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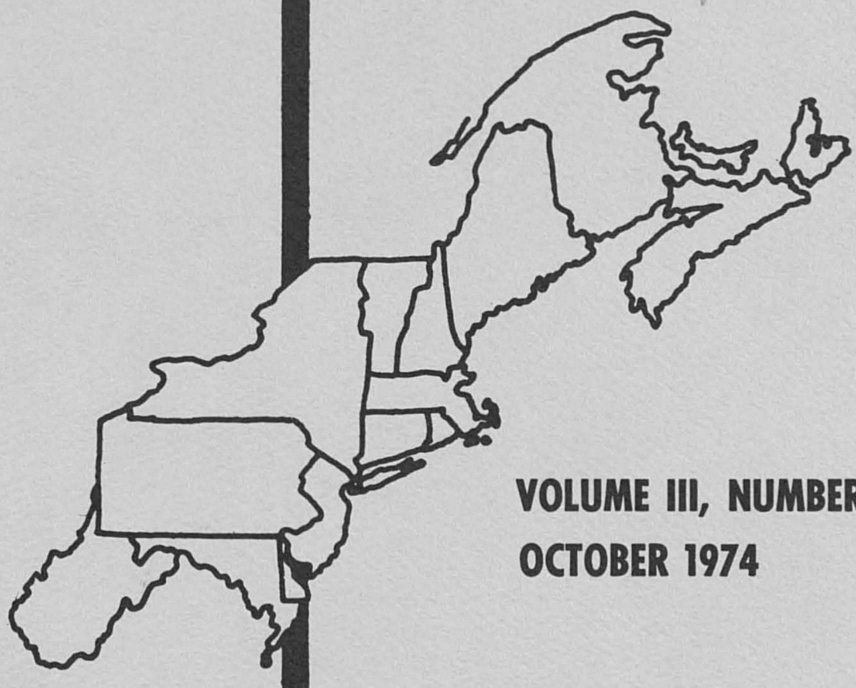

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COST MINIMIZATION IN WASTEWATER TREATMENT VIA REGIONALIZED TREATMENT FACILITIES: AN APPLICATION OF ZERO-ONE MIXED INTEGER PROGRAMMING

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INTRODUCTION[1/]

The disposal of industrial and municipal wastes is a complex and costly problem. The combination of increases in population, affluence, and industrial activity is generating growing volumes of water borne waste that must be disposed of or recycled. In 1972 for example, the estimated volume of wastewater generated in Rhode Island was 179 million gallons per day (MGD).[2/] This represented an average of 185 gallons per day for each Rhode Island resident and indications are that this volume is increasing each year.

Not unlike other parts of the nation, Rhode Island has most of its population and industrial activity concentrated along waterways. In Rhode Island this concentration is primarily around Narragansett Bay. Many Rhode Island residents are increasingly concerned with the quality of Narragansett Bay and its contributing waters. In response to this concern and the 1977 wastewater emission standards of the Federal Government, extensive investments in secondary sewage treatment facilities are planned by local communities. In addition, the more stringent 1983 standards imply tertiary treatment of wastewater which will require incremental investments of two to three times those planned for secondary treatment. It is these tertiary treatment costs which are analyzed in this paper.

The operating assumptions are that cost minimization in meeting water quality standards is a legitimate concern of public decision-makers and that the provision of information pertinent to this concern is a useful service. Among the alternatives that should be considered by public officials and the electorate are the following (including combinations thereof):

[1/]The authors wish to acknowledge the constructive comments of R. G. Cummings and J. McFarland. We also wish to thank N. Meade for his assistance in interviewing, data collection and preparation. Funding support for research was received from the University of Rhode Island Sea Grant Program, the New England Interstate Water Pollution Control Commission and the Rhode Island Agricultural Experiment Station. This paper is based on Norton, et at (1).

[2/]Rhode Island Department of Health and authors' estimate.

1) water pricing policies to slow growth rates in per capita waste generation and/or to even out peak loads

2) zoning policies to encourage use of the natural assimilative capacity of the soil

3) investment strategies in wastewater treatment facilities.

This paper addresses only the third of these viz. investment strategies.

More specifically, the purpose of this paper is to report our estimates of the potential savings that could be realized by communities on the west side of Narragansett Bay through regionalized treatment facilities. To estimate these potential savings an economic model is formulated for cost minimization. The paper can be regarded as a formalization for Palm and Jansma analysis (2). To reflect the existence of indivisible investments associated with treatment plants and inter-community pipelines, which imply economies of size, the model is a zero-one mixed integer linear programming model outlined in the following section.[3/] The model evaluates the trade off between lower per unit treatment costs as communities are combined, and the higher transportation cost required.

II. DESCRIPTION OF THE ECONOMIC MODEL

The model outlined represents a modification of the model proposed by Bhalla and Rikkers (3). The principal modifications are first, transhipment is permitted and second, the cost curves for treatment plants are segmented to more accurately reflect decreasing average unit costs. The model is a (0,1) mixed integer linear programming model. A computer program for solving the model was obtained from McCarl and Barton (4).

An algebraic statement of the model is as follows:

$$\text{Minimize } Z = \sum_{j,k} F_k Y_{jk} + \sum_{i,j,\ell} H_{ij\ell} J_{ij\ell} + \sum_{j,k} a_k A_{jk}$$

where:

Y_{jk} is a (0,1) variable associated with choice of a plant of the k^{th} size at the j^{th} site.

$J_{ij\ell}$ is a (0,1) variable associated with choice of a pipeline of the ℓ^{th} size between sites i and j.

A_{jk} is a non-integer variable which measures the units of wastewater treatment capacity in MGD, at site j associated with a plant of the k^{th} size.

3/ (0,1) will be used in the following discussion instead of zero-one. A (0,1) variable is one which is restricted to values of zero or unity.

F_k is the present worth of total treatment plant costs at the lower end of the k^{th} plant interval. F_k is the unit cost of the (0,1) variable Y_{jk}.

H_{ij} is the present worth of total pipeline costs and pumping station costs (when required) between sites i and j associated with a pipeline of the th capacity range. H_{ij} is the unit cost of the (0,1) variable J_{ij} .

a_k is the difference between present worths of treatment costs at the k^{th} and $(k+1)^{th}$ plant sizes divided by the $k + 1^{th}$ plant capacity. Thus, a_k is the unit cost of the variable A_{jk}.

The objective of the model is to minimize Z, the present worth of total treatment costs (capital costs of treatment facilities and plant operating and maintenance costs) and shipping costs (capital costs of interceptor sewers, pumping charges and maintenance costs), subject to the following sets of constraints:[4]

(1) $\sum\limits_{\substack{i \\ i \neq j}} X_{ji} + TR_j - \sum\limits_{\substack{i \\ i \neq j}} X_{ij} \geq D_j$ for all j

where:

X_{ji} is the wastewater export, in MGD, by site j to site i.

TR_j is the volume of wastewater treated at site j in MGD.

X_{ij} is the wastewater import, in MGD, by site j from site i.

D_j is the supply of wastewater, in MGD, originating at site J.

(2) $-A_{jk} + M_{k+1} * Y_{jk} > \underline{\underline{0}}$ for all j,k

where M_{k+1} is the upper bound on plant capacity for a plant of the k^{th} size.

(3) $\sum\limits_{k} A_{jk} - TR_j \geq 0$ all j

(4) $-N_{ij\ell} + M_\ell * J_{ij\ell} \geq 0$ all i, j,

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[4] Shipping costs do not include the costs of initial collection at each site.

where:

N_{ij} is the pipeline capacity in MGD, between sites i and j if the ℓ^{th} pipe size is selected.

M_ℓ is the upper bound on pipeline capacity, in MGD, for a pipeline or interceptor of the ℓ^{th} size.

$$(5) \quad \sum_{\ell} N_{ij\ell} - X_{ij} \geq 0 \qquad \text{all } i, j$$

$$(6) \quad \sum_{j,\ell} J_{ij\ell} + \sum_{k} Y_{ik} \leq 1 \qquad \text{all } i$$

III. APPLICATION OF THE MODEL TO WEST BAY COMMUNITIES IN RHODE ISLAND

Description of Demographic Patterns in the State in Relation to Modelling Procedures

Limitations on high speed memory capacity and execution time of the computer system at the University of Rhode Island precluded inclusion of all communities in a single statewide planning model. Consequently, we restricted our preliminary analysis in four ways. First, the analysis was restricted to communities of 10,000 or more population. Second, the analysis was divided into separate analyses of West Bay and East Bay communities reflecting the natural barrier to transhipments represented by Narragansett Bay. This paper reports the results of our analysis of West Bay communities. Third, certain West Bay communities which are contiguous were aggregated into single "supply points." The fourth way in which our analysis was simplified was that only selected shipment possibilities were permitted. For example, direct shipment between any two points was permitted only if there were no intervening supply points or "nodes." If intervening points existed, shipment between extreme points was possible only indirectly via the intervening node with subsequent transhipment.

The West Bay model included fifteen communities represented by ten supply points. These communities ranged from Woonsocket in the extreme northern end of the State to Westerly in the extreme southwest of the State. Most, however, are close to Providence. These supply points with their associated wastewater supplies (D_j) are listed in Table 1.

Table 1
Waste Water Supply Points for West Bay Model

Supply Point	Waste Water Supplies in MGD[5/]
Providence (includes North Providence and Johnston)	60
Warwick	23
Cranston	11
Pawtucket (includes Central Falls, Cumberland and Lincoln)	33
Woonsocket	8
Smithfield	2
West Warwick	3
North Kingstown	4
South Kingstown	3
Westerly	3

5/ 1990 Projections based on current per capita supplies and population projections of the Rhode Island Statewide Planning Office.

The communities included in the West Bay model include approximately 70 percent of the total State population and 73 percent of the State population in communities of 10,000 or more. It is assumed that all of the supply points have secondary treatment capability. Thus, if any sewage is transmitted or treated in this model it is secondary effluent. The reason for excluding secondary treatment costs is that most communities in Rhode Island are already committed to plans for secondary treatment facilities.

Data Sources and Procedures

The economic model requires data on treatment plant costs. Furthermore, since the model is a linear programming model, cost curves for treatment facilities were approximated by a series of linear segments. If the k^{th} linear segment enters at site j, the associated (0,1) variable Y_{jk} must also enter. The unit cost of the integer variable Y_{jk} represents total cost at the lower end of the linear segment. The unit cost of the associated non integer variable, A_{jk}, represents the incremental cost of moving along the k^{th} linear segment. The treatment cost curve is for tertiary treatment exclusive of secondary treatment. A plant cost curve was derived from data from Wanielista and Sheffield (5), representing the present value, at six percent over 25 years, of the total additional cost of tertiary treatment. This cost curve was then divided into fifteen linear segments as indicated in Table 2. Column 1 indicates the design size. Column 2 indicates the present value of costs for tertiary treatment. The remaining columns indicate the associated unit costs (F_k) of the zero-one variables (Y_{jk}) and the unit costs (a_k) of the non integer variables (A_{jk}).

The costs of shipping wastewater depend on the volumes to be shipped, the distances over which shipment must be made, and whether the flow is by gravity or requires pumping stations. The point to point distances between communities were calculated by a computer program from longitude and latitude coordinates of communities. Pumping stations were assumed whenever slope gradients required it.

(6) The data source for the costs of pipelines and pumping station was Smith (7). Table 3 presents the estimated shipment costs for wastewater. Column 1 indicates the design size of pipes. Columns 2 and 3 indicate the associated costs per mile for force mains and gravity sewers. Column 4 indicates the present worth of the costs of various size pumping stations.

Table 2
Present Worth of Total Treatment Costs for
Tertiary Treatment Exclusive of Secondary Treatment

Values for F_k and a_k

Design Size in MGD (M_{k+1})	Total Cost at Bound	F_k	a_k
$\leq$ 5	10,498,037	3,266,056	1,446,396
$\leq$ 10	15,833,697	10,498,037	533,566
$\leq$ 20	26,098,437	15,833,697	513,237
$\leq$ 30	34,963,437	26,098,437	295,500
$\leq$ 40	42,963,437	34,963,437	200,000
$\leq$ 50	46,038,123	42,963,437	61,493
$\leq$ 60	53,038,123	46,038,123	116,666
$\leq$ 70	58,818,123	53,038,123	82,571
$\leq$ 80	67,187,000	58,818,123	104,610
$\leq$ 90	75,585,330	67,187,000	93,315
$\leq$100	83,783,700	75,585,330	83,983
$\leq$110	92,382,070	83,783,700	76,348
$\leq$120	100,780,440	92,382,070	69,986
$\leq$130	109,178,810	100,780,440	64,602
$\leq$150	126,060,560	109,178,810	112,545

Table 3
Present Worth of Total Cost Per Mile for Gravity
Sewers and Force Mains:
Present Worth of Total Costs for Pumping Stations[6/]

Design Size	Force Mains	Gravity Sewers	Pumping Stations
MGD	$/Mile	$/mile Slope=.005ft/ft	$
1	86,296	92,050	373,263
5	230,125	201,359	1,283,093
10	345,187	287,656	2,239,581
15	466,003	345,187	2,939,450
20	552,300	402,719	3,732,636
25	647,227	431,484	4,432,505
30	690,375	483,262	5,039,058
40	828,450	552,300	6,345,481
50	978,032	632,844	7,465,272
60	1,035,563	690,375	8,398,431
70	1,127,613	724,894	8,818,352

6/ Total cost represents the present worth of capital cost and operating and maintenance expense. For pipelines a 50 year life is assumed. For pumping stations a 25 year life is assumed. The rate of interest used is six percent.

IV. RESULTS

Potential Cost Savings via Regionalized Treatment Cost System

If each of the communities (supply points) listed in Table 1 would construct its own tertiary treatment facilities to comply with 1983 emission standards, the estimated cost would be $201.78 million. On an equivalent annual basis this would be $15.7 million per year.[7/] This provides a basis of comparison for the potential cost savings via regionalized treatment systems.

The solution to the economic model for cost minimization is summarized in Table 4. As indicated, the optimum solution involves a single tertiary treatment plant located in Providence. All other communities would ship directly, or indirectly via intermediate supply

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7/ The equivalent annual annuity factor for 6 percent, 25 years is 0.07823.

Table 4
Estimated Present Worth of the Least Cost Regionalized Tertiary Treatment System
for West Bay Communities in Rhode Island

Municipality	Waste Water Supply (D_j)	Treats	Ships to	Sewage Transmitted MGD	Pipeline and Pumping Costs	Treatment Costs	Total Costs	Sewage Treated MGD
					-Present value in mil. dol.-			
Providence	60	Yes		0	0	126.00	174.74	150
Warwick	23		Cranston	36	6.60			
Cranston	11		Providence	46	10.25			
Pawtucket	33		Providence	43	9.90			
Woonsocket	8		Pawtucket	8	4.50			
Smithfield	2		Pawtucket	2	1.28			
West Warwick	3		Warwick	3	1.28			
North Kingstown	4		Warwick	10	5.90			
South Kingstown	3		North Kingstown	6	4.39			
Westerly	3		South Kingstown	3	4.64			
Totals	150				48.74	126.00	174.74	150

points, to Providence. The present value of costs under this configuration is $174.7 million. On an equivalent annual basis this represents $13.66 million per year. Thus, the potential cost savings via regionalized treatment are $26.26 million ($201 million minus $174.7 million). On an equivalent annual basis, the cost savings would be $2.05 million per year. This represents cost savings of approximately 14 percent. This cost saving is conservative in that our pipeline cost estimates were based on the most costly of three methods reviewed.

Cost of Avoiding Discharge into Upper Narragansett Bay

Although the effluent from tertiary treatment plants is of relatively high quality, some residuals would remain. Based on a discharge volume of 150 MGD this would represent substantial daily discharges in a localized area at the head of Narragansett Bay.

The precise ecological impacts of these discharges on Narragansett Bay are unknown. An alternative to discharge at Providence would be to force the regional system to discharge into the open ocean where assimilative capacity is greater. To explore this alternative we forced the regional treatment plant to be at South Kingstown-Narragansett. The total cost of this alternative was $244 million or $70 million more than the least cost solution. This tremendous increase in cost is due primarily to the cost of pumping and piping, for most of the wastes are in the northern end of the state, but pumping is required due to the flat terrains throughout the State. On an equivalent annual basis, therefore, the marginal cost of avoiding tertiary discharge into Narragansett Bay would be $5.5 million per year.

Areas for Further Research

There are several areas where further research seems appropriate. The first of these is in the pricing of water supplies and wastewater treatment. Most of the cost of treatment is associated with the volume of water which must be processed rather than the residual material in the water. This in turn reflects in part the technology of water using household appliances and the design of flush toilets; the latter requiring approximately eight gallons of water for each use. It seems plausible that price incentives might induce some long run substitutions via technological innovation. Peak load pricing to even out peak discharges and reduce the need for excess plant capacity during most of the day is another possibility in connection with pricing.

A second area for investigation concerns the interconnection between zoning regulations, housing density and the need to provide public treatment facilities as opposed to less costly, private septic tank systems. This aspect is discussed in some detail in Norton, *et al.* (1).

A third area concerns the possible need for streamflow augmentation when groundwater and surface supplies are exported from an area due to a regionalized treatment system. In some streams in the State, the emission from existing secondary treatment plants comprises as much as 40 percent of the minimum stream flow.[8/]

A fourth area for research concerns dynamic, as contrasted with spatial investment strategy. Plant design capacity is typically based on projected supplies in 25-30 years. Consequently, there usually is substantial excess capacity for one or two decades. This excess capacity could be reduced by phased investment over time. The question this raises is, what is an optimal phasing of investment over time?

A fifth area concerns possible complementarity with electric power generation which requires enormous volumes of cooling water. None of the individual communities has a large enough volume to be useful for even a modest sized power plant. However, it is possible that the effluent from a regionalized system could be useful in this connection.

Finally, an additional area for research is the economics of alternative technologies for wastewater disposal. For example, it has been noted that soils comprise a natural biological "filter." Golf courses, forest land, agricultural lands are obvious filters on which to spray the effluent of secondary treatment plants. The City of Chicago for example recently received an analysis indicating enormous cost savings from buying agricultural land for this purpose (8). Land treatment alternatives could be analyzed by introducing supply sites with zero supplies at geographic locations where land treatment is a viable alternative. At these sites the treatment cost coefficients would be adjusted to reflect the costs of land treatment technologies. We did not examine land treatment alternatives because of time and data limitations.

[8/] Personal communication, Rhode Island Statewide Planning Office.

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