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**Economies of Size in Water Treatment vs. Diseconomies of
Dispersion for Small Public Water Systems**

by

Richard N. Boisvert and Todd M. Schmit

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Abstract

This paper outlines a method to determine the tradeoff between economies of size in water treatment and diseconomies of distribution. Empirical results for New York are used to identify the implications for the rehabilitation and consolidation of rural water systems.

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Introduction

We know that the financial burden facing small public water systems in complying with the 1986 and subsequent amendments to the Safe Drinking Water Act can be substantial, in large measure because they are unable to take full advantage of the economies of size in water treatment (EPA, 1993a). To capture the benefits of these economies of size, it is often suggested that costs of water supply can be minimized through the formation of regional water systems consisting of a group of small systems or one or more systems hooked to a larger system (Clark and Stevie, 1981). In this way, the costs to all users can be reduced.

To perform their function, however, water utilities also must be physically connected to their customers, and for purposes of economic analysis, we must define two separate components to a water supply system: the treatment plant and the delivery system. The cost functions for the components differ substantially. While the unit costs of treatment generally decline with the quantity of service, the cost of delivery (transmission and distribution) is affected by the nature of the service area (Clark and Stevie, 1981). The delivery cost may very well rise as the service territory increases in size and spatial complexity, and the economies of size in treatment may well be offset by the diseconomies of water transmission and distribution. Strictly from an economic perspective, a water system's optimal size must be determined by the tradeoff between the economies of size for water production and treatment and any diseconomies of delivery to the point of use (Dajani and Gemmell, 1973).

The purpose of this paper is to identify a method by which to determine the size for small water systems in New York that will minimize the combined cost treatment and delivery for commonly used treatment options and representative differences in the characteristics of rural service areas. To our knowledge, the tradeoffs between economies of size and the diseconomies of delivery have only been examined for much larger systems than those examined here, and this work is nearly 20 years old (Clark and Stevie, 1981).

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The treatment options that are examined include chlorination, slow sand, direct, and other types of filtration suitable for small systems, and aeration. The differences in the service territories are captured for the most part by population density. Data from which the cost equations for treatment and delivery are estimated come from loan files for community drinking water improvements from the Rural Development offices across New York. Rural Development's Water and Waste Disposal Loan and Grant Program, along with the data for these water systems and a theoretical discussion of indirect cost functions and appropriate measures of economies of size, are described in other reports prepared for EPA in support of this ongoing research (Boisvert *et al.* 1996; Schmit and Boisvert, 1996).

This paper begins with a discussion of the nature of the cost functions for treatment and delivery. Next, there is a discussion of the appropriate way to combine the costs of these components. After the estimated cost functions are described, the empirical results are presented. The paper concludes with a statement of the important policy implications.

The Components of the Cost of Water Supply

As stated above, the costs of a community water system can be separated into two major components: those related to water treatment and other activities at the water plant and those related to water transportation or distribution to point of use. We begin with a discussion of treatment costs.

Treatment Cost Functions

For purposes of discussion and empirical estimation below, treatment costs can be divided into two main elements: capital costs for construction, which can be put on an annual basis, and annual operation and maintenance (O&M) costs. In the literature, the relationship between total treatment cost on an annualized basis to some measure of system size (e.g. plant design capacity, average daily flow, or population served) is generally represented by an exponential function, which is linear in logarithms:

$$(1) \quad TC_t = \beta P^\alpha,$$

where TC_t is the total annualized cost of treatment and P is a measure of output. If we define economies of size (SCE) by the proportional increase in cost for a small proportional increase in output, then, following Christensen and Green (1976),

$$(2) \quad SCE = 1 - \partial \ln TC_t / \partial \ln P,$$

which is equal to $1-\alpha$ for the cost function given in equation (1). Economies of size exist if $SCE = 1-\alpha > 0$, and diseconomies exist if the SCE is negative. It is also true that economies of size in this case are invariant regardless of the level of output (Boisvert *et al.*, 1996; and Christensen and Greene, 1976). The practical implication of this specification is that if economies of size are estimated to exist, average costs will continue to fall regardless of how large the system becomes. This may not, however, be a reasonable assumption, because for a given treatment technology, economies of size may be exhausted at a certain point, implying that average costs should begin to rise as the size of the system expands beyond this point. To deal with this potential difficulty, we can re-specify the cost function as:

$$(3) \quad TC_t = \beta P^{\alpha + \delta \ln P}.$$

For this specification, we have:

$$(4) \quad SCE = 1 - (\alpha + 2\delta \ln P),$$

and the economies of size can vary with the level of output.¹ Besides its flexibility, this function can be used to test the hypothesis that returns to size are invariant with respect to output through a simple *t*-test on the parameter δ . Further, the parameters in equation (3) can be estimated by ordinary least squares by transforming it into logarithmic form:

$$(5) \quad \ln TC_t = \ln \beta + \alpha \ln P + \delta (\ln P)^2.$$

From an empirical point of view, there are two issues that must be addressed in using this formulation to estimate water system treatment costs. First, to estimate treatment cost functions empirically for various water treatment technologies, we need a single measure of output that is related both to capital and O&M costs. In the engineering equations accompanying the BAT document prepared for EPA for small water systems (Malcolm Pirnie, Inc., 1993) and elsewhere, system design capacity is used as the measure of system size in order to estimate certain components of capital cost, and average daily flow is the measure of size used to estimate the variable costs of operation and maintenance. Neither is an ideal measure for both, nor for a measure of size for delivery costs. Therefore, as a compromise, and to be as meaningful as possible from a policy perspective, system size or output, for much of the work in this larger

¹ The cost function in equation (1) and (3) are most often written in logarithmic form--taking the natural logarithms of both sides (Boisvert *et al.*, 1996). It is in the logarithmic form that the expressions for the economies of size are most easily derived. It is also in this way that the parameters of the two functions are estimated econometrically.

research project for EPA, is specified in terms of the population served. This, after all, is the measure used by EPA and others to classify systems by size. This measure of output is also directly related to the number of service connections. The fact that this measure of output works well for many analytical purposes is well documented by Boisvert *et al.* (1996), where they estimate the relationship between population served and both average daily flow and design capacity nationally and regionally based on data from the FRDS-II data system (EPA, 1993b).

Although this first issue would have to be addressed regardless of the nature of the cost functions being estimated or the nature of the data, the second issue relates to the fact that in the sample of Rural Development water systems, there were generally insufficient observations for a particular type of treatment to allow for the estimation of separate equations for each type of treatment. To deal with this difficulty, equation (3) was re-specified as:

$$(6) \quad TC_i = \beta P^{\delta \ln P + \sum \alpha_i d_i}.$$

In this specification, differences in costs by treatment are reflected by coefficients associated with the zero-one variables d_i . That is, the variable d_i takes on a value of 1 if the observation in the data is associated with treatment i , and is zero otherwise. In logarithmic form, this equation becomes:

$$(7) \quad \ln TC_i = \ln \beta + \delta (\ln P)^2 + \sum_i \alpha_i d_i \ln P.$$

For any treatment i , the measure of economies of size becomes:

$$(8) \quad SCE = 1 - (\alpha_i + 2\delta \ln P).$$

Delivery System Cost Function

In some respects, estimating the costs of water delivery is more complex than treatment. Water is transported to point of use through a system of transmission pipelines and distribution mains. The transmission pipelines are the major trunk lines that transport large volumes of water and connect the treatment plant to the pumping station and ultimately to the distribution system. Thus, the major components of distribution system costs include pipelines, pumping stations and water towers, and energy to move the water through the system. Costs of supplying water to customers also rises with the distance from the water source. To capture much of this complexity in a cost function for water distribution, Clark and Stevie (1981) assume that capital costs are determined by pipe length alone, while the energy costs are a function of both flow and distance.

Because of the availability of data, and the small-size of the systems studied here, we rely on a different specification. More is said about this below and in Schmit and Boisvert (1996), but it was impossible to disentangle energy costs from other O&M costs in the grant and loan files. Thus, while energy costs for distribution are embodied in the entire analysis and are related directly to output (as measured by population served), the effect of distance on energy costs of distribution is reflected only indirectly through a measure of population density.

The cost function for water system delivery is also specified in exponential form as:

$$(9) \quad TC_d = \gamma P^\lambda \left[\frac{L}{P} \right]^\eta \left[\frac{H}{P} \right]^\omega,$$

where TC_d is total cost of delivery, P is population served, L is linear feet of pipe, and H is the number of water hydrants. Thus, according to this specification, the total cost of delivery is a function of population served, as well as the linear feet of pipe and the number of hydrants per person served. These latter two variables reflect the density of population in the service territory, and combined with the population itself in the equation account for the increasing size of the service territory as population served rises and population density falls. Although quite dissimilar algebraically from the cost functions for delivery specified by Clark and Stevie (1981) and by Ford and Warford (1969), this specification is consistent with what they believed were the primary determinants of water delivery cost. This cost function is also much more convenient to work with analytically.

As with the cost for treatment, equation (9) is also linear in logarithms, and in that form its parameters can be estimated by ordinary least squares. The function can be written as:

$$(10) \quad \ln TC_d = \ln \gamma + \lambda \ln P + \eta [\ln L - \ln P] + \omega [\ln H - \ln P],$$

In this form $\ln P$ appears three times in the equation, and estimating it in this form (with the differences in logarithms of L and P and H and P being specified as separate variables) is equivalent to estimating the function:

$$(11) \quad \ln TC_d = \ln \gamma + (\lambda - \eta - \omega) \ln P + \eta \ln L + \omega \ln H,$$

In this form, we are able to estimate the parameters $\ln \gamma$, η , and ω , but the proportional net effect on delivery cost of a proportional change in population served is now seen to be $(\lambda - \eta - \omega)$. The total cost of water delivery is now specified as a function of population served, the total length of water pipe and the number of hydrants. To estimate total system costs below, we use this

equation, but manipulate it in such a way so that the population density of the service territory is specified directly.

Total Costs for the System

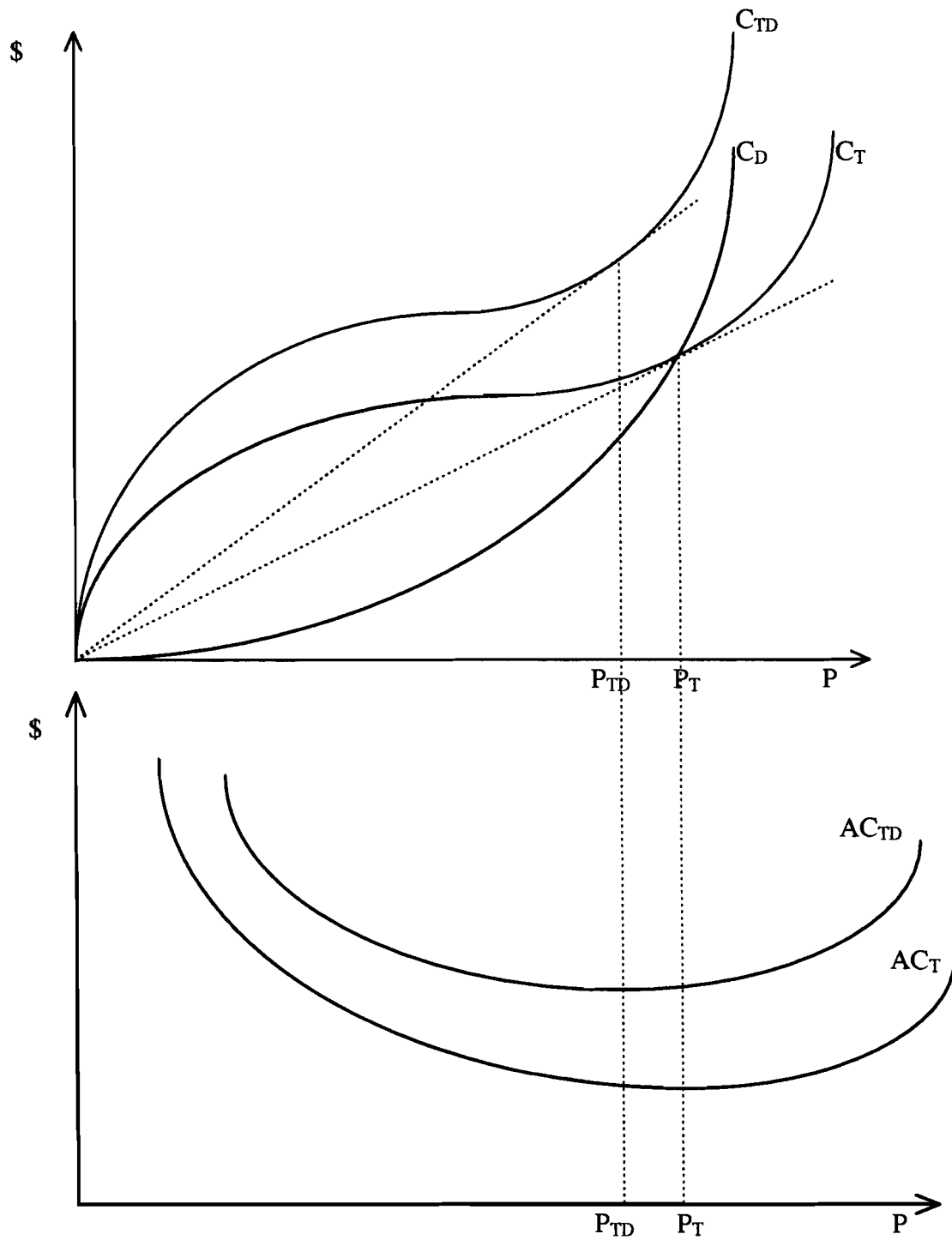
Having specified these two cost components as functions of population served, total system costs can be obtained by adding equations (6) and (9). Having done this, it is conceptually possible to define expressions for the system's average and marginal costs, as well as for the measure of economies of size given in equation (2). These expressions, however, are complicated algebraically, and are not very enlightening. Therefore, they are not reproduced here.

It is also possible using the total cost relationship to identify the optimal size for a water system (the point at which average cost per person served is a minimum) once the treatment technology and population density (as measured by L/P and H/P) are known. To understand the relative importance of the economies of size for treatment and the diseconomies of size associated with transmission and distribution, one can easily compare the optimal size here with the optimal size considering only the cost of treatment. If the hypothesis by Clark and Stevie (1981) and others is true, then the optimal system size based on total cost should be substantially below that when only treatment costs are considered. This situation is pictured in Figure 1.

In Figure 1, treatment costs, C_T , rise first at a decreasing rate, and then at an increasing rate. Thus, average costs per person served initially falls and then rises as system size increases. The minimum average cost size is at P_T , where a ray out of the origin is tangent to the C_T curve. Distribution costs, C_D , rise at an increasing rate throughout; thus, average costs always increase with system size. For this reason, when the two components of cost are added together, average total costs increase initially at a decreasing rate, but begin to increase at an increasing rate at a system size below that when treatment costs are considered in isolation. This means that the minimum average cost system size when both cost components are considered will be below that when only treatment costs are considered (i.e., at P_{TD} rather than P_T). Some empirical evidence supporting the hypothesis represented in this figure is presented in the empirical section below.

Once the optimal system sizes are determined in this way, water systems around the country in places with similar treatment needs and population densities would in theory all construct systems of this size. Unfortunately, this country's rural populations are not scattered so neatly across the landscape so as to accommodate replication of these optimal size water systems organized around well defined service territories. Rather, rural population centers would rarely

Figure 1. Total and Average Cost Curves for Water Treatment (T), Water Distribution (D), and Combined Treatment and Distribution (TD)



contain people in the optimal numbers or in regular multiples of these optimal numbers for purposes of water system design.

One way to understand the essence of this issue is through the use of the system cost curves in Figure 2. Here, we have a total cost curve for treatment and distribution combined. But, from the previous two figures, we know that the optimal size, P_{TD} , is below what it would be for treatment costs alone. Suppose, however, the rural area's total population is actually P_2 , somewhere between P_{TD} and P_T on Figure 1. To serve this population at minimum cost, the question becomes one of whether to expand a single plant's service territory to accommodate the extra population $P_2 - P_{TD}$, or to build one plant to serve population P_{TD} , and a second smaller plant to serve the residual population $P_2 - P_{TD}$. In the single plant case, one is essentially taking advantage of additional economies of size in treatment, but the diseconomies of distribution are increasing. In the two system case, average treatment costs for the second system will be larger, but the diseconomies of distribution will be smaller.

To examine this tradeoff between falling treatment costs and rising distribution costs, one can construct a combined cost curve for the two systems (C_{TD^*} in Figure 2). The cost for the minimum average cost plant is at point $(P_{TD}, \$_{TD})$, and the costs for the second plant follow the cost curve C_{TD} between 0 and P_{TD} . Thus, the combined cost curve C_{TD^*} is constructed by transposing this initial segment of the existing cost curve to the point $(P_{TD}, \$_{TD})$. Accordingly, as long as the population to be served is below P_{TD^*} then the additional economies of size for treatment outweigh the diseconomies of distribution, and the population should be served by one plant. At a population of P_{TD^*} the costs of the two alternatives are the same, and beyond this point, and up to a system size of $2P_{TD}$, two systems are the minimum cost strategy.

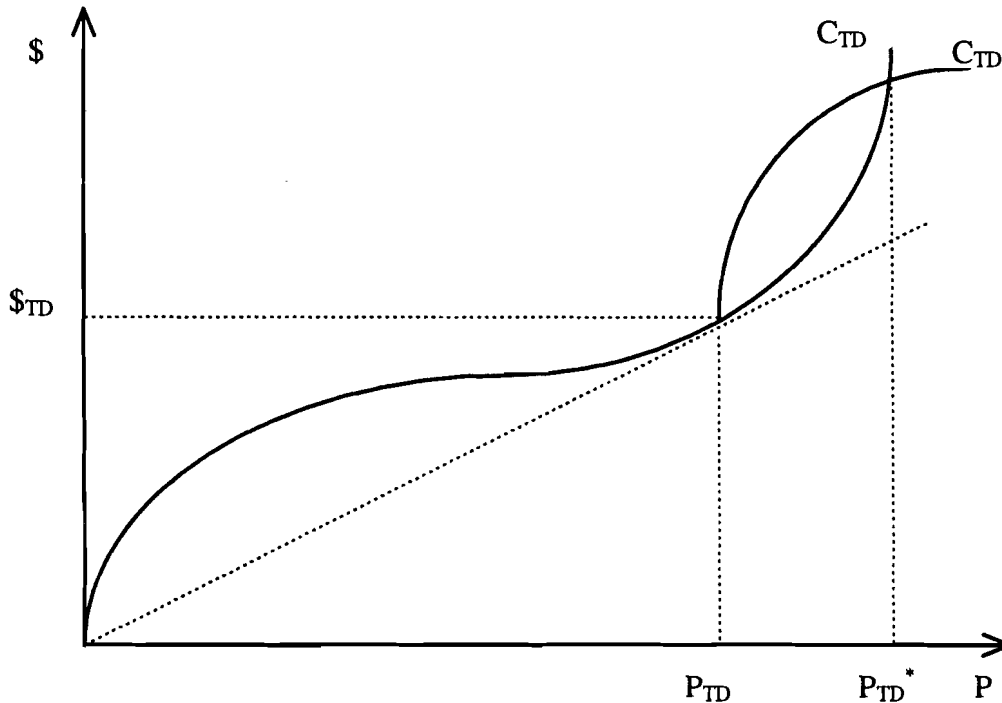
The Empirical Analysis

For the empirical analysis, it was necessary to have estimates of equations (6) and (9) for one, if not several water treatment processes. The data to estimate these functions were collected as part of another phase of this overall work for EPA.

Treatment Cost Function

The treatment cost equation is borrowed from Schmit and Boisvert (1996), which provides estimates of the combined annualized capital and operation and maintenance costs (O&M) for slow sand filtration, aeration, direct filtration, and a final category that includes several other types of filtration. Differences in costs by treatment are reflected in the equation through a series of dummy variables. The data used to estimate this treatment equation are from

Figure 2. Cost Curves for Water Treatment and Distribution (TD) and an Extension Beyond the Minimum Cost Size (TD')



37 loan and grant files for water system improvement projects financed by New York's Rural Development offices.

To estimate this translog cost function, data from the 37 new treatment project observations were entered into a SAS data set. Some summary statistics are in Appendix Table A1. Capital and operating costs were converted to constant 1992 dollars by deflating the capital and operating cost data using the ENR Construction Cost Index and ENR Wage History, respectively (ENR, 1995). Capital costs were annualized based on a useful life of 20 years and discount rate of 8%.² As is seen in Table A1, total capital project costs for these systems average just over \$2 million, the treatment portion representing two-thirds of the total, or about \$1.4 million. Treatment cost improvements range from only \$22,000 to nearly \$8 million. On an annualized basis, the average annual cost is nearly \$140,000. Combined with annual system

² Though these values represent a shorter time horizon and higher interest rate than those resulting from particular financing arrangements, they do reflect more realistic depreciation schedules for the equipment installed and existing market conditions. In addition, they allow for an applicable comparison to the EPA's Best Available Technology Document (Malcolm Pirnie, Inc., 1993) for the treatments considered.

operating expenditures, the total system annualized cost averages nearly \$309,000, and ranges from \$7,400 to over \$1.7 million. On average, capital accounts for about 45% of costs, while operating costs account for the remaining 55%.

For the estimation, annualized costs are regressed on population served. This is used as a proxy for output, and it is one that has performed well in other studies (Boisvert *et al.*, 1996). All cost and size variables are converted to their natural logarithms. The regression explains about 89% of the variation in the dependent variable (Table 1), and the standard errors of the coefficients are quite low relative to the size of the coefficients themselves.

Although this estimated function has the general translog form, the logarithm of population is not included as a separate regressor. Rather, it is included several times in interaction terms with the dummy variables for the various treatment categories. (Chlorine is the omitted treatment variable and assumed is inherent in the intercept.) With the model specified in this way, the economies of size vary with output, as well as type of treatment. Further, the coefficients on the treatment regressors provide the incremental annualized cost for the associated treatments at a particular size of system.

The economies of size, which differ by treatment and system size, are described in detail in Schmit and Boisvert (1996). The water system sizes at which average treatment costs are a minimum differ as well (Table 2). For example, average costs are minimized at a population of 16,800 for slow sand filtration. Average costs are minimized at 22,300 people for other filtration, at 31,800 for direct filtration, and at 57,000 for aeration.

Table 1. New Treatment Annualized Cost Function

Regressors	Description	Coefficient	Std. Error	t-ratio
INTERCEPT	Intercept term	8.49	0.32	26.94
SURFACE	Surface water dummy variable	0.27	0.24	1.13
LPOPNSQ	[Ln (Population)] squared	0.04	0.01	5.16
LPOPAERA	[Ln (Population)] * AERAT	0.10	0.05	1.93
LPOPDIR	[Ln (Population)] * DIRFILT	0.15	0.05	3.05
LPOPSSF	[Ln (Population)] * SSFILT	0.20	0.04	4.59
LPOPOFIL	[Ln (Population)] * OFILT	0.18	0.04	3.94
R-square	0.89			

Note: Annualized cost function based on 8% discount rate and 20 year time period

Equally important for the analysis below is the fact that the economies of size in all cases are nearly exhausted rather quickly as system size increases. When system size reaches only 10% of the size that minimizes average treatment cost, average costs are only 25% above minimum cost (Table 2). At a size of 7,500 people, average costs are only 3%, 9%, 5%, and 18% for slow sand filtration, direct filtration, other filtration, and aeration, respectively.

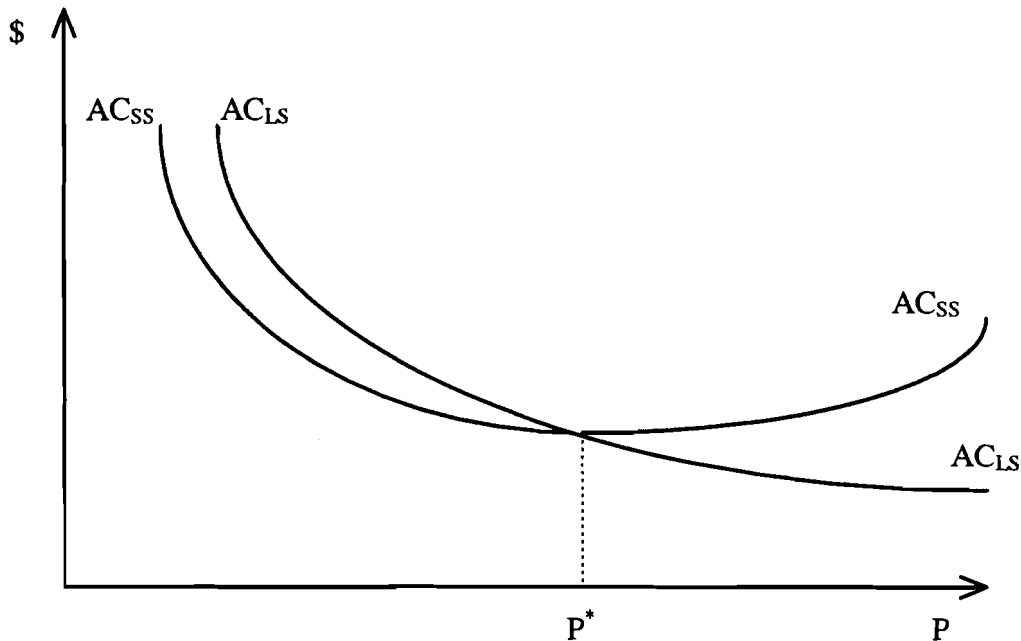
The fact that economies of size are nearly exhausted for systems serving 7,500 people may seem contrary to the belief that economies of size persist for much larger systems. This apparent contradiction is probably due to the fact that data on which the cost function was estimated were for systems serving fewer than 10,000 people. Thus, extrapolation beyond this size is probably not warranted. Further, one might very well argue that when applied on a larger scale, these treatments involve substantially different processes (e.g. small-scale vs. large-scale applications of the same process. If this is the case, the average costs for these two "scales" of application may look like those in Figure 3. For systems below (above) size P^* , the small-scale (large-scale) application of the technology is appropriate. The average cost curve for the entire range of system sizes is the minimum envelope formed by the cost curves of the two scale-specific applications of the technologies. This envelope, and the economies of size implied by it

Table 2. Population Levels and Average Costs Per Capita for Annualized Treatment Costs

Category	Slow Sand Filtration		Direct Filtration		Other Filtration		Aeration	
	Popn. (No.)	AC (\$)	Popn. (No.)	AC (\$)	Popn. (No.)	AC (\$)	Popn. (No.)	AC (\$)
Minimum AC	16,800	130	31,800	76	22,300	103	57,000	35
Population Limit	7,500	133	7,500	83	7,500	108	7,500	42
% of Minimum AC Level	45%	103%	24%	109%	34%	105%	13%	118%
AC 110% of Minimum	3,600	143	6,900	84	5,000	113	11,400	39
% of Minimum AC Level	21%	110%	22%	110%	22%	110%	20%	110%
AC 125% of Minimum	1,600	162	3,200	95	2,200	129	5,400	44
% of Minimum AC Level	10%	125%	10%	125%	10%	125%	9%	125%
AC 150% of Minimum	700	195	1,400	115	1,000	155	2,400	53
% of Minimum AC Level	4%	150%	4%	150%	4%	150%	4%	150%
AC 200% of Minimum	300	259	500	153	400	206	900	70
% of Minimum AC Level	2%	200%	2%	200%	2%	200%	2%	200%

Note: These results are from the treatment only regression, no transmission/distribution costs are included.

Figure 3. Average Cost Curves for Small-System Technology (SS) and Large-System Technology (LS)



could only be identified if the estimated cost function were based on data from both large and small systems employing similar treatments. This might be possible from the data in the most recent national water system survey. Despite these potential limitations of the function estimated here, the analysis below is affected very little as long as we focus on systems serving fewer than 10,000 people.

The Transmission and Distribution Cost Function

Data to estimate the cost function for transmission and distribution are from the Rural Development loan and grant files described in Schmit and Boisvert (1996) as well. In that report, the authors use the data to estimate the costs of distribution per linear foot of service, assumed to be a function of water demand, service connection per foot, size of pipe, number of hydrants, etc. While this form of the cost function is useful for some purposes, it is to our advantage here to estimate total cost as a function of population and population density, as measured by the feet of pipe and number of hydrants per person served.

In order to specify and estimate the regression equation to identify the factors that affect distribution costs, data for 33 New York water systems were combined into a single data set. For

a system to be included, it was necessary that the project include distribution or transmission installation or improvement and for there to be included in the loan file enough detailed information to identify:

- System size and water flow demand
- Costs of excavation, backfill, restoration, and boring
- Transmission and distribution line specifications and cost
- Costs of pipe fittings, valves, and existing system connection
- Costs of water service and meter installation
- Number and per unit costs of hydrant installation
- Costs of specialized altitude, pressure, and other valves
- Construction, administration, and engineering contingency levels

The data are summarized in Appendix Table A2. Average distribution costs are nearly \$930,000, ranging from \$82,000 to over \$2.6 million. The average number of people served is 317, in an average number of households of 127. The number of hydrants installed ranges from zero to 84; the average is about 25. For systems connecting to a neighboring system, water hydrants and service connections may not be necessary. However, for an extension to a new district, service laterals and hydrants for fire protection potentially constitute a large share of total distribution costs. The average length of transmission and distribution main (not including service lateral distances) is almost 19,500 linear feet (lf) or over 3.5 miles. About one-fifth of the projects involved storage or booster pump stations.

The estimated equation for total transmission and distribution costs is given in Table 3. Overall, the equation explains about 81% of the variation in the dependent variable. The two most important variables, as one would expect, are population served and linear feet of transmission main. Three other variables were also included, the number of hydrants and dummy

Table 3. Transmission and Distribution Annualized Capital Cost Function

Regressors	Description	Coefficient	Std. Error	t-ratio
INTERCEPT	Intercept term	3.13	1.09	2.87
LPOP	Ln (Population)	0.43	0.14	3.05
LTDMAIN	Ln (Linear Feet of Transmission Main)	0.57	0.16	3.64
LHYDRNT	Ln (Number of Hydrants Installed)	0.02	0.02	1.09
STORAGE	Storage Dummy Variable	0.22	0.17	1.28
BPSD	Booster Pump Station Dummy Variable	0.19	0.16	1.22
R-square =	0.81			

Note: Annualized cost functions based on 8% discount rate and 20 year time period.

variables for whether or not storage and booster pump stations were part of the project. These variables performed much worse as measured by the *t*-ratios. However, this is more of a reflection of the fact that there was not sufficient variation in these variables to measure their effects on costs accurately, rather than whether they should be included.

To understand the nature of this cost function, it is important to recall that the individual regression coefficients on the logarithmic variables reflects the proportional change in cost as the variable is changed by one percent. In this case, as population served increases by one percent, cost increases by 0.43%. At first, this may seem counter intuitive, but if it is only population that changes and not the feet of transmission main or the number of hydrants, then the population density is increasing as well. Under these conditions, one would expect cost to increase less rapidly than population served. On the other hand, if population, feet of transmission main, and the number of hydrants all increase by the one percent (keeping population density the same), then, cost is increased by the sum of their respective regression coefficients, 1.02%, just slightly more than proportionately. If as the distribution network expands, the feet of transmission main and the number of hydrants both increase by a larger proportion than does population, then population density falls and costs increase faster than the rate of increase in population served.

Combining Treatment and Distribution Costs

We can begin to see the tradeoff between economies of size in treatment and diseconomies in distribution by examining Table 4.³ In this table, there are four sections of data for each of four treatments. In the first section, the minimum cost system size considering treatment costs only is indicated, along with average cost per capita. This is the same information as in Table 2 and is repeated mostly for ease of comparison. Clearly, these costs would not vary with the population density of the service territory, as defined in column 1 by the people per hundred feet of transmission/distribution pipe. Defined in this way, the population density falls as one reads down the table.

It is in the second section of the table that we really see the effects of distribution costs. That is, when both costs are combined, the optimal size of system is reduced substantially when compared with the optimal size considering only treatment costs. The reduction in size is more pronounced as population density falls.

³ For completeness, the Table B1 below contains similar data only assuming that storage and pumping station costs are included in the transmission and distribution cost calculations. Tables C1 through C4 repeat the entire analysis assuming that capital costs are annualized using a 6% discount rate rather than an 8% rate. This rate is more consistent with Rural Development's interest rates. The effect of this discount rate change is minimal.

Table 4. Minimum Average Cost Population Levels for Alternative Treatments and Transmission and Distribution Costs

Population Density	Treatment Only (b)		Treatment Plus Trans. and Distribution (c)				Extension Beyond Minimum Cost (d)			
			Average Cost Per Capita				Average Cost Per Capita			
	Population	AC	Population	Treatment	Trans. & Dist'n.	Total	Population	Treatment	Trans. & Dist'n.	Total
Slow Sand Filtration										
5.0	16,800	\$130	11,700	\$130	\$150	\$280	17,600	\$130	\$151	\$281
2.0	16,800	\$130	9,100	\$132	\$256	\$388	13,700	\$130	\$259	\$389
1.3	16,800	\$130	7,800	\$133	\$324	\$457	11,800	\$130	\$327	\$458
0.7	16,800	\$130	5,500	\$137	\$484	\$620	8,400	\$132	\$489	\$621
0.5	16,800	\$130	4,500	\$139	\$587	\$726	6,800	\$134	\$593	\$727
Direct Filtration										
5.0	31,800	\$76	17,200	\$78	\$151	\$229	26,000	\$77	\$153	\$230
2.0	31,800	\$76	11,500	\$80	\$258	\$337	17,400	\$78	\$260	\$338
1.3	31,800	\$76	9,100	\$81	\$325	\$407	13,800	\$79	\$329	\$407
0.7	31,800	\$76	5,500	\$87	\$484	\$570	8,400	\$82	\$489	\$571
0.5	31,800	\$76	4,200	\$90	\$586	\$676	6,400	\$85	\$592	\$677
Other Filtration										
5.0	22,300	\$103	14,100	\$104	\$151	\$255	21,300	\$103	\$152	\$255
2.0	22,300	\$103	10,400	\$106	\$257	\$362	15,700	\$104	\$260	\$363
1.3	22,300	\$103	8,600	\$107	\$325	\$432	13,000	\$104	\$328	\$433
0.7	22,300	\$103	5,700	\$111	\$484	\$595	8,600	\$107	\$489	\$596
0.5	22,300	\$103	4,500	\$115	\$587	\$702	6,800	\$109	\$593	\$703
Aeration										
5.0	57,000	\$35	16,000	\$37	\$151	\$189	24,200	\$36	\$153	\$189
2.0	57,000	\$35	8,000	\$41	\$255	\$296	12,200	\$39	\$258	\$297
1.3	57,000	\$35	5,600	\$44	\$321	\$365	8,600	\$41	\$325	\$365
0.7	57,000	\$35	2,900	\$50	\$476	\$526	4,500	\$46	\$481	\$527
0.5	57,000	\$35	2,100	\$55	\$576	\$630	3,200	\$49	\$582	\$631

(a) Population density is defined as people per hundred lf of transmission and distribution pipe, evaluated over the range in the data.

People per hydrant is adjusted proportionately to the changes in the density levels.

(b) Annualized cost functions assume a 20 year time period and 8% discount rate.

(c) Transmission and distribution costs do not include storage or booster pump station components.

(d) Extension limit refers to the maximum population extension for consolidation, after which lower costs result from constructing a separate treatment and transmission/distribution system for the extension considered.

For the Rural Development systems in the data set, the average density is about 2 people/100 feet of pipe. For this population density, the optimal size water systems range from serving 8,000 people to 11,500 people, depending on the type of treatment. By cutting back to these sizes, per capita treatment costs rise only slightly. On the other hand, the reduction in treatment costs realized for extensions of systems beyond minimum cost size (e.g. by the analysis in Figure 2) is quite small as well. (See the third section of Table 4.) These results are somewhat unexpected, but obtain primarily because, as seen above, the economies of size in treatment are nearly exhausted for systems serving about 7,500 people.

The other important result evident from the empirical analysis is that regardless of the type of treatment and population density, the annual minimum per capita total cost of treatment and distribution for water systems in rural areas ranges anywhere from \$300 to \$700. Thus, the financial burden on rural residents can be substantial. However, cost estimates assume that systems are financed over a 20-year period at an 8% interest rate. These assumptions were made to be consistent with EPA's cost estimates in their recent BAT document (Malcolm Pirnie, 1993), and compare favorably with other recent estimates of distribution cost extensions (EPA, 1994). Furthermore, these cost assumptions are likely to be close to the terms that small systems might face in regular commercial credit markets. Costs could be reduced substantially, however, if rural water systems have access to loan funds from Rural Development, which, as of 1995, were making some loans at 5% for up to 38 years. The differential interest rate alone would cut costs by 20%, while almost doubling the loan period would do about the same. This only serves to underscore the need for programs of this kind in financing public services in rural areas.

The other important result from this table is that regardless of the type of treatment and population density represented in the table, the transmission and distribution costs per capita are always greater than per capita treatment costs. And, with the exception of slow sand filtration, they would remain greater for much higher population densities. Thus, it would only be in the most densely populated areas that any remaining economies of size in treatment would outweigh the diseconomies in transmission and distribution. It is unlikely that such population densities would be found in rural areas of New York or elsewhere.

The major implications of this result is that in designing systems for rural areas or in considering system consolidation, the spatial configuration of the population to be served may be the real constraint, particularly in light of the fact that economies of size in treatment are exhausted quite rapidly. This latter observation also explains the fact that extensions of system size beyond the minimum cost size (as discussed above) can be substantial, but that ability falls rapidly with population density. It is variations on this kind of analysis that could be used to

identify which adjacent small rural systems should be expanded to serve new developments or developments currently on private wells that lie in-between the existing systems.

Summary and Policy Implications

The purpose of this paper is to identify a method by which to determine the size for small water systems in New York that will minimize the combined cost treatment and delivery for commonly used treatment options and representative differences in the characteristics of rural service areas. Based on this analysis, it is clear that transmission and distribution costs are perhaps a more critical factor than treatment costs in rural water system consolidation. Regardless of the type of treatment and population density, the lion's share of total system cost is due to transmission and distribution, not treatment. Thus, as water systems expand their service territories, it would only be in the most densely populated areas that any remaining economies of size in treatment would outweigh the diseconomies in transmission and distribution.

This result has major implications for designing water treatment systems for rural areas and considering system consolidation. There is also evidence that the infrastructure of many existing small systems has been allowed to deteriorate, and EPA estimates that for every dollar spent on treatment there would need to be an additional dollar spent on rehabilitation and repair (EPA, 1993a). Put differently, it is the spatial configuration of the population to be served that may be the real constraint in improving the quality of drinking water for rural residents, particularly in light of the fact that economies of size in treatment are exhausted quite rapidly. This latter observation also explains that while extending systems somewhat beyond the minimum cost size can be an important strategy in consolidation, that potential vanishes as population density falls. For more sparsely populated areas, the costs of installing a new distribution system may be prohibitive, and installation of point of entry treatment can be a more viable alternative than a centralized treatment technology. EPA recently estimated that for new distribution requirements significantly greater than 200 feet per household, point of entry treatment may be a more cost-effective alternative, depending on total system capacity and contaminants to be removed (EPA, 1994).

However, in demonstrating this, we have only begun to understand how best to use the estimated equations to study, in a simulation context, the economics of system consolidation. One of the challenges is to identify the appropriate way to adjust the transmission and distribution cost functions which were estimated assuming average population densities to reflect population density gradients that are likely to be substantial in rural areas. In this sense, the work described in this report is most surely a work in progress. The full implications of the analysis are far from known.

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Table A1. Descriptive Statistics for New Treatment Annualized Cost Function Estimation

Variable Name	Variable Definition	Mean	Standard Deviation	Minimum	Maximum
<u>Project and Operating Costs</u>					
TCAP	Total capital cost (\$)	2,048,874	1,619,653	176,982	7,938,883
CAPTRT	Treatment capital cost (\$)	1,363,646	1,556,858	22,232	7,938,883
ANCAPTRT	Annualized treatment capital cost (\$)	138,891	158,570	2,264	808,597
OM	Annual system operation and maintenance cost (\$)	169,146	193,916	5,475	902,145
TOTCOST	Total system annualized cost (\$)	308,037	335,699	16,122	1,710,742
<u>Size and Demand Characteristics</u>					
ADD	Average daily demand (gpd)	393,658	512,202	15,000	2,700,000
POP	System population served	2,475	2,281	143	9,470
HSHLDS	System households served	890	790	46	3,266
SURFACE	Dummy variable for surface water system	0.76	0.43	0.00	1.00
GROUND	Dummy variable for ground water system	0.24	0.43	0.00	1.00
<u>Capital Cost Treatments Installed</u>					
CHLOR	Chlorination dummy variable	0.65	0.48	0.00	1.00
AERAT	Aeration dummy variable	0.11	0.31	0.00	1.00
DIRFILT	Direct filtration dummy variable	0.14	0.35	0.00	1.00
SSFILT	Slow sand filtration dummy variable	0.35	0.48	0.00	1.00
DEFILT	Diatomaceous earth filtration dummy variable	0.08	0.28	0.00	1.00
RSFILT	Rapid sand filtration dummy variable	0.08	0.28	0.00	1.00
COAGFILT	Coagulation/Filtration dummy variable	0.08	0.28	0.00	1.00
OFILT	Other filtration = DEFILT+RSFILT+COAGFILT	0.24	0.43	0.00	1.00

Source: Primary data obtained from New York Rural Development district offices.

Note: All costs are in 1992 dollars, capital costs are converted by the ENR Cost Construction Index, and operation and maintenance costs are converted by the ENR Wage History Index (ENR, 1995). Households and water demand are included for reference here, but are not included in the cost function estimation. Treatment dummy variables are equal to one if the treatment was included in the capital project, zero otherwise.

Table A2. Descriptive Statistics for New Transmission and Distribution Annualized Cost Function Estimation

Variable Name	Variable Definition	Mean	Standard Deviation	Minimum	Maximum
<u>Project Costs</u>					
TDISRCOS	Total transmission & distribution project cost (\$)	930,394	687,837	82,025	2,653,413
TDREXCOS	Transmission & distribution main cost (\$)	568,225	433,276	57,704	1,815,220
HYDRCOS	Hydrant cost (\$)	39,210	31,066	0	129,027
STORCOS	Storage cost (\$)	42,567	85,439	0	250,040
BPSRCOS	Booster pump station cost (\$)	16,565	32,839	0	95,681
SLATRCOS	Service lateral cost (\$)	60,431	50,379	0	202,792
OTHRCOS	Other transmission & distribution cost (\$)	13,612	22,805	0	96,786
CELRCOS	Contingency, engineering, and legal cost (\$)	189,784	145,891	18,929	643,252
<u>Annualized Costs of Transmission & Distribution</u>					
ATDSTOR	Total annualized costs	94,763	70,058	8,354	270,256
ATDSTOLF	Total annualized costs per linear foot	4.85	2.16	2.20	10.61
ATDSTOPC	Total annualized costs per capita	324.05	134.27	77.57	750.54
<u>Size and Demand Characteristics</u>					
ADD	Average daily demand (gpd)	56,998	103,777	3,600	600,000
POP	System population served	317	272	45	1,353
HSHLDS	System households served	127	109	18	541
TDMAIN	Transmission & distribution main installed (lf)	19,562	11,824	3,400	61,000
HYDRANT	Hydrants installed	25	18	0	84
<u>Pressure Station Dummy Variables</u>					
STORAGE	Storage structure; 1 if included, else 0	.21	.42	0	1
BPS	Booster pump station; 1 if included, else 0	.21	.42	0	1

Source: Primary data obtained from New York Rural Development district offices.

Note: All costs are in 1992 dollars, capital costs are converted by the ENR Cost Construction Index, and operation and maintenance costs are converted by the ENR Wage History Index (ENR, 1995). Households and water demand are included for reference here, but are not included in the cost function estimation. Annualized costs are based on an 8% discount rate and 20 year time horizon. Pressure station dummy variables are equal to one if the component was included in the capital project, zero otherwise.

Table B1. Minimum Average Cost Population Levels for Alternative Treatments and Transmission and Distribution Costs

Population Density	Treatment Only (b)		Treatment Plus Trans. and Distribution (c)				Extension Beyond Minimum Cost (d)			
			Average Cost Per Capita			Average Cost Per Capita				
	Population	AC	Population	Treatment	Trans. & Dist'n.	Total	Population	Total	Trans. & Dist'n.	Total
Slow Sand Filtration										
5.0	16,800	\$130	9,800	\$131	\$226	\$357	14,800	\$130	\$228	\$358
2.0	16,800	\$130	6,800	\$134	\$384	\$518	10,300	\$131	\$388	\$519
1.3	16,800	\$130	5,500	\$137	\$485	\$622	8,300	\$132	\$490	\$623
0.7	16,800	\$130	3,500	\$144	\$722	\$866	5,300	\$137	\$730	\$867
0.5	16,800	\$130	2,700	\$149	\$875	\$1,024	4,100	\$141	\$885	\$1,026
Direct Filtration										
5.0	31,800	\$76	12,900	\$79	\$227	\$306	19,500	\$77	\$230	\$307
2.0	31,800	\$76	7,400	\$83	\$385	\$468	11,300	\$80	\$389	\$469
1.3	31,800	\$76	5,500	\$87	\$485	\$572	8,400	\$82	\$491	\$573
0.7	31,800	\$76	3,000	\$96	\$720	\$816	4,600	\$89	\$728	\$817
0.5	31,800	\$76	2,200	\$102	\$871	\$973	3,400	\$94	\$881	\$975
Other Filtration										
5.0	22,300	\$103	11,300	\$105	\$226	\$331	17,100	\$103	\$229	\$332
2.0	22,300	\$103	7,300	\$109	\$385	\$493	11,100	\$105	\$389	\$494
1.3	22,300	\$103	5,600	\$112	\$485	\$597	8,600	\$107	\$491	\$598
0.7	22,300	\$103	3,300	\$120	\$721	\$841	5,100	\$113	\$729	\$842
0.5	22,300	\$103	2,500	\$126	\$874	\$999	3,800	\$117	\$883	\$1,000
Aeration										
5.0	57,000	\$35	9,600	\$40	\$225	\$265	14,600	\$38	\$228	\$266
2.0	57,000	\$35	4,300	\$46	\$379	\$426	6,600	\$42	\$384	\$426
1.3	57,000	\$35	2,900	\$50	\$477	\$528	4,500	\$46	\$483	\$528
0.7	57,000	\$35	1,500	\$60	\$707	\$767	2,300	\$54	\$715	\$768
0.5	57,000	\$35	1,100	\$67	\$855	\$922	1,700	\$58	\$865	\$923

(a) Population density is defined as people per hundred lf of transmission and distribution pipe, evaluated over the range in the data.

People per hydrant is adjusted proportionately to the changes in the density levels.

(b) Annualized cost functions assume a 20 year time period and 8% discount rate.

(c) Transmission and distribution costs include storage and pump station components.

(d) Extension limit refers to the maximum population extension for consolidation, after which lower costs result from constructing a separate treatment and transmission/distribution system for the extension considered.

Table C1. New Treatment Annualized Cost Function

Regressors	Description	Coefficient	Std. Error	t-ratio
INTERCEPT	Intercept term	8.40	0.31	26.87
SURFACE	Surface water dummy variable	0.27	0.24	1.12
LPOPNSQ	[Ln (Population)] squared	0.04	0.01	5.39
LPOPAERA	[Ln (Population)] * AERAT	0.10	0.05	1.90
LPOPDIR	[Ln (Population)] * DIRFILT	0.14	0.05	2.96
LPOPSSF	[Ln (Population)] * SSFILT	0.19	0.04	4.42
LPOPOFIL	[Ln (Population)] * OFILT	0.17	0.04	3.77
R-square =	0.89			

Note: Annualized cost functions based on 6% discount rate and 20 year time period.

Table C2. Transmission and Distribution Annualized Capital Cost Function

Regressors	Description	Coefficient	Std. Error	t-ratio
INTERCEPT	Intercept term	2.98	1.09	2.72
LPOP	Ln (Population)	0.43	0.14	3.05
LTDMAIN	Ln (Linear Feet of Transmission Main)	0.57	0.16	3.64
LHYDRNT	Ln (Number of Hydrants Installed)	0.02	0.02	1.09
STORAGE	Storage Dummy Variable	0.22	0.17	1.28
BPSD	Booster Pump Station Dummy Variable	0.19	0.16	1.22
R-square =	0.81			

Note: Annualized cost functions based on 6% discount rate and 20 year time period.

Table C3. Minimum Average Cost Population Levels for Alternative Treatments and Transmission and Distribution Costs

Population Density	Treatment Only (b)		Treatment Plus Trans. and Distribution (c)				Extension Beyond Minimum Cost (d)			
			Average Cost Per Capita			Average Cost Per Capita				
	Population	AC	Population	Treatment	Trans. & Dist'n.	Total	Population	Treatment	Trans. & Dist'n.	Total
Slow Sand Filtration										
5.0	16,800	\$130	9,800	\$124	\$128	\$251	14,800	\$123	\$129	\$252
2.0	16,800	\$130	7,900	\$125	\$218	\$343	11,900	\$123	\$221	\$344
1.3	16,800	\$130	6,900	\$125	\$276	\$402	10,400	\$123	\$279	\$403
0.7	16,800	\$130	5,100	\$128	\$413	\$541	7,700	\$125	\$418	\$542
0.5	16,800	\$130	4,200	\$130	\$502	\$632	6,400	\$126	\$507	\$633
Direct Filtration										
5.0	31,800	\$76	14,400	\$77	\$129	\$206	21,700	\$76	\$130	\$207
2.0	31,800	\$76	10,200	\$79	\$220	\$298	15,400	\$77	\$222	\$299
1.3	31,800	\$76	8,300	\$80	\$278	\$358	12,600	\$78	\$281	\$358
0.7	31,800	\$76	5,300	\$84	\$414	\$498	8,100	\$80	\$418	\$498
0.5	31,800	\$76	4,100	\$87	\$501	\$588	6,300	\$82	\$507	\$589
Other Filtration										
5.0	22,300	\$103	11,900	\$99	\$128	\$228	17,900	\$99	\$130	\$229
2.0	22,300	\$103	9,100	\$101	\$219	\$320	13,700	\$99	\$221	\$320
1.3	22,300	\$103	7,700	\$102	\$277	\$379	11,600	\$100	\$280	\$380
0.7	22,300	\$103	5,300	\$105	\$414	\$519	8,100	\$101	\$418	\$520
0.5	22,300	\$103	4,300	\$108	\$502	\$609	6,500	\$103	\$507	\$610
Aeration										
5.0	57,000	\$35	14,600	\$38	\$129	\$168	22,000	\$37	\$130	\$168
2.0	57,000	\$35	8,000	\$41	\$218	\$260	12,200	\$39	\$221	\$260
1.3	57,000	\$35	5,800	\$43	\$275	\$318	8,900	\$41	\$278	\$319
0.7	57,000	\$35	3,100	\$49	\$408	\$457	4,800	\$45	\$413	\$457
0.5	57,000	\$35	2,300	\$52	\$494	\$546	3,500	\$47	\$499	\$547

(a) Population density is defined as people per hundred lf of transmission and distribution pipe, evaluated over the range in the data.

People per hydrant is adjusted proportionately to the changes in the density levels.

(b) Annualized cost functions assume a 20 year time period and 6% discount rate.

(c) Transmission and distribution costs do not include storage or pump station components.

(d) Extension limit refers to the maximum population extension for consolidation, after which lower costs result from constructing a separate treatment and transmission/distribution system for the extension considered.

Table C4. Minimum Average Cost Population Levels for Alternative Treatments and Transmission and Distribution Costs

Population Density	Treatment Only (b)		Treatment Plus Trans. and Distribution (c)				Extension Beyond Minimum Cost (d)			
			Average Cost Per Capita			Average Cost Per Capita				
	Population	AC	Population	Treatment	Trans. & Dist'n.	Total	Population	Treatment	Trans. & Dist'n.	Total
Slow Sand Filtration										
5.0	16,800	\$130	8,400	\$124	\$192	\$316	12,700	\$123	\$194	\$317
2.0	16,800	\$130	6,100	\$126	\$328	\$454	9,300	\$124	\$331	\$455
1.3	16,800	\$130	5,000	\$128	\$414	\$543	7,600	\$125	\$419	\$544
0.7	16,800	\$130	3,300	\$134	\$617	\$751	5,100	\$128	\$624	\$752
0.5	16,800	\$130	2,600	\$138	\$749	\$887	4,000	\$131	\$757	\$888
Direct Filtration										
5.0	31,800	\$76	11,300	\$78	\$194	\$272	17,000	\$77	\$196	\$272
2.0	31,800	\$76	7,000	\$81	\$329	\$410	10,600	\$78	\$332	\$411
1.3	31,800	\$76	5,300	\$84	\$415	\$499	8,100	\$80	\$420	\$500
0.7	31,800	\$76	3,100	\$91	\$616	\$707	4,700	\$85	\$623	\$708
0.5	31,800	\$76	2,300	\$96	\$746	\$843	3,500	\$89	\$754	\$844
Other Filtration										
5.0	22,300	\$103	9,800	\$100	\$193	\$293	14,800	\$99	\$195	\$294
2.0	22,300	\$103	6,700	\$103	\$329	\$431	10,100	\$100	\$332	\$432
1.3	22,300	\$103	5,300	\$105	\$415	\$520	8,000	\$101	\$419	\$521
0.7	22,300	\$103	3,300	\$111	\$617	\$729	5,000	\$106	\$624	\$730
0.5	22,300	\$103	2,500	\$116	\$748	\$864	3,800	\$109	\$756	\$865
Aeration										
5.0	57,000	\$35	9,400	\$40	\$193	\$233	14,300	\$39	\$195	\$233
2.0	57,000	\$35	4,500	\$45	\$325	\$370	6,900	\$42	\$329	\$371
1.3	57,000	\$35	3,100	\$49	\$409	\$458	4,800	\$45	\$414	\$459
0.7	57,000	\$35	1,600	\$57	\$606	\$663	2,500	\$51	\$613	\$664
0.5	57,000	\$35	1,200	\$62	\$734	\$796	1,800	\$56	\$742	\$797

(a) Population density is defined as people per hundred lf of transmission and distribution pipe, evaluated over the range in the data.

People per hydrant is adjusted proportionately to the changes in the density levels.

(b) Annualized cost functions assume a 20 year time period and 6% discount rate.

(c) Transmission and distribution costs include storage and pump station components.

(d) Extension limit refers to the maximum population extension for consolidation, after which lower costs result from constructing a separate treatment and transmission/distribution system for the extension considered.

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