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Tradeoff between Economies of Size in Treatment and Diseconomies of Distribution for Rural Water Systems

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This paper outlines a method to determine the tradeoff between economies of size in water treatment and diseconomies of distribution. Cost equations are estimated for several treatment technologies and distribution extensions. Empirical results are used to identify optimal system size where average total costs are minimized. Regardless of treatment, most costs are due to distribution. As water systems expand service territories, only in the most densely populated areas would remaining economies of size in treatment outweigh the diseconomies in distribution.

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 such systems 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. 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. From a

strictly economic perspective, a water system's optimal size, where average total costs are minimized, 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). This subject was examined, for large systems only, nearly twenty years ago (Clark and Stevie 1981).

This paper outlines a method to determine the size for small water systems that will minimize the combined cost of treatment and delivery for commonly used treatment options and differences in rural service areas. In this way, small rural water systems can evaluate the additional costs of environmental regulations and plans for expansion of their service territories to determine the size at which average costs for treatment and delivery are minimized. We begin with a discussion of the nature of the cost functions for treatment and delivery and an appropriate way to combine the costs of these components. After the estimated cost functions based on New York data 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

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.

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Treatment Cost Functions

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:

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

where TC_i 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,

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

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, Tsao, and Schmit 1996; Christensen and Greene 1976). The practical implication of this specification is that if economies of size exist, average costs will continue to fall regardless of how large the system becomes. This may not 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:

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

For this specification, we have:

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

and the economies of size can vary with the level of output.¹ Besides being flexible, 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 the equation into logarithmic form:

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

Unfortunately, the sample of water systems to be used in the empirical analysis below contains 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 problem, 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 unity 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:

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

Before proceeding to the discussion of distribution costs, it is important to comment on the measure of output. For analytical purposes, we need a measure of output related to both operating and capital costs of treatment as well as to distribution costs. From an engineering point of view, Malcolm Pirnie (1993) suggests that the two major components of treatment costs are related to different measures of size or output. Operating costs are most directly related to average daily flow, while capital costs are more a function of design capacity. Since annual costs in this analysis include both operating and annual capital costs, neither of these measures seemed appropriate. Population, however, is the measure used by EPA and others to classify systems by size for policy purposes; Boisvert, Tsao, and Schmit (1996) demonstrate that population is also directly related to average daily flow, design capacity, and the number of service connections. Their estimated relationships between population served and average daily flow, design capacity, and service connections, based on data from the FRDS-II data system (EPA 1993b), are in the appendix to enable conversion concerning different measures of output. Finally, using population as a measure of output facilitates comparisons of treatment costs with distribution costs, which are also appropriately assumed to be a function of population served.

¹The cost function in equations (1) and (3) are most often written in logarithmic form—taking the natural logarithms of both sides (Boisvert, Tsao, and Schmit 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.

Delivery System Cost Function

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, service connections, and energy to move the water through the system. Costs of supplying water to customers also rise 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, we rely on a different specification, since it is impossible to disentangle energy costs from other O&M costs in the data, which are described in greater detail in Schmit and Boisvert (1996). Thus, while energy costs for distribution are embodied in the entire analysis and are related directly to output, the effect of distance on energy costs of distribution is reflected only indirectly through a measure of population density. Since population density is related to both flow and distance, this assumption is as close to Clark and Stevie's (1981) specification as the available data would allow. To gain some understanding of the sensitivity of the results, we do compare average total costs for several alternative population density levels over the range in the data.

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, and it is 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:

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

The $\ln P$ term 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:

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

Here, 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.

Total Costs for the System

By adding the cost equations (6) and (9), it is possible to identify the optimal size for a water system, once the treatment technology and population density (L/P and H/P) are known, and to understand the importance of economies of size for treatment and diseconomies associated with distribution. If Clark and Stevie's hypothesis is true, optimal system size based on total cost is below that when only treatment costs are considered.

In figure 1, for example, treatment costs, C_T , rise first at a decreasing rate, and then at an increasing rate. Thus, average costs per person served initially fall and then rise 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. When the two costs 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).

Once the optimal system sizes are determined in this way, water systems around the country in

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

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

One way to understand this issue is with the total cost curve for treatment and distribution in figure 2. From figure 1, we know that the optimal size, P_{TD} , is below what it would be for treatment costs alone. Suppose 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.

Figure 2. Cost Curves for Water Treatment and Distribution (TD) and an Extension beyond the Minimum Cost Size (TD^*)

In the two-system case, average treatment costs for the second system will be larger, but the diseconomies of distribution will be smaller.

This tradeoff is shown in the 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.

Empirical Analysis

For the empirical analysis, it was necessary to have estimates of equation (6) and (9) for at least one water treatment process.

Treatment Cost Function

The treatment cost equation provides estimates of the combined annualized capital and O&M costs for slow sand filtration (SSFILT), aeration (AERAT), direct filtration (DIRFILT), and a final category that includes several other types of filtration (OFILT), such as rapid sand, diatomaceous earth, and coagulation filtration (table 1). These are the treatments most commonly used by small sys-

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 ²	0.89			

NOTE: Annualized cost function is based on an 8% discount rate and a twenty-year time period.

tems across New York (Boisvert and Schmit 1996a).

The data used to estimate this treatment equation (equation 6) are from thirty-seven Rural Development loan and grant files for rural New York water system treatment improvement projects (Schmit and Boisvert 1996). Rural Development is an agency that administers the Water and Waste Disposal Loan and Grant Program (WWD), which provides loans and grants for water and waste water systems primarily serving rural areas or communities of fewer than 10,000 people. Applicants must demonstrate that they are unable to finance the proposed project from their own resources or through commercial credit at reasonable rates and terms. Since this research focuses on small rural water systems and the predominant lending agency for these systems is Rural Development, costs estimates based on these data certainly are consistent with costs for small rural water systems, although they may not be representative of small water systems throughout the country.

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 twenty years and a discount rate of 8%.² 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. On an annualized basis, the average annual cost is nearly \$140,000. Combined with annual system operating expenditures, the total system annualized cost averages nearly \$309,000, and ranges from \$7,400 to over \$1.7 million. Average project costs for the sample of

systems used here are similar to the average costs of water and waste water projects funded by Rural Development over the past twenty years (\$1.4 million in New York and \$1.6 million nationally, in 1995 constant dollars (GAO 1995)). On average, capital accounts for about 45% of costs, while operating costs account for the remaining 55%. AWWA (1992) estimates suggest that operation and maintenance costs are higher in relative terms (78%) for small water utilities, but its data reflect current expenditures prior to many system treatment capital upgrades.

All cost and size variables are converted to their natural logarithms. The logarithm of population is included in the interaction terms with the dummy variables for the various treatment categories. (Chlorine is the omitted treatment variable and is assumed to be inherent in the intercept.) The economies of size vary with output, as well as type of treatment, while the coefficients on the treatment regressors provide the incremental annualized cost for the associated treatments at a particular size of system. The regression explains about 89% of the variation in the dependent variable, and the standard errors of the coefficients are quite low relative to the size of the coefficients themselves.

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, but are minimized at 22,300 people for other filtration, at 31,800 for direct filtration, and at 57,000 for aeration.

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. At a size of 7,500 people, average costs are only 3%, 9%, 5%, and 18% above minimum cost for slow sand

²Though 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 1993) for the treatments considered.

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	75,00	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 minimm	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.

filtration, direct filtration, other filtration, and aeration, respectively. This finding may seem contrary to the belief that economies of size persist for much larger systems. This result is likely due to the fact that the cost function was estimated using only systems serving fewer than 10,000 people and extrapolation beyond this size is probably not warranted.

One might very well argue that when applied on a larger scale, these treatments involve substantially different applications (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 could be identified only if the estimated cost function were based on data from both large and small systems employing similar treatments. 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 thirty-three Rural Development loan and grant files described in Schmit and Boisvert (1996). Average distribution costs per project 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 0 to 84; the average is about 25. For systems connecting to neighboring systems, 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. Average costs per household were approximately \$730 for a density of 1.6 people per hundred feet of pipe. This figure is just slightly below EPA’s (1994) national estimate of per household transmission and distribution costs of \$775 for a similar population density and pipe footage.

The estimated equation for total transmission and distribution costs (equation 9) explains about 81% of the variation in the dependent variable

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

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
LPOPEN	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 ²	0.81			

NOTE: Annualized cost function is based on an 8% discount rate and a twenty-year time period.

(table 3). The two most important variables are population served and linear feet of transmission main. Three other variables, the number of hydrants and dummy variables for whether or not storage and booster pump stations were part of the project, were also included. These variables performed much worse as measured by the *t*-ratios, probably because there was not sufficient variation in these variables to measure their effects on costs accurately, rather than because they should not be included.

As population served increases by 1%, 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. However, if population, feet of transmission main, and the number of hydrants all increase by 1% (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. These costs do not change as the population density falls

(as one reads down column 1). From the second section of the table, when both costs are combined, the optimal size is reduced substantially from the optimal size when treatment costs alone are considered. The reduction in size is more pronounced as population density falls.

For all 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. At these sizes, per capita treatment costs rise only slightly. 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 twenty-year period at an 8% interest rate. These assumptions were made to be consistent with EPA's cost estimates in its recent Best Available Technology document (Malcolm Pirnie 1993) and are similar to those made by others in estimating the costs 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. Cost can be reduced substantially, however, if rural water systems have access to loan funds from Rural Development, which, as of 1995, was making some loans at 5% for up to thirty-eight years. The differential interest rate alone would cut costs by 20%, while almost doubling the loan period would do about the same. These cost reductions only

³See Boisvert and Schmit (1996b) for additional simulations using alternative discount rates and assuming that storage and pumping station costs are included in the transmission and distribution cost calculations.

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

Population Density ^a	Treatment Only ^b		Treatment Plus Trans. and Distribution ^c				Extension beyond Minimum Cost ^d			
	Population	AC	Population	Average Cost Per Capita			Total Population	Average Cost Per Capita		
				Treatment	Trans. & Dist'n.	Total		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

^aPopulation 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.

^bAnnualized cost functions assume a twenty-year time period and an 8% discount rate.

^cTransmission and distribution costs do not include storage or booster pump station components.

^dExtension 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.

serve to underscore the need for such programs in financing public services in rural areas.

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

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 con-

straint, particularly since we have seen that economies of size in treatment are exhausted quite rapidly. This latter observation also explains that while extensions of system size beyond the minimum cost size (as discussed above) can be substantial, that ability falls rapidly with population density. Variations on this kind of analysis 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 between existing systems.

Summary and Policy Implications

The purpose of this paper is to identify a method by which to determine, for small water systems in New York, the size that will minimize the combined cost of treatment and delivery for commonly

used treatment options and to examine representative differences in the characteristics of rural service areas. This analysis shows clearly 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, only in the most densely populated areas would any remaining economies of size in treatment outweigh the diseconomies in transmission and distribution.

This result has major implications for designing water treatment systems for rural areas and considering system consolidation. Moreover, 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, an additional dollar would need to be 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 to 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. For example, 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).

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Appendix

Regression Equations for Average Daily Flow and Design Capacity

Variable	Average Daily Flow		Design Capacity	
	Coefficient	Std. Error	Coefficient	Std. Error
	$R^2 = 0.92$		$R^2 = 0.80$	
Intercept	5.20	0.08	7.55	0.10
$\log[(\text{average daily flow})]^2$			0.01	0.00
$\log(\text{population})$	0.69	0.02	0.29	0.03
$\log(\text{hookups})$	0.10	0.02	0.23	0.02
Dummy Variables:				
Surface water = 1	0.20	0.02	-0.11	0.03
Purchase water = 1	-0.23	0.02	-0.22	0.04
Federal government owned = 1	0.54	0.07	0.41	0.10
State government owned = 1	0.48	0.07	0.56	0.10
Local government owned = 1	0.25	0.01	0.13	0.02
Residential service area = 1	-0.12	0.06	-0.20	0.09
Semi-residential service area = 1	0.21	0.08	-0.27	0.11
Located in MSA = 1	0.03	0.01	0.12	0.02
EPA southern regions = 1	0.07	0.01	0.06	0.02
EPA western regions = 1	0.17	0.01	0.40	0.02
$\log(\text{population}) \times \log(\text{hookups})$	0.02	0.00		

SOURCE: Boisvert, Tsao, and Schmit (1996).