9 =E= 0;
DefineF10.. F10 - 0.691*L10 =E= 0;

QualCons1.. 0.063*L1 + 0.787*D1 =L= Da1;
QualCons2.. 0.204*L2 + 0.478*D2 =L= Da2;
QualCons3.. 0.034*L3 + 0.927*D3 =L= Da3;
QualCons4.. 0.089*L4 + 0.802*D4 =L= Da4;
QualCons5.. 0.012*L5 + 0.978*D5 =L= Da5;
QualCons6.. 0.228*L6 + 0.504*D6 =L= Da6;
QualCons7.. 0.031*L7 + 0.953*D7 =L= Da7;
QualCons8.. 0.277*L8 + 0.450*D8 =L= Da8;
QualCons9.. 0.466*L9 + 0.830*D9 =L= Da9;
QualCons10.. 0.286*L10 + 0.863*D10 =L= Da10;
QualCons11.. 0.795*L11 + 0.912*D11 =L= Da11;

Quality1.. D1 =L= Da1;
Quality2.. D2 =L= Da2;
Quality3.. D3 =L= Da3;
Quality4.. D4 =L= Da4;
Quality5.. D5 =L= Da5;
Quality6.. D6 =L= Da6;
Quality7.. D7 =L= Da7;
Quality8.. D8 =L= Da8;
Quality9.. D9 =L= Da9;
Quality10.. D10 =L= Da10;
Quality11.. D11 =L= Da11;

*REACH 1 EXISTED 0.67 ALREADY
```

```
EffCons1.. X1 =E= 0.67;
EffCons2.. X2 =G= 0.35;
EffCons31.. X31 =G= 0.35;
EffCons32.. X32 =G= 0;
EffCons4.. X4 =G= 0.35;
EffCons51.. X51 =G= 0.35;
EffCons52.. X52 =G= 0;
EffCons6.. X6 =G= 0.35;
EffCons7.. X7 =G= 0.35;
EffCons8.. X8 =G= 0.35;
EffCons91.. X91 =G= 0.35;
EffCons92.. X92 =G= 0;
EffCons101.. X101 =G= 0.35;
EffCons102.. X102 =G= 0;
EffCons11.. X11 =G= 0.35;


EffCont2.. X2 =L= 0.85;
EffCont31.. X31 =L=0.82;
EffCont32.. X32 =L= 0.08;
EffCont4.. X4 =L= 0.9;
EffCont51.. X51 =L= 0.74;
EffCont52.. X52 =L= 0.16;
EffCont6.. X6 =L= 0.9;
EffCont7.. X7 =L= 0.85;
EffCont8.. X8 =L= 0.75;
EffCont91.. X91 =L= 0.75;
EffCont92.. X92 =L= 0.15;
EffCont101.. X101 =L= 0.85;
EffCont102.. X102 =L= 0.05;
EffCont11.. X11 =L= 0.9;

CostCont3.. X3 - X32 - X31 =E= 0;
CostCont5.. X5 - X52 - X51 =E= 0;
CostCont9.. X9 - X92 - X91 =E= 0;
CostCont10.. X10 - X102 - X101 =E= 0;

MODEL COST /ALL/;
SOLVE COST USING LP MINIMIZING Z;


     S O L V E     S U M M A R Y

   MODEL   COST              OBJECTIVE  Z
   TYPE    LP              DIRECTION  MINIMIZE
   SOLVER  BDMLP               FROM LINE  218
```

```
**** SOLVER STATUS     1 NORMAL COMPLETION
**** MODEL STATUS      1 OPTIMAL
**** OBJECTIVE VALUE            1.0759

 RESOURCE USAGE, LIMIT         0.211     1000.000
 ITERATION COUNT, LIMIT       45         10000

 BDMLP 1.1     Mar  1, 2000 WIN.BD.BD 19.1 054.038.038.WAT

 (A. Brooke, A. Drud, and A. Meeraus,
 Analytic Support Unit,
 Development Research Department,
 World Bank,
 Washington, D.C. 20433, U.S.A.

 Work space allocated          --   0.07 Mb

 EXIT -- OPTIMAL SOLUTION FOUND.
```

GAMS Program
Constraint Method of Multi-objective Programming

```
$offupper offsymxref offsymlist offuellist offuelxref
option limcol=0,limrow=0;
*See (Cohon and Marks, 1973, p. 833) for the methdology, Constrain Method.
*Max one of the two objectives, and the other objective becomes the constrin.
*Then, increase the right hand side value of the constrain.
*The allowable deficit,Da,depends on both the DO standard and on C(S),
* where C(S) is Sat Do in top of reach. That is Da = C(S) - DO Standard.
*2 objectives: Min emission(Q), and Min treatment cost(C)
*The tax revenue can be got after the multiobjective model has been solved.

scalars CS /1.076/

 Da1     /1.20/
 Da2     /1.31/
 Da3     /1.00/
 Da4     /1.12/
 Da5     /1.00/
 Da6     /1.20/
 Da7     /1.00/
 Da8     /2.54/
 Da9     /2.35/
 Da10     /2.24/
 Da11     /4.17/
* Reach 1 has not cost(fixed and variable).Since the firm has already clean 67%.

Parameters
* whereQ_1 is the total flow rate in the 1st reach
Q_1     /1360/
Q_2     /2681/
Q_3     /2717/
Q_4     /2730/
Q_5     /2776 /
Q_6     /3430/
Q_7     /3606/
Q_8     /3643/
Q_9    /3841/
Q_10     /3938/
Q_11     /4495/
*where Q_Q1 is the total flow rate minus the flow rate being withdrawn by
*community i
Q_Q1      /1355.17 /
Q_Q2      /2649.7/
Q_Q3      /2712.84/
```

```
Q_Q4        /2717.1/
Q_Q5        /2762 /
Q_Q6        / 3421.6 /
Q_Q7        / 3591.8 /
Q_Q8        /3606.2/
Q_Q9        / 3837 /
Q_Q10        /3937.67/
Q_Q11        /4454.3/
*Pi is the BOD concentration in the waste flow entering the ith treatment
*plant, mg/liter
P1     /   248     /
P2     /   284     /
P3     /   118     /
P4     /   121     /
P5     /    93     /
P6     /   240     /
P7     /    65     /
P8     /   408     /
P9     /  1440     /
P10     /  2180     /
P11     /   279     /

T1     /9.15/
T2     /8.95/
T3     /8.64/
T4     /8.66/
T5     /8.54/
T6     /8.74/
T7     /8.54/
T8     /8.54/
T9     /8.35/
T10     /8.24/
T11     /8.17/

*MCi is the margial cost(efficiency)of each reach i. It can be two stages cost.
MC2          /0.425/
MC31          /0.0149/
MC32          /0.5/
MC4          /0.451/
MC51          /0.061/
MC52          /1.3063/
MC6          /0.114/
MC7          /0.431/
MC8          /0.352/
MC91          /0.0435/
MC92          /0.17/
```

```
MC101          /0.0089/
MC102          /0.06/
MC11           /0.806/;
VARIABLES  M;
POSITIVE VARIABLES
X1, X2, X31, X32, X3, X4, X51, X52, X5, X6, X7, X8, X91, X92, X9,
X101, X102, X10, X11,
M1, M2, M3, M4, M5, M6, M7, M8, M9, M10, M11,
*Mi1, Mi2 is the amount of emission for margial cost(=margial tax)
M31, M32, M51,M52, M91, M92, M101, M102,
L1, L2, L3, L4, L5, L6, L7, L8, L9, L10, L11,
D1, D2, D3, D4, D5, D6, D7, D8, D9, D10, D11,
E1, E2, E3, E4, E5, E6, E7, E8, E9, E10,E11,
F1, F2, F3, F4, F5, F6, F7, F8, F9, F10,F11,
C;
EQUATIONS
OBJ,
EFFICIEN1, EFFICIEN2, EFFICIEN3, EFFICIEN4, EFFICIEN5,
EFFICIEN6, EFFICIEN7, EFFICIEN8, EFFICIEN9, EFFICIEN10,EFFICIEN11,
InvenBOD1, InvenBOD2, InvenBOD3, InvenBOD4, InvenBOD5,
InvenBOD6, InvenBOD7, InvenBOD8,
InvenBOD9, InvenBOD10,InvenBOD11,
InvenDef1, InvenDef2, InvenDef3,InvenDef4, InvenDef5, InvenDef6,
InvenDef7, InvenDef8, InvenDef9,InvenDef10, InvenDef11,
DefineE1, DefineE2, DefineE3, DefineE4, DefineE5, DefineE6,
DefineE7, DefineE8, DefineE9, DefineE10, DefineE11,
DefineF1, DefineF2, DefineF3, DefineF4, DefineF5, DefineF6,
DefineF7, DefineF8, DefineF9, DefineF10, DefineF11,
QualCons1, QualCons2, QualCons3,QualCons4, QualCons5, QualCons6,
QualCons7, QualCons8, QualCons9,QualCons10, QualCons11,
Quality1, Quality2, Quality3, Quality4, Quality5, Quality6, Quality7,
Quality8, Quality9, Quality10, Quality11,
EffCons1, EffCons2, EffCons31, EffCons32, EffCons4, EffCons51,
EffCons52, EffCons6, EffCons7, EffCons8, EffCons91, EffCons92,
EffCons101,EffCons102, EffCons11,
EffCont2,EffCont31,EffCont32,
EffCont4,EffCont51,EffCont52,EffCont6,
EffCont7,EffCont8,EffCont91,EffCont92,
EffCont101,EffCont102 ,EffCont11,
CostCont3, CostCont5, CostCont9, CostCont10,
VarCost,
Emission;

* M is total emission.
Obj..  M =e= M2 + M3 + M4 + M5 + M6 + M7 + M8 + M9 + M10 + M11;
EFFICIEN1.. X1 + (1/P1 )*M1 =E= 1;
```

```
EFFICIEN2.. X2 + (1/P2 )*M2 =E= 1;
EFFICIEN3.. X3 + (1/P3 )*M3 =E= 1;
EFFICIEN4.. X4 + (1/P4 )*M4 =E= 1;
EFFICIEN5.. X5 + (1/P5 )*M5 =E= 1;
EFFICIEN6.. X6 + (1/P6 )*M6 =E= 1;
EFFICIEN7.. X7 + (1/P7 )*M7 =E= 1;
EFFICIEN8.. X8 + (1/P8 )*M8 =E= 1;
EFFICIEN9.. X9 + (1/P9 )*M9 =E= 1;
EFFICIEN10.. X10 + (1/P10 )*M10 =E= 1;
EFFICIEN11.. X11 + (1/P11 )*M11 =E= 1;

InvenBOD1.. Q_Q1*0 + 4.83*M1 - Q_1*L1 =E= 0;
InvenBOD2.. Q_Q2*F1 + 31.3*M2 - Q_2*L2 =E= 0;
InvenBOD3.. Q_Q3*F2 + 4.16*M3 - Q_3*L3 =E= 0;
InvenBOD4.. Q_Q4*F3 + 12.9*M4 - Q_4*L4 =E= 0;
InvenBOD5.. Q_Q5*F4 + 14.0*M5 - Q_5*L5 =E= 0;
InvenBOD6.. Q_Q6*F5 + 8.4*M6 - Q_6*L6 =E= 0;
InvenBOD7.. Q_Q7*F6 + 14.2*M7 - Q_7*L7 =E= 0;
InvenBOD8.. Q_Q8*F7 + 36.8*M8 - Q_8*L8 =E= 0;
InvenBOD9.. Q_Q9*F8 + 4.0*M9 - Q_9*L9 =E= 0;
InvenBOD10.. Q_Q10*F9 + 0.33*M10 - Q_10*L10 =E= 0;
InvenBOD11.. Q_Q11*F10 + 40.7*M11- Q_11*L11 =E= 0;

InvenDef1.. -1*Q_Q1*0 + Q_1*D1=E=T1*4.83;
InvenDef2.. -1*Q_Q2*E1 + Q_2*D2=E=T2*31.3;
InvenDef3.. -1*Q_Q3*E2 + Q_3*D3=E=T3*4.16;
InvenDef4.. -1*Q_Q4*E3 + Q_4*D4=E=T4*12.9;
InvenDef5.. -1*Q_Q5*E4 + Q_5*D5=E=T5*14.0;
InvenDef6.. -1*Q_Q6*E5 + Q_6*D6=E=T6*8.4;
InvenDef7.. -1*Q_Q7*E6 + Q_7*D7=E=T7*14.2;
InvenDef8.. -1*Q_Q8*E7 + Q_8*D8=E=T8*36.8;
InvenDef9.. -1*Q_Q9*E8 + Q_9*D9=E=T9*4.0;
InvenDef10.. -1*Q_Q10*E9 + Q_10*D10=E=T10*0.33;
InvenDef11.. -1*Q_Q11*E10 + Q_11*D11=E=T11*40.4;

DefineE1.. E1 - 0.063*L1 - 0.787*D1 =E= 0;
DefineE2.. E2 - 0.204*L2 - 0.478*D2 =E= 0;
DefineE3.. E3 - 0.034*L3 - 0.927*D3 =E= 0;
DefineE4.. E4 - 0.089*L4 - 0.802*D4 =E= 0;
DefineE5.. E5 - 0.012*L5 - 0.978*D5 =E= 0;
DefineE6.. E6 - 0.228*L6 - 0.504*D6 =E= 0;
DefineE7.. E7 - 0.031*L7 - 0.953*D7 =E= 0;
DefineE8.. E8 - 0.277*L8 - 0.450*D8 =E= 0;
DefineE9.. E9 - 0.466*L9 - 0.830*D9 =E= 0;
DefineE10.. E10 - 0.286*L10 - 0.863*D10 =E= 0;
DefineE11.. E11 - 0.795*L11 - 0.912*D11 =E= 0;
```

```
DefineF1.. F1 - 0.929*L1 =E= 0;
DefineF2.. F2 - 0.706*L2 =E= 0;
DefineF3.. F3 - 0.965*L3 =E= 0;
DefineF4.. F4 - 0.901*L4 =E= 0;
DefineF5.. F5 - 0.988*L5 =E= 0;
DefineF6.. F6 - 0.678*L6 =E= 0;
DefineF7.. F7 - 0.968*L7 =E= 0;
DefineF8.. F8 - 0.584*L8 =E= 0;
DefineF9.. F9 - 0.483*L9 =E= 0;
DefineF10.. F10 - 0.691*L10 =E= 0;
DefineF11.. F11 - 0.157*L11 =E= 0;

QualCons1.. 0.063*L1 + 0.787*D1 =L= Da1;
QualCons2.. 0.204*L2 + 0.478*D2 =L= Da2;
QualCons3.. 0.034*L3 + 0.927*D3 =L= Da3;
QualCons4.. 0.089*L4 + 0.802*D4 =L= Da4;
QualCons5.. 0.012*L5 + 0.978*D5 =L= Da5;
QualCons6.. 0.228*L6 + 0.504*D6 =L= Da6;
QualCons7.. 0.031*L7 + 0.953*D7 =L= Da7;
QualCons8.. 0.277*L8 + 0.450*D8 =L= Da8;
QualCons9.. 0.466*L9 + 0.830*D9 =L= Da9;
QualCons10.. 0.286*L10 + 0.863*D10 =L= Da10;
QualCons11.. 0.795*L11 + 0.912*D11 =L= Da11;

Quality1.. D1 =L= Da1;
Quality2.. D2 =L= Da2;
Quality3.. D3 =L= Da3;
Quality4.. D4 =L= Da4;
Quality5.. D5 =L= Da5;
Quality6.. D6 =L= Da6;
Quality7.. D7 =L= Da7;
Quality8.. D8 =L= Da8;
Quality9.. D9 =L= Da9;
Quality10.. D10 =L= Da10;
Quality11.. D11 =L= Da11;

*REACH 1 EXISTED 0.67 ALREADY
EffCons1.. X1 =E= 0.67;
EffCons2.. X2 =G= 0.35;
EffCons31.. X31 =G= 0.35;
EffCons32.. X32 =G= 0;
EffCons4.. X4 =G= 0.35;
EffCons51.. X51 =G= 0.35;
EffCons52.. X52 =G= 0;
EffCons6.. X6 =G= 0.35;
```

```
EffCons7.. X7 =G= 0.35;
EffCons8.. X8 =G= 0.35;
EffCons91.. X91 =G= 0.35;
EffCons92.. X92 =G= 0;
EffCons101.. X101 =G= 0.35;
EffCons102.. X102 =G= 0;
EffCons11.. X11 =G= 0.35;

EffCont2.. X2 =L= 0.85;
EffCont31.. X31 =L=0.82;
EffCont32.. X32 =L= 0.08;
EffCont4.. X4 =L= 0.9;
EffCont51.. X51 =L= 0.74;
EffCont52.. X52 =L= 0.16;
EffCont6.. X6 =L= 0.9;
EffCont7.. X7 =L= 0.85;
EffCont8.. X8 =L= 0.75;
EffCont91.. X91 =L= 0.75;
EffCont92.. X92 =L= 0.15;
EffCont101.. X101 =L= 0.85;
EffCont102.. X102 =L= 0.05;
EffCont11.. X11 =L= 0.9;

CostCont3.. X3 - X32 - X31 =E= 0;
CostCont5.. X5 - X52 - X51 =E= 0;
CostCont9.. X9 - X92 - X91 =E= 0;
CostCont10.. X10 - X102 - X101 =E= 0;

Emission..  M =e= M2 + M3 + M4 + M5 + M6 + M7 + M8 + M9
                + M10 + M11;

* Reach 1 has no cost(fixed and variable), see 1966, Liebman,p.587
VarCost..  0*X1 + MC2*X2 +  MC31*X31 + MC32*X32 + MC4*X4 +
           MC51*X51 +  MC52*X52 + MC6*X6 +  MC7*X7
           + MC8*X8 + MC91*X91+ MC92*X92 + MC101*X101
           + MC102*X102 + MC11*X11 =e= CS;

MODEL Goal /ALL/;
SOLVE Goal USING LP Minimizing M;
```

S O L V E   S U M M A R Y

MODEL   Goal   OBJECTIVE M

TYPE LP DIRECTION MINIMIZE
SOLVER BDMLP FROM LINE 263

**** SOLVER STATUS 1 NORMAL COMPLETION
**** MODEL STATUS 1 OPTIMAL
**** OBJECTIVE VALUE 2053.7323

RESOURCE USAGE, LIMIT 0.313 1000.000
ITERATION COUNT, LIMIT 44 10000

BDMLP 1.1 Mar 1, 2000 WIN.BD.BD 19.1 054.038.038.WAT

(A. Brooke, A. Drud, and A. Meeraus,
Analytic Support Unit,
Development Research Department,
World Bank,
Washington, D.C. 20433, U.S.A.

Work space allocated -- 0.07 Mb

EXIT -- OPTIMAL SOLUTION FOUND.

	LOWER	LEVEL	UPPER	MARGINAL
---- VAR M	-INF	2053.732	+INF	.
---- VAR X1	.	0.670	+INF	.
---- VAR X2	.	0.350	+INF	.
---- VAR X31	.	0.608	+INF	.
---- VAR X32	.	.	+INF	.
---- VAR X3	.	0.608	+INF	.
---- VAR X4	.	0.350	+INF	.
---- VAR X51	.	0.350	+INF	.
---- VAR X52	.	.	+INF	.
---- VAR X5	.	0.350	+INF	.
---- VAR X6	.	0.350	+INF	.
---- VAR X7	.	0.350	+INF	.
---- VAR X8	.	0.647	+INF	.
---- VAR X91	.	0.750	+INF	.
---- VAR X92	.	.	+INF	3.6634E+5
---- VAR X9	.	0.750	+INF	.
---- VAR X101	.	0.633	+INF	.
---- VAR X102	.	.	+INF	.
---- VAR X10	.	0.633	+INF	.
---- VAR X11	.	0.350	+INF	.

---- VAR M1	.	81.840	+INF	.
---- VAR M2	.	184.600	+INF	.
---- VAR M3	.	46.289	+INF	.
---- VAR M4	.	78.650	+INF	.
---- VAR M5	.	60.450	+INF	.
---- VAR M6	.	156.000	+INF	.
---- VAR M7	.	42.250	+INF	.
---- VAR M8	.	143.858	+INF	.
---- VAR M9	.	360.000	+INF	.
---- VAR M10	.	800.286	+INF	.
---- VAR M11	.	181.350	+INF	.

GAMS Program

Nearly Optimal Solutions – HSJ method

```
$offupper offsymxref offsymlist offuellist offuelxref
option limcol=0,limrow=0;
*See(Cohon and Marks, 1973, p. 833) for the methdology, Constrain Method.
*Max one of the two objectives, and the other objective becomes the constraint.
*Then, increase the right hand side value of the constraint.
*The allowable deficit depends on both the DO standard and on C(S),
* where C(S) is Sat Do in top of reach. That is D(A) = C(S) - DO Standard.
* Da = D(A)
*2 objectives: Min emission(Q), and Min treatment cost(C)
*The tax revenue can be got after the multiobjective model has been solved.
*HSJ method (Jeffrey et al. 1992 , p 5), Let j =0.05.
*Chose point B, whcih is one of the optimal solution in the non-inferior set.
*To structure the objective function in an attempt to force certain results
*that are of direct interest to the decision maker. For example,HSJ1 is for
*miniminzing the emission in the first three dischargers, because of the
*recreation purpose.

scalar CS /1.3/;
SCALARS
 Da1      /1.20/
 Da2      /1.31/
 Da3      /1.00/
 Da4      /1.12/
 Da5      /1.00/
 Da6      /1.20/
 Da7      /1.00/
 Da8      /2.54/
 Da9      /2.35/
 Da10      /2.24/
 Da11      /4.17/
* Reach 1 has not cost(fixed and variable).Since the firm has clean 67%.

Parameters
* whereQ_1 is the total flow rate in the 1st reach
Q_1      /1360/
Q_2      /2681/
Q_3      /2717/
Q_4      /2730/
Q_5      /2776 /
Q_6      /3430/
Q_7      /3606/
Q_8      /3643/
```

Q_9 /3841/
Q_10 /3938/
Q_11 /4495/
*where Q_Q1 is the total flow rate minus the flow rate being withdrawn by
*community i
Q_Q1 /1355.17 /
Q_Q2 /2649.7/
Q_Q3 /2712.84/
Q_Q4 /2717.1/
Q_Q5 /2762 /
Q_Q6 / 3421.6 /
Q_Q7 / 3591.8 /
Q_Q8 /3606.2/
Q_Q9 / 3837 /
Q_Q10 /3937.67/
Q_Q11 /4454.3/
*Pi is the BOD concentration in the waste flow entering the ith treatment
*plant, mg/liter
P1 / 248 /
P2 / 284 /
P3 / 118 /
P4 / 121 /
P5 / 93 /
P6 / 240 /
P7 / 65 /
P8 / 408 /
P9 / 1440 /
P10 / 2180 /
P11 / 279 /

T1 /9.15/
T2 /8.95/
T3 /8.64/
T4 /8.66/
T5 /8.54/
T6 /8.74/
T7 /8.54/
T8 /8.54/
T9 /8.35/
T10 /8.24/
T11 /8.17/

*MCi is the marginal cost(efficiency)of each reach i. It can be two stages cost.
MC2 /0.425/
MC31 /0.0149/
MC32 /0.5/

```
MC4          /0.451/
MC51          /0.061/
MC52          /1.3063/
MC6          /0.114/
MC7          /0.431/
MC8          /0.352/
MC91          /0.0435/
MC92          /0.17/
MC101          /0.0089/
MC102          /0.06/
MC11         /0.806/;
VARIABLES Z;
POSITIVE VARIABLES
X1, X2, X31, X32, X3, X4, X51, X52, X5, X6, X7, X8, X91, X92, X9,
X101, X102, X10, X11,
M,M1, M2, M3, M4, M5, M6, M7, M8, M9, M10, M11,
L1, L2, L3, L4, L5, L6, L7, L8, L9, L10, L11,
D1, D2, D3, D4, D5, D6, D7, D8, D9, D10, D11,
E1, E2, E3, E4, E5, E6, E7, E8, E9, E10,E11,
F1, F2, F3, F4, F5, F6, F7, F8, F9, F10,F11;

EQUATIONS
OBJ,
Alter,
EFFICIEN1, EFFICIEN2, EFFICIEN3, EFFICIEN4, EFFICIEN5,
EFFICIEN6, EFFICIEN7, EFFICIEN8, EFFICIEN9, EFFICIEN10,EFFICIEN11,
InvenBOD1, InvenBOD2, InvenBOD3, InvenBOD4, InvenBOD5,
InvenBOD6, InvenBOD7, InvenBOD8,
InvenBOD9, InvenBOD10,InvenBOD11,
InvenDef1, InvenDef2, InvenDef3,InvenDef4, InvenDef5, InvenDef6,
InvenDef7, InvenDef8, InvenDef9,InvenDef10, InvenDef11,
DefineE1, DefineE2, DefineE3, DefineE4, DefineE5, DefineE6,
DefineE7, DefineE8, DefineE9, DefineE10, DefineE11,
DefineF1, DefineF2, DefineF3, DefineF4, DefineF5, DefineF6,
DefineF7, DefineF8, DefineF9, DefineF10, DefineF11,
QualCons1, QualCons2, QualCons3,QualCons4, QualCons5, QualCons6,
QualCons7, QualCons8, QualCons9,QualCons10, QualCons11,
Quality1, Quality2, Quality3, Quality4, Quality5, Quality6, Quality7,
Quality8, Quality9, Quality10, Quality11,
EffCons1, EffCons2, EffCons31, EffCons32, EffCons4, EffCons51,
EffCons52, EffCons6, EffCons7, EffCons8, EffCons91, EffCons92,
EffCons101,EffCons102, EffCons11,
EffCont2,EffCont31,EffCont32,
EffCont4,EffCont51,EffCont52,EffCont6,
EffCont7,EffCont8,EffCont91,EffCont92,
EffCont101,EffCont102 ,EffCont11,
```

```
CostCont3, CostCont5, CostCont9, CostCont10,
VarCost,
Emission;
* M is total emission.
Obj.. Z =e= M1 + M2 + M3 ;
Alter.. M2 + M3 + M4 + M5 + M6 + M7 + M8 + M9 + M10 + M11
        =l= (1+ 0.05)*975;
*min z = c'x
*c'x <= (1+j)z* , where z* is the optimal value,975.
EFFICIEN1.. X1 + (1/P1 )*M1 =E= 1;
EFFICIEN2.. X2 + (1/P2 )*M2 =E= 1;
EFFICIEN3.. X3 + (1/P3 )*M3 =E= 1;
EFFICIEN4.. X4 + (1/P4 )*M4 =E= 1;
EFFICIEN5.. X5 + (1/P5 )*M5 =E= 1;
EFFICIEN6.. X6 + (1/P6 )*M6 =E= 1;
EFFICIEN7.. X7 + (1/P7 )*M7 =E= 1;
EFFICIEN8.. X8 + (1/P8 )*M8 =E= 1;
EFFICIEN9.. X9 + (1/P9 )*M9 =E= 1;
EFFICIEN10.. X10 + (1/P10 )*M10 =E= 1;
EFFICIEN11.. X11 + (1/P11 )*M11 =E= 1;

InvenBOD1.. Q_Q1*0 + 4.83*M1 - Q_1*L1 =E= 0;
InvenBOD2.. Q_Q2*F1 + 31.3*M2 - Q_2*L2 =E= 0;
InvenBOD3.. Q_Q3*F2 + 4.16*M3 - Q_3*L3 =E= 0;
InvenBOD4.. Q_Q4*F3 + 12.9*M4 - Q_4*L4 =E= 0;
InvenBOD5.. Q_Q5*F4 + 14.0*M5 - Q_5*L5 =E= 0;
InvenBOD6.. Q_Q6*F5 + 8.4*M6 - Q_6*L6 =E= 0;
InvenBOD7.. Q_Q7*F6 + 14.2*M7 - Q_7*L7 =E= 0;
InvenBOD8.. Q_Q8*F7 + 36.8*M8 - Q_8*L8 =E= 0;
InvenBOD9.. Q_Q9*F8 + 4.0*M9 - Q_9*L9 =E= 0;
InvenBOD10.. Q_Q10*F9 + 0.33*M10 - Q_10*L10 =E= 0;
InvenBOD11.. Q_Q11*F10 + 40.7*M11- Q_11*L11 =E= 0;

InvenDef1.. -1*Q_Q1*0 + Q_1*D1=E=T1*4.83;
InvenDef2.. -1*Q_Q2*E1 + Q_2*D2=E=T2*31.3;
InvenDef3.. -1*Q_Q3*E2 + Q_3*D3=E=T3*4.16;
InvenDef4.. -1*Q_Q4*E3 + Q_4*D4=E=T4*12.9;
InvenDef5.. -1*Q_Q5*E4 + Q_5*D5=E=T5*14.0;
InvenDef6.. -1*Q_Q6*E5 + Q_6*D6=E=T6*8.4;
InvenDef7.. -1*Q_Q7*E6 + Q_7*D7=E=T7*14.2;
InvenDef8.. -1*Q_Q8*E7 + Q_8*D8=E=T8*36.8;
InvenDef9.. -1*Q_Q9*E8 + Q_9*D9=E=T9*4.0;
InvenDef10.. -1*Q_Q10*E9 + Q_10*D10=E=T10*0.33;
InvenDef11.. -1*Q_Q11*E10 + Q_11*D11=E=T11*40.4;

DefineE1.. E1 - 0.063*L1 - 0.787*D1 =E= 0;
```

```
DefineE2.. E2 - 0.204*L2 - 0.478*D2 =E= 0;
DefineE3.. E3 - 0.034*L3 - 0.927*D3 =E= 0;
DefineE4.. E4 - 0.089*L4 - 0.802*D4 =E= 0;
DefineE5.. E5 - 0.012*L5 - 0.978*D5 =E= 0;
DefineE6.. E6 - 0.228*L6 - 0.504*D6 =E= 0;
DefineE7.. E7 - 0.031*L7 - 0.953*D7 =E= 0;
DefineE8.. E8 - 0.277*L8 - 0.450*D8 =E= 0;
DefineE9.. E9 - 0.466*L9 - 0.830*D9 =E= 0;
DefineE10.. E10 - 0.286*L10 - 0.863*D10 =E= 0;
DefineE11.. E11 - 0.795*L11 - 0.912*D11 =E= 0;

DefineF1.. F1 - 0.929*L1 =E= 0;
DefineF2.. F2 - 0.706*L2 =E= 0;
DefineF3.. F3 - 0.965*L3 =E= 0;
DefineF4.. F4 - 0.901*L4 =E= 0;
DefineF5.. F5 - 0.988*L5 =E= 0;
DefineF6.. F6 - 0.678*L6 =E= 0;
DefineF7.. F7 - 0.968*L7 =E= 0;
DefineF8.. F8 - 0.584*L8 =E= 0;
DefineF9.. F9 - 0.483*L9 =E= 0;
DefineF10.. F10 - 0.691*L10 =E= 0;
DefineF11.. F11 - 0.157*L11 =E= 0;

QualCons1.. 0.063*L1 + 0.787*D1 =L= Da1;
QualCons2.. 0.204*L2 + 0.478*D2 =L= Da2;
QualCons3.. 0.034*L3 + 0.927*D3 =L= Da3;
QualCons4.. 0.089*L4 + 0.802*D4 =L= Da4;
QualCons5.. 0.012*L5 + 0.978*D5 =L= Da5;
QualCons6.. 0.228*L6 + 0.504*D6 =L= Da6;
QualCons7.. 0.031*L7 + 0.953*D7 =L= Da7;
QualCons8.. 0.277*L8 + 0.450*D8 =L= Da8;
QualCons9.. 0.466*L9 + 0.830*D9 =L= Da9;
QualCons10.. 0.286*L10 + 0.863*D10 =L= Da10;
QualCons11.. 0.795*L11 + 0.912*D11 =L= Da11;

Quality1.. D1 =L= Da1;
Quality2.. D2 =L= Da2;
Quality3.. D3 =L= Da3;
Quality4.. D4 =L= Da4;
Quality5.. D5 =L= Da5;
Quality6.. D6 =L= Da6;
Quality7.. D7 =L= Da7;
Quality8.. D8 =L= Da8;
Quality9.. D9 =L= Da9;
Quality10.. D10 =L= Da10;
Quality11.. D11 =L= Da11;
```

```
*REACH 1 EXISTED 0.67 ALREADY
EffCons1.. X1 =E= 0.67;
EffCons2.. X2 =G= 0.35;
EffCons31.. X31 =G= 0.35;
EffCons32.. X32 =G= 0;
EffCons4.. X4 =G= 0.35;
EffCons51.. X51 =G= 0.35;
EffCons52.. X52 =G= 0;
EffCons6.. X6 =G= 0.35;
EffCons7.. X7 =G= 0.35;
EffCons8.. X8 =G= 0.35;
EffCons91.. X91 =G= 0.35;
EffCons92.. X92 =G= 0;
EffCons101.. X101 =G= 0.35;
EffCons102.. X102 =G= 0;
EffCons11.. X11 =G= 0.35;

EffCont2.. X2 =L= 0.85;
EffCont31.. X31 =L=0.82;
EffCont32 . X32 =L= 0.08;
EffCont4.. X4 =L= 0.9;
EffCont51.. X51 =L= 0.74;
EffCont52.. X52 =L= 0.16;
EffCont6.. X6 =L= 0.9;
EffCont7.. X7 =L= 0.85;
EffCont8.. X8 =L= 0.75;
EffCont91.. X91 =L= 0.75;
EffCont92.. X92 =L= 0.15;
EffCont101.. X101 =L= 0.85;
EffCont102.. X102 =L= 0.05;
EffCont11.. X11 =L= 0.9;

CostCont3.. X3 - X32 - X31 =E= 0;
CostCont5.. X5 - X52 - X51 =E= 0;
CostCont9.. X9 - X92 - X91 =E= 0;
CostCont10.. X10 - X102 - X101 =E= 0;

Emission..  M =e= M2 + M3 + M4 + M5 + M6 + M7 + M8 + M9
                 + M10 + M11;

* Reach 1 has no cost(fixed and variable), see 1966, Liebman,p.587
VarCost..  0*X1 + MC2*X2 +  MC31*X31 + MC32*X32 + MC4*X4 +
           MC51*X51+  MC52*X52 + MC6*X6 +  MC7*X7 + MC8*X8 +
           MC91*X91+ MC92*X92 + MC101*X101 + MC102*X102 +
           MC11*X11 =e= CS;
```

MODEL HSJ /ALL/;
SOLVE HSJ USING LP MinIMIZING Z;

S O L V E   S U M M A R Y

MODEL HSJ   OBJECTIVE Z
TYPE LP   DIRECTION MINIMIZE
SOLVER BDMLP   FROM LINE 271

**** SOLVER STATUS 1 NORMAL COMPLETION
**** MODEL STATUS 1 OPTIMAL
**** OBJECTIVE VALUE 175.9543

	LOWER	LEVEL	UPPER	MARGINAL
---- VAR Z	-INF	175.954	+INF	.
---- VAR X1	.	0.670	+INF	.
---- VAR X2	.	0.743	+INF	.
---- VAR X31	.	0.820	+INF	.
---- VAR X32	.	.	+INF	.
---- VAR X3	.	0.820	+INF	.
---- VAR X4	.	0.350	+INF	.
---- VAR X51	.	0.740	+INF	.
---- VAR X52	.	.	+INF	.
---- VAR X5	.	0.740	+INF	.
---- VAR X6	.	0.900	+INF	.
---- VAR X7	.	0.350	+INF	.
---- VAR X8	.	0.468	+INF	.
---- VAR X91	.	0.750	+INF	.
---- VAR X92	.	0.150	+INF	.
---- VAR X9	.	0.900	+INF	.
---- VAR X101	.	0.850	+INF	.
---- VAR X102	.	0.050	+INF	.
---- VAR X10	.	0.900	+INF	.
---- VAR X11	.	0.350	+INF	.
---- VAR M	.	1023.750	+INF	.
---- VAR M1	.	81.840	+INF	.
---- VAR M2	.	72.874	+INF	.
---- VAR M3	.	21.240	+INF	.
---- VAR M4	.	78.650	+INF	.
---- VAR M5	.	24.180	+INF	.
---- VAR M6	.	24.000	+INF	.
---- VAR M7	.	42.250	+INF	.
---- VAR M8	.	217.206	+INF	.

---- VAR M9	.	144.000	+INF	.
---- VAR M10	.	218.000	+INF	.
---- VAR M11	.	181.350	+INF	.

VITA

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Doctor of Philosophy

Thesis: TWO ESSAYS OF POLICIES IN WATER RESOURCE MANAGEMENT

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Biographical:

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