

**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 technology, costs and emissions reductions of wastewater treatment plants around the Chesapeake Bay.

Specifically, this project aims to:

- Explain the determinants of the capital cost of building a wastewater treatment plant, including:
  - whether some types of nitrogen removal technologies are less costly than others, and
  - whether capital costs are influenced by plant characteristics such as flow size.
- Examine whether wastewater treatment plants exhibit scale economies using capital costs.
- Examine the determinants of plant nitrogen effluent<sup>1</sup>, including:
  - whether some nitrogen removal technologies are more efficient at reducing nitrogen, and
  - whether there are plant specific factors that influence the nitrogen effluent levels

**Significance:**

Many factors contribute to the health of the Bay's waters like nutrient levels, sediments, dissolved oxygen level and salinity. One of the biggest problems is that levels of nitrogen are high, and wastewater treatment plants (WWTP) are a major contributor of nitrogen.

Nitrogen stimulates 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).

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<sup>1</sup> Effluent is the concentration of the pollutant flowing out of the plant. Influent is the concentration of the pollutant flowing into the plant.

Currently, no specified limit is imposed on the amount of nitrogen allowed in effluent, or outgoing, concentrations from wastewater treatment plants, but the Chesapeake Bay Foundation has set target maximum effluent levels in the range of three to eight mg/l for nitrogen (Nutrient, 2002). Wastewater treatment plants are designed to remove harmful pollutants from wastewaters before they are released back into nature. Wastewater from urban sewer systems contain concentrated organic and chemical compounds that flow into treatment plants. Treatment plants reduce concentrations substantially by the use of a variety of removal processes. Plants currently reduce total suspended solids, five-day biological oxygen demand, total phosphorus, total nitrogen, ammonia nitrogen, oil and grease (CGER, 1996).

Biological nutrient removal (BNR) is a specific technology that is currently utilized in forty-five of Maryland's 269 wastewater treatment plants, and twenty more are in the process of being built and designed. BNR technology modifies an old technology called activated sludge. The activated sludge process uses natural microbes to remove harmful nutrients from water before it is released in to a river. The process allows water to flow through a series of tanks, each with a different type of microbe. Then, 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 concentrations of nitrogen are approximately 18 mg/l or more. BNR can reduce nitrogen to 8mg/l or less.

Ideally, the Chesapeake Bay Foundation would like concentrations to soon reach 3 mg/l, which is below the recommended target level of 4 to 8 mg/l currently in place (Blankenship, 2003). This goal can often be reached through further modifications to the

wastewater treatment plant. Ideally, the Modified-Ludzack-Ettinger (MLE) technique can reduce nitrogen to a level of 4mg/l. It adds onto the activated sludge system by increasing the rate at which water is cycled through the plant. Other processes are “Cyclical Nitrogen Removal” processes like Oxidation Ditches (OD) or Sequencing Batch Reactors (SBR) that use alternating aerobic and anoxic conditions to reduce nitrogen. OD and SBR can reduce effluent nitrogen to 3 to 5 mg/l.<sup>2</sup>

Another way to achieve concentrations of 3 mg/l or less recently introduced in wastewater treatment plant upgrade designs is Enhanced Nutrient Removal (ENR). ENR uses methanol to reduce nitrogen loads, and it is on the agenda to be added to many plants in the next ten years. It is expected that ENR plants will reach lower levels of effluent reduction than any other technology.

Before BNR or ENR, methods of removing nutrients included activated sludge trickling filters, primary sedimentation and screening. The plants used studied in this project focus on BNR technology, but used one or more of these processes in the past. The most commonly used method was activated sludge.

Reducing nitrogen levels will help prevent the Bay’s water quality from further deterioration. 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 and abilities of different types of BNR technology, and allow policy makers to compare the costs of removing nitrogen from WWTP to the costs of other sources of nitrogen control.

This study only focuses on data from the Maryland area because Maryland is currently one of the few states with widespread use of BNR technology and is one of the

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<sup>2</sup> For more information on how these and other modifications to BNR work, see Grady, et. al (1999).

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 from WWTPs, 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 Biological Oxygen Demand (BOD). Capital costs and Operation and Maintenance (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. Their general equation is:

$$C = f(F, I, E, P)$$

In which

C = cost of wastewater treatment

F= flow size of the waste stream

I = concentration of pollutant in the influent stream

E= concentration of pollutant in the effluent stream

P = vector of prices for factor inputs.

Ordinary least squares was used to estimate a log-linear cost function, with costs as a function of plant flow, BOD 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 to 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 Fraas and Munley's 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. A vector of exogenous factors affecting capital costs was created and used as an instrument for effluent concentrations of BOD. Treating effluent levels as endogenous through instrumental variables provided an unbiased measure of marginal costs of pollution control. The cost function also allows the authors to estimate a cost per unit change in BOD effluent reduction.

Unlike in Fraas and Munley, McConnell and Schwartz demonstrated 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 of effluent levels 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, the "event" was the restriction of BOD levels, 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 the 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.

The National Academy’s paper extends this literature by examining the costs and effluent reductions from WWTP equipped with new BNR technologies. Maryland is one of the only states in the country to use these technologies, and even Maryland has only 65 plants in operation or under construction. As the population grows around the Chesapeake Bay region, these technologies will be critical to future nitrogen control. The analysis here draws most directly from the Fraas and Munley and McConnell and

Schwarz papers. Like their papers, this paper focuses on estimating the costs and effluent reduction of WWTP control but for nitrogen removal. The costs include only capital costs, because O&M cost information is not currently collected for WWTP plants in Maryland.

## **Data**

The data set from the Maryland Department of the Environment includes information on 65 plants with BNR technology across Maryland. Some of the data were available through the Department of Natural Resource's Data Hub (<http://www.chesapeakebay.net/wquality.htm>). This website allows the researcher to choose certain data for each plant by month or year. The flow size by month was collected for the plant for two years (the fifth and sixth years before the plant was built).<sup>3</sup> The data were used to calculate a coefficient of variation for flow by finding the standard deviation of the monthly flow and dividing it by the yearly average flow and multiplying by 100.

Total nitrogen effluent levels from the year the plant was built until 2002 are also available from the Data Hub. These nitrogen concentrations average 10.6 mg/l and vary from a low of 2.26 mg/l to a high of 27.95 mg/l. From this information, it can be inferred that some plants are already able to meet the target effluent levels of 3 to 8 mg/l of nitrogen, while some are very far from this level.

The plant's county and the date of the BNR addition were provided by the Maryland Department of the Environment, as was the "Design Flow" or maximum flow

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<sup>3</sup> It is estimated by Levelev (2004) that a WWTP upgrade for a plant with a 5 million gallon/day flow will take 1 year to plan, 1 year to design, 1.5 years to construct and 1 year start up/evaluation time to add up to a total of 4.5 years, assuming money was no object. A plant with a 10 mg/day flow will take 6.5 years.

level the plant is designed to handle. Eligible costs and project costs were already compiled by the Maryland Department of the Environment. Total costs are provided for each wastewater treatment project, which indicate the actual costs to the plant for the addition of BNR technology. The costs were deflated using the Producer Price Index for capital equipment in the year 2002 and annualized over a 15 year period using a five % discount rate. In addition, the date that the original plant was built and the date that the BNR technology addition was completed are provided.

The effluent level of nitrogen (for the fifth and sixth years prior to the date that BNR was added) is part of the data set as well. These levels will be used as a before or influent concentration. The percent of the plant capacity in use, on average, was calculated by dividing the average actual flow by the design flow and multiplying by 100. Information on whether or not the plant treats waste from an industrial area is also included.

The averages, minimum and maximum values of the dataset are included in Table 1:

<b>Table 1: Data Summary</b>			
	<b>Average</b>	<b>Minimum</b>	<b>Maximum</b>
<b>Total Eligible Cost</b>	\$7,160,206.97	\$2,000.00	\$32,596,340.00
<b>BNR Cost/ Cap Cost</b>	0.65	0.08	1
<b>Design Capacity (MGD)</b>	11.30	0.38	180.00
<b>Percent Capacity Utilization</b>	61.72	4.43	66.86
<b>Influent</b>	13.01	1.85	27.70
<b>Effluent</b>	10.06	2.21	25.06
<b>Coefficient of Variation</b>	0.18	0.01	0.68
<b>Months with BNR</b>	63.35	0	173
<b>Age of plant (months)</b>	224.04	84	792

## **Empirical Models**

There are two equations that can be estimated with the data for the BNR plants. The first is a capital cost equation that examines the determinants of capital costs of adding BNR technologies to existing plants. The second is an effluent equation that identifies the influences on the actual concentration of nitrogen emitted by BNR plants over time, including fixed effects particular to each plant. It is not possible to estimate O&M costs because the data on O&M costs is not available.

### **Capital Cost model:**

Following the approach of Fraas and Munley, the capital costs of adding BNR technology are expected to be a function of factors influencing the size of the plant and extent and level of treatment. The BNR capital costs will depend on the design flow or size of the plant, the influent concentration of the wastewater entering the plant, whether the plant treats industrial waste in addition of household waste, and the BNR technology employed. It is important to note that the design effluent itself should be an important determinant of the capital cost of the plant, but all plants are, in principle, designed to meet the regulatory target of 8 mg/liter of effluent. In addition, several other factors that are likely to influence the cost of a given size plant are included. These are the share of the addition to the plant accounted for by the BNR technology, the time period at which the BNR was added, the variation in flow to the plant throughout the year, and a proxy for land costs at the site of the plant. Each of these variables will be discussed in more detail below.

Capital cost equation can then be written as a function of maximum flow, influent concentrations, industrial waste treatment, technology, land cost, and year that BNR was added.

The capital cost equation for plants with BNR technology is:

$$C^{BNRcap} = \alpha + \beta_1 F_d + \beta_2 D_1 + \beta_3 A_{BNR} + \beta_4 P + \beta_5 I_d + \beta_6 MLE + \beta_7 OD + \beta_8 SBR + \beta_9 O + \varepsilon$$

**(Eq. 1)**

In which:

$C^{BNRcap}$  = Capital cost of BNR

$F_d$  = Maximum Flow plant is designed for (million of gallons/day)

$A_{BNR}$  = age of BNR addition (months)

$P$  = Population Density of County (persons/sq. mi.)

$I_d$  = Design Influent Concentration of Nitrogen (mg/l)

$D_1$  = Dummy equal to one if plant is treating industrial waste, zero if it is not

Four Technology Dummies:

$MLE$  = Dummy equal to one if plant has Modified Lutzak Ettinger, zero if not

$OD$  = Dummy equal to one if plant has Oxidation Ditch, zero if not

$SBR$  = Dummy equal to one if plant has Sequencing Batch Reactor, zero if not

$O$  = Dummy equal to one if plant has another technology, zero if not

Because of the underlying production technology and economic factors, I expect all of the coefficients to have positive signs. Flow size (measured millions of gallons per day) is the largest amount of water that has flowed through the plant in the design and planning period. It is expected to be positive because costs of building the plant vary directly with the flow the plant has coming in.

The age of the BNR addition ( $A_{BNR}$ ) is included to see if costs are increasing or decreasing with time. It is expected that the plants with BNR added earlier (higher values) will have higher capital costs and those with newer BNR additions will have lower costs, because of learning about efficient use of new technologies over time. It is

expected that as BNR additions became more common they would have become more efficient and less costly to build.

The cost of land is important in determining capital costs. The population density of each county (P) was found through the Maryland Department of Planning for the year 2000. This number was used as a proxy for the level of urbanization in the cost equation to account for cost of land. It is expected that the higher the population density of the county is, the more expensive the land should be because the opportunity cost of building a large plant in a highly populated area is greater than in a sparsely populated area.

Next, influent concentration of nitrogen ( $I_d$ ) is expected to be positively related to cost. It is anticipated that the higher the influent concentration is, the higher the capital costs will be to build a plant that effectively reduces nitrogen.

The dummy for industry ( $D_1$ ) 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. It is expected that industrial areas will have higher concentrations of nitrogen and higher capital costs.

The dummies for technology indicate the level of nitrogen removal possible. Three of the most common methods of BNR technology which modify activated sludge are called Sequencing Batch Reactors (SBR), Oxidation Ditches (OD) and Modified Ludzak Ettinger (MLE). A dummy was included for the presence of these technologies and the rest were grouped into the category "Other." The dummy for the presence of activated sludge was dropped so that these method's coefficients can be seen as the difference in the cost of adding the modification (Grady, 1999). These three common modifications are expected to reduce nitrogen to lower levels and therefore expected to

cost more than activated sludge. For other technologies and their frequency of occurrence, see Table 4.

**Table 4: Number of Plants in Sample with Each Technology**

Sequencing Batch Reactor (SBR)	4
Modified Ludzack Ettinger (MLE)	16
Oxidation Ditch (OD)	6
Activated Sludge Only	8
Other	22
<b>Total:</b>	<b>56</b>

**Methodology for Capital Cost:**

The capital cost's 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 approximations for the costs at those plants with BNR technology to reduce nitrogen levels. The cost estimates will be used to find which technologies have the lowest capital costs and what factors drive the cost of building a plant.

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.

**Capital Cost Results:**

The capital cost equation's results in a linear form are summarized in Table 5.

**Capital Cost Regression Results**

n=65 R-Squared=0.6170

	Expected Sign	Actual value		Std. Error
Intercept		-254957.17		431532.08
Maximum Flow	+	1712.39		1635.82
Industrial	+	517388.54	**	192703.03
Age of BNR	+	38947.39		25397.96
Influent (mg/l)	+	-609.70		17822.33
Population Density	+	83.97		86.01
MLE	+	550913.19	**	257037.07
OD	+	-318323.00		413687.49
SBR	+	-31087.45		380577.77
Other	+	165820.48		278307.08

\*\*Significant at the 5% level.

The coefficients of the dummy for industry and the MLE technology are significant at the 5% level. The coefficient on industry is positive, indicating that those plants that treat industrial waste have higher capital costs. The coefficient on flow size was positive as expected, yet insignificant, as were the coefficients on age of the BNR addition, population density and “other” technologies. The coefficients on OD, SBR and Influent concentration were negative, yet insignificant.

The variable for variation in flow, which was part of the initial regression was dropped because the measurement of maximum flow explained the variation, according to WWTP cost analysts at the Department of Natural Resources.<sup>4</sup>

Sometimes a high value of R-squared and few statistically significant coefficients is an indication of high collinearity between the variables. However, no high correlations between the variables were found.

It was hoped that some information about the costs of different technologies could be inferred from this regression, but none of the coefficients on technology were significant. The coefficients indicate that MLE additions may increase capital costs. It is

<sup>4</sup> According to Dr. Ta-Shan Yu, Maryland Department of Natural Resources, June 8, 2004.

suspected that the data set was too small to pick up any differences in these technologies. A basic analysis of the data was done to give a general idea of the costs of nitrogen removal for each technology in Table 6.

The results of Table 6 indicate that Oxidation Ditches and Other technologies in this sample have the lowest cost per 100 mg of nitrogen reduction. Sequencing Batch Reactors had a noticeably higher cost per 100 mg of nitrogen reduced, which indicates that they would probably not be the most cost effective method for a wastewater treatment plant to implement.

**Table 6:**

<b>Technology</b>	<b>Annualized Average Cost<sup>5</sup></b>	<b>Nitrogen Load (grams)</b>	<b>Cost per 100 Mg reduced</b>
MLE	\$1,159,491.66	565,160,488.50	\$0.21
OD	\$219,346.67	190,398,733.00	\$0.12
SBR	\$423,288.38	29,751,115.2579	\$1.42
Other	\$621,215.54	544,068,780.62	\$0.11

The hypothesis that scale economies exist for capital costs is supported by these results. When the average flow increased by 100%, capital costs increase by only 8.8%. This result was found by finding the average value of each variable. Plugging these values into the estimated equation and solving for costs resulted in a capital cost increase of only 8.8%. If costs had increased by more than 100%, the hypothesis of scale economies for capital costs would not have held.

The results of the capital cost equation were very disappointing. Despite having an R-squared of 0.6170, the regression did not provide much information on technology

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<sup>5</sup> Cost annualized using a 5% discount rate over a 15 year period.

costs. Unfortunately, the sample size was small and nothing could be done to correct the problems.

**Effluent Model:**

Equation 2 expresses the actual effluent level as a function of actual flow and flow variation and dummies the type of BNR technology.

$$E_d^N = \alpha + \beta_0(F_a F_d * 100) + \beta_1 F_{var} + \beta_2 MLE + \beta_3 OD + \beta_4 SBR + \beta_5 AT + \beta_5 Other + \epsilon$$

**(Eq. 2)**

In the effluent equation, flow is expressed as a capacity utilization percentage for the plant ( $F_a F_d * 100$ ). The actual yearly flow for the plant is divided by the design flow and multiplied by one hundred to get the percentage of the plant in use. It is hypothesized that as this number increases, the effluent concentration will decrease.

The coefficient of variation, which is calculated the same way as in the capital cost equation, is expected to be positively related to effluent concentrations. The more variation there is in the flow, the more difficult it will be for the plant to reduce nitrogen and effluent levels will be higher.

The presence of SBR, OD and MLE modifications are expected to have a negative relationship to the concentration of nitrogen released because they have the capability of reaching lower levels of effluent nitrogen. AT are “Alternative Technologies” which are not typically used and are classified as “unproven” according to the Department of Natural Resources. The coefficient on AT is expected to be negative, but these plants are some of the first ever to implement these technologies and are still in the test phases.

**Effluent Methodology:**

In the effluent equation, the data set was set up as a panel from 1985 until 2002 and was estimated using OLS, fixed effects and random effects. A linear model and a log-linear model were tested, but the linear model had a better fit for the data. The fixed effect model was needed because the data set had variation over time within each plant that may have been affecting the results. The fixed effects and OLS models were compared using an F-test, which indicated that fixed effects estimation captured more of the variation. The coefficient on flow in the OLS model is suspected to be picking up unobservable variations from plant to plant that the fixed effects model was able to account for because the fixed effects model allows for variation across time and across observations. Although this model's data should not have any random variation because the sample covers all of Maryland's BNR plants, a random effects model was estimated to rule out the possibility of random variation. The results of the random effects model and the Hausman test confirmed that fixed effects is the correct specification. The results of all three of these models are included in Appendix A.

It is expected that the coefficient on capacity utilization will be negatively related to effluent nitrogen. As the plant gets closer to its maximum capacity, the plant will be able to remove nitrogen more effectively as it would at lower capacity utilization. The coefficient of flow variation is expected to be positively related to effluent nitrogen as well. As the variation of flow increases, it will be more difficult for the plant to remove nitrogen.

The coefficients on technologies will show the additional reduction in effluent concentrations when compared to activated sludge. The technologies that will be studied are Sequencing Batch Reactors (SBR), Oxidation Ditches (OD) and Modified Ludzack

Ettinger (MLE). MLE is a process that increases the rate of water cycled through the activated sludge process. It is expected to help effluent levels reach five to eight mg/l, which is lower than the effluent level expected of activated sludge. The dummy for activated sludge was dropped for this comparison. SBR, OD, and MLE are additions which are added to plants with activated sludge to reduce nitrogen to even lower levels. The AT category indicates “Alternative Technologies” which are still in experimental stages. The “Other” category covers those plants which do not fall into the four above categories.

### **Effluent Results:**

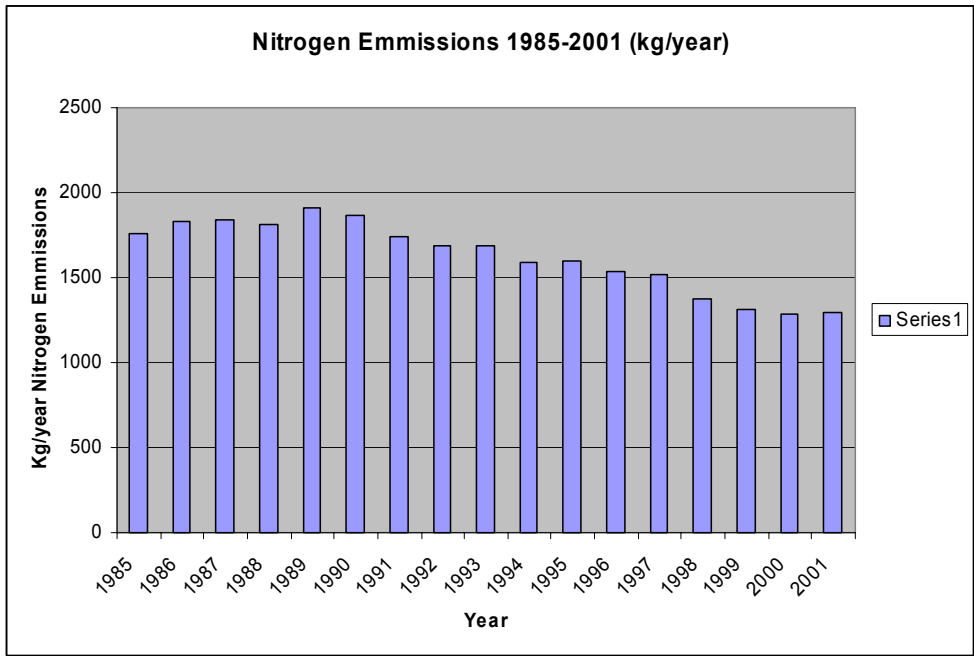
The results of the effluent regression are shown in Table 7. The coefficients were significant at the 5% level or better, except for Alternative technologies, which were significant at the 10% level and SBR, which was insignificant. The signs were all what was expected. The hypothesis that the coefficient on capacity utilization ( $FaFd*100$ ) is negative was supported. As the percentage of the plant used increased, the effluent concentration decreased. This may be an indication that the plants were specifically designed to handle the maximum capacity and flow levels below the design capacity are less efficient at removing nitrogen. Since the average capacity utilization was 61.72% and the maximum was 66.86%, it could be that only part of the data range is visible. At these middle utilization rates, there is a small negative impact on the effluent concentration, but it is possible that if capacity utilization was closer to 100%, the impact on effluent levels would be positive.

<b>Table 7: Effluent N=925</b>				
	<b><u>Expected Sign</u></b>	<b><u>Actual Value</u></b>		<b><u>Std. Error</u></b>
<b>Intercept</b>		20.4113	**	0.699
<b>Flow Capacity</b>	-	-0.0924	**	0.011
<b>Coefficient of Flow Variation</b>	+	0.4804	**	0.199
<b>MLE</b>	-	-5.3284	**	0.6776
<b>OD</b>	-	-9.3048	**	0.9421
<b>SBR</b>	-	-1.6323		1.2041
<b>AT</b>	-	-2.8227	*	1.1412
<b>Other</b>	?	-5.1604	**	0.6995
** significant at the 5% level				
* significant at 10% level				

Those plants that have a large variation in flow have a higher level of effluent nitrogen flowing out of the plant. This is an indication that plants should have tight controls for excess flow. The technology dummies' coefficients show that additions to Activated Sludge can reduce nitrogen levels significantly. The coefficients on MLE, OD, and SBR are additional reductions in nitrogen beyond Activated Sludge's effluent capabilities. The results indicate that Oxidation Ditches are most effective at reducing nitrogen, averaging a 9.3 mg/l reduction in effluent concentration. Modified Ludzak Ettinger and Other technologies were second and third, respectively, while Sequencing Batch Reactors and Alternative Technologies were still able to reduce nitrogen below the Activated Sludge levels.

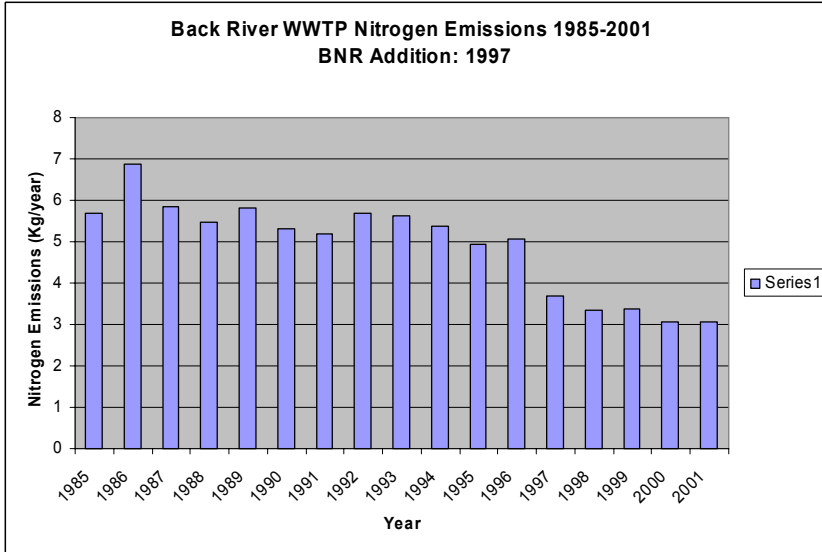
Graph 1 provides an overall picture of nitrogen reduction of WWTPs in the sample from 1985 to 2001. It shows a reduction of approximately 32% in nitrogen levels since 1985 from BNR plants.

Graph 1

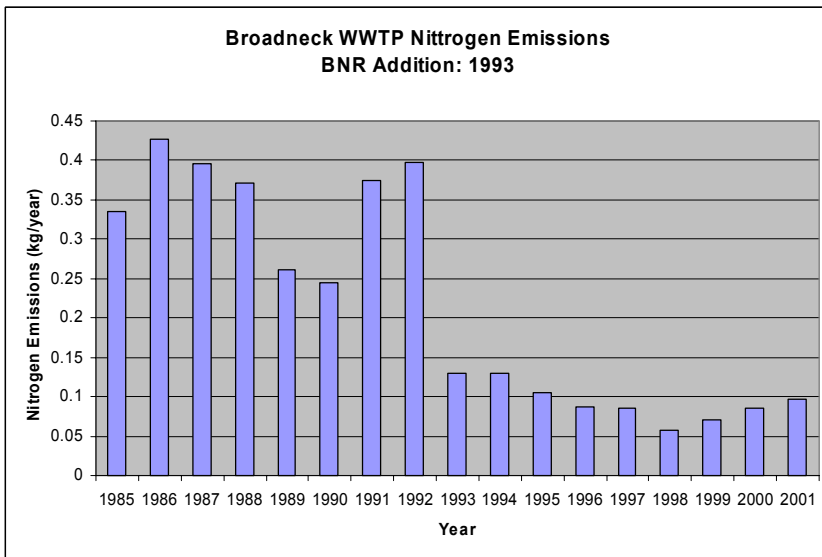


Graphs 2 and 3 are examples of plants in the data set. Back River, for instance, had an MLE addition in 1997. It is evident from the graph that a drastic reduction in nitrogen effluent levels occurred after and even during that year. Graph 3 shows Broadneck's nitrogen effluent concentrations before and after its OD addition in 1993. It should be noted that Broadneck is a much smaller plant than Back River. This is why the overall nitrogen emissions are so much higher from Back River. Broadneck has a design flow size of 6 MGD while Back River's design flow is thirty times larger at 180 MGD.

Graph 2



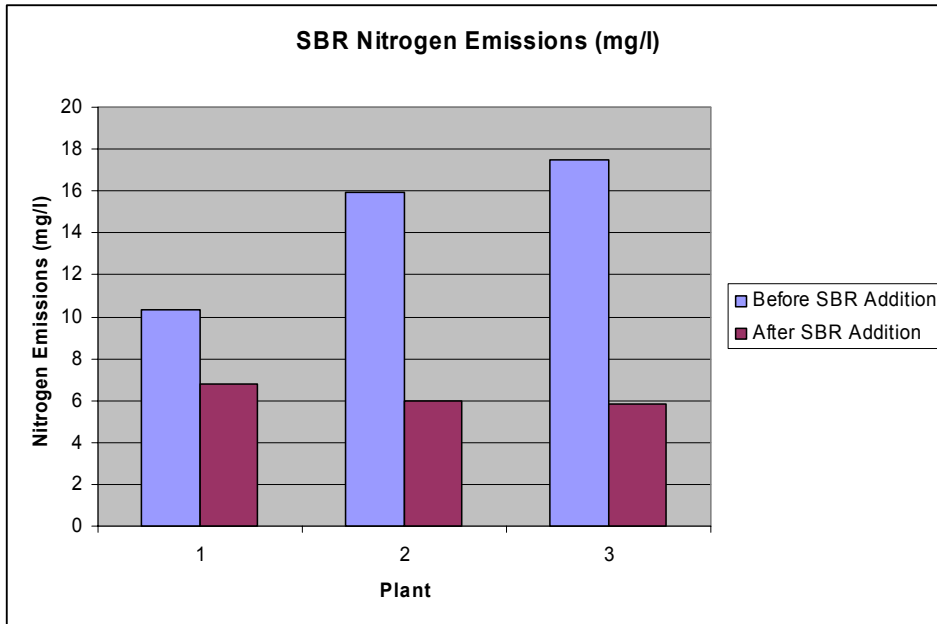
Graph 3



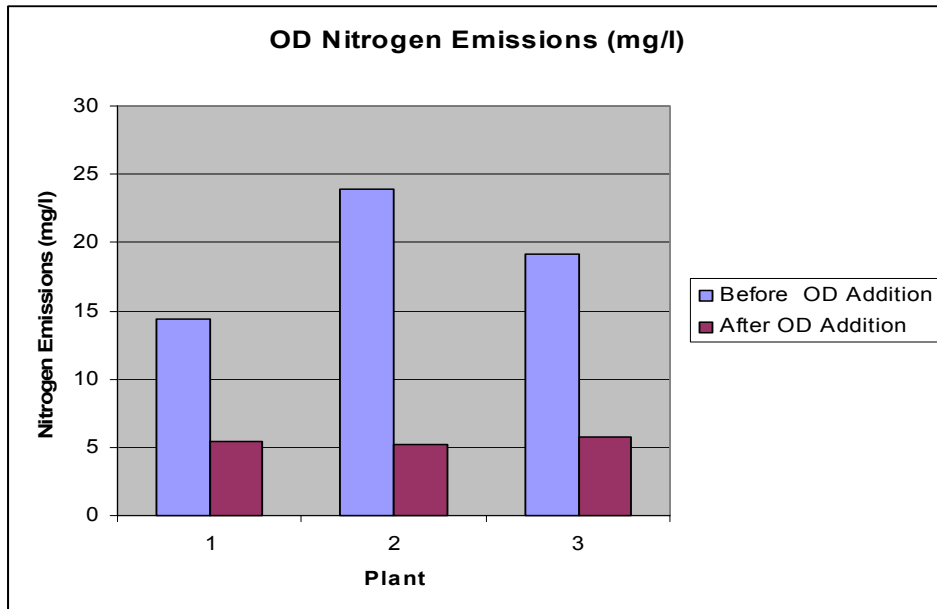
Graphs 4, 5, and 6 show the emissions of nitrogen before and after the BNR additions. Graph 4 shows the reduction for SBR plants in the sample, while Graphs 5 and 6 show the reductions for OD and MLE, respectively. Some of the MLE plants have higher ‘after’ concentrations than ‘before,’ but after looking at the dates each of these plants had their MLE additions built, it was evident that these plants’ additions were put

in in the very late years of our sample, so the full effects of the nitrogen reductions were not yet evident.

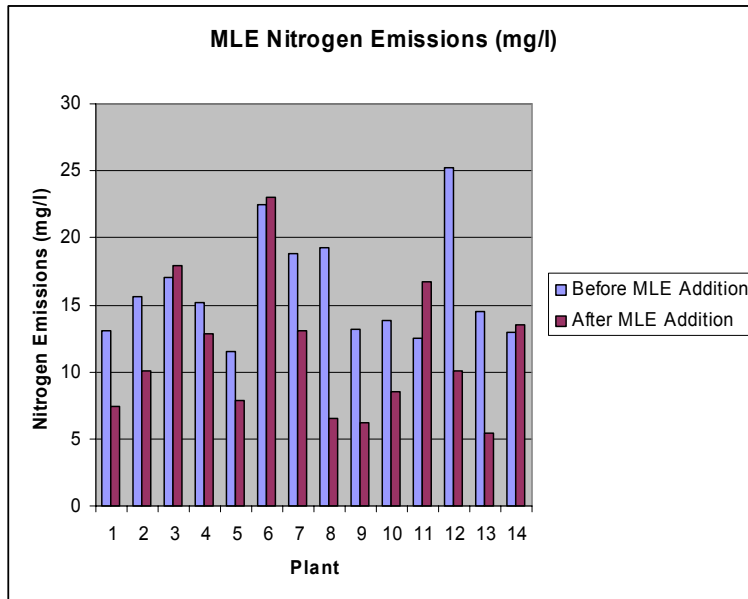
Graph 4



Graph 5



Graph 6



### Conclusions and Future Work

Several conclusions were made about nitrogen removal in WWTPs from this project. Unfortunately, all of the hypotheses initially made were not supported by this study. First, the important determinants of capital cost are: flow size, presence of industrial waste, age of the plant, and population density. Capital cost is influenced by plant characteristics like these and less influenced by technology type and influent nitrogen levels than originally thought. It is not completely evident that one BNR technology is more efficient or less costly than another, but it seems that oxidation ditches or 'other' technologies are the most economical of choice from the data available due to their low cost of nitrogen removal. Next, the hypothesis that scale economies in capital costs exist for WWTPs is supported by this study.

Finally, it was concluded that oxidation ditches are the most effective nitrogen removal technology, while Sequencing Batch Reactors are the least effective. Plant

factors that influence nitrogen removal include technology type, capacity utilization, and flow variation.

This project has focused on estimating the costs of nutrient removal from BNR plants, which reflect the best and newest technology for reducing nutrients currently in use in 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 could be studied using a dummy variable for the presence of BNR technology in the cost functions.

Another helpful extension to this project would be to estimate of the Operation and Maintenance (O&M) costs for the plants. This information would be useful in determining which plants have the lowest day-to-day upkeep costs, which may contribute to lower long run costs despite high capital costs. Unfortunately, the data on O&M costs is not readily available for these plants and would be challenging to collect. Table 8 provides a brief comparison between O&M and capital costs for those few plants that O&M data is available.

### **O&M Costs Compared to Capital Costs**

<b>Plant</b>	<b>O&amp;M cost</b>	<b>Capital Cost (2003 fiscal year)</b>
LaPlata	\$960,750.00 (2002 dollars)	\$4,120,970.00
Fruitland	\$518,980.00 (2003 dollars)	\$6,200,000.00
Leonardtown	\$366,764.00	\$2,511,529.00

	(2003 dollars)	
	\$401,314.00	
Westminster	(2001 dollars)	\$4,229,124.00
	\$1,419,382.00	
Aberdeen	(1998 dollars)	\$2,377,394.00

Finally, just as BNR has become a more common way to remove nitrogen from wastewater, a new technology, “Enhanced Nitrogen Removal,” or ENR, has been introduced. ENR can reduce nitrogen levels even further than BNR, usually down to 3 mg/l. This process, which is slowly becoming common, uses methanol to reduce nitrogen loads. In the near future, when more plants are using ENR, a study similar to this could be used to estimate its costs.

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**Data:**

Maryland Department of the Environment :[www.mde.org](http://www.mde.org)

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## Appendix A

### OLS regression:

**. reg effluent stddevflow fafd100 mle od sbr at other**

Source	SS	df	MS		Number of obs =	925
-----+-----					F( 7, 917) =	50.79
Model	9909.54384	7	1415.64912		Prob > F =	0.0000
Residual	25557.7792	917	27.8710788		R-squared =	0.2794
-----+-----					Adj R-squared =	0.2739
Total	35467.3231	924	38.3845488		Root MSE =	5.2793

effluent	Coef.	Std. Err.	t	P> t	[95% Conf. Interval]
-----+-----					
stddevflow	-.0070059	.2293777	-0.03	0.976	-.4571721 .4431603
fafd100	-.0346306	.0066689	-5.19	0.000	-.0477187 -.0215425
mle	-4.890366	.8160301	-5.99	0.000	-6.49187 -3.288863
od	-8.491733	.8391443	-10.12	0.000	-10.1386 -6.844866
sbr	-1.762734	1.433984	-1.23	0.219	-4.577006 1.051538
at	-4.478513	1.214923	-3.69	0.000	-6.862865 -2.09416
other	-8.03392	.5729491	-14.02	0.000	-9.158364 -6.909476
_cons	17.32933	.4608131	37.61	0.000	16.42496 18.2337

### Fixed Effects Regression:

**. xtreg effluent stddevflow fafd100 mle od sbr at other, fe i(id1)**

Fixed-effects (within) regression		Number of obs =	925
Group variable (i): id1		Number of groups =	56
R-sq: within = 0.3181		Obs per group: min =	6
between = 0.0959		avg =	16.5
overall = 0.2023		max =	17
		F(7,862) =	57.46
corr(u_i, Xb) = -0.2087		Prob > F =	0.0000

effluent	Coef.	Std. Err.	t	P> t	[95% Conf. Interval]
-----+-----					
stddevflow	.4804896	.189924	2.53	0.012	.107722 .8532573
fafd100	-.0924304	.011299	-8.18	0.000	-.1146072 -.0702536
mle	-5.328479	.677559	-7.86	0.000	-6.658338 -3.998621
od	-9.304793	.94214	-9.88	0.000	-11.15395 -7.455636
sbr	-1.632388	1.204136	-1.36	0.176	-3.99577 .7309938
at	-2.822785	1.141166	-2.47	0.014	-5.062573 -.5829969
other	-5.160382	.546736	-9.44	0.000	-6.233471 -4.087292
_cons	20.41133	.6995456	29.18	0.000	19.03832 21.78434

```

-----+-----
sigma_u | 4.1422068
      sigma_e | 3.9581717
          rho | .5227076 (fraction of variance due to u_i)
-----+-----
F test that all u_i=0:      F(55, 862) =    13.99          Prob > F = 0.0000

```

## Random Effects Regression:

**. xtreg effluent stddevflow fafd100 mle od sbr at other, re i(id1)**

```

Random-effects GLS regression              Number of obs   =    925
Group variable (i): id1                   Number of groups =    56

R-sq:  within = 0.3157                    Obs per group:  min =    6
      between = 0.1307                      avg   =   16.5
      overall = 0.2294                      max   =   17

Random effects u_i ~ Gaussian              Wald chi2(7)    =   399.55
corr(u_i, X) = 0 (assumed)                Prob > chi2     =    0.0000

```

```

-----+-----
effluent |      Coef.   Std. Err.      z    P>|z|    [95% Conf. Interval]
-----+-----
stddevflow | .4480687   .1898298     2.36  0.018    .0760091   .8201283
fafd100 | -.0741535  .0099096    -7.48  0.000   -.0935759  -.0547311
mle | -5.324977  .6769835    -7.87  0.000   -6.65184  -3.998114
od | -9.331513  .9053169   -10.31  0.000   -11.1059  -7.557124
sbr | -1.722037  1.202468    -1.43  0.152   -4.078831  .6347568
at | -3.00819   1.126834    -2.67  0.008   -5.216744  -.799636
other | -5.650317  .5361451   -10.54  0.000   -6.701142  -4.599492
_cons | 19.28645   .7684311    25.10  0.000   17.78035  20.79254
-----+-----
sigma_u | 3.4115542
sigma_e | 3.9581717
rho | .42623513 (fraction of variance due to u_i)
-----+-----

```

## Hausman Specification Test:

```

---- Coefficients ----
|      Fixed      Random
|      Effects    Effects    Difference
-----+-----
stddevflow | .4804896   .4480687   .0324209
fafd100 | -.0924304  -.0741535  -.0182769
mle | -5.328479  -5.324977  -.0035022
od | -9.304793  -9.331513  .0267204
sbr | -1.632388  -1.722037  .0896489
at | -2.822785  -3.00819   .1854048

```

```
other | -5.160382 -5.650317 .4899354
```

```
Test: Ho: difference in coefficients not systematic
```

```
chi2( 7) = (b-B)'[S^(-1)](b-B), S = (S_fe - S_re)  
= 523.07  
Prob>chi2 = 0.0000
```

```
.
```