The Costs of Nitrogen Control from Point Sources in the Chesapeake Bay Region:

Estimates from Wastewater Treatment Plants in Maryland

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Issue Statement:

The purpose of this project is to study the costs associated with clean up of the Chesapeake Bay. Specifically, it will look at the costs of reducing nitrogen and phosphorus levels for wastewater treatment plants in the Bay area. This project will estimate cost functions for capital and operation and maintenance (O&M) costs for the major plants that employ nitrogen and phosphorous controls in the Chesapeake Bay region. After estimating the marginal costs of nitrogen reduction at successively higher levels of control, this project will estimate the extent of economies of scale for nitrogen control. Finally, the costs of different types of nitrogen control will be estimated.

For almost all pollutants, the marginal costs of greater levels of control are increasing. It is hypothesized that this will be the case for nitrogen controls at wastewater treatment plants as well. It is also predicted that wastewater treatment plants exhibit economies of scale, meaning that larger plants in terms of flow size will have lower costs per unit reduction, at any level of reduction. Finally, to the extent data are available, this paper will explore which biological nutrient reduction technologies have the lowest average cost of removal.

Significance:

Many factors contribute to the health of the Bay's waters like nutrient level, sediments, dissolved oxygen level and salinity. One of the biggest problems is that levels of nitrogen and phosphorus are too high.

Nitrogen and phosphorus stimulate the growth of algae blooms which cloud the water of the Chesapeake Bay. The cloudiness prevents sunlight from penetrating to underwater vegetation, a habitat for aquatic life (Morgan, 2001). In addition, the dead algae sink to the bottom of the bay and decompose, using dissolved oxygen that aquatic organisms require to live. Already, some areas of the Chesapeake Bay are completely without dissolved oxygen (Stephenson, 1996).

Wastewater treatment plants contribute the majority of nutrients flowing into the Bay (Stephenson, 1996). Wastewater treatment plants are designed to remove harmful chemicals from residential, commercial and industrial wastewaters before they are released back into rivers, lakes or the ocean. Removal processes focus on the reduction of total suspended solids, five-day biological oxygen demand, total phosphorus, total nitrogen, ammonia nitrogen, and oil and grease (CGER,1996).

Currently, no specified limit is imposed on the amount of nitrogen and phosphorus allowed in effluent concentrations from wastewater treatment plants, but the Chesapeake Bay Foundation has set target effluent levels in the range of three to eight mg/l for nitrogen and 1.0 to 0.1 mg/l for phosphorus (Nutrient, 2002).

Biological nutrient removal (BNR) is a specific technology that is currently utilized in sixty-five of Maryland’s 269 wastewater treatment plants. BNR technology uses natural microbes to remove harmful nutrients from water before it is released in to a river. The processes allow water to flow through a series of tanks, each with a different type of microbe. The microbes change ammonia nitrogen into a harmless nitrogen gas that can be emitted into the atmosphere without damage (Blakenship, 1997). With no treatment, effluent is about 18 mg/l or more. BNR can reduce nitrogen to 8mg/l or less. Ideally, the Chesapeake Bay Foundation would like concentrations to reach 3 mg/l (Blankenship, 2003).

Other methods of removing nutrients include chemical treatments, sludge treatments and filtering. These methods are not specifically measured in the data available and are not as widely used as BNR.

Reducing nitrogen and phosphorus levels will help prevent the Bay's water quality from further deterioration. It is the duty of the wastewater treatment plants to reduce the levels of nitrogen and phosphorus. This project's estimates of reduction costs will help policy makers determine efficient levels of reduction for the funds they have available to build or improve plants. This project will provide insight into the costs of BNR technology compared to other removal techniques to help policy makers decide whether or not to upgrade the plants to include this technology. Although this study only focuses on data from the Maryland area, Maryland is currently one of the few states with widespread use of BNR technology and is one of the leading states in improving water quality. This project's results will be useful as a future model for estimating costs for other states.

Literature Review:

There has been no past empirical work examining the cost of nutrient removal, but other studies have looked at the costs of reducing BOD and the benefits of nutrient removal.

Fraas and Munley (1984) estimated municipal wastewater treatment costs for controlling pollutants. They calculated the marginal costs per pound of cleaning up BOD. Capital costs and O&M costs for BOD were estimated separately because capital costs are a function of design flow and performance of the plant, while O&M costs are associated with actual flow and performance. Ordinary least squares was used to estimate a log-linear cost function, with costs as a function of plant flow, influent concentration and effluent concentration. Economies of scale were found for both capital and O&M costs, and the coefficient on effluent was negative (as expected) and significant. The average values of influent and flow variables were averaged across all the plants in the sample. These averages created an estimated equation that could be used calculate the marginal costs of control from varying plant sizes. The result is that marginal cost estimates for BOD reduction rise sharply as effluent reductions increase.

An expansion of this paper was done by McConnell and Schwartz (1991), which treats effluent levels as endogenous in order to model how regulators choose levels of BOD pollution reduction from wastewater treatment plant design. Treating effluent levels as endogenous provided an unbiased measure of marginal costs of pollution control. The cost function also provides a price estimate for pollution reduction for regulators to use as an estimate for pollution control demand.

Unlike in Fraas and Munley, it is demonstrated by McConnell and Schwartz that effluent flow should be treated as endogenous. Removal of BOD by wastewater treatment plants depends upon size of the wastewater treatment plant, the flow rate of the incoming water, the local population density, regional growth, the state's environmental policies, and state income. The level of effluent reduction that a plant is designed to reach is dependent upon capital costs. The marginal cost estimates for removal were much higher when effluent levels are treated as endogenous, demonstrating that the Fraas and Munley assumption of exogeneity may have been incorrect.

Similarly, Macal (1984) develops wastewater treatment cost functions that depict treatment cost as a function of pollutant effluent level. Macal's function for wastewater treatment costs includes effluent standards for multiple pollutants, plant location, expansion schedules, regional economic parameters and cost functions for each treatment process. Macal's model is solved at "event times" to demonstrate a treatment plant operator's response to regulations. "Event times" can include, for example, new plant construction, capacity expansion and changes in effluent regulations. The results can be used to demonstrate the most efficient use of funds available, as Macal does in an application to the Dupage River Basin. In this example, BOD levels were restricted, and the plant had to decide which technologies to employ to meet the new standards. For the Dupage River Basin, reducing runoff from roadways, rather than changing wastewater treatment plant technology, was recommended for the most cost efficient solution. Macal's model could be applied to other similar situations.

Reed and Young (1983) provide helpful insight to the problem of funding wastewater treatment plants. Their study states that although grants by the EPA can help communities with up to 75% of the costs to construct a wastewater treatment plant, the delays associated with the grants' approval can cost more than the grant's original value because of inflation. Using several different analytical procedures to estimate these costs and losses, they conclude that communities should influence construction lags for their own benefit, speeding up the process for projects they desire and slowing it down for those projects they deem undesirable.

Morgan and Owens (2001) estimated the overall benefits of water quality regulation for the Bay from 1972 to 1996 using modeled changes in ambient water quality, specifically changes in nitrogen and phosphorus. They found that with a sixty percent improvement in water quality, benefits for those living in Virginia, Maryland and the District of Columbia would range from $357.9 million to $1.8 billion annually in terms of use value. “Use value” was estimated through willingness to pay for six categories of benefits: recreation, commercial fishing, health, non-use value, property values and regional economic impacts. The cost of pollution control for these benefits would range from $1.0 to $1.3 billion dollars annually. The costs were assumed to be equivalent to expenditures of water quality improvements in the entire Bay region. The overall conclusion was that although Macal’s methods for calculating costs and benefits do not correlate exactly, the estimates indicate that water quality improvements could have positive net benefits. Overall, this study could be useful in determining whether or not a new wastewater treatment project should be funded in the future.

A final example of cost functions for wastewater treatment plants was calculated by the National Academy of Sciences on Wastewater Treatment in 1993. The study expressed the costs as both capital and Operation and Maintenance (O&M), which were calculated using an assumed interest rate, flow size and design period. The study divided the plant types into ten categories of reduction systems. The costs were estimated after averaging the effluent concentrations in each category of system or technology. The total costs ranged from $450 to $5,500 per million gallons of flow, with the low estimate reflecting “primary” removal and the high estimate reflecting the cost of combining nutrient removal, “high lime,” filtration, Granular Activated Carbon, and reverse osmosis processes.

Data

The data on plants with BNR technology is from the Department of the Environment. It provides information on average flow, total nitrogen and total phosphorus effluent levels. This data set includes information on 65 plants across Maryland from 1999 to 2002. The data includes total “eligible” costs of each wastewater treatment project, which indicate the actual costs to the plant for the addition of BNR technology and total “project” cost which is the cost of the retrofit or upgrade the plant for other treatment methods. The most recent data from 2002 has a wide range of effluent concentrations. Total nitrogen concentrations vary from a low of 2.26 mg/l to a high of 27.95 mg/l, while total phosphorus levels vary from 0.08 mg/l to 4.96 mg/l.

The other data to be used in this project are from the Office of Wastewater Management, which conducts the Clean Watersheds Needs Survey (CWNS) on a periodic basis. The CWNS has information on publicly-owned wastewater collection and treatment facilities, facilities for control of sanitary sewer overflows (SSOs), combined sewer overflows (CSOs), stormwater control activities, non-point sources, and programs designed to protect the nation's estuaries. The 1996 survey information includes 16,024 wastewater treatment facilities across the United States. The data include information on the facility, its city, county, present and future populations receiving collection, existing flow and present and future design flows for all plants in Maryland. It lists the types of technology and reduction available in each plant, which will be used to compare to the BNR data to confirm existing available technology at treatment plants in the sample.

Empirical Model

The cost equations will be estimated by OLS, similar to the approach Fraas and Munley (1984). Capital cost and O&M cost will be estimated separately as a function of effluent concentration, influent concentration, and flow size. In general,

$$C = f(E_a, E_d, I_a, I_d, F_a, F_d). \qquad \textbf{(Eq. 4)}$$

$\mathbf{C}^{\mathbf{BNRcap}}$ =Capital cost of BNR
$\mathbf{C}^{\mathbf{O\&M}}$ = Operation and Maintenance Cost
$\mathbf{C}^{\mathbf{Red}}$ = Cost per ton reduction of nutrient
F_d=Design Flow
F_a=Actual Flow
I_d^P=Design Influent Concentration of Phosphorus
I_a^P=Actual Influent Concentration of Phosphorus
E_d^P=Design Effluent Concentration of Phosphorus
$E_a^{P=}$ Actual Effluent Concentration of Phosphorus
E_d^N= Design Effluent Concentration of Nitrogen
E_a^N = Actual Effluent Concentration of Nitrogen
A= age of the plant
D_I =Dummy equal to one if plant is treating industrial waste, zero if it is not
T= Type of technology present
W = Watershed in which the plant is located

The function for capital costs for plants with BNR technology is:

$$\ln \mathbf{C}^{\mathbf{BNRcap}} = \ln\alpha + \beta_0 \ln F_d + \beta_1 \ln I_d^P + \beta_2 \ln E_d^P + \beta_3 \ln E_d^N + \beta_4 \ln I_d^N + \beta_5 D_I + \beta_6 \ln A + \varepsilon \qquad \textbf{(Eq. 4)}$$

The function is expressed in log-linear form because this is the form used by Fraas and Munley (1984) and McConnell and Schwartz (1991). The coefficients can be easily interpreted as elasticities. Design concentrations and flow size are included. It is not expected that capital costs are related to actual concentrations and flow, so the actual measurements are left out of this equation. The age of the plant (A) will be used as an indicator of plant modernization because older plants will typically be harder to upgrade with technology. The dummy (D_I) will prevent the results from being influenced by higher costs in industrial areas when the results are compared to those plants in residential areas with presumably lower influent concentrations.

The O&M cost function for all Maryland plants is:

$$\ln \mathbf{C}^{\mathbf{O\&M}} = \ln\gamma + \delta_1 \ln F_d + \delta_2 \ln F_a + \delta_3 \ln I_d^P + \delta_4 \ln I_a^P + \delta_5 \ln E_d^P + \delta_6 \ln E_a^P + \delta_7 \ln E_d^N + \delta_8 \ln E_a^N + \delta_9 \ln I_a^N + \delta_{10} \ln I_d^N + \delta_{11} D_I + \delta_{12} W + \varepsilon \qquad \textbf{(Eq. 5)}$$

The O&M costs can be expected to relate to both actual and design concentrations and flow levels, so both are included in the model. "W" is a possible variable to be included as an indicator of the plant's watershed. It will capture part of the costs related to urbanization level. For example, one watershed's sewer system could be substantially older and less stable than another's, resulting in significantly higher influent concentrations of nutrients released into that area's water.

Finally, the function for cost per ton of nutrient reduced is:

$$\ln C^{Red} = \ln\theta + \lambda_1 \ln F_d + \lambda_2 \ln T + \varepsilon \qquad \textbf{(Eq. 6)}$$

Equation 6 will be useful in determining which technologies are the most cost effective.

Methodology

The data will be regressed using ordinary least squares in a linear and a log linear form, similar to the estimations done by Fraas and Munley (1984) and McConnell and Schwartz (1991).

The results of the OLS estimates will provide cost estimates for the capital and O&M costs at those plants with BNR technology to reduce both nitrogen and phosphorus levels. The costs will be used to estimate costs for plants to meet possible future regulations imposed upon them. If costs increase as nutrient levels increase, the first of the original hypotheses is supported.

Several predictions about the signs of the coefficients have been made. The coefficients are all expected to be positively related to cost in Equation 4 and Equation 5. If the coefficient δ_2 is greater than one in Equation 5, economies of scale exist for wastewater treatment plants. The prediction for the Flow coefficient (in Equation 6) is that it will be positive. It is expected that as levels of technology increase, costs decrease, so this coefficient is expected to be negative.

The Chesapeake Bay Foundation has studied the feasible target effluent levels of nitrogen of 8, 5 and 3 mg/l and estimated the costs of reaching each level. Similarly, feasible phosphorus levels' costs were estimated at 1.0, 0.5 and 0.1 mg/l. The estimates from this study will provide a useful comparison to the other rough estimates of costs of nutrient reduction at these plants for different levels of control.

All of the right hand side variables are assumed to be exogenous because the estimates here are based upon water quality measures. This means that the choice of effluent reduction levels of any given community is assumed to be independent of community characteristics. Relaxation of this assumption is something that can be considered in future extensions of this work.

Future Work

To date, this project has focused on estimating the costs of nutrient removal from BNR plants, which reflect the best and newest technology for reducing nutrients to the Chesapeake Bay region. It would be interesting to compare the costs of nitrogen removal from these plants to plants which use older alternative techniques to remove nitrogen. Data may be available for BOD and for influent concentrations of all nutrient sources for many plants around the Bay, in which case other useful information may be possible. With the BOD data, interaction terms between BOD removal and Nitrogen removal will be studied using a dummy variable for the presence of BNR technology in the cost functions. Any data collected in the future will provide more opportunities for cost estimates and comparison with the data already available.

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