Water quality

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The Demand for Land Treatment of Municipal Wastewater

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Federal law is requiring increased levels of treatment for municipal wastewaters. The 1972 Water Pollution Control Act Amendments established the goal to prevent, reduce, and finally eliminate water pollution by 1985 [Scranton Gillette, Inc., 1973]. Federal funds provide up to 75 percent of the construction costs of municipal treatment plants. Cities and towns are examining alternative treatment techniques to meet the higher treatment standards and to qualify for federal financial support.

One such technique is land treatment. Land treatment is the controlled application of partially treated wastes to the land for the purposes of purification and crop production. As the wastes move through the soil, they are purified by bacterial decomposition, soil particle fixation, and plant removal of nutrients. Crops are produced and sold as a by-product of the operation. This is a long established treatment technology which is being extended to other sections of the United States.

Municipal sewer system officials are usually thought to have the objective of collecting and treating a given volume of wastes to a given level of treatment at the lowest possible operating and construction cost.[1] Little attention seems to have been given to the influence of federal funding, or by-product production and sales on the economics of wastewater treatment. This paper presents a model of local waste treatment production and the

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[1]See Smith, 1969, for estimated of operating and construction cost relationships in conventional treatment plants. See Downing, 1969, for a discussion of collection and treatment costs over peak-flow periods.

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derived demand for land-intensive technology. The adoption of land treatment in the southern part of the United States provides a test of the applicability of the model.

Land Treatment Technology

The land treatment sites for municipal effluents range from agricultural crops to golf courses. Table 1 presents a summary of the uses of land treatment in California. The most prevalent activity is pasture and fodder crops which make up 37 percent of the total. Urban as well as rural sites are used. Note that 30 municipalities use treated sewerage effluent to irrigate golf courses or landscaped grounds. The land receiving the effluent is used daily by the general public. The major precautions are chlorination and spraying at times when the facilities are not being used.

There is concern that pathogens of infectious diseases in sewerage will be spread over large land areas and threaten the public more than from conventional treatment plants. Several states have laws dealing with chlorination of wastes, consumption of crop produce, and establishing barriers of unused land between the application site and the public (see Sullivan, et.al., 1973). Glennon [1974] has reported on research which indicates that spray equipment modification and high levels of disinfection can significantly reduce the dangers from airborne pathogens. Chlorination prior to land treatment appears more cost effective than large buffer zones in reducing health hazards.

The necessity to purchase land near a town is often given as an obstacle to low cost land treatment. The specialized labor and management skills to operate a farm are thought to be a prerequisite for municipal land treatment.

However, there are many land and labor lease arrangements which municipalities are using to reduce these problems. In addition to self operation of a land site, municipal officials can either sell or give the effluent to others. Table 2 shows various land and operation arrangements of a size-stratified random sample of municipal land treatment sites in the southern United States [Young, 1974]. Notice that about 50 percent of the municipalities used privately owned land for treatment purposes. Sixty-four percent of the facilities were operated by non-municipal employees.

In the past, purchase of land was not considered to be part of construction cost eligible for federal support.[2] One would suspect that local governments would avoid treatment technologies which have high operating relative to construction cost if federal support is available only for the latter. Data from Sullivan, et al. and Young, 1974, suggest that the ratio of operating and maintenance to total cost may be higher for land treatment facilities than for conventional facilities. Thus, a hypothesis to consider is that federal grants for construction may have discouraged adoption of land treatment systems.

The decision to select land treatment rather than in-plant treatment is a long-run decision. Future prices of by-products, required degree of treatment over the life of the facilities, and growth in volume of wastes must be considered. The basic assumption of this article is that economic incentives will help explain past choices and will enable one to interpret how changes in economic parameters will affect future adoption of land treatment.

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[2] Although current federal legislation expressly states that land treatment as an alternative technique must be considered, it is not clear if land purchase, land leasing, and spray equipment costs will be eligible for federal support.

Table 1. Land treatment crops and activities in California, 1971

Use	Number of Municipalities	Percentage of Total
Pasture and Fodder Crops	50	37.3
Agricultural Crops	40	29.8
Golf Courses and Landscape	30	22.4
Recreational Lakes	6	4.5
Combinations	8	6.0
Total	134	

Source: Compiled from Deaner [1971]

Table 2. Institutional arrangements for municipal effluent disposal

Municipally owned land:	
Purchased for waste treatment and operated by municipality	13
Purchases for waste treatment and leased to farmers	8
Land purchased for other purposes	5
Privately owned land:	
Effluent sold to farmers or others	10
Effluent given to farmers or others	14

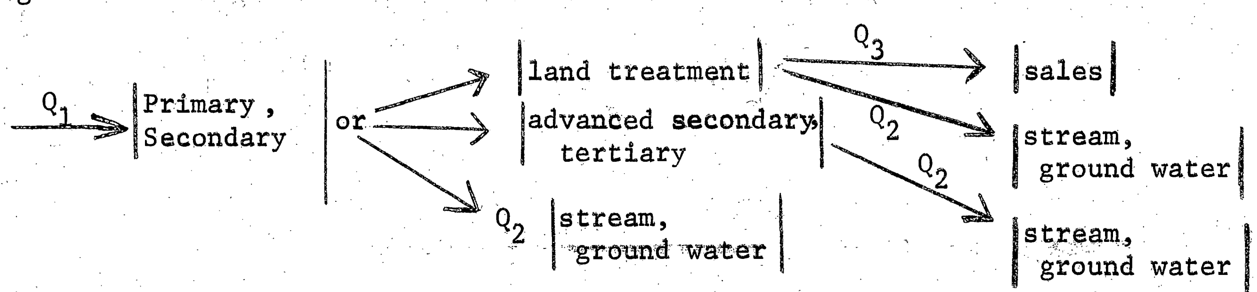
Source: Compiled from survey of municipalities [Young, 1974]

Economic Model

Economic models of public services are difficult to specify because units of output and prices are ambiguous. Under ideal conditions it would be desirable to measure wastewater treatment services by the quantity of elements per unit of sewerage entering the treatment facility, the flow per day, the rate of flow of total treatment and the concentration of elements remaining following treatment. This would provide data for an engineering model of the costs of removing elements from wastewaters. However, Young, 1974, has shown that treatment costs for a large sample of treatment plants vary with rate of influent flow (Q_1) and quantity of elements remaining (Q_2).

With land treatment of wastes there is a third dimension of output - saleable by-products (Q_3). If the treatment officials operate an irrigation system following primary and secondary treatment, the measures of output are shown in the upper level of the treatment chain of Figure 1.

Figure 1. Wastewater treatment chain with land treatment



Alternatively, municipal treatment officials can sell the effluent prior to land treatment. Also, they may choose advanced secondary or tertiary or direct disposal.

Technically, the three products (Q_1, Q_2, Q_3) are jointly produced, but not in fixed proportions. Output of a crop (Q_3) might rise then fall as more flow (Q_1) is applied with all other inputs and Q_2 fixed. If nutrients remaining in the effluent (Q_2) are allowed to rise, then the crops yield (Q_3) might eventually decline from lack of nutrients. Given inputs designated as those primarily used in land treatment, L (land and labor) and those used in in-plant treatment, K (capital), and uncontrollable environmental conditions (S) the production function (f) can be written as:

$$Q_3 = f(Q_1, Q_2, L, K, S) \qquad (1)$$

From an institutional viewpoint, the minimum level of treatment is determined outside the municipal authority. All volumes of influent (Q_1) must be treated. That is in describing construction and operation of treatment facilities over the past twenty years it is assumed that population growth and wastewater flows are not significantly affected by decisions of the municipal wastewater officials.[3] Thus, the flow is given as an exogenously determined constant (k):

$$Q_1 = k \qquad (2)$$

The degree of treatment (Q_2) is often determined by regulatory agencies. Municipalities must treat their influent so that their discharges to streams

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[3]A model of treatment decisions over recent history for some cities would need to include the optimum level of water and industrial surcharges to regulate the flow and quantity of suspended wastes entering the treatment facility. Most of the construction decisions in the empirical portion of this study took place prior to implementation of surcharge systems. See Elliott and Seagraves [1972] for estimates of the effects of surcharges.

do not cause the streams to fall below minimum standards; usually specified as minimum levels of dissolved oxygen (E_M). Dissolved oxygen levels in streams are functionally related to waste discharge (Q_2) and dilution capacity of the stream (R). Assuming that stream standards are fairly constant geographically (E), the constraint for required level of treatment can be written as:

$$Q_2 \leq E(R) \qquad (3)$$

As seen in Figure 1 there are several choices of technologies and inputs to obtain required levels of treatment (Q_2). High volumes (Q_1) will raise final contaminant concentration assuming other inputs are fixed. If more nutrients are taken up by plants on land treatment raising saleable by-product yield (Q_3), then Q_2 should fall. The technical possibilities for achieving various effluent concentrations can be written as another production function (h) and substituted into equation 3 to obtain:

$$h\ (Q_1,\ Q_3,\ L,\ K,\ S) \leq E(R) \qquad (4)$$

The treatment authority profit relationship (Z) which can potentially sell by-products, but has constant service charges (C) is:

$$Z = P_3 \cdot Q_3 - P_L \cdot L - P_K \cdot K \cdot G + C \qquad (5)$$

where P_3 = price of by-products, P_L = price of land inputs, P_K = price of capital for non-land technology and G = share of capital costs paid by the local government. In the past, construction costs were partially offset by federal support, and it is assumed that only local costs concern local public decision makers.

To find optimal combinations of land inputs, capital, and production of Q_3 one can maximize equation 5 subject to the treatment constraint 4 by the

Lagrangian method:[4]

$$P_L - P_3 f'_L - \lambda h'_L = 0$$

$$GP_K - P_3 f'_K - \lambda h'_K = 0 \qquad (6)$$

$$- P_3 - \lambda h'_{Q_3} = 0$$

$$h(Q_1, Q_3, L, K, S) - E(R) \leq 0$$

The set of equations in (6) can be solved for the land input.[5] By reintroducing the required level of flow ($Q_1 = k$) to treat and assuming that the production relationships in equations (1) and (4) are of the power function form with constant term α_o, the derived form for the land input (L) is:

$$L = \alpha_o \; P_L^{\alpha_1} \; P_K^{\alpha_2} \; G^{\alpha_3} \; P_3^{\alpha_4} \; Q_1^{\alpha_5} \; Q_2^{\alpha_6} \; E(R)^{\alpha_7} \; S^{\alpha_8} \qquad (7)$$

When one considers L to be an input to the land treatment technology such as land, then expression (7) is equivalent to a factor demand relationship. As for any demand relationship, one would expect α_1 to be negative, and the substitute price coefficient, $\alpha_2 > 0$. Land sites may have higher operating and lower capital costs relative to conventional plants. Therefore, less land treatment would be adopted with a rise in non-local support

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[4] f'_L is the partial derivation of equation 1 with respect to land input (L). λ is the Lagrangian multiplier equal to the marginal cost of a more stringent degree of treatment (E(R)) constraint.

[5] Solution of the system of equations with an inequality requires that the following condition be met: $\lambda[h(Q_1, Q_3, K, L, S)] - E(R) = 0$. For this equation to equal zero the municipality must be providing the minimum allowable level of treatment given the particular river flow: $Q_2 = E(R)$. If the municipality acts as a loss minimizer over the long run, this equality appears reasonable.

for construction; that is, α_3, the coefficient on local share is expected to be positive. α_4 represents the effect of changes in the price of by-products on the demand for land treatment; its sign is expected to be positive from standard derived demand theory.

The remaining variables are expected to have negative effects on land treatment. The effect of increased waste flow (Q_1) on adoption of land treatment is not unambiguous. If costs of land treatment relative to in-plant treatment are less favorable as waste volumes increases as Young [1974] found, then one would expect $\alpha_5 < 0$. Young [1974] and others have found that at high levels of BOD_5 removal, costs increase at an increasing rate in conventional treatment plants. Thus, as final concentration requirements become more stringent (less BOD_5 allowed into receiving waters) one would expect land treatment to become less costly relative to in-plant secondary or tertiary treatment ($\alpha_6 < 0$). Among cities situated on streams of various flow one would expect lower flows to be associated with higher dissolved oxygen standards which would favor land treatment ($\alpha_7 < 0$). The environmental variable (S) is total rainfall. Additional rainfall will increase land acreage and storage costs ($\alpha_8 < 0$).

Land treatment inputs (L) are used when the plant adopts land treatment technology. If many randomly chosen cities are included in an analysis, equation seven can be estimated as a probability (range zero to one) of adoption function.

Empirical Analysis

Over the past twenty to thirty years most cities and towns have built and financed wastewater treatment facilities. Most have not used large amounts of land, yet many in the southwestern part of the United States have. To apply the above model, a sample of 500 southern cities were surveyed in 1973 to obtain data on wastewater treatment costs. One hundred and twenty-five cities responsed of which 50 used land treatments.[6]

Both questionnaire responses and secondary data sources were used to compile input measures for each treatment facility. Land (P_L) and labor (P_{L1}) prices utilized were county agricultural land and skilled worker wage rates, respectively [U. S. Department of Commerce, 1972a, 1973]. The price of capital or non-land inputs (P_K) was taken to be the product of local interest rate on sewerage plant construction bonds times the regional construction cost index [Young, 1974 and Federal Water Pollution Control Administration, 1968]. A more complete description of the effect of input prices (including electricity and chemicals) on treatment plant costs can be found in Young and Carlson, 1974.

The local relative cost of land treatment to conventional treatment was expected to change as subsidy level changed. The measure used for local share (G) was all municipalities contribution to treatment plant construction divided by total construction cost for a given year.[7]

By-product prices for the many different commodities produced were difficult to quantify because of crop rotations and unpriced commodities

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[6]Is is essential to distinguish between the decision to adopt land treatment and the shorter-run decision of the intensity of its use once installed. In this case the former is being evaluated. The problem of bias sampling due to higher response rates from larger plants was corrected for by size stratifying the sample, and following mail questionnaires with telephone requests to all respondents equally. The sample distribution had a very similar size distribution to the parent population.

[7]Shares were constant for all municipalities in a given year due to data limitations. Local shares varied from 47 to 100 percent of construction cost [Environmental Protection Agency, 1971].

such as landscape irrigation. The procedure followed was to assume that the by-product was irrigation water, not crops. Local irrigation water price per acre foot was used [Heady and Agrawal, 1972]. Nutrient values in the irrigation water were assumed constant across all locations.[8]

Municipal sewerage officials were able to supply data on treatment volume (Q_1) and treatment level (Q_2) after secondary treatment [Young, 1974]. Treatment volume was measured as average million gallons per day treated. The treatment level measure desired for the analysis was final concentration of BOD_5 (mg/l) returning to streams and ground water.[9] Most land sites did not monitor final BOD_5 in the return waters; this value was estimated for each land facility using characteristics such as application rate, crop type, soil type, degree of pretreatment and other variables [Young, 1974].

The environmental constraint (R) was taken to be proportional to average river flow of the stream nearest the municipality [U. S. Department of Interior, 1973]. Annual rainfall estimates (S) were from nearest weather stations [U. S. Department of Commerce, 1972b].

Estimation of the parameters of equation seven was conducted by linear and non-linear multiple regression. Non-linear regression was attempted

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[8] This does not imply that fertilizer prices do not influence land treatment decisions. For most years when the sample of cities were considering land treatment, fertilizer prices were relatively constant. For an evaluation of estimated effects of fertilizer price changes for 1973-74 on profitability of operating land sites see [Young and Carlson, 1974].

[9] Attempts were made to determine concentration of nutrients and heavy metals. Only a few sites measured these after secondary treatment and none after land treatment. BOD_5 was used as a rough approximation of treatment level since data were available.

because the dependent variable is interpreted as the probability of land treatment adoption; a variable with a zero to one range. Both the linear and non-linear specifications will have error disturbances which are heteroscedastic. The advantage of the non-linear technique is that the predicted value lies between zero and one, and, thus, is a probability measure. The parameter estimates will be unbiased and efficient [Gallant, 1973].

Table 3 gives the parameter estimates for the linear and non-linear techniques. The nonlinear parameter estimates are preferred because of the effective zero-one probability constraint, and the model yields a lower level of unexplained error (SSE) than the linear form. The linear model parameter estimates were used as start values for the non-linear estimation and are given for comparison. All variables have the expected signs. The coefficients for the price of capital (P_K), local share of capital costs (G), price of by-product (P_3), volume of wastes (Q_1), final BOD_5 concentration (Q_2), river flow (R) and annual rainfall (S) all were significantly different from zero at the .1 or lower levels for the non-linear case.

The coefficient for the price of land was not significantly different from zero. The agricultural price of land or the median housing value (which was also tried) may not have represented the cost of land easements for treatment purposes. Examination of Tables 1 and 2 reveals that in many cases land used for treatment was not purchased, or if purchased was used for high value activities in addition to land treatment. The additional cost of using golf courses or parks for land treatment is less than the purchase price in many cases.

Table 3. Estimated Demand Curves for Land Treatment Adoption[a]

Independent Variables		Mean value of variables	Use of Land Treatment[b] Log Linear	Non linear[c]
Constant	α_o		0.665	-1.211
Price of land	P_L	1123.74	-0.007 (-0.180)	-0.110 (-0.693)
Price of labor	P_{L1}	3.49	-0.158 (-0.914)	-0.752 (-1.185)
Price of capital	P_K	875.17	0.142 (1.019)	0.882*** (1.364)
Local share of capital costs	G	0.84	0.2882*** (1.469)	1.361** (1.738)
Price of by-product	P_3	9.30	0.022** (2.087)	0.101** (2.206)
Volume of wastes	Q_1	10.97	-0.008 (0.311)	-0.129*** (-1.347)
Final BOD_5 concentration	Q_2	41.92	-0.087* (-2.408)	-0.501* (-3.146)
River flow	R	37856.58	-0.018** (-2.291)	-0.067** (-2.142)
Annual rainfall	S	30.67	-0.166* (-2.601)	-0.382** (-1.792)
R^2			0.368	d
SSE			18.830	18.137

[a]Values in parentheses are t values for test of significance from zero. Sample size is 125.

*,**,***denote significance at .01, .05 and .1 level, respectively with a one-tailed test.

[b]The dependent variable is the probability in the log linear case. In the non-linear case the dependent variable is the standard normal deviate.

[c]Interpretation of the non-linear regression requires a table of standard normal deviates. $d[1-F(L)]/dX_i$ = elasticity, where F(L) is a cumulative normal distribution for the standardized normal random variable (L). $L = \sum_{i=o}^{9} \hat{\alpha}_i \cdot L_n(\bar{X}_i)$, X_i = the independent variable, and $\hat{\alpha}_i$ are the estimated coefficients. This leads to the following elasticities at the means: P_{L1} = 1.51, P_K = +1.59, G = +2.30, P_3 = +.33, Q_1 = 1.99, Q_2 = -1.09, R = -.15, S = -.77.

[d]R^2 is undefined in the non-linear case.

The parameter estimates for the non-linear model can be given elasticity interpretations by referring to a table of standard normal deviates (see bottom of Table 3). The variable to which land treatment is most responsive is local construction cost share (G). A 10 percent decline in the share paid by local government (i.e., increase in federal or state subsidy) would result in about a 23 percent <u>decrease</u> in the probability of land treatment. Thus, federal policy with respect to which types of treatment costs are eligible for federal support has been a major force in local decisions on selecting or not selecting land treatment.

The decision makers did appear to be responsive to the prices of labor (P_{L1}) and capital (P_K) in selecting treatment technology. (elasticity = -1.51 and + 1.59, respectively). Although these variables are not as significant as others, this does give limited support for the belief that treatment system designers consider relative factor prices.

The price of irrigation water (price of by-product, P_3) had a highly significant effect on the adoption of land treatment ($t = 2.21$). This, plus significance of G and P_K, substantiates the profit maximizing motive of the sewerage treatment managers specified in the economic model of equation 5. The elasticity for P_3 is + .33 meaning that a 10 percent increase in the price of irrigation prices will increase the probability of land treatment by 3.3 percent. Areas such as Florida where irrigation productivity is high and land treatment is low will probably adopt land treatment rapidly. This trend will be reinforced by higher fertilizer prices and crop prices [Young and Carlson, 1974].

Both the level of treatment (Q_2) and environmental constraint variables

(R) indicate that as policies on the maximum allowable effluent levels and use of stream dilution potential are restricted, land treatment will rise. A 10 percent lowering of the BOD_5 allowed (lowering Q_2) increases the probability of adopting land treatment by about 11 percent. Reduction in stream flow for dilution purposes by 10 percent has been associated with a 1.5 percent increase in land technology acceptance.

There is also evidence in Table 3 for higher probability of cities with smaller volumes (Q_1) and less annual rainfall (S) to accept land treatment more readily. Young and Carlson [1974] also found evidence from cost curves to indicate that land treatment is better suited for small towns. In comparison with conventional treatment plants a .5 million gallon a day land system would save $.07/1000 gallons treated, while a 10 mgd. system would only have a $.05/1000 gallon cost differential at 85 percent BOD removal. This size association may be due to lower transportation cost or higher availability of land easements in smaller towns. Further evaluation is needed, since a simple population density variable had no effect in a previous estimate of equation 7 [Young, 1974].

Implications for Wastewater Treatment Investments

Municipal wastewater officials have responded to economic incentives in selecting technology in the past. Irrigation prices, federal subsidies and relative labor and capital prices help explain the adoption of land treatment systems. However, the purchase price of land has not been a major consideration in accepting or rejecting land treatment. There seem to be many ways to obtain land treatment rights to private and public land other than purchase.

The major decision making change which land treatment introduces is design and operation for profit maximization (loss minimization), rather than cost minimization. Quite often this will involve the use of specialized labor and management through contracts with farm managers, lawyers and engineers. Land treatment systems have more variable inputs (labor and maintenance) than conventional plants which allows closer adjustment to relative input prices. (Young and Carlson, 1974, provide tests of marginal value products for land and non-land treatment sites which substantiates this observation).

This analysis strongly indicates that municipal officials should try to determine what degree of treatment (BOD_5 and nutrient removal) will be required by the state and federal regulatory officials in the future. Likewise, policies on use of streams for dilution will be critical in choice of treatment systems. A forecast of the growth rate in volume of wastes (Q_1) does not appear to be as critical to the technology decision.

Choice of treatment system has been responsive to federal financing in the past. This is likely to continue. Consequently, granting agencies have a responsibility to insure that by-product production is included in the evaluation of alternative systems.

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