Social Costs of the 1972 Water Pollution Control Act Amendments*

WALTER P. PAGE AND AUSTRIN H. MONTGOMERY, JR.
Department of Economics and Department of Management and Marketing,
West Virginia University.

Senate and house deliberations on the Water Pollution Control Act Amendments of 1972 reflected little if any concern with the cost and efficiency aspects of the amendments [see 9, pp. 56-57]. The reliance on uniform emission standards and the neglect of system wide cost minimizing solutions, it is contended, imposes heavy social costs. Some high quality research had been conducted on matters of cost and efficiency in waste water treatment during the decade of the 1960s [see, e.g., 8], yet little or none of this material figured prominently in congressional deliberation. The theoretical and empirical justifications for this and related points has been developed in the literature [see, e.g., 1,3,6,7,8,9]. The empirical studies, however, have been very limited in number and have not dealt with a number of waterways distinguished according to the relative degree of water quality.

The purpose of this paper is to report the results of an empirical study of a highly polluted river, comparing the cost of achieving specified water quality according to the 1973 amendment procedures with a least cost solution. Cost differences due to several parametric characteristics of waterways and the degree of pollution in waterways will undoubtedly arise. For example, reported differences between least cost solutions and uniform treatment costs are as high as 212 percent greater for uniform treatment with 2 ppm as the dissolved oxygen (DO) objective or 185 percent greater for a 3-4 ppm DO objective [see 3,6,8]. The question is, do we expect such large differences in most U.S. waterways between least cost solutions and uniform treatment? A priori considerations suggest cost savings will be less for a very heavily polluted river than for the case of less polluted streams. We wish to examine this hypothesis using one of the most heavily polluted rivers in the U.S. Further, our modeling of the inventory and constraint sets for each reach of the river is much more detailed than in previous research. We believe this may again reduce the extent of cost savings between the efficient and uniform treatment solutions.

While many criticisms of the 1972 Amendments have emerged--failure to utilize a regional water basin approach, an unrealistic goal requiring discharges into navigable waters be eliminated by 1985, neglect of the total residuals management perspective, neglect of effluent charge systems, failure to use cost minimizing solutions, etc.--which influence costs or effectiveness, we are not in a position to suggest which criticism, in terms of cost, is most critical. It will require further

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extensive work in all these areas to determine the full social costs of the 1972 Amendments and the relative importance, to cost, of these criticisms. We seek only to make a contribution to the estimation of the social costs associated with neglect of least cost solutions for extremely polluted waterways.

Because we wish to compare our results from a heavily polluted waterway with those obtained from other studies (see 1, 3, 6, or 8), we use similar modeling techniques, linear programming techniques, in particular. Along with others, we emphasize Biochemical Oxygen Demand (BOD) because it is the single most common waterborne material and often serves as a good index of other waterborne pollutants.

The problem to be solved is one of determining the minimum system cost of BOD removal distribution for specified outfalls along designated reaches of a river to achieve a specified DO deficit. This cost calculation can be compared with calculations of the system cost for uniform treatment requirements at all outfalls. The difference represents a dollar estimate of the inefficiency associated with uniform treatment requirements for a heavily polluted river.

Model

We model the relationship between BOD removal and the total annual cost and constraint equations for the reaction of the river to different degrees of waste treatment. River standards are based on DO and how it is affected by BOD discharge. Constraints include (1) treatment efficiencies and relationships between BOD generated and treatment efficiencies, (2) inventory equations of BOD and DO deficit for the beginning of each reach in the river and (3) equations defining water quality within each reach.

Treatemnt Costs

It is known that annual treatment costs vs. percent BOD removal can be adequately represented by relatively linear segments [for justification, see 11, 12]. This is illustrated in Fig. 1.

Cost functions of this nature may be developed for different sizes of the treatment plants. If it is assumed that 35 percent treatment (based on BOD) is required at all outfalls, only the portions of the function above 35 percent are of interest. The objective function in the program is the sum of costs for all treatment plants for the river system, where each individual plant has its own cost function. The degrees of treatment of the separate plants are variables. The primary procedure followed in this study is to require a minimum of 35 percent removal (we also report the results when no minimum discharge is assumed).

Objective Function

The objective function in this linear program is the sum of the cost of treating each discharge at its treatment level. This annual cost is:

\[
\begin{align*}
  c = a_1 + b_1 (x_1 - u_1) + a_2 + b_2 (x_2 - u_2) + \ldots + a_n + b_n (x_n - u_n) + b_d (x_d - u_d)
\end{align*}
\]

where:
- \( a_i \) = the fixed cost for each plant,
- \( b_i \) = the appropriate cost coefficient for each plant,
- \( x_i \) = the degree of treatment at each plant, and
- \( u_i \) = 35 or 85, as appropriate for each plant.

As the \( a_i \) and \( b_i \) values are known at each treatment plant for any (individual) run of the model, and a trial value of \( u_i \) can be assumed.

\[
\begin{align*}
  c = \sum_{i=1}^{n} a_i + b_i (x_i - u_i) \text{ or } \sum_{i=1}^{n} (a_i + b_i u_i - b_i u_i)
\end{align*}
\]

which can be simplified to

\[
\begin{align*}
  c = \sum_{i=1}^{n} b_i x_i + A
\end{align*}
\]

where,

\[
A = \sum_{i=1}^{n} a_i - b_i u_i
\]

The approach taken here—common to other studies of this nature—is to let the annual cost at each site depend only upon the size of the discharge and the amount of treatment to be applied. Thus, the model's procedure differs little whether the wastewater generated is presently being treated or is being discharged raw. We can also constrain the model to require at least the existing treatment to take place at a site. A further assumption is to constrain each site to a minimum of primary treatment (i.e., removal of 35 percent of BOD) as it is unlikely that a lesser amount will be approved, despite the economics of the problem. For completeness, however, we do report results where minimum standards are 0.

The model, then, assumes the total annual cost the site should be experiencing, based on data which reflect the size of the discharge and the degree of treatment assigned by the model. These costs are a perpetual nature, as they include amortization.

Constraint Set

In this problem, the constraint set is used to force the solution to meet river standards. The standards in this model are based on DO and how it is affected by BOD discharged. The first group of constraints defines treatment efficiencies and the relationship between BOD generated and treatment efficiency. There is one of each of equations (1), (2), and (3) for each discharge.

Definition of efficiencies:

\[
100(\frac{M_i - EP_i}{P_i}) - 100
\]

where:
- \( M_i \) = BOD concentration discharged at outfall (mg/l)
- \( P_i \) = raw BOD concentration of discharge i prior to treatment (mg/l)
- \( EP_i \) = treatment efficiency for discharge i (%)

The range for treatment efficiencies must also be defined. As an example, for the 35–85 percent line segment they would appear as follows:

\[
\text{Only sample constraint equations are provided in this paper. Detailed equations with parametric values may be obtained directly from the authors.}
\]

\[
\text{This discussion generally follows the model described in reference 11.}
\]
In addition to the treatment constraints represented by (1), (2), and (3), it is necessary to write a series of constraints to ensure quality standards in each reach. The following, controlling oxygen deficit and BOD concentration, respectively, are typical:

\[ E_i - \alpha_i L_i - (e_i^L)D_i = 0 \]  
\[ F_i - (e_i^F)L_i = 0 \]

where \( E_i \) is the oxygen deficit; \( \alpha_i \) is a coefficient based on natural reaeration, the time of flow through the reach, and the bio-oxidation rate; \( L_i \) is the concentration of BOD in the river after mixing; \( s_i \) is the size of the natural reaeration constant and the time of flow through the reach; \( D_i \) is the reach's oxygen deficit after mixing; \( F_i \) is the BOD concentration at the end of the reach; and \( c_i \) is the product of the bio-oxidation rate and the time of flow through the reach. Equation (5) defines the BOD entering the next reach in the watershed.

Other constraints were written to define \( L_i \) and \( D_i \). In all, over 130 constraints were required to model the stretch of the Kanawha River under study. The linear relationships among the variables adhered to the long accepted Streeter-Phelps formulation for predicting oxygen deficits. For a detailed treatment of this subject see [10].

Application to the Kanawha River

This linear optimization technique was applied to the Kanawha River near Charleston, West Virginia. This is one of the most polluted rivers in the country. This section of river was shown by the Horne Model to be quality limiting [4]; because of heavy waste loading in this area, the river will not meet a 5.0 mg/l DO standard even if best practical treatment (i.e., 85% BOD removal) is applied. The linear programming was based on BOD, and at least 35 percent removal was required at all discharges. Maximum treatment was not limited to 85 percent removal, as both necessity and economy required that some discharges go to higher levels. The decision was made to solve the above problem from a simple linear programming problem to a separable linear programming problem in order to select the appropriate line segment in the cost function for each discharge.

The data used in the Kanawha model were waste loading at the 85 percent level, as was done in the first study done by BMI for the West Virginia Department of Natural Resources [5]. The river's characteristics were taken from Environmental Protection Agency (EPA) data used in the Horne Model [4]. The Kanawha River was divided into 12 reaches from Milepoint 70.5 (above Charleston) to Milepoint 25.0 (below Charleston). Discharges were assumed injected at the head of each reach. Detailed tables on the characteristics of each of the 12 reaches may be obtained from the authors.

The model was run assuming a temperature of 30°C and upstream BOD and DO deficit values of 4.0 and 0.5 mg/l, respectively. A summary of waste discharges and the reaches in which they occur is available from the author.

Cost data were taken from Smith [12]. The values for cost vs. percent removal for treatment above 85 percent were developed from Smith's cost functions for 10 MGD activated sludge plants with lime coagulation and carbon absorption. To reflect economies of scale for different size plants, these costs were adjusted by multiplying by a ratio of the cost of a 10 MGD plant and the cost of a plant of the size desired. Data for cost vs. plant size were taken from unpublished work by Smith. A summary of these data for plant sizes and treatment efficiencies used in this study may be obtained directly from the authors. The cost functions are based on municipal wastes. Although much of the waste discharge in the river is from industry, no known bias has been introduced, and no major element has been omitted, so these costs can be considered an approximation of the area’s BOD abatement needs.

Results of the Separable Linear Programming Model

In this model the variable name identifies the reach and discharge by containing a coded number for each variable (such as EP1, the treatment efficiency for a given discharge). The first digit refers to the first and the second to discharge number within that reach. For example, EP41 identifies the treatment efficiency for the fourth reach's first discharge. The objective function resulted in a coded cost of $2,981.838, to which the constant, $2,250,266 was added to yield a total annual cost of $5,232.104. The optimum treatment levels were:

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Waste Level</th>
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<tbody>
<tr>
<td>Source (%)</td>
<td>Source (%)</td>
<td>EP1</td>
<td>35</td>
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<tr>
<td>EP2</td>
<td>85</td>
<td>EP9</td>
<td>85</td>
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<td>EP3</td>
<td>90</td>
<td>EP10</td>
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<td>EP4</td>
<td>55</td>
<td>EP8</td>
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<td>EP41</td>
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<td>EP43</td>
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<tr>
<td>EP51</td>
<td>85</td>
<td>EP9</td>
<td>35</td>
</tr>
</tbody>
</table>

The results show that the optimum plan for meeting river standards at minimum cost is to let a large number of discharges receive only minimal (primary) treatment while requiring much higher levels of other discharges.

For purposes of comparison, the model was run with the minimum constraint of 85 percent removal, as required by regulations. The results were the EP51 was to achieve 92 percent and that all others were satisfactory at 85 percent. This result of relatively little advanced treatment is inconsistent with some other model results on the Kanawha River. The difference may lie in the fact that the linear programming model is more adept at handling conventional (municipal) wastes, and does not model nitrogenous oxygen demand, which is present in various industrial wastes along the River.

The total annual cost of the 85 percent minimum removal solution was $5,845,978, an increase of 11.7 percent over the optimum solution. Further, the results may be drawn by considering the fact that, in the long run, there is no need to maintain EP12, 41, and 43 at the optimum levels, but that the 85 percent concentration of the first run. These could be replaced with optimum treatment levels when the plants reach the end of their economic lives. Changing their minimum constraints to 35 percent and re-running the model yields a cost of $5,175,660. The plan of treating to a minimum of 85 percent exceeds this figure by 12.9 percent.

Some authorities would argue that no minimum should be set. To test this idea, the model was run with all minimum constraints set at zero. This procedure would not bring the cost of no treatment to zero, as it would leave a minimum cost (i.e., the fixed cost) for each facility. The run resulted in a total annual cost of $4,885,108. The cost of treating at a minimum of 85 percent exceeds this figure by 19.7 percent. This difference appears to be conservative, as it is likely that minimum costs less than those specified in our work could be justified at each site.

Conclusions

As noted earlier, streams which are relatively less seriously polluted can show greater cost savings associated with optimal treatment than can optimal treatment for heavily polluted waterways. Our results verify this hypothesis. Nonetheless, one of the most heavily polluted rivers in the country—
the Kanawha in Western Virginia still shows very substantial cost savings for optimum treatment levels as compared to uniform treatment requirements. In particular, the total annual cost with uniform treatment was $11.7 percent greater than that found in the optimum solution; $5,843,978 compared with $5,232,104. Such a cost difference represents, in absolute numbers, a very substantial saving over time. Further, through time certain treatment efficiencies could be reduced by replacing certain plants at the end of their economic lives with optimum treatment levels further reducing the annual cost to $5,175,660; 12.9 percent lower than the uniform treatment requirements. While we have not dealt with the problem of industrial wastes in this study, the cost difference probably represents a lower bound on the true cost difference due to the relatively higher costs of industrial waste treatment. Further, our careful modeling of the inventory and constraint sets for each reach of the river lends credence to our resulting cost differences. The picture emerging from the literature dealing with this matter, then, strongly suggests very high social costs associated with the uniform treatment requirements of the 1972 Water Pollution Control Act Amendments. From an efficiency and cost perspective, the characterization of the Amendments as “silly” and “ridiculous” certainly strikes one as reasonably accurate.

References Cited
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The International Allocation of Economic Activity: A Review Article
H. PETER GRAY
Doughton College, Ruters University

In June, 1976, a Nobel Symposium was held in Stockholm. The theme and title of the Symposium were The International Allocation of Economic Activity. The Symposium owes its existence to Professor Bertil Ohlin and is devoted to a modern assessment of the state of the art in international trade theory. Prior to the award of the Nobel Prize in 1977, this Symposium may be said to be the apogee of Ohlin's professional career since modern trade theory still enjoys a remarkable degree on his 1933 classic, Interregional and International Trade. This Symposium shifts the emphasis by explicitly recognizing the close interrelationship between trade theory and location theory. This shift in emphasis explains the presence of eight well-known location theorists and economic geographers in addition to what was virtually an all-star cast of international trade theorists. The emphasis given to location theory was deliberate. It was foreseen in Ohlin’s excellent review of the state of international trade theory in the mid-sixties and constitutes a stroke of great enlightenment since the subject matter of trade theory has tended to become excessively narrow and ingrown in recent years and a broadening of scope could restore some lost realism and vitality.

Fifteen major papers were presented together with a substantial valedictory. Each of the papers was the beneficiary of at least one comment and a general discussion. In order to keep the analysis well-defined, the subject matter was limited to positive problems in trade and location theory in the absence of imbalanced trade and under assumed conditions of satisfactory rates of capacity utilization. The effects of imperfections in competition were also excluded. These restrictions meant that the discussion among forty-one scholars (of whom thirty-one were). From Sweden or the United States and only two from outside the developed world) was conducted in a full-equilibrium framework that was usually static or comparative static.

The papers were not uniformly insightful but the Symposium must be judged very successful. The book will amply repay any reader time spent reading it.

This review article will attempt to provide a working guide to the almost six hundred pages so that the potential reader may have the benefit of one signpost in the selection of passages that will be of particular relevance to the reader's own research interests. Section I