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SMALL SCALE WASTE MANAGEMENT PROJECT

Cost Comparison of Wastewater Collection and Disposal Alternatives

by

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COST COMPARISON OF WASTEWATER COLLECTION AND DISPOSAL ALTERNATIVES

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By way of introduction, when site limitations make conventional on-site disposal impractical, one option may be a collection system for transport and treatment off-site. Computer methods have been described elsewhere for the design and costing of both gravity and induced flow systems. This paper describes the use of a tool for the optimal selection and sizing of components to be incorporated into a complex wastewater management system to provide a variety of collection, treatment and disposal alternatives to satisfy the needs of a geographically diverse service district. A specific design example is analyzed, namely that of periodic surface vehicle transport of wastewater from domestic holding tanks to regional wastewater treatment facilities.

The study area selected is Washington Island in Lake Michigan north of Green Bay; it combines many of the above characteristics and presents a uniquely bounded region for investigation. The island is experiencing intensive development of seasonal recreational activities, and its soil conditions are largely unsuited to conventional spetic tank and soil absorption field installations (Becker-Hoppe 1972) (Institute For Environmental Studies 1973).

PROBLEM DESCRIPTION

The objective of this study is to identify and assess the usefulness and cost of alternatives to conventional septic tank-soil absorption systems in an area where conventional on-site disposal system performance is limited by shallow bedrock. Washington Island is sparsely settled, except for the southwest corner, as shown in Fig. 1. A consulting engineer had previously studied the island wastewater problem and proposed a partially sewered system for the more populated areas where soil conditions were appropriate for subsurface pipeline construction. He further recommended consideration of other approaches to wastewater collection and disposal for the more sparsely settled and difficult to sewer portions of the island such as some surface transport of wastewater for the remaining dispersed residences on the eastern portion of the island.

The writers describe a generalized planning tool and its application to identify other potentially cost-effective systems for an area where a variety of surface transport configurations can be evaluated. For purposes of investigating the utility of surface transport of wastewater, the number and location of dwellings in the service area were estimated from the USGS quadrangle map for 1960. While these figures are not current, the distribution of the dwellings was taken as representative of present development. The dwellings were then grouped into 35 clusters as shown by the squares with single or two letter lables in Fig. 1. Potentially feasible treatment plant sites were then chosen by a preliminary analysis; in-depth local investigations might mitigate against some of these sites and identify others. The sites are identified as

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circles having indices 1 to 13 in Fig. 1, also. To simplify the illustration, it was further assumed that the treatment facility which could be constructed at each site was a biodisc unit; use of the methodology described below for rigorous cost-effectiveness analysis would of course entail selecting the most suitable treatment method for each site, based on cost and local environmental considerations. However, this can be done without loss of generalization.

Fig. 1 Map of Washington Island

The shortest road distance between each cluster of dwellings and every potential treatment plant site was then determined for the given road network and is shown in Table 1.

Table 1. Matrix of Shortest Routes Between Housing Clusters And Treatment Plant Sites. U.S. Statute Miles[a]

Housing Clusters	Treatment Plants 1	2	3	4	5	6	7	8	9	10	11	12	13
A	0.4	1.8	3.2	4.0	5.4	4.6	2.5	3.1	5.1	4.6	5.8	7.6	3.5
B	1.2	.3	1.7	2.5	3.9	3.1	1.6	1.6	3.6	3.1	4.3	6.1	2.0
C	1.5	.3	1.4	2.2	3.6	2.8	1.9	1.9	2.9	3.4	3.9	5.9	1.7
D	2.1	.9	.8	2.1	3.5	2.7	2.5	2.5	3.5	4.0	3.9	5.7	2.0
E	3.0	1.8	.2	2.6	4.0	3.1	2.3	3.2	4.3	4.8	4.3	6.1	2.9
F	2.9	2.1	0.5	2.9	4.3	3.5	2.6	3.5	4.6	5.1	4.6	6.4	3.2
G	0.8	1.6	2.9	3.8	5.2	4.4	2.3	2.7	4.9	4.4	5.6	7.4	3.3
H	1.6	1.2	2.6	3.4	4.8	4.0	1.0	2.0	4.2	4.1	5.0	7.6	2.8
I	1.7	1.3	2.7	3.6	4.0	3.2	0.4	1.4	3.7	3.5	4.4	7.0	2.2
J	2.0	1.6	3.0	3.3	3.7	2.9	0.1	1.1	3.4	3.2	4.1	6.7	1.9
K	2.3	1.9	3.3	3.6	4.0	3.2	0.2	1.3	3.6	3.4	4.3	6.9	2.1
L	2.8	2.4	4.4	4.1	4.1	3.0	0.6	1.1	3.3	2.7	2.9	5.4	1.8
M	3.2	2.8	4.4	4.2	4.1	3.1	0.9	1.2	3.4	2.8	3.0	5.5	1.9
N	1.9	0.8	1.9	2.5	3.2	2.3	0.9	0.9	2.9	2.3	3.6	5.4	1.3
O	2.4	1.4	3.1	2.9	3.3	1.9	1.0	0.4	2.4	1.8	3.1	5.0	0.8
P	2.7	1.7	3.3	3.2	3.5	1.7	1.3	0.1	2.1	1.5	2.8	4.7	0.8
Q	3.1	2.1	3.7	3.6	3.9	2.1	1.7	0.5	1.7	1.1	2.4	4.3	1.2
R	3.7	2.7	4.3	4.2	4.5	2.7	2.3	1.1	1.1	0.5	1.8	3.7	1.8
S	4.1	3.1	4.3	4.1	4.5	2.7	2.7	1.5	1.2	0.2	1.4	3.4	1.4
T	4.1	3.1	4.7	4.5	4.9	3.1	2.7	1.5	1.0	0.7	1.9	3.9	2.2
U	4.8	3.8	5.4	5.5	5.9	4.1	3.4	2.6	0.2	1.2	2.4	4.4	2.4
V	5.1	4.1	5.7	5.8	6.2	4.4	3.7	2.9	0.3	1.5	2.7	4.7	2.7
W	4.7	3.7	4.3	4.1	4.5	2.8	3.3	2.1	1.8	0.3	1.5	3.4	1.5
X	5.2	4.2	5.0	4.8	5.2	3.2	3.9	2.7	2.4	0.8	1.8	3.7	1.8
Y	3.1	2.1	2.7	2.5	2.9	1.2	1.6	0.8	2.7	1.5	2.3	4.3	0.2
Z	4.5	3.5	3.2	2.9	3.4	1.4	3.0	2.2	2.3	1.0	1.0	2.9	1.4
AA	3.1	2.4	1.8	1.6	2.0	1.2	1.7	1.3	3.7	2.4	2.4	4.2	1.0
BB	3.3	2.7	1.6	0.4	1.8	1.8	2.9	2.5	4.9	3.6	2.9	4.0	2.2
CC	4.1	3.4	2.8	0.8	1.0	0.9	2.7	2.3	4.7	3.4	2.0	3.2	2.0
DD	4.7	4.0	3.4	1.4	1.4	0.6	2.3	2.6	4.5	3.0	1.9	2.6	1.8
EE	6.7	5.7	5.2	3.8	1.8	2.9	5.3	4.1	3.8	1.8	1.3	0.8	3.5
FF	7.8	6.8	6.5	4.8	3.0	3.7	6.4	5.2	4.9	2.[illegible]	2.4	0.7	4.6
GG	8.3	7.3	7.0	5.3	3.5	4.2	6.9	5.7	5.4	3.4	2.9	3.2	5.1
HH	7.7	6.7	6.2	4.5	2.7	3.9	6.3	5.1	4.8	2.8	2.3	0.6	4.5
II	8.7	7.7	6.9	4.9	3.1	3.2	6.8	5.2	5.5	3.5	3.0	1.3	4.4

[a]Note: One U.S. Statute Mile = 1.609344 kilometers.

Recently quoted costs of biodisc units are shown in Fig. 2 which gives total initial plant cost as a function of installed capacity. The lower values are local cost contributions assuming that the current Grant-in-Aid program provides 75 percent of initial cost. Operating costs shown in Fig. 3 include energy costs. To illustrate the method of analysis advocated here, reasonable approximations for the capital and operating cost curves must be assumed as shown in Fig. 4.

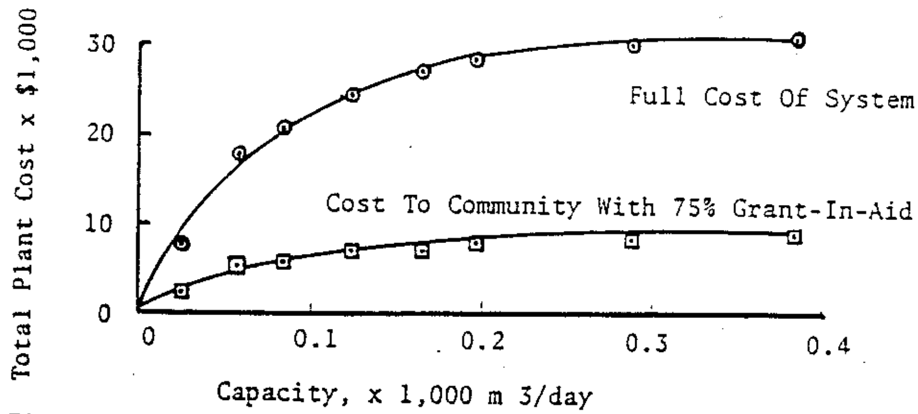

Fig. 2. Initial Biodisc Capital Cost v. Plant Capacity

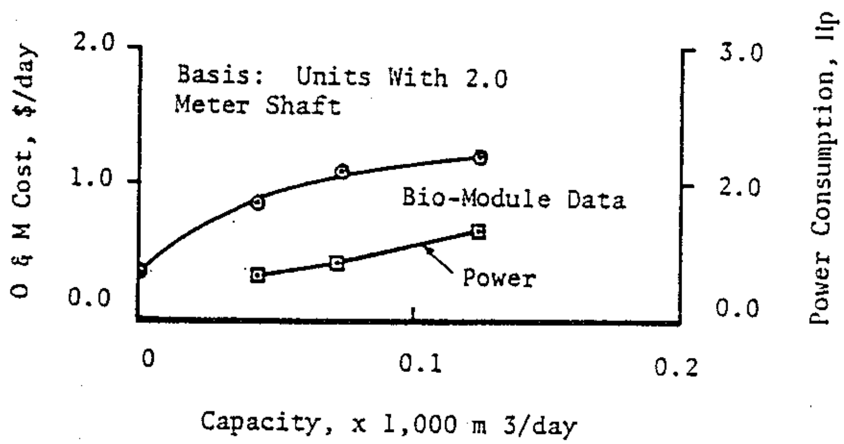

Fig. 3. Biodisc Power Consumption and Daily Operating Cost v. Plant Capacity

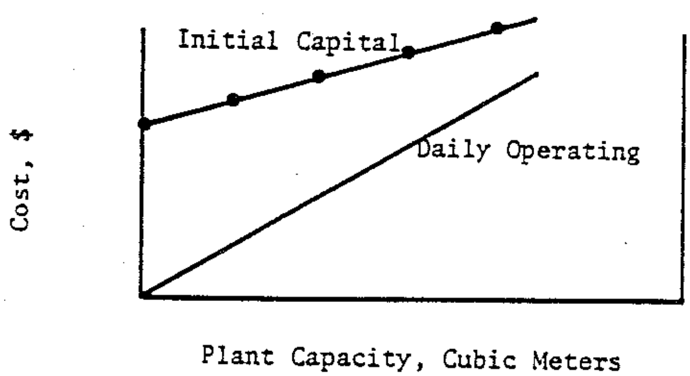

Fig. 4. Initial Biodisc Capital Cost v. Plant Capacity

The data shown here are sufficient for this simplified illustration. If a more complex system including individual residential on-site disposal facilities and other control treatment and/or disposal alternatives, then these multiple data inputs would be required. However, the model would serve just as well except that run costs would increase slightly.

These curves are seen to approximate the more recently cited costs quite well, especially since cost slopes for both curves and the fixed cost intercept for the capital cost curve may be set individually for each site. Transportation costs were reduced to a unit cost in $\$/km/m^3$ (\$/mile/gallon). Here, a fixed operating cost per kilometer (mile) traveled was combined with a given truck capacity and shortest distance traveled between every housing cluster and potential treatment site. Alternative plans are then generated with the given information for a variety of future demand conditions and cost projections by means of a computer model (MACC 1973).

The Mathematical Model

In formulating a waste-management system using surface transportation to deliver wastewater to regional treatment plants, the problem becomes one of examining trade-offs between number of plants vs. transportation costs*. Solutions at the extremes of the spectrum can readily be imagined. They will either consist of a single, large treatment facility with sufficient capacity to allow all wastes of the island to be brought to it, or alternatively, one could build all of the possible facilities each at very small capacity, resulting in much reduced transportation costs to ship wastes from dwelling units to nearby treatment plants.

The mathematical formulation must account for the fixed-charge cost curves shown to be characteristic of treatment plants. Fig. 4 shows the capital cost vs. plant capacity which accrues initially when the facility is constructed. It should be noted that the initial capital investment is taken as a fixed charge independent of capacity, plus an initial investment which is a linear function of plant size. Once the plant is in operation, there are daily operational costs (i.e. power costs) which are a direct function of capacity. Daily operating costs are shown in Fig. 4. Here, too, fixed costs could be considered, such as the wage rate of a plant operator which must be paid whether the plant is operating or not.

The final cost considered in the model is the transportation cost. To compute a unit cost t_{ij} in \$/cubic meter (\$/gallon) of shipping waste from housing cluster j to treatment service facility i, one simply takes

$$t_{ij} = (\text{distance}) \times \frac{\text{cost per meter}}{\text{truck capacity}} \quad (1)$$

*In setting up the problem, reasonably closely clustered individual homes are grouped into housing clusters. All possible and reasonable sites for treatment facilities are identified, as well as the associated maximum plant capacity. The latter would very likely be a function of local site characteristics. Once these points (fixing either demand points for waste treatment service or supply points where this service could be provided) are determined, the mileage of the most convenient transportation route between every housing cluster j and every plant i is established. This could in itself be an optimization problem, but in many cases can probably easily be determined by map and site inspection.

Given that plant costs (capital and operating) are linear with respect to capacity, the unit cost of treating one gallon of wastewater from housing cluster j at facility i, c_{ij}, is simply the sum of the variable costs

$$c_{ij} = t_{ij} + o_i + k_i \tag{2}$$

where t_{ij} is as before, o_i and k_i are respectively, the \$/cubic meter (\$/gallon) variable expansion costs of the plant i operating and capital cost curves. Here the initial capital cost curve of Fig. 4 has been converted to a daily average capital cost curve by converting plotted ordinates to average daily values by

$$\text{Daily cost} = K \quad \frac{r/365}{1-(\frac{1}{1+r/365})} \quad T \times 365 \tag{3}$$

where K is the ordinate in dollars from the initial capital cost curve, r is the annual interest rate, and T is the economic life of the facility in years. For the example problem, i = 5 percent and T = 25 years were chosen.

If the service provided by plant i to housing cluster j is defined as X_{im} cubic meters/day (gallons/day), and S_i is the maximum allowable plant capacity in cubic meters (gallons), then all waste transported to i must be less than or equal to S_i

$$\sum_{j=1}^{n} X_{ij} \leq S_i \, Y_i \quad \text{for } i = 1, \ldots, m \tag{4}$$

where n is the total number of housing clusters, and m is the total number of potential treatment facilities. S_i is the maximum allowable capacity of the treatment facility at location i and Y_i is an integer variable restricted to values of zero or one, such that if

$Y_i = 0$ treatment facility i will not be constructed

$Y_i = 1$ a treatment facility will exist at site i in the final solution

Since the $X_{ij} = 0$ for all possible wastewater transfers on the island (i.e., negative flows would imply transport from treatment plants back to housing clusters), the above constraint also insures that no waste can be transported to site i if no treatment facility is constructed there.

An additional requirement is that the demand D_j for waste treatment service at each housing cluster j must be satisfied.

$$\sum_{i-1}^{m} X_{ij} = D_j \quad \text{for } j = 1, \ldots n \tag{5}$$

Also note that any X_{ij} associated with a demand D_j has an upper bound of D_j, i.e., any one "shipment" of waste in the above sum can not be larger than D_j.

Finally, the problem can not be solved unless the total treatment capacity at all sites which could be constructed equals or exceeds the total generated demand for service, i.e.,

$$\sum_{i=1}^{m} S_i \geq \sum_{j=1}^{n} D_j \tag{6}$$

Given the above, the problem is then to find values of the X_{ij} and associated Y_i to minimize the total fixed and variable costs

$$\text{Minimize} \sum_{i=1}^{m} F_i Y_i + \sum_{i=1}^{m} \sum_{j=1}^{n} C_{ij} X_{ij} \tag{7}$$

where F_i is the fixed cost intercept of the average daily total cost curve of treatment facility i (incorporating initial capital costs and running operating costs).

APPLICATION

In the example problem for Washington Island, Wisconsin, the problem was set up with

- n = 6 potential treatment facilities
- m = 35 housing clusters, where in each cluster contiguous houses are lumped together and assumed to act as a single wastewater demand point.

A number of the parameters defining the problem are assumed to be derived in a planning context and thus will have inherent uncertainty associated with them. In order to allow for maximum flexibility in examining potential future developments, the model was structured as an interactive program, allowing ready use of it in a planning framework, where the effects of a variety of changes in input parameters on system configuration and overall cost can be studied. It incorporates the use of a mixed-integer optimization subroutine in the University of Wisconsin computing center program library called IPMIXD; other comparable routines could be substituted.

The following parameters have been selected to be adjustable in the program.

- CAPINT - Fixed capital cost of treatment plants
- CAPRIS - Variable capital cost of treatment plants
- CSTPMI - Unit transportation cost per mile
- OPRIS - Variable operating costs
- MAXCAP - Maximum plant capacities

N Source - Number of potential plants in a trial examination, (presently limited to a maximum of six) selected from the set of usable sites.

DMDF - Demand growth of the thirteen housing clusters (A to M) on the western side of Washington Island.

Parameters which are presently fixed in the program are:

Interest rate = 5 percent per year

Economic time horizon = 25 years

Fixed operating cost = 0

Truck capacity = 13.63 cubic meters (3600 gallons)

Number of housing clusters = 35

Data requirements, in addition to the treatment facility cost functions and maximum capacities described above, include the wastewater generated at each housing cluster, and the shortest route distances in miles from every housing cluster j to every potential treatment site i. The latter are given for the example problem in Table 1. For illustrative purposes, all facilities were taken as biodisc units, each having the same capital and operating cost characteristics. To consider different installations, different cost data for each site can be supplied to the program.

DISCUSSION

Table 2 is a compilation of results for different values of some of the input parameters. In the example printout, the planner first provides a particular input set of those planning parameters allowed to vary in the program. The second data entry pertaining to sources consists of a maximum of six indeces identifying the potential subset of sites to be considered in this run. For the given demand projection cost, and potential site figures provided an optimal configuration is then calculated based on the criterian of lowest overall system cost. For example, Run No. 3 shows that plants 4, 6 and 10 should not be built, while the needed capacities of 100.84 cubic meters (26,640 gallons), 140.06 cubic meters (37,000 gallons) and 45.425 cubic meters (12,000 gallons) are to be installed, respectively, at sites 2, 8 and 12. For each of these sites, the housing clusters contributing wastewater are identified by an index (1 to 35) and their alphabetic label. Note that a housing cluster will ship all of its wastewater to a single site, i.e. all of flow from site A will go to plant 2, all of flow from site C will go to plant 8 and so on. Total installed capacity of 286.33 cubic meters (75,640 gallons) per day is exactly equal to the total volume of wastewater generated and the daily cost of $21.59 is the minimum cost for this set of input data. Table 2 summarizes the results of nine separate runs showing the versatility in examining alternative future development and cost. In each case, the solution shown is the optimal configuration for the given input parameters. The explicit solution to run No. 1 is illustrated in Fig. 1.

CONCLUSION

A versatile planning tool has been demonstrated for purposes of cost-effectiveness comparisons among unlike alternatives to solve increasingly important small community waste-management problems. Rather than selecting what may be a rational engineering solution by experience alone, and thus possibly overlooking less obvious alternatives such as on-site disposal, the program explicitly considers every possible transportation-treatment-disposal solution for a given set of planning options and for each source cluster to derive a true least cost alternative. Given the uncertainty implicit in planning parameter determination, the program can readily provide alternative projections at a nominal cost per run. The resulting information not only identifies alternative optimal systems for possible future development, but it also allows ready examination of the sensitivity of selected planning parameter estimates on treatment system configuration and cost. Another possible use for this approach is the determination of the most reasonable alternative treatment system under various water conservation regimens. Although general indications are that truck hauling of wastewater is always less expensive than piping for small flows, these cost savings could be made explicit for a variety of water use options and housing cluster treatment site transportation modes.

Table 2.

Synopsis Of System Costs And Characteristics Resulting From Different Input Specifications

Run #	No. of sites (treatment)	System flow rate g/day	Plant(each) capacity g/day	Initial cap. inv. $	Transp. cost $/mile	Operating cost slope	Cost/day (operation) entire system	Remarks
1	2,4,6,8,10,12 6	75,640	50,000	20,000	0.25	3.8	25.09	sites picked 2, 10
2	2,4,6,8,10,12 6	75,640	100,000	20,000	0.25	3.8	24.98	site picked 8
3	2,4,6,8,10,12 6	75,640	100,000	10,000	0.25	3.8	21.59	sites picked 2, 8, 12
4	2,4,6,8,10,12 6	110,200	100,000	10,000	0.25	3.8	28.67	flow rate[a] changed A
5	2,4,6,8,10,12 6	75,640	100,000	10,000	–	8.0	27.95	op.cost slope changed
6	2,4,6,8,10,12 6	75,640	100,000	10,000	0.50	3.8	27.54	transp. cost doubled
7	7,2,6,8,10,12 6	75,640	50,000	20,000	0.20	3.8	22.91	sites picked 2, 10
8	7,2,6,8,10,12 6	75,640	50,000	20,000	0.60	3.8	35.36	sites picked 2, 10
9	7,2,6,8,10,12 6	75,640	50,000	20,000	1.00	3.8	45.20	sites picked 7, 2, 10, 12
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[a] system flow rate from sites A→M doubled.

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