A Hedonic Approach to Estimating Operation and Maintenance Costs for New York Municipal Water Systems

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A hedonic cost function is used to isolate the operation and maintenance costs for water treatments. For small systems, costs are substantial for some technologies, but not for others. When regional differences in input costs are accounted for, small systems located in rural areas may have a cost advantage over similar systems closer to urban centers; however, costs of water treatment to meet Safe Drinking Water Act amendments may still be substantial.

The ability of small public water systems to comply with monitoring and treatment requirements under the Safe Drinking Water Act (SDWA) continues to be an open question for national, state, and local policymakers and government officials. Based on EPA's recent survey of the need for improvements in the public water system infrastructure (1997), the nation's 55,000 community water systems must invest about $140 billion (1995 dollars) over the next twenty years to install, upgrade, or replace infrastructure to insure the provision of safe drinking water. Estimates of average costs per household range from $970 for large systems to $3,300 for small systems, those serving fewer than 3,300 people.

Just over half of this total investment is needed for treatment or distribution expenses related to the SDWA. About $12 billion is needed immediately to comply with current SDWA regulations. Total twenty-year costs for SDWA and SDWA-related needs, including proposed regulations of the Enhanced Surface Water Treatment Rule (ESWTR), Disinfectant/Disinfection By-Product Rule (D/DBP), and radionuclides, are estimated at over $30 billion nationally. An additional $36 billion are needed over twenty years for SDWA-related distribution improvements under the Total Coliform Rule (TCR) (EPA 1997).

About 86% of all community water systems nationwide serve populations under 3,300 people. Many believe that systems below this size are unable to take advantage of economies of size and/or have insufficient resources to finance SDWA requirements at a reasonable cost to consumers (Boisvert and Schmit 1996; EPA 1993b). Current and future costs for both treatment and distribution are substantial. Thus, policymakers need specific information about the cost implications of the regulatory requirements and potential dramatic increases in water rates for system users, particularly for small systems.

This research contributes to an understanding of public water system treatment costs by accounting for size, population densities, factor prices, and water treatment in estimating public water utility cost functions. The differential costs of alternative water treatments (including aeration, ion exchange, and several filtration processes) are accounted for in a hedonic fashion. This model specification is made possible through a combination of financial data for New York water systems from the Division of Municipal Affairs and data on current treatment from the Federal Reporting Data System (FRDS-II) national data base. Because of data availability, the focus must be limited to operation and maintenance (O&M) costs, but the study is unique in that it is based on data for both small and large systems. The inferences to be made about treatment costs for small systems are of particular importance.

We continue this report with a brief review of the literature on the estimation of water system cost functions, focusing primary attention on hedonic functions for public water supply utilities. This review is followed by the development of the

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O&M cost model and a discussion of the data used for parameter estimation. We then discuss the results of the model and cost differences across treatment alternatives and system size. Finally, we articulate some general conclusions and policy implications.

Background

Research into water supply costs and implications of drinking water regulations was underway well before the 1986 amendments to the SDWA (e.g., Clark and Goddard 1977; Clark and Stevie 1981; Stevie and Clark 1982; Bruggink 1982; Feigenbaum and Teeples 1983). The substantial new monitoring and treatment requirements embodied in the amendments, however, have heightened the interest in this type of research because the cost implications are directly related to the ability of small water systems to adhere to the expanded regulations while increasing water revenues to pay for the higher costs of operation. Numerous national-level estimates of the costs of compliance have been completed, but few models have concentrated on estimating the individual system response to various treatment concerns and water quality considerations. There has been some limited evaluation of treatment technologies suitable to small water systems, and they serve as a good starting point for further research (Logsdon, Songe, and Clark 1990; Goodrich et al. 1992; Malcolm Pirnie 1993). For the most part, these studies examine the costs for individual treatments and are based on economic engineering methodologies, rather than actual cost data. Furthermore, they do little to address the costs associated with multiple treatments. These types of comparisons of costs across treatments and system sizes are essential for any meaningful policy analysis.

As an alternative, one can envision a hedonic approach whereby costs are assumed to be a function of various water treatments. In this way, the additional costs due to treatments or multiple treatments are reflected in a treatment-adjusted index of water output. This hedonic approach has received only limited attention, especially with respect to the treatment technology specification. Bruggink (1982), for example, evaluated the comparative efficiency of public and private ownership in the municipal water industry by estimating a multivariate operating cost model. Treatment concerns were addressed through a simplified treatment index variable, reflecting primarily the number of treatments applied rather than specific treatment effects. The results were based on eighty-six large water systems, all serving more than ten thousand people.

In 1988 Holmes examined the relationship between soil erosion and water treatment from two perspectives. First, he estimated the relationship between water quality, as measured by water turbidity levels, and typical treatment costs using a cubic spline regression; he used these results to estimate national turbidity-related water production expenses. He then estimated a hedonic Cobb-Douglas (C-D) cost function with a variable representing influent water quality, along with output and input prices. Holmes evaluated the relationship between treatment costs and different levels of raw water quality, rather than looking at the specific treatments applied. Typical treatment costs were calculated based on the types of treatments required (coagulation, filtration, etc.) for the associated level of turbidity. These parameter estimates were used to estimate the costs of turbidity mitigation measures and further used to estimate national damage costs induced by suspended sediments.

Hedonic cost approaches for water utilities were also used by Feigenbaum and Teeples (1983) and Teeples, Feigenbaum, and Glyer (1986); they examined the effect of ownership on cost structure. A hedonic model incorporating a translog cost function with factor prices and quality-adjusted production was specified. The functional form used is adapted from Spady and Friedlaender's (1978) hedonic cost model for the regulated trucking industry. Spady and Friedlaender argued that failing to account for industry characteristics creates serious specification errors and incorrect inferences regarding economies of size.[1] The hedonic coefficients in the cost function are representations of technology, and if the technologies affect costs, their inclusion in the specification is necessary for accurate cost predictions and estimates of economies of size.

The quality and service attributes specified by Feigenbaum and Teeples (1983) are limited in terms of treatment technologies; these authors adopted a treatment index approach similar to that of Bruggink (1982). The treatment quality attribute was weighted by costs obtained from engineering data for each firm's treatment activities. Data from the American Water Works Association on actual O&M costs for 1970 were obtained for 320 large

[1] Spady and Friedlaender (1978) favor hedonic representations of outputs and qualities as arguments, compared with conventional cost functions with exogenously specified quality adjusted outputs as arguments. The hedonic specification permits various quantity-technology combinations to reflect the same level of quality.

water supply firms. The hedonic specification was superior to the nonhedonic specification, and costs were shown to increase significantly with the level of treatment.

The Hedonic Cost Model

Here, we adopt a model similar to the one used by Feigenbaum and Teeples (1983), but the hedonic specification is in terms of several specific treatment technologies used frequently in New York State. We also incorporate fixed factors of production into the cost specification. The hedonic cost model for water systems is derived from the production function:

(1) $Q(Y;z_1, z_2, \ldots, z_s) = f(L, E, F, K, W),$

where $Q(\ )$ is an index of firm output, Y is average daily water flow, z_s is water treatment and source attributes, L is labor, E is energy, F is other fixed factors of production, K is capital input, and W is water input. Water output, Q, reflects both water production measured in gallons per day (Y) and its associated treatment characteristics (z_s). The production technology is represented by $f(\ )$, and for our purposes need not be given further specification.

Since most public water utilities are legally obligated to supply all water demanded at regulated rates, one can assume that they minimize cost in the short run (adjusting inputs) subject to this demand constraint. Applying economic duality, there is an indirect cost function:

(2) $C = C(Q(Y;z_1, z_2, \ldots, z_s); r_1, r_2, \ldots r_i; F_1, F_2, \ldots F_m),$

which depends only on exogenously determined input prices (r_i), treatment adjusted output (Q), and a set of fixed factors (F_m) (Christensen and Greene 1976). Since costs depend only on exogenous variables, parameter estimates are free of simultaneity bias (Feigenbaum and Teeples 1983). The translog specification of this general form is:

(3)
$$\ln C = b_0 + b_1 \ln Q + b_2 \left[\frac{1}{2}(\ln Q)^2\right] + \sum_i c_i \ln r_i + \frac{1}{2}\sum_i \sum_j c_{ij} \ln r_i \ln r_j + \sum_i d_i \ln Q \ln r_i + \sum_m f_m \ln F_m + \frac{1}{2}\sum_m \sum_n f_{mn} \ln F_m \ln F_n + \sum_m g_m \ln Q \ln F_m + \sum_m \sum_i h_{mi} \ln F_m \ln r_i,$$

where:

(4) $\ln Q = \ln Y + \phi(z_1, z_2, \ldots, z_s)$, and

(5) $\phi = \sum_s a_s z_s.$

$Q(\ )$ is a treatment-adjusted water index and $\phi(\ )$ is a hedonic function aggregating the various treatment attributes provided by the firm.[2] To improve statistical efficiency in estimation, the cost function is estimated jointly with $n - 1$ factor share equations:

(6)
$$\frac{r_i x_i}{C} = c_i + \frac{1}{2}\sum_j c_{ij} \ln r_j + d_i \ln Q + \sum_m h_{mi} \ln F_m.$$

These share equations are transformations of the partial derivatives of the cost function with respect to input prices. From duality theory, we also know that they are transformations of the input demand functions, and by including them in the system to be estimated, we implicitly embody the assumption of cost minimization.

To ensure that the cost function is homogeneous of degree one in factor prices and that the symmetry conditions hold, we impose:

(7) $\sum_i c_i = 1; \sum_i d_i = 0; \sum_i h_{mi} = 0; c_{ij} = c_{ji};$ $f_{mn} = f_{nm};$ *and* $\sum_j c_{ij} = 0.$

Cross-equation constraints are imposed on the parameters, and those of the n^{th} share equation are identified analytically from equation (7). Finally, because Q is not observed, we substitute (5) into (4) and (4) into (3) to arrive at the final form of the cost equation. See the appendix for this derivation. The resulting equation, nonlinear in its parameters, is estimated by nonlinear two-stage least squares. The full hedonic specification is estimated, and we test restrictions on unitary elasticities of substitution between the inputs and homotheticity and homogeneity of the production process. A nonhedonic specification is also estimated by restricting $a_s = 0$ for all s.

[2] Since the water source and treatment attributes in this specification are going to be (1,0) dummy variables, the natural logarithm is avoided for the hedonic component. The hedonic function is $Q = Ye^{\Sigma a_s z_s}$, implying that Q is quality separable and is homogeneous of degree one in volume. This latter assumption implies that the quantity of output is proportional to water volume.

The Data

Empirically, we need data on O&M costs and cost shares and input prices for labor and energy. There is only one fixed factor, the population density of the service area. The nine treatment attributes (z_s) include aeration, ion exchange, and several filtration technologies.

For more than three hundred New York community water systems, annual financial data, including revenue, appropriation, and general ledger accounts, for fiscal years 1987 through 1992 were available from the Office of the State Comptroller for New York. Data on population served, connections, average daily water flow and design capacity, and treatments applied to source water prior to distribution to the service area were obtained from EPA's Federal Reporting Data System (EPA 1993a).

Finding data for wage and electricity rates (prices for the two major inputs) for individual water systems was more problematic. The only potential source for specific water system wage rates was an American Water Work Association (AWWA) data base; these data are only for a sample of large systems. As an alternative, since one might expect similarity in wage rates across water systems by locality or region, county local government earnings were divided by local government employment to obtain an implicit annual rate of compensation for labor (REIS 1987–92). This proxy should be highly correlated with local government wage rates and should reflect important differences in wage rates by region and over the five-year period. Using community-specific electricity rates was less problematic as these rates would be constant for systems within the service areas of New York's electric utilities (EIA 1987–92).

The average size of the communities served was 6,500 persons, but size ranged from 100 to over 190,000 (table 1). This wide range in size is significantly greater than accommodated in previous studies and allows for an analysis of small systems to be conducted on an equal footing with larger ones. By combining data in this fashion, one

Table 1. Descriptive Statistics for Variables in Cost Function Estimation

Variable	Description	Mean	Std. Dev.	Minimum	Maximum
TOTCOST	Total O&M cost excluding debt service (1992 $)	349,908	781,922	1,629	8,948,502
ADMCOST	Administrative costs (1992 $)	51,624	138,085	0	1,566,288
PURCOST	Purification costs (1992 $)	68,740	208,736	100	2,531,345
TRDCOST	Transmission and distribution costs (1992 $)	86,248	281,640	0	4,535,152
SSPCOST	Source supply and pumping costs (1992 $)	52,720	110,646	0	1,595,619
CSUCOST	Common water supply costs (1992 $)	206	2,212	0	343,394
UNOMCOST	Undistributed O&M costs (1992 $)	60,287	145,121	0	1,253,607
UNEBCOST	Undistributed employee benefit costs (1992 $)	30,083	80,215	0	1,129,797
TCSTPGAL	Total O&M cost per gallon (1992 $)	0.38	0.34	0.06	5.98
TCSTPCAP	Total O&M cost per capita (1992 $)	51.21	33.16	10.59	448.44
WAGSHARE	Labor cost share of total O&M cost	0.43	0.17	0.00	0.86
POPDEN	Population density (people per square mile)	1,559	1,787	2	13,693
TOTLPOP	Water system population	6,467	16,750	100	192,000
TOTLHU	Water system hookups	1,829	4,398	28	45,503
TOTLPROD	Average daily water production (gpd)	1,231,679	3,833,594	10,000	50,090,000
TOTLDESC	System design capacity (gpd)	2,161,436	5,883,143	42,413	64,000,000
RESRAT	Community residential electric rate ($/kwh)	0.097	0.023	0.021	0.160
GOVWAGE	County government wage rate (1,000's 1992 $)	28.246	3.071	22.126	40.491
Treatment process dummy variables:					
Z1	Aeration treatment[a]	0.144	0.351	0	1
Z2	DE filtration treatment	0.057	0.233	0	1
Z3C	Rapid sand filtration treatment w/CFS[b]	0.144	0.351	0	1
Z4	Slow sand filtration treatment	0.023	0.150	0	1
Z4C	Slow sand filtration treatment w/CFS[b]	0.011	0.107	0	1
Z5	Other filtration treatment[a]	0.032	0.175	0	1
Z5C	Other filtration treatment w/CFS[b]	0.011	0.107	0	1
Z6C	Ultra filtration treatment w/CFS[b]	0.070	0.254	0	1
Z7	Ion exchange treatment	0.043	0.203	0	1

NOTE: The average values for the dummy variables are equal to the proportions of the systems with those attributes.
[a]Aeration treatment includes packed tower and diffused aeration; other filtration includes pressure sand and direct filtration.
[b]CFS includes the processes of coagulation, flocculation, and sedimentation.

Table 2. Treatment Frequencies by Population Category

Population Category	Number of Systems	Percentage of Systems Currently Using Treatments[a]						
		Aeration	DE Filtration	Rapid Sand Filtration[b]	Slow Sand Filtration[b]	Other Filtration[b]	Ultrafiltration[b]	Ion Exchange
<500	39	0.0	0.0	0.0	2.6	2.6	0.0	0.0
500 to 999	82	4.9	6.1	3.7	1.2	4.8	1.2	2.4
1,000 to 4,999	145	15.2	5.5	11.7	3.5	4.1	5.5	5.5
5,000 to 9,999	32	15.6	9.4	28.1	3.1	6.3	6.3	9.4
10,000 to 24,999	29	37.9	13.8	44.8	10.3	6.9	17.2	6.9
25,000 to 49,999	14	42.9	0.0	42.9	7.1	0.0	28.6	0.0
50,000 to 99,999	4	25.0	0.0	0.0	0.0	0.0	100.0	0.0
100,000 +	3	33.3	0.0	66.7	0.0	0.0	0.0	0.0
All systems	348	14.4	5.7	14.4	3.4	4.2	7.0	4.3

[a]All systems currently disinfect with either gas or liquid chlorination processes.
[b]All rapid sand filtration and ultrafiltration observations use coagulation, flocculation, and sedimentation processes, while a portion of the slow sand filtration and other filtration processes do.

should be able to generate the minimum cost envelope of cost structures for both small- and large-scale treatment technologies.

Total O&M costs, excluding debt service, averaged nearly $350,000 (1992 dollars), and ranged from under $2,000 to nearly $9 million. On a per capita basis, these costs averaged about $51, and ranged from $11 to nearly $450. The cost data also show that labor and labor-related expenditures (i.e., employee benefits, etc.) constitute over 40% of the total operation costs on average; the range was from nearly zero to 86%. Table 1 also distributes O&M costs by type of expenditure as reflected in New York State audit codes.

Average water production is over 1.2 million gallons per day (mgpd), ranging from only 10,000 gallons per day (gpd) to over 50 mgpd. On a per capita basis, average water production was approximately 160 gpd, or 45% higher than the average for the state (Boisvert and Schmit 1996). This finding was not unexpected because the data sent to the comptroller by many of the smallest systems were often incomplete, or the costs of running the water system could not be disentangled from those of other government functions. Thus, very small systems are slightly underrepresented in the sample relative to the state, and the small systems included tend to be those that are better managed and with higher per capita demands. About half of the systems in the sample have surface water as their primary water source; this is slightly less than the state average of 60%.

The water treatment attributes, as reflected in the specification of the dummy variables, are summarized at the bottom of table 1. The means of these dummy variables reflect the proportions of systems currently using the treatment. Chlorination (gas or liquid) is used by all systems in the sample. Other simple and inexpensive non-SDWA specific type treatments, such as pH control or fluoride, were not specified individually and are included along with chlorination as a reference point for the dummy variable regression. Aeration, ion exchange, and several types of filtration are also used by systems in the sample. A more detailed description of the treatments is in Boisvert, Tsao, and Schmit (1996) and EPA (1993b). In what follows, we briefly describe the treatments and compare their frequencies of occurrence in the sample with those statewide (table 2).

Aeration is used by 14% of the systems in the sample, slightly above a statewide estimate of 11% (Boisvert and Schmit 1996). It is used mainly by groundwater systems, and in some cases is combined with ion exchange. Surprisingly, in a few cases aeration is combined with filtration.[3] Aeration is a process that transfers contaminants from the water into the air, at which time they are removed. Two types of aeration, packed tower (PTA) and diffused aeration (DA), are found in the sample. Neither requires any chemical cost, but both require capital investment in blowing equipment and towers (PTA) or holding tanks (DA). For PTA, raw water is pumped to the top of the tower; as water falls by gravity, air is blown upward from the bottom to remove the contaminants. DA is less efficient than PTA but operates on the same principles, except that water is run on a bed containing air jets. Power costs are the most significant por-

[3] In the few cases such as these, the treatment combinations are most likely explained by the fact that some systems use multiple water sources, but only the primary surface or groundwater source is reported in the data.

tion of O&M costs. Aeration is predominantly used for the removal of volatile organic compounds but can also be used to reduce concentrations of taste and odor compounds and to remove some inorganic compounds, including radon, carbon dioxide, and hydrogen sulfide gas.

Diatomaceous earth (DE) filtration was used by 6% of the sample systems, nearly the same as the statewide frequency. DE filtration uses a thin layer of DE supported by a filter to remove particulates and microorganisms from the water. A continuous feed of DE is mixed with the raw water. As the added DE mixes with contaminants, new layers of filters are produced. Eventually the filter must be cleaned, recoated, and replaced. While most common for medium-sized systems, DE is also used to a limited extent by small systems. For many small systems, the operating requirements are too high; there is too much sludge production; and DE can be used only when there are low turbidity and low bacteria levels in the raw water. Thus, water is usually not pretreated with coagulation, flocculation, and sedimentation processes (CFS).

Rapid sand filtration, always in combination with CFS, was used by 14% of the sample systems (10% state average).[4] In this process, specific contaminants are agglomerated and then removed by the sand filtration media. Pretreating with CFS increases the flow rate for filtration and allows for larger porous capacity in the sand filtration media. Rapid sand filtration is used to remove iron, inorganics, organics, particulate, and radionuclides. While rapid sand with CFS pretreatment can be used for a wide range of raw water qualities, the higher maintenance requirements, power, and chemical costs makes this largely unsuitable for small systems.

Slow sand filtration was used by less than 4% of the systems (3% state average) and one-third of those systems treated the water with CFS prior to filtration. For slow sand filtration, water is percolated through a deep bed of sand, which filters out particulates and microorganisms. Filter loading rates are low and the technology requires high initial raw water quality and a large amount of land available for the filter area. When water is relatively turbid, raw water can be treated with CFS prior to filtration to reduce filter media maintenance and scraping requirements. There are no chemical or power costs associated with slow sand filtration, but sand must be increased as water demand rises, and operators should be highly trained in its use to control O&M costs.

The higher water quality requirement for membrane filtration technologies was evident in the ultrafiltration category. All these systems were operated in conjunction with CFS. In total, 7% of sample systems were using this treatment, compared with a statewide average of 9%. This category includes microfiltration and ultrafiltration processes that use membrane filters for removal of particulates, microorganisms, and certain organics as well. Micro- and ultrafiltration have relatively large pore membrane filters and thus have high flow rates under low pressure. The use of these filters is common practice, since dissolved organics removal is enhanced by using a coagulant. Operating requirements include periodic back flushing and chemically soaking filter membranes.

The other filtration category includes pressure sand and direct filtration technologies, which were used by 4% of the sample systems (4% state average). As with slow sand filtration, some systems combined this treatment with CFS (25%), while others did not (75%). Direct filtration commonly applies CFS treatment prior to filtration, although the sedimentation process is skipped. As such, direct filtration is more suited for water sources lower in turbidity and other contaminants. Pressure sand filtration was used less frequently; it generally requires higher quality sources for increased flow rates, without CFS treatment. These treatments are used to remove turbidity, microbes, certain organics and inorganics, and some radionuclides.

Finally, ion exchange was used by 4% of the sample systems (5% state average). While predominantly used in isolation, in a few cases, it was combined with aeration or filtration. What is perhaps more surprising is that this predominantly groundwater treatment was used with surface water sources by nearly 30% of the systems treated by ion exchange. This finding, too, is probably explained by the fact that a number of systems rely on multiple water sources. Ion exchange is a process that relies on exchange resins to remove ions from water. Synthetic ions are used to replace ions in the feed water with ions of similar charge fixed to a resin matrix. The main costs for ion exchange are for the resin and regeneration materials, both of which vary proportionally with water flow. Ion exchange is commonly used to remove inorganic compounds and radionuclides from drinking water and to soften hard water. Ion exchange is well

[4] Depending on raw water quality, other filtration technologies may also pretreat water with CFS prior to filtration. Coagulants are added to the raw water and mixed to form larger particles. The larger particles (floc) separate out by gravity in a sedimentation tank, and the resulting water is filtered.

suited for small water systems and is common with groundwater sources since it can be easily installed on an individual well or group of wells.

Estimated Cost Equations

For estimation, the six years of data for the 348 systems in the sample were treated as a pooled time series of cross-sections. In so doing, econometric estimation of the hedonic O&M cost model was based on a data set with nearly two thousand observations. System O&M costs and government wage rates and electricity rates were converted to 1992 dollars by the *Index of Average Hourly Compensation* and the *Producer Price Index for Intermediate Materials,* respectively (BEA 1987–92). The estimated equations for the hedonic and nonhedonic specifications are reported in table 3.

The hedonic equations explain more than 90% of the variation in the dependent variable; the coefficients have expected signs and relatively high t-ratios. Tests of unitary elasticities of substitution between the two inputs (Model 2 from table 3) as

Table 3. Community Water System Annual Operation and Maintenance Hedonic Cost Estimation Results

		Hedonic Specifications				Nonhedonic Specifications			
		Model 1		Model 2		Model 1		Model 2	
Parameter	Variable	Coefficient	t-ratio	Coefficient	t-ratio	Coefficient	t-ratio	Coefficient	t-ratio
b0	Intercept	3.314	6.420	5.134	9.630	3.025	5.190	4.877	8.200
b1	Average daily flow (ADF)	0.378	4.900	0.414	5.120	0.395	4.490	0.414	4.530
b2	1/2 ADF squared	0.022	3.770	0.019	3.080	0.026	3.880	0.023	3.430
c1	Wage rate	0.267	8.570	−0.017	−0.600	0.256	7.680	−0.020	−0.660
c11	1/2 wage rate squared	0.042	15.550	na	na	0.040	14.050	na	na
c2	Electric rate	0.733	23.539	1.017	35.894	0.744	22.322	1.020	33.512
c22	1/2 electric rage squared	0.042	15.550	na	na	0.040	14.050	na	na
c12	Wage rate* electric rate	−0.042	−15.550	na	na	−0.040	−14.050	na	na
d1	Wage rate* ADF	0.026	9.530	0.029	10.240	0.026	8.750	0.030	9.610
d2	Electric rate* ADF	−0.026	−9.530	−0.029	−10.240	−0.026	−8.750	−0.030	−9.610
f1	Population density	−0.075	−4.390	−0.109	−6.100	−0.079	−4.500	−0.110	−6.080
h1	Wage rate* popn. density	0.010	3.830	0.018	6.360	0.011	4.000	0.018	6.400
h2	Electric rate* popn. density	−0.010	−3.830	−0.018	−6.360	−0.011	−4.000	−0.018	−6.400
a1	Aeration	0.098	2.590	0.083	2.120				
a2	DE filtration	0.375	6.370	0.404	6.670				
a3c	Rapid sand filtration w/ CFS	0.534	12.050	0.494	10.900				
a4	Slow sand filtration	0.144	1.610	0.166	1.800				
a4c	Slow sand filtration w/ CFS	0.162	1.360	0.156	1.270				
a5	Other filtration	0.314	3.940	0.235	2.880				
a5c	Other filtration w/ CFS	0.403	3.180	0.311	2.390				
a6c	Ultrafiltration w/CFS	0.415	7.330	0.432	7.370				
a7	Ion exchange	0.524	8.150	0.522	7.900				
Cost equation:									
R^2		0.911		0.902		0.899		0.891	
RSS		414.139		454.287		473.666		510.684	
Root MSE		0.460		0.481		0.491		0.510	
Wage factor share equation:									
R^2		0.088		0.019		0.091		0.028	
RSS		50.022		53.839		49.978		53.471	
Root MSE		0.160		0.166		0.159		0.165	

NOTE: Model 1 refers to the original specification, while Model 2 imposes unitary elasticities of substitution with respect to inputs. The ADF* density interaction term and the density squared term were removed from the final specification because of relatively high standard errors and low t-ratios.

well as tests for homogeneity and homotheticity in production were rejected, providing evidence that Model 1 (table 3) is appropriate.[5] Furthermore, since only two input prices (labor and electricity) are specified, it was necessary to estimate only one cost share equation. The regression statistics for the cost share equation are at the bottom of table 3.[6]

From Model 1, it is clear that total O&M costs rise with water volume and input prices, and they fall, *ceterus paribus,* with an increase in population density. All water treatments add to O&M costs. The size of the increase varies substantially by treatment classification, but given the hedonic structure of the model and the interaction variables, cost increases can only be derived by examining several of the coefficients.

Where applicable, the model includes dummy variables for filtration both with and without CFS treatment. The dummy variable for ultra- and rapid sand filtration reflects costs for CFS treatment, while separate variables are included for slow sand and other filtration treatments both with and without CFS treatment prior to filtration. In general, CFS treatment adds between 15 and 30% to the incremental costs when combined with other treatments.

The smallest incremental treatment costs are associated with aeration and slow sand filtration. Aeration requires few chemical inputs, and labor requirements are low. Similarly, slow sand filtration has no chemical or power requirements specifically tied to the treatment, and minimal maintenance is required. Other filtration is the next most expensive filtration technology, approximately twice that of slow sand filtration. The higher coefficients seem reasonable given the moderately higher operating requirements. The incremental costs for diatomaceous earth filtration are between the cost estimates for other filtration with CFS treatment and other filtration without CFS treatment. This finding is reasonable given DE's larger operator requirements and sludge production expenses. However, for water with low turbidity (requiring no CFS treatment), the operating requirements of diatomaceous earth filtration are scaled back below those of the remaining filtration technologies. The incremental cost estimate for ultrafiltration with CFS treatment is slightly above diatomaceous earth filtration without CFS treatment. Its higher operating costs stem from the need for frequent membrane flushing. The incremental cost of rapid sand filtration with CFS is the highest of all treatments, primarily because of its high water flow rate, need for periodic back flushing, and increased operating requirements. Estimated incremental costs for ion exchange are slightly below those for rapid sand filtration. Although ion exchange may be well suited for small systems (exchange units can be installed on an individual well or groups of wells), maintenance of the resin capacity and regeneration materials is relatively expensive.

Estimating the Marginal O&M Costs of Treatment by System Size

As public water systems across the country attempt to comply with the 1986 and subsequent amendments to the SDWA, additional treatment requirements will be affected most significantly by the surface water treatment rules, existing and enhanced (SWTR and ESWTR), by the Disinfectant/Disinfection By-Product Rule (D/DBP), and by the Total Coliform Rule (TCR) (EPA 1997). To comply with these rules, most surface water systems will need to install filtration, as will many groundwater systems under the proposed groundwater treatment rules. Aeration and ion exchange are also needed to comply with the lead and copper rule. Therefore, to assist policymakers in evaluating the costs of meeting these regulatory requirements, table 4 contains estimates of the added O&M costs of these treatments, for system sizes corresponding to seven of the twelve EPA size categories established for policymaking (EPA 1993b). We emphasize the very small through medium-size systems, but costs for a couple of larger systems are provided for purposes of comparison. To isolate the additional costs of treatment, the "AC1" estimates in table 4 are based on sample mean levels of input prices, population density, and per capita water demand. Finally, it must be remembered that these estimated costs are total O&M costs (i.e., distribution, source supply and pumping, and treatment), not just those associated with treatment. They also reflect existing expenditures for maintenance and repair, costs that may rise substantially in the future as compliance with SDWA regulations are enforced.

The per capita average O&M costs decrease as the population served increases (table 4). Base sys-

[5] F-tests were completed by comparing the unrestricted model (Model I) with the three alternative specifications. In all cases the null hypothesis was rejected at a significance level of $\alpha = 0.01$. For simplicity, only the restricted models with unitary elasticities of substitution with respect to the inputs for the hedonic and nonhedonic specifications are reported.

[6] Although the R^2s on the cost functions are high, they are low on the share equation. This is not unusual since the estimation method does not simply minimize the sum of squared residuals, but also takes into account the covariance across equations (Spady and Friedlaender 1978).

Table 4. Average Operation and Maintenance Costs per Capita by Treatment Technology

Population Served	Base Scenario		Aeration		DE Filtration		Rapid Sand Filtration	
	AC1	AC2	AC1	AC2	AC1	AC2	AC1	AC2
100	$75.91	$63.61	$81.59	$68.32	$99.99	$83.55	$112.37	$93.78
500	$50.88	$49.32	$54.87	$53.18	$67.90	$65.78	$76.73	$74.32
1,000	$43.57	$42.20	$47.06	$45.57	$58.47	$56.60	$66.23	$64.10
3,300	$34.17	$34.58	$37.00	$37.44	$46.30	$46.86	$52.66	$53.31
10,000	$28.03	$31.42	$30.42	$34.10	$38.32	$43.00	$43.75	$49.11
50,000	$22.03	$35.96	$23.99	$39.21	$30.52	$50.05	$35.03	$57.57
100,000	$20.21	$27.77	$22.04	$30.32	$28.15	$38.83	$32.39	$44.74
Population Served	**Slow Sand Filtration**		**Other Filtration**		**Ultrafiltration**		**Ion Exchange**	
	AC1	AC2	AC1	AC2	AC1	AC2	AC1	AC2
100	$85.50	$71.56	$102.01	$85.22	$102.98	$86.02	$111.52	$93.07
500	$57.63	$55.85	$69.34	$67.17	$70.03	$67.84	$76.12	$73.73
1,000	$49.47	$47.90	$59.73	$57.82	$60.34	$58.41	$65.69	$63.58
3,300	$38.96	$39.43	$47.33	$47.91	$47.83	$48.41	$52.22	$52.86
10,000	$32.08	$35.97	$39.20	$43.99	$39.62	$44.46	$43.37	$48.69
50,000	$25.36	$41.48	$31.25	$51.26	$31.60	$51.85	$34.72	$57.05
100,000	$23.32	$32.10	$28.83	$39.78	$29.16	$40.24	$32.09	$44.33

NOTE: All costs are expressed in constant 1992 dollars.
AC1 = average cost per capita, where water production, population density, wage rate, and electricity rate are assumed at overall mean levels in the sample data.
AC2 = average cost per capita, with the same variables as in AC1, but measured at mean levels of population category. For these seven categories, the population ranges used to establish mean levels are: 100, under 500; 500 and 1,000, 500–1,000; 3,300, 1,000–5,000; 10,000, 10,000–25,000; 50,000, 50,000–75,000; and 100,000, over 100,000
All scenarios include disinfection by chlorine. All filtration processes, with the exception of DE filtration, pretreat with CFS prior to filtration.

tems (i.e., systems treating only with chlorination) have per capita costs of over $75 when serving 100 people, while systems serving 3,300 people have costs less than half this amount; costs drop below $25 for systems serving 50,000 people or more.

The other "AC1" columns in table 4 show what happens when other treatments are added to chlorination. O&M costs per capita increase, and the differences between these cost estimates and the ones for the base case are due to the additional treatment. The largest increases over the base cost are for ion exchange and rapid sand filtration. Rapid sand filtration's additional cost over the base is nearly $37 (48% increase over base) for the smallest system and about $12 (60% increase over the base) for the largest.

The additional O&M per capita costs for ultrafiltration, diatomaceous earth filtration, and other filtration are quite similar, ranging from $24 to $27 for systems serving 100 people. The additional costs are about $8 to $9 for the largest systems. In all cases, these additional costs are between 85% and 90% of those for rapid sand filtration. For the cost estimates in table 4, all filtration technologies, with the exception of diatomaceous earth filtration, are assumed to pretreat with CFS prior to filtration. Finally, the marginal costs of adding aeration and slow sand filtration are the smallest compared with the base case, and these additional costs range from $6 to $10 for the very small systems, and only $2 to $3 for the large systems. While the capital costs of these systems may be a bit higher than other treatments (Boisvert, Tsao, and Schmit 1996), annual unit operational cost increases seem to be affected much less. This is evident when comparing across treatments, where the added costs of other treatments are up to seven to eight times those of slow sand filtration and aeration. Although the incremental dollar costs are higher for smaller systems over all treatments, relative to the base case, percentage increases in costs rise as system size increases.

While this information in table 4 captures the additions to O&M costs as treatment processes are added, variables other than system size are held at mean levels. If, however, for each of the system sizes, wages, electricity rates, population densities, etc., are set at mean levels for the corresponding EPA size groups, the results change. (Which systems were combined into which groups is delineated in a footnote to table 4.) When evaluated at the group means rather than the overall sample means (the "AC2" columns in table 4), the per capita O&M costs fall for small systems, but rise for larger ones. One plausible explanation is that larger systems are concentrated in urban areas, where labor and energy costs and population densities are higher. In addition, transmission and distribution costs rise rapidly as system size increases (for a given population density), overwhelming the costs of treatment as system size increases beyond 10,000 people.[7]

Conclusions

The primary purpose of this paper was to demonstrate that an indirect cost function for community water systems with a hedonic specification for alternative water treatment can be used to isolate the additional O&M costs for various water treatments. By all conventional measures, the modeling exercise was a success, and additional O&M costs attributable to aeration, ion exchange, and several types of filtration processes were identified. Since these treatments can be used to comply with the most widely applicable regulatory requirements of the SDWA (SWTR, ESWTR, D/DBP, and TCR), this model can be a valuable tool in further research and policy analysis for examining the effects on O&M costs of current EPA regulations associated with the SDWA. Furthermore, when combined with estimates of the number of systems requiring such treatment, the model could be used to provide better estimates of cost of compliance by system size, both regionally and nationally, and to assist EPA in identifying cost-efficient technologies applicable to meeting various maximum contaminant levels for small systems.

Incremental costs due to filtration ranged from 15% to 60% above baseline disinfection treatment costs. Aeration and ion exchange treatments resulted in incremental costs of 8% and 60% above baseline estimates, respectively. Thus, from a policy perspective, it is clear that for some treatment technologies, the additional O&M costs are substantial, particularly for small systems, but for some technologies additional O&M costs are not. While used on only 4% of the systems currently, slow sand filtration is likely to be adopted increasingly by small water systems because of its substantially lower cost. Should systems combine with neighboring systems to take advantage of economies of size in treatment, alternative treatments such as direct filtration or diatomaceous earth filtration could be adopted more widely as well. Given the high flow requirements of large systems, such systems will likely continue to adopt filtration technologies similar to rapid sand or membrane type filtration. It is also clear that aeration is attractive to a wide range of groundwater system sizes, given its relatively low operating cost requirements. However, should incremental costs of ion exchange be reduced in the future, increased use of this technology may be adapted by smaller water utilities.

It is also evident from the analysis that when regional differences in the cost of inputs are accounted for, many small systems located in rural areas may have a cost advantage over systems of similar size located closer to urban centers. Cost estimates determined by the model also indicate that distribution costs may overshadow treatment costs as systems increase in population served above 10,000 people. Even so, additional costs above baseline treatment, i.e., chlorination, range anywhere from 8 to 60% over all treatments and sizes. Since the technologies specified can be used to satisfy various SDWA requirements, these incremental costs may pose a financial burden on rural local governments complying with SDWA regulatory requirements.

[7] Under these assumptions, it is also true that for all treatments average per capita costs are higher for systems serving 50,000 people than for systems serving 100,000. This result was unexpected, but is due to the fact that water demand per capita is considerably larger for systems in the 50,000 population category (265 gpd per capita) than for systems in the 100,000 category (201 gpd per capita). We could not disentangle why flow rates are considerably higher here, but the reason is likely the higher industrial water demand in the 50,000 population category for systems in this particular sample.

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Appendix
Derivation of the Estimated Model

The form of the model is:

(1*a*)

$$\ln C = b_0 + b_1 \ln Q + b_2 \left[\frac{1}{2}(\ln Q)^2\right] + \sum_i c_i \ln r_i + \frac{1}{2}\sum_i \sum_j c_{ij} \ln r_i \ln r_j + \sum_i d_i \ln Q \ln r_i + \sum_m f_m \ln F_m + \frac{1}{2}\sum_m \sum_n f_{mn} \ln F_m \ln F_n + \sum_m g_m \ln Q \ln F_m + \sum_m \sum_i h_{mi} \ln F_m \ln r_i,$$

where:

(2*a*) $\ln Q = \ln Y + \phi\,(z_1, z_2, \ldots, z_s)$, and

(3*a*) $\phi = \sum_s a_s z_s.$

The cost function is estimated jointly with n − 1 factor equations of the form:

(4*a*)

$$\frac{r_i x_i}{C} = c_i + \frac{1}{2}\sum_j c_{ij} \ln r_j + d_i \ln Q + \sum_m h_{mi} \ln F_m.$$

To ensure symmetry and homogeneity of degree one in factor prices, we impose:

(5) $\sum_i c_i = 1;\ \sum_i d_i = 0;\ \sum_i h_{mi} = 0;\ c_{ij} = c_{ji};$ $f_{mn} = f_{nm};$ and $\sum_j c_{ij} = 0.$

Substituting (2*a*) and (3*a*) into (1*a*) and (4*a*) results in the following cost and factor-share equations:

(6*a*)

$$\ln C = b_0 + b_1 \ln Y + b_2 \left[\frac{1}{2}(\ln Y)^2\right] + \sum_i c_i \ln r_i + \frac{1}{2}\sum_i \sum_j c_{ij} \ln r_i \ln r_j + \sum_s b_1 a_s z_s + \frac{1}{2}\sum_s \sum_t b_2 a_s a_t z_s z_t + \sum_i d_i \ln Y \ln r_i + \sum_s b_2 a_s (\ln Y) z_s + \frac{1}{2}\sum_i \sum_s d_i a_s (\ln r_i) z_s + \sum_m f_m \ln F_m + \frac{1}{2}\sum_m \sum_n f_{mn} \ln F_m \ln F_n + \sum_m g_m \ln Y \ln F_m + \sum_m \sum_i h_{mi} \ln F_m \ln r_i + \sum_m \sum_s g_m a_s (\ln F_m) z_s, \text{ and}$$

(7*a*)

$$\frac{r_i x_i}{C} = c_i + \frac{1}{2}\sum_j c_{ij} \ln r_j + d_i \ln Y + \sum_s d_i a_s z_s + \sum_m h_{mi} \ln F_m.$$

Imposing the restrictions in (5a), the model estimated by nonlinear two-stage least squares, for two input prices (r_1 and r_2) and one fixed factor (F) reduced to:

$$(8a)\quad \ln C - \ln r_2 = b_0 + b_1 \ln Y + b_2\left[\frac{1}{2}(\ln Y)^2\right] + c_1(\ln r_1 - \ln r_2) + c_{12}\left[\ln r_1 \ln r_2 - \left(\frac{1}{2}(\ln r_1)^2\right) - \left(\frac{1}{2}(\ln r_2)^2\right)\right] + \sum_s b_1 a_s z_s + \frac{1}{2}\sum_s\sum_t b_2 a_s a_t z_s z_t + d_1[\ln Y(\ln r_1 - \ln r_2)] + \sum_s b_2 a_s (\ln Y) z_s + \sum_s d_1 a_s [z_s(\ln r_1 - \ln r_2)] + f_1 \ln F + f_2\left[\frac{1}{2}(\ln F)^2\right] + h_1[\ln F(\ln r_1 - \ln r_2)] + g_1 \ln Y \ln F + \sum_s g_1 a_s (\ln F) z_s,$$ and

$$(9a)\quad \frac{r_1 x_1}{C} = c_1 + c_{12}(\ln r_1 - \ln r_2) + d_1 \ln Y + \sum_s d_1 a_s z_s + h_1 \ln F.$$