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Costs of water treatment due to diminished water quality: A case study in Texas

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Abstract. The cost of municipal water treatment due to diminished water quality represents an important component of the societal costs of water pollution. Here the chemical costs of municipal water treatment are expressed as a function of raw surface water quality. Data are used for a 3-year period for 12 water treatment plants in Texas. Results show that when regional raw water contamination is present, the chemical cost of water treatment is increased by $95 per million gallons (per 3785 m^3) from a base of $75. A 1% increase in turbidity is shown to increase chemical costs by 0.25%.

1. Introduction

The cost of municipal water treatment due to diminished water quality represents an important component of the societal costs of water pollution. Efficient management of water supplies must balance the costs of cleaning, using, or avoiding use of polluted water. The marginal cost of improving raw water quality generally should not exceed the marginal benefit of such an improvement. An increase in municipal water quality standards, holding other things constant, will increase the benefit from improved raw water quality but will also increase treatment cost. This study provides information on the marginal municipal costs of treating polluted water as affected by pollutant volume. This cost should provide a lower bound on the benefits of cleaner water. In this paper we ignore other nonmunicipal uses, such as recreation and wildlife management.

In this paper we estimate the costs of municipal water treatment as a function of raw surface water quality. Following other studies, we use sediment as a primary indicator of water quality. Sediment carried by runoff from crops, forests, pasture, and range accounts for approximately 68% of total suspended solids in waterways [*Gianessi and Peskin*, 1981]. Sediment is also a source of chemical contamination, as fertilizers and pesticides attach to it [*Kenimer et al.*, 1989; *Gianessi and Peskin*, 1981]. A number of estimates of the water treatment plants' cost of sediment, measured as turbidity, has been developed. *Holmes* [1988], *Forster et al.* [1987], *Moore and McCarl* [1987], and *Clark et al.* [1985] documented billions of dollars of losses.

Parallel studies on the costs of contaminants other than sediment do not appear in the literature. This study examines the costs of municipal water treatment associated with sediment and chemical contaminants over an area of Texas.

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2. Data Sources

This study focuses on Texas cities that use surface water as their source of municipal water. Of 191 Texas cities that use surface water for municipal supply, we identified 142 that treat surface water separate from supplemental groundwater supplies [*Texas Water Systems*, 1990]. These 142 cities supply water for 4,363,000 customers and treat, on average, 205 million gallons (776,000 m^3) per month. From these we drew a sample of 10 cities. Because Texas is a large state and because water treatment costs vary with such geographical factors as soil type, rainfall, and temperature, we wanted our sample to be geographically representative. To ensure this, we limited our sample to the Red, Brazos, Colorado, and Rio Grande River systems. These rivers generally flow from northwest to southeast across Texas, and in drawing our sample we paid attention to geographical distribution. We randomly drew two cities from each of the four river systems, except for the Brazos system, where we randomly drew three cities and also had data on Brenham, the pilot plant for our study. Two cities had more than one water treatment facility. Thus data on 12 water treatment plants were used. These plants average treating approximately 222 million gallons (840,000 m^3) per month. Table 1 identifies the plant locations.

2.1. Treatment Cost Data

Data from monthly water reports filed by treatment plant operators were obtained from the Texas Department of Health, Division of Water Hygiene. These reports include daily information on (1) number of gallons of water treated, (2) type and amount of chemicals used, and (3) observed turbidity, pH, and alkalinity levels for raw and treated water. We used these reports to calculate monthly averages for each item. The final data set consists of 45 monthly observations from January 1988 through September 1991 for 12 water treatment plants, providing a total of 540 observations.

Costs for each of the treatment chemicals were determined by contacting sales representatives of chemical companies. In general, three types of chemicals are used: coagulants, disin-

Table 1. Plant Locations and Characteristics

City Where Plant is Located	River System From Which Raw Water Is Drawn	Average Monthly Production, 1000 Gallons	Raw Water Turbidity	Raw Water *p*H	Chemical Cost per Million Gallons	Chemical Cost per Million Gallons per Turbidity Unit
Archer City	Red	8,684	89.16	7.9	71.46	0.80
Ballinger*	Colorado	19,201	16.74	7.8	20.21	1.21
Big Spring	Colorado	177,000	35.00	8.2	25.66	0.73
Brenham	Brazos	63,925	6.22	7.8	133.53	21.47
Edinburg*	Rio Grande	130,380	9.30	7.8	32.63	3.51
Harlingen 1*	Rio Grande	190,460	36.20	8.2	197.51	5.46
Harlingen 2*	Rio Grande	114,730	27.89	8.2	286.14	10.26
Henrietta	Red	15,654	25.75	8.2	134.65	5.23
Lubbock*	Brazos	881,930	7.34	8.4	32.32	4.40
Temple	Brazos	416,630	5.85	7.7	58.30	9.97
Waco 1	Brazos	343,870	11.22	7.8	34.88	3.11
Waco 26	Brazos	305,730	9.79	7.8	32.23	3.29
Mean, 12 Plants		222,350	23.05	8.0	88.38	5.79

One gallon equals 0.003785 m^3, or 3.785 L.
*Denotes plant with potential or actual groundwater contamination as reported by the *Texas Water Commission* [1989].

fectants, and *p*H adjusters. Coagulants bind with impurities to form particles of sufficient size and mass for removal by sedimentation and filtration. Disinfectants kill bacteria and other organisms. Chemical bases, such as lime, readjust the *p*H by removing the acidity induced by chemical coagulation agents. Table 2 lists the treatment chemicals used by the plants in this study, the cost per unit of each chemical, and its general use.

Because a number of different alum and polymer formulations were used, these inputs were standardized. For alum we used a dry alum formulation as the base and adjusted the use of other formulations on the basis of the amount of active ingredient. The polymer category covers many different compounds, and the exact one used was not always specified in the reports. We used a cost of $3.00 per gallon (per 3.785 L), based on detailed data available at the Brenham plant.

Table 1 contains summary statistics including average monthly water production (in thousands of gallons), raw turbidity, and *p*H levels, chemical cost per million gallons, and chemical cost per unit of turbidity. The chemical cost per million gallons (3785 m^3) ranged from $286.14 at Harlingen to $20.21 at Ballinger, with an average for the 12 plants of $88.38.

This study uses turbidity as an indicator of water quality following *Moore and McCarl* [1987], *Holmes* [1988], and *Forester et al.* [1987]. Turbidity indicates the presence of suspended clay, silt, finely divided organic matter, algae, and other microorganisms [*Tiner*, 1979, p. 337]. Turbidity is measured in nephelometric turbidity units (NTUs), which relate to how light from a tungsten lamp is scattered in water. High turbidity levels interfere with chlorination and make water unsuitable for human consumption. In addition, chemical contaminants often find their way into surface water sources with the constituents of turbidity. In our study turbidity ranges from 5.85 NTUs at Temple to 89.16 at Archer City, averaging 23.05 NTUs over the 12 plants. Cost per million gallons (3785 m^3) treated per NTU averages $3.83, and ranges from $0.73 at Big Spring to $21.47 at Brenham.

Table 2. Water Treatment Chemical and Costs per Unit

Chemical	Cost/Unit	Use
Alum (aluminum sulfate)	0.10	coagulation
Lime	0.10	*p*H adjustment
Chlorine	0.10	disinfection
Polymer	3.00	coagulation
Caustic soda	0.32	coagulation
Ferric sulfate	0.18	disinfection
Activated carbon	0.58	coagulation
Ammonia	0.24	disinfection
Potassium permanganate	1.58	coagulation
Copper sulfate	0.06	disinfection
Soda Ash	0.10	*p*H adjustment
Sodium chlorite	0.14	disinfection

2.2. Chemical Analysis Data

In addition to data on treatment costs and water production levels, the Division of Water Hygiene also collects data on chemical analyses of water supplies. Water supplies are tested for a number of organic and inorganic chemical contaminants. These inorganic contaminants include arsenic, barium, lead, mercury, and nitrate. Organic contaminants include a number of pesticides such as Endrin, Lindane, 2,4,5-TP (Silvex), and 2,4-D.

Municipal water treatment plants submit chemical analysis reports periodically. Period length varies between once every 3 years down to once per quarter. Frequency is determined by (1) previous monitoring results, (2) population served by the water system, (3) proximity to industrial use, disposal, or storage of volatile chemicals, (4) proximity to larger water systems, and (5) protection of water source. When contaminants are detected in a sample, the water system reports on a quarterly basis, or at the discretion of the state [*Texas Department of Health*, 1991].

One difficulty of using these chemical analysis data deals with testing procedure sensitivity. Chemicals tested are reported only if they exceed the threshold reporting level. For example, the limit for cadmium is 0.01 mg/L, and the threshold reporting level is 0.005 mg/L. The lack of data in the lower half of the detection range negatively impacts the usefulness of these data.

None of the municipal water systems in our sample had levels of chemical contaminants greater than the maximum contaminant level (MCL) for any chemical in their raw water supplies. Furthermore, Division of Water Hygiene personnel were unaware of any surface water supplies in Texas that exceeded the MCL for any chemical contaminant. However, a number of water treatment systems used treatment methods that are quite costly and are designed to remove contaminants. Thus we sought out a alternative measure of chemical contamination.

Texas Water Commission (TWC) information suggests that some plant operators in locations where the potential for groundwater contamination exists are treating water in a manner consistent with contamination. Five of the sample plants are in counties identified as having potential groundwater contamination [*TWC*, 1989]. Three of these five plants use treatments recommended for removing the potential chemical contaminant. For example, the Harlingen plants use activated carbon and are located in a region where the TWC identifies pesticide contamination of groundwater. Activated carbon is a recommended treatment for pesticides [*Tiner*, 1979]. Similarly the TWC identifies arsenic contaminants in the groundwater in the Lubbock area, and the Lubbock treatment plant uses ferric sulfate in the coagulation process, a recommended treatment for arsenic contamination.

Thus locations with potential groundwater contamination may indicate locations where surface water treatment costs may be influenced by potential chemical contamination. Thus we used TWC information on groundwater contamination as an indicator of the likelihood of chemical contamination of regional surface water supplies.

3. Treatment Cost Model

We estimate a model that relates chemical cost per unit of treated water to raw water supply characteristics. Per unit chemical cost is expressed as a function of gallons treated, turbidity, pH, a proxy variable for chemical contamination, and rainfall. These variables will be discussed in more detail below.

This model should not be confused with a formal model of a cost equation or a cost function from production economics [*Henderson and Quandt*, 1980]. Models of economic cost relationships require that we have costs for all inputs. This presents a problem because we do not have data on surface water, labor, energy, and other costs due, in cases, to the unavailability of prices; the difficulty of relating the use of some of these items to water volume; and the multicolinearity induced by fixed relative prices during the short timeframe of the study with relatively constant levels of input usage. Thus we use an empirical approach to explain the per unit chemical treatment cost in terms of the quality of the raw water supply. Biases may arise in the coefficients due to a lack of treatment of other input items.

Our model of chemical water treatment costs is

$$\text{cost}/1000\text{ gallons} = b_0 + b_{1*}(\text{total gallons}) + b_{2*}(\text{turbidity} \times p\text{H}) + b_{3*}(\text{turbidity} \times p\text{H})^2 + b_{4*}(\text{turbidity} \times p\text{H})^3 + b_{5*}(\text{contamination dummy}) + b_{6*}(\text{average annual rainfall}),$$

where "total gallons" is the number of gallons treated; "turbidity $\times$ pH" is the interaction multiplication of the difference in turbidity level between raw and treated water, times the pH level of the raw water; "contamination dummy" is a 0–1 dummy variable, where a 1 represents counties identified by the TWC as having potential or actual groundwater contamination, that serves as a proxy for chemical contamination of surface water supplies; and "average annual rainfall" is the annual rainfall for the county where the plant is located.

Several comments on model specification are in order. First, total volume is included to account for scale effects. Second, the polynomial form is used because of information we had about the sedimentation process. A low-turbidity raw water supply requires more coagulant than a more turbid raw water supply. Thus, as turbidity increases, less coagulant is needed. However, once turbidity increases above some point, the needed amount of coagulant rises. Third, turbidity and pH are treated in an interaction term because of the chemical relationship between coagulants and pH adjusters. Generally, coagulation agents are acidic; their use lowers pH. If pH falls below 7.5, lime or some other basic substances must be added. However, a high pH level reduces the need to do this, thus lowering chemical treatment costs. Thus an interaction term seems best. Fourth, annual rainfall is included in the model because water treatment costs may be affected by runoff and sediment levels. This variable is the average annual rainfall for the county in which the plant is located. The values range from 18 to 40 inches (45.7–101.6 cm) of annual precipitation [*Clements*, 1984]. Finally, we added a dummy variable for the TWC report of potential chemical contamination, where a 1 indicates potential groundwater contamination. This variable captures the change in the intercept of the regression line representing additional treatment cost due to potential contamination of the surface water supply.

4. Model Estimation

These data are of a pooled cross-section time series nature. Because the data consists of cross sections at 12 sites, heteroskedasticity was anticipated because of differences in raw water quality between cross sections. Diagnostic tests were performed to test for heteroskedasticity and autocorrelation. Homoskedastic errors were rejected according to the Harvey and Glejser tests [*Judge et al.*, 1985]. Autocorrelated errors were anticipated because seasonal weather patterns affect runoff and hence lead to correlated observations on water quality in adjoining months. (See work by *Moore and McCarl* [1987] for a discussion of this phenomenon in daily data.) Durbin-Watson tests were performed on each cross section [*Judge et al.*, 1985]. The results of these tests failed to reject the null hypothesis of no autocorrelation in only 1 of the 12 plants. Six of the tests rejected the null hypothesis, and five were inconclusive. Therefore we choose an estimation procedure that allows for different degrees of serial correlation in different cross sections.

Our cost estimate was made using the cross-sectional heteroskedastic and time-wise autocorrelation model described by *Judge et al.* [1985, p. 518]. This model corrects for autocorrelation of differing degrees in each cross section and for heteroskedasticity. This allows for unbiased and efficient estimation of the model across time and cross sections.

5. Estimation Results

The estimation results are given in Table 3. All coefficients are significant at the 95% level, except the cube of turbidity $\times$ pH. The estimated chemical cost of water treatment is approximately $74.15 per million gallons (3785 m^3). The R^2 measure for the model is 0.1865.

Partial derivatives of cost with respect to turbidity, total

Table 3. Estimation Results for Chemical Cost of Treatment per Thousand Gallons

Variable	Estimated Coefficient	*t* Ratio
Constant	-0.1314	-6.5053
Total gallons	-1.6950×10^{-8}	-4.1604
Turbidity × *p*H	1.3496×10^{-4}	4.3989
(Turbidity × *p*H)^2	-1.5130×10^{-7}	-2.6375
(Turbidity × *p*H)^3	5.3013×10^{-11}	1.9374
Contamination dummy	0.0947	7.7713
Average annual rainfall	5.6024×10^{-3}	8.3164

One gallon equals 0.003785 m^3, or 3.785 L.

gallons treated, the contamination proxy, and annual rainfall are calculated. The elasticities of cost associated with turbidity and total gallons treated are calculated. The derivative of cost with respect to turbidity is 0.0010, and the second derivative is -2.36×10^{-6}. Together, these imply that the chemical treatment costs increase at a decreasing rate as the level of turbidity increases. The elasticity of chemical cost with respect to turbidity is 0.27, which implies that a 1% reduction in turbidity will reduce the cost of treating water by 0.27%. The derivative of cost with respect to total gallons produced is -1.695×10^{-8}, and the elasticity of cost associated with total gallons treated is -0.04. This implies that a 1% increase in total gallons treated reduces treatment costs by 0.04%. This should not be taken to imply that chemical treatment costs could be reduced to zero by treating enough water. Elasticity measures are valid only in the neighborhood of the mean values of the regression and a fortiori should not be considered outside the range of the data.

The coefficient of the variable for average annual rainfall is 5.6×10^{-3}. This indicates that costs are higher in higher-precipitation areas. The sign on this coefficient was expected, since rainfall is related to runoff and turbidity levels. The elasticity of cost with respect to rainfall is 1.74, which implies that costs increase by 1.74% for a 1% increase in annual precipitation.

The proxy variable for chemical contamination shifts the intercept term of the regression line. The value of the coefficient is 0.09475. This implies that when regional groundwater contamination is present, the cost of water treatment is increased by $94.75 per million gallons (3785 m^3).

6. Discussion

A number of studies have attempted to estimate the costs of treating surface water on the basis of turbidity or sediment load in the water supply. *Holmes* [1988] considered the total cost of water production, including operating and maintenance costs, on the basis of 430 large utilities in the United States and estimated a treatment cost of $113.12 per million gallons (3785 m^3). *Forster et al.* [1987] surveyed 12 plants over a 25-month period in Ohio. Factors included in their cost function are gallons produced, storage time before treatment, turbidity removed, and the soil erosion rate in the watershed. Their analysis considered only variable costs of water treatment; labor and maintenance were considered fixed. Forster et al.'s cost estimate is $92.28 per million gallons treated. *Moore and McCarl* [1987] calculated the costs of water treatment at one plant in Corvallis, Oregon. The costs for alum, lime, and sediment removal are estimated to be $20.00 per million gallons. Our estimate of the chemical costs of water treatment of $74.15 per million gallons is in the range of these estimates.

These studies also report cost elasticities for turbidity. *Holmes* [1988] reports an estimate of 0.07; *Forster et al.* [1987] report values of 0.119 for turbidity and 0.406 for the rate of erosion, which indirectly affects turbidity level; and *Moore and McCarl* [1987] report an elasticity of 0.333. Our estimate is 0.27. Estimates of elasticities represent the percentage change in cost for a 1% change in turbidity. This implies that in our study, a 1% reduction in turbidity from an average level of 23.05 NTUs to 22.82 NTUs reduces chemical costs by $0.20 per million gallons (3785 m^3). Because the mean monthly production of the plants in this study is 222.35 million gallons, a 1% decrease in turbidity would reduce chemical costs by $534 annually for the average plant.

Perspective can be gained by extrapolating from our stratified random sample to the population. Note that such an inference is not statistically rigorous. Nevertheless, if these results held for all 142 Texas cities that treat and use surface water, a 1% reduction in turbidity would reduce statewide chemical costs of water treatment by $69,826 per year for production of 349,131 million gallons (1,321,460,835 m^3). If the 191 cities that use surface water face similar costs, and have little or no groundwater to supplement their surface supplies, this statewide savings could be as high as $93,972 annually for an annual production of 469,860 million gallons (1,778,420,100 m^3). Consideration of the effects of turbidity on nonchemical costs would raise these damage estimates.

One issue not addressed by the previous studies relates to the cost of chemical contamination of the surface water supply. As previously stated, the cost of water treatment increases by $94.75 per million gallons (3785 m^3) when chemical contamination is present in local groundwater supplies. Three of the 10 cities in our survey were in areas identified as having potential or actual groundwater contamination. This increased cost of water treatment for a municipality is $233,085 annually for treating an average of 205 million gallons (768,355 m^3) per month. If 30% of the cities in Texas had such problems, then annual treatment costs would increase by $10 million state wide for 142 cities and by $13.3 million for the 191 cities using surface water supplies. If similar levels of contamination were to occur statewide, then the added costs of treatment would amount to $33.1 and $44.5 million annually for 142 and 191 cities, respectively. Finally, note that the total costs of turbidity and chemical contamination would likely be higher if nonchemical costs were also considered.

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References

Clark, E. H., II, J. A. Havercamp, and W. Chapman, *Eroding Soils: The Off-Farm Impacts*, Conserv. Found., Washington, D. C., 1985.

Clements, J., *Flying the Colors: Texas Facts*, Clements Res., Dallas, Tex., 1984.

Forster, D. L., C. P. Bardos, and D. D. Southgate, Soil erosion and water treatment costs, *J. Soil Water Conserv.*, *42*, 349–352, 1987.

Gianessi, L. P., and H. M. Peskin, Analysis of national water pollution control policies, 2, Agricultural sediment, *Water Resour. Res.*, *17*, 9–27, 1981.

Henderson, J., and R. Quandt, *Microeconomic Theory: A Mathematical Approach*, 3rd ed., McGraw-Hill, New York, 1980.

Holmes, T. P., The offsite impact of soil erosion on the water treatment industry, *Land Econ.*, *64*, 356–366, 1988.

Judge, G. G., W. E. Griffiths, R. C. Hill, H. Lütkepohl, and T. C. Lee,

The Theory and Practice of Econometrics, 2nd ed., John Wiley, New York, 1985.
Kenimer, A. L., S. Mostaghimi, T. A. Dillaha, and V. O. Shanholtz, PLIERS: Pesticide losses in erosion and runoff simulator, *Trans. Am. Soc. Agric. Eng.*, *32*, 127–136, 1989.
Moore, W. B., and B. A. McCarl, Off-site costs of soil erosion: A case study in the Willamette Valley, *West. J. Agric. Econ.*, *12*, 42–49, 1987.
Texas Department of Health, Division of Water Hygiene, Drinking water standards governing drinking water quality and reporting requirements for public water supply systems, Austin, 1991.
Texas Water Commission, Ground-water quality of Texas, *Rep. 89-01*, Austin, 1989.
Texas Water Systems, Austin Publ., Austin, Tex., 1990.
Tiner, T. D. (Ed.), Manual of water utilities operations, Tex. Water Utilities Assoc., Austin, 1979.

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