

**Municipal wastewater treatment plants' nitrogen removal response to financial incentives
in Maryland and Virginia**

Frances Sinclair Dowd

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K. Stephenson, Chair
E. Peterson
D. Taylor

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As one of the largest and most productive estuaries in the United States, the Chesapeake Bay is a great economic, ecological, and cultural asset to the Mid-Atlantic region. Excess nitrogen and phosphorus discharge, however, has contributed to reduced levels of dissolved oxygen in various locations throughout the Bay. In 2010, the EPA developed a Total Maximum Daily Load (TMDL) for the entire watershed that established nutrient reduction targets to achieve Bay water quality objectives. The TMDL required states in the Chesapeake Bay watershed to create implementation plans to meet nutrient reductions. Maryland and Virginia specifically established stringent point source regulatory policies designed to meet point source reduction targets. Point source control programs created financial incentives for reducing nutrient discharge beyond regulatory requirements. This thesis will examine the extent to which Maryland and Virginia wastewater treatment plants undertake operational improvements to increase nutrient removal in response to state program incentives. Through quantitative and qualitative analysis, this thesis found evidence of lowered nitrogen discharges in response to financial incentives presented by each states' point source control programs at municipal wastewater treatment plants. Maryland achieves modest improvements at a subset of advanced treatment WWTPs as a result of financial incentives presented by the state's public subsidy program. Although Virginia advanced treatment plants operating within a nutrient trading program have little incentive to over-comply, there is some evidence of operational improvements at less advanced nitrogen removal plants.

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CHAPTER 1: INTRODUCTION

Nutrient Pollution

Nutrient pollution, specifically from nitrogen and phosphorus, poses a large obstacle in achieving water quality standards throughout the United States. Unlike chemical toxins from industry, nutrients are a natural part of aquatic ecosystems and provide food for all forms of aquatic life, such as fish, shellfish, and smaller organisms. Nutrients become a problem when levels exceed the carrying capacity of a water body, typically a direct result of human activities such as agriculture, stormwater and urban runoff, and wastewater. Over the past 30 years, nutrient pollution has become a serious environmental problem as it depletes the oxygen that aquatic life needs to thrive (Howarth, 2008). Nutrient pollution also has consequences for human health and affects the economy, as many coastal areas rely on aquatic ecosystems as a source of income for residents (EPA, 2015). The federal government, with cooperation from states, is implementing water quality policies that aim to minimize and mitigate nutrient pollution from human activities.

On a national scale, the Clean Water Act (CWA) provides the umbrella statute that all states must operate under to address nutrient discharge. Under Section 303(d) of this legislation, individual states must monitor their water bodies to ensure compliance with water quality standards, or requirements that ensure a water body is swimmable and fishable, the primary national standards. Water quality standards establish designated uses for different water bodies and establish criteria to ensure achievement of those uses over the long term. If a waterway does

not meet water quality standards, the Environmental Protection Agency (EPA) places it on the “impaired waters” list and a Total Maximum Daily Load (TMDL) is developed. TMDLs identify the pollutant stressors causing the impairment and then designate the maximum amount of a specific pollutant that a water body can receive and still safely meet water quality standards. The TMDL then allocates between discharge sources regulated under the federal CWA, called point sources (PS), and sources without mandatory discharge control requirements, or non-point sources (NPS). Since October 1995, the EPA has issued 5,695 TMDLs to address nutrient impairment in US waterways (EPA Watershed Assessment, Tracking & Environmental Results, 2015).

The CWA authorizes point sources discharge through the National Discharge Elimination System (NPDES) permit system. When TMDLs identify nutrients as the stressor pollutant, regulatory agencies require numeric nutrient limitations in municipal and industrial point sources permits. Nutrient mass load limits assigned to each source are called wasteload allocations (WLA). Point sources, however, often are responsible for only a relatively small share of the total nutrient load.

Nonpoint sources (NPS) represent the largest source of nutrient loads in many of the nation’s nutrient-related water quality impairments (EPA, 2015). The EPA defines NPS as pollution resulting from land run off, precipitation, atmospheric deposition, drainage, and any other source not expressly labeled as a point source. The imposition of mandatory pollutant control requirements on non-point sources, such as agricultural operations, is politically unpopular and logistically difficult to regulate through conventional permitting. Given this regulatory structure, regulatory agencies implementing nutrient-related TMDLs face significant

pressure to secure substantial reductions in nutrient loads from the subset of sources subject to regulatory requirements (point sources).

Because of this pressure, water quality managers have a broad interest in understanding the nutrient control performance at point sources, including municipal wastewater treatment plants (WWTPs). Most WWTPs were designed and built to treat pollutants originally listed in the CWA including total suspended solids, biological oxygen demand (BOD), pH, and temperature. To achieve large reductions in nutrient discharges, municipal and industrial sources typically need to install additional capital upgrades to the existing wastewater treatment process. Once installed, point source operators may be able to achieve additional nutrient reductions through operational performance. Market-based or incentive-based programs have been proposed and implemented, at numerous locations, in an effort to provide financial incentives to comply with new nutrient permit limitations. To date, relatively little is known about the extent to which financial incentives can induce additional nitrogen removal from municipal WWTP operators.

Point Source Nitrogen Control Efforts in the Chesapeake Bay

The Chesapeake Bay is the largest and most productive estuary in the United States with great economic, ecological, and cultural value. Over the past 50 years, the Bay has experienced serious problems with nutrient pollution, specifically from nitrogen. In response to this degradation, governors from Virginia, Maryland, Pennsylvania, and Washington, D.C. along with a representative from the EPA and chairperson of the Chesapeake Bay Commission founded the Chesapeake Bay Program in 1983. The program's "agreement" established the need for a coordinated effort to improve water quality in the Bay. Since 1983, Virginia, Pennsylvania, DC, and Maryland have signed these written agreements to guide the restoration of the Bay and

set targets for nutrient reduction with the most recent agreement signed in June 2014 (Chesapeake Bay Program, 2014).

Maryland's and Virginia's point source regulatory programs represent policy cornerstones to state efforts to achieve Bay water quality goals. Both states have established aggressive nutrient load caps for municipal and industrial point sources within the major tributary watersheds of each state. In both states, existing point sources are assigned nitrogen and phosphorus WLAs based on a target concentration standard and the facility design flow. WLA is defined as the total pounds of total nitrogen and total phosphorus that can be discharged and delivered to the Chesapeake Bay in one calendar year. The sum of the individual WLA for each regulated discharge source represents the total mass load cap for point source in each tributary. Target nitrogen concentration standards are based on estimated performance of near limits of technology performance. Maryland assigns WLA based on a concentration standard of 4 mg/l of nitrogen to all upgraded plants (Personal communication Elaine Dietz, Maryland Department of the Environment (MDE) 2014). Concentration standards in Virginia exhibit more variation, but tend to be set at or around 4 mg/l for point sources located in the Shenandoah/Potomac and Rappahannock watersheds. Waste load allocations for sources in the southern tributaries (York and James) tended to be based on slightly higher concentration levels based on published WLA calculations.

Both Virginia and Maryland employ substantial capital grant subsidy programs to help fund point source nutrient removal technology upgrades at municipal WWTPs. Plants may upgrade to Enhanced Nutrient Removal (ENR) technologies (target nitrogen concentration of 3-5 mg/l) or Biological Nutrient Removal (BNR) technologies (target nitrogen concentration of 8 mg/l). The states provide between 30 to 100% grants for all nutrient-related plant upgrades.

Once capital upgrades are completed, both states impose similar regulatory requirements on WWTPs. Both states require any ENR upgraded WWTP to comply with the WLA *and* numeric nitrogen and phosphorus concentration limits (mg/l). For example, both states strictly require a point source to stay below a concentration limit, even if the total mass load discharge (measured in pounds) remains well below their WLA. These numeric concentration limits cannot be modified, amended, or traded with another point source to remain in compliance, regardless if it is more cost effective for another source to undertake more incremental nutrient control. The individual concentration limit reflects the treatment design level of the capital upgrade (BNR or ENR).

Capital upgrades are needed to meet overall basin caps, but not every WWTP must immediately implement a capital upgrade to advanced nutrient removal in order to meet the overall basin point source cap. Virginia and Maryland utilize different approaches to accommodate the non-uniform nutrient removal capacity among municipal WWTPs. Maryland requires WWTP compliance with individual nitrogen and phosphorus WLAs only after the completion of an ENR capital upgrade. In contrast, Virginia requires every point source to meet their individual nitrogen and phosphorus WLA, regardless of whether or not the plant has received a capital upgrade, beginning in 2011. Virginia utilizes a point source nutrient trading program to enable non-upgraded plants to comply with their WLA. State law requires a point source whose nitrogen and/or phosphorus discharge exceeds the WLA to buy nutrient credits from other point sources to be in compliance. Nutrient credits are created when a point source (typically with nutrient capital upgrades) reduces nutrient dischargers below their individual WLA (# credits = WLA – Mass load of discharge). Given the stringency of the WLA, this

generally means that any Virginia WWTP without advanced nutrient removal technology (BNR or ENR) will need to purchase credits from plants with advanced treatment.

A point source discharge association was created in Virginia in response to point source regulation, called the Virginia Nutrient Credit Exchange Association, to facilitate point source planning and trading. As of 2007, the Association's members constituted 87% of all point source dischargers in Virginia, representing over 95% of total nutrient discharge in the state (Pomeroy, et. al. 2007). The Association operates to establish credit prices and facilitate the trades between point sources (Code of Virginia 62.1-44.19:13). Prices for nutrient credits may provide incentives for plant operators to achieve incremental reductions within existing treatment technologies.

Maryland offers financial incentives for nutrient reductions achieved by operational changes through a state operational grant program. The state offers wastewater treatment plants with enhanced nutrient removal technologies (ENR) an annual lump sum payment based on design flow, called an Operational and Maintenance grant, if the plant achieves an annual average concentration of 3 mg/l for nitrogen. The operational grant acts as a financial incentive to reduce nutrient discharges below regulatory concentration and load limits. Maryland offers no performance incentives for other (non-ENR) plants.

Problem Statement

In terms of water quality regulatory policy, relatively little empirical analysis exists that examines how different program rules impact observed nutrient prevention behaviors and performance at municipal wastewater treatment plants. State point source control incentive payments and nutrient trading programs developed in the Chesapeake Bay provide an

opportunity to examine the extent to which financial incentives can induce nitrogen reductions from municipal wastewater treatment plants operating in similar biophysical environments.

Regulatory programs that induce more plant level operational improvements may achieve nutrient reductions at a lower cost, as process changes and refinements often are less expensive relative to large capital improvement projects (Chesapeake Bay, 2002). Furthermore, additional nutrient removal at WWTPs may delay or offset the need for states to achieve nutrient reduction at more expensive sources such as municipal stormwater (Wainger et al, 2013). Maryland uses the operational grant program as a direct subsidy for ENR enhancement in operational performance. Virginia employs a point source exchange program, which may provide financial incentives for operational improvements. In particular, Virginia WWTPs with BNR level technologies have financial incentives, in the form of credit prices, to lower concentrations, whereas Maryland BNR plants do not.

Objectives

The objective of this research is to evaluate the extent to which municipal wastewater treatment plants lower nitrogen discharges in response to financial incentives. Specifically, this research aims to identify the extent to which financial incentives created from nutrient trading and public subsidy programs induce additional reductions in nitrogen concentrations in effluent from operational changes in municipal wastewater treatment plants with three levels of nitrogen treatment technology: ENR, BNR, and non-upgraded (conventional secondary treatment) plants. This research proposes to estimate the responsiveness of WWTPs, both with and without enhanced/specialized nutrient control technologies, to financial incentives.

Methods

Chapter 2 describes the nitrogen BNR and ENR technologies and their operation for municipal WWTPs. Chapter 3 will explain the design and implementation of point source regulatory programs in Virginia and Maryland and the operational choices confronted by WWTPs operators in each state. Chapter 4 will describe a statistical model to estimate the degree to which ENR plant operators reduce nitrogen concentrations below required levels given grant payments. To isolate the effect of financial incentives on discharges, a variety of factors will be controlled for such as capital upgrades, design flow, seasonality, and operational capacity. Chapters 5 extends this analysis to BNR and Virginia non-upgraded plants, respectively. Using discharge data obtained from the EPA, MDE, and Virginia Department of Environmental Quality (VADEQ), analysis will be conducted through the creation of an explanatory model for ENR and BNR WWTPs' performance over time.

CHAPTER 2: NITROGEN REMOVAL TECHNOLOGIES AT MUNICIPAL WASTEWATER TREATMENT PLANTS

The CWA originally only required municipal wastewater treatment plants to limit discharge from “conventional” pollutants, such as suspended solids and organics. The CWA instructs the EPA to identify specific treatment technologies capable of limiting these conventional pollutants and devise effluent limitations consistent with those technologies to be met by permitted facilities. Nutrients are not explicitly regulated under the CWA, but as the scientific understanding about the relationship between nutrient discharge and water quality impairments expanded in 1972, a new regulatory emphasis on nutrient control evolved (ESA, 2000). Regulatory programs to address nutrient pollution have been increasingly required to establish concentration and load limits to meet reduction targets set by the 2010 TMDL. To reach these limits, facilities must be upgraded.

This chapter describes the general process by which nitrogen can be removed from municipal wastewater streams. General BNR and ENR technologies are first described, followed by a summary of the operational changes available to WWTP operators for making incremental reductions in nutrient loads. Inter-WWTP performance variability as a function of operator discretion in running ENR and BNR technology introduces response flexibility to external influences, such as financial incentives, from Virginia’s nutrient credit prices or Maryland’s operational grant program. The technological process for incremental nitrogen reduction will be used to inform the development of explanatory statistical models and analysis in Chapters 4 and 5.

Primary and Secondary Treatment

Both BNR and ENR go further in terms of nutrient removal than the existing primary treatment technology. The primary treatment process occurs when wastewater goes through preliminary treatment and removes suspended solids and reduces the Biochemical Oxygen Demand (BOD) of the wastewater. BOD represents the amount of oxygen needed by microorganisms to decompose organic matter in a water body. At high levels of BOD, oxygen is depleted rapidly in a water body, making it much more difficult for aquatic life to survive (EPA, 2012). Effluent first goes through a sequence of screens to remove large items present in the wastewater. It then flows to a grit chamber to allow for removal of grit and gravel that may have washed off the streets, specifically for plants operating with combined sewer systems. Finally, the effluent sits in a sedimentation tank where the plant slows down the flow to allow gravity to cause the suspended solids, or minute particles of matter, to settle out of the wastewater and form primary sludge. Secondary treatment removes any dissolved organic matter that primary treatment misses using biological processes. Microbes consume the organic matter, converting it to carbon dioxide, water, and energy. Secondary treatment technologies vary, but all require a final “settling” period to remove additional suspended solids (Malik, 2014). These treatment processes do not remove nutrients (EPA, 2004).

Tertiary Treatment

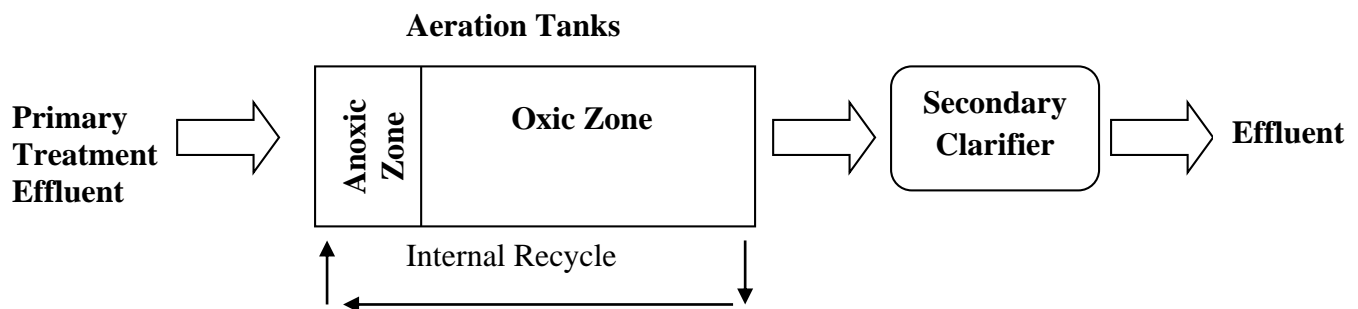
Biological Nutrient Removal (BNR).

After primary and secondary treatment, plants with BNR technology allow wastewater to flow into additional treatment basins where biological processes can remove up to 90% of organic matter. WWTPs use bacteria to perform processes of nitrification and denitrification to enhance

nutrient removal. In the oxic zone of the aeration tank, plant operators mix wastewater with microorganisms and air, which allows ammonia-oxidizing bacteria to oxidize the ammonia (NH_3) present in the effluent to nitrites (NO_2) through nitrification. The next step of nitrification occurs when nitrite-oxidizing bacteria oxidize nitrite to nitrate (NO_3) (EPA Fact Sheet, 2015).

Nitrates (NO_2 and NO_3) are all biologically available forms of nitrogen and, if discharged, would directly contribute to algae production and, potentially, to eutrophication processes. An additional process, called denitrification, is required to convert biologically reactive nitrogen into inert nitrogen gas (N_2). Denitrification occurs in the anoxic zone of the aeration tank, as denitrifying organisms only metabolize nitrates in the presence of very low amounts of oxygen. Plant operators must minimize oxygen in the effluent to allow for efficient denitrification (Sedlak et. al. 1991). Figure 1 summarizes a typical BNR process.

FIGURE 1. Typical BNR Nitrogen Removal Process



Source: Brown and Atherton, 2009.

BNR technology can take many forms, as plant operators may use different technological treatment processes to perform the nitrification and denitrification processes. For example, plants may use internal recycle, which increases removal (Saffouri, 2005; Constantine, 2008). They may use the oxic zones of the aeration basin first, followed by the anoxic zone, or vice versa. In

addition, plant operators must control for a variety of factors that affect BNR performance, such as effluent alkalinity, which, if too low, may inhibit the nitrification process. Operators can add lime or bicarbonate to address this problem (Sedlak, et. al. 1991).

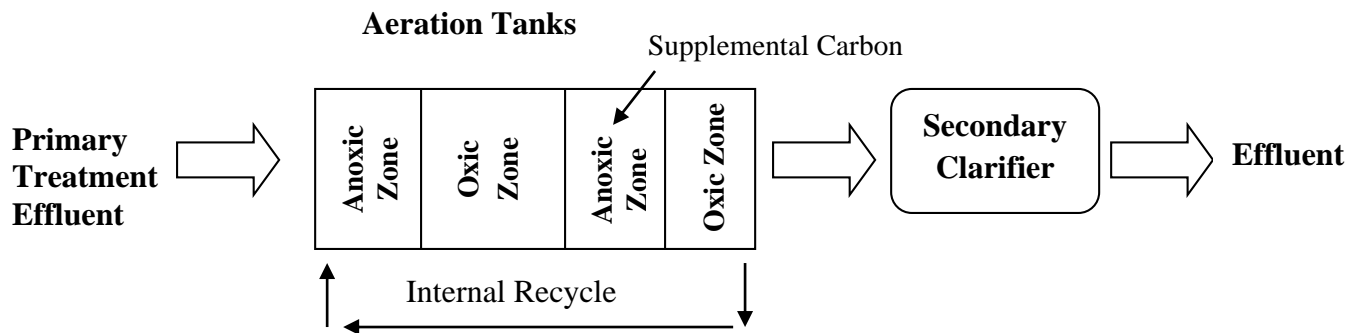
Substances present in effluent may inhibit nitrification/denitrification processes, and plant operators must balance solids retention time with nitrifying bacteria growth rates (Sedlak, et al 1991). WWTPs anoxic/aeration tanks must have sufficient capacity to react to changes in flow and temperature. Biological processes, such as those used in BNR nutrient removal technology, are sensitive to temperature and the flow variability in WWTPs (Grote, 2010). For example, when temperatures dip below 13 degrees Celsius (55 degrees Fahrenheit), effluent must spend more time in the aeration tank to achieve adequate removal as bacteria do not function as efficiently at colder temperatures (DC Water, 2015).

Once a BNR plant becomes operational, plant managers may choose from various operational methods to achieve and optimize removal capacity of BNR technology. Typically, BNR WWTPs can achieve 8-10 mg/l nitrogen concentrations but different options for removal and maintenance may cause variability in performance from plant to plant (Grote, 2010). Plant operators can achieve greater reductions by improving denitrification, nitrification, and primary treatment processes within a given BNR technology (Chesapeake Bay Report, 2002). For example, operators can manipulate excess capacity (the difference in a plant's design flow and their actual flows) at low flow times of the day to increase effluent detention time and enhance the nitrification process (Sedlak, et. al. 1991).

Enhanced Nutrient Removal (ENR).

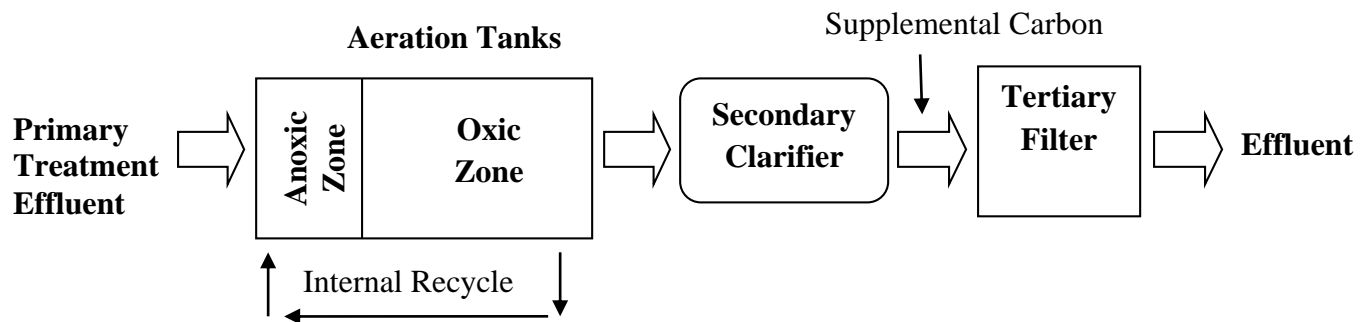
Enhanced nutrient removal technology removes nitrogen at greater levels than BNR through plant modifications that enhance the nitrification and denitrification processes. ENR plants can typically operate at 3 to 4 mg/l nitrogen concentrations (Freed, 2007). Typically, plants construct ENR upgrades by installing a tertiary filter that aids in denitrification through the addition of a carbon source, typically methanol, to increase bacterial growth and, ultimately, nutrient removal (Saffouri, 2005). Plant operators may also opt to intensify the nitrification/denitrification process through the addition of more aeration tanks (Brown and Atherton, 2009). Figures 2 and 3 show typical ENR processes.

FIGURE 2. Typical ENR Nitrogen Removal Process with Addition of Aeration Tanks



Source: Brown and Atherton, 2009.

FIGURE 3. Typical ENR Nitrogen Removal Process with Addition of Tertiary Filter



Source: Brown and Atherton, 2009.

WWTP operators encounter challenges with weather and influent variability in operating both ENR and BNR technologies at respective concentration standards. Each BNR/ENR plant also faces different localized influent characteristics and must use a certain level of operator discretion to run these technologies to address plant-specific issues or obstacles in removal efficiency (Grote, 2010). Adjusting alkalinity through increased lime/bicarbonate, taking advantage of low flow periods for nitrification, or adjusting oxygen content at different stages of the nitrification and denitrification processes are just a few of the options available to increase nutrient removal. Plant operators may use different methods to minimize operation costs or to maximize removal capacities when utilizing these upgrade technologies (Randall, 2004). Given the flexibility in removal performance within ENR and BNR technologies, plant operators can respond to external influences, such as incentives for over-performance.

CHAPTER 3: POINT SOURCE NITROGEN CONTROL POLICIES IN MARYLAND AND VIRGINIA

In response to pressure to clean up the Bay and the 2010 TMDL, both Maryland and Virginia set aggressive point source caps, allocated among significant municipal and industrial WWTPs as individual WLAs. Municipal WWTP WLAs were calculated based on ENR-level nutrient concentration levels. Both states developed regulatory systems to meet clean up goals with different incentive structures for plant operational performance. This chapter will explain the design and implementation of Virginia's and Maryland's point source nutrient regulatory programs. The different aspects of each state's program will inform the development of the key explanatory variables for comparative analysis of plant performance.

Point Source Nitrogen Control Program in Virginia

Design.

In 2005, Virginia passed the Chesapeake Bay Watershed Nutrient Credit Exchange Program Act which instructed VADEQ to develop individual WLA (lbs/year of nitrogen and phosphorus) for all significant point sources (design flow greater than 0.5 millions of gallons per day, MGD) to help achieve water quality goals in the Chesapeake Bay. VADEQ assigned WLA based on reference nutrient concentration levels and plant design flows (see Table 1). Virginia DEQ established WLAs across and within tributaries based on the relative potential contribution of point sources discharge to the Bay water quality (Table 1). The WLAs became binding regulatory requirements in 2011 and must be achieved regardless of nutrient removal technology installed at the plant.

In addition to WLAs, DEQ sets nutrient concentration limits based on the designed nutrient removal capabilities of each WWTP. Nitrogen concentration limits typically range between 3 and 4 mg/l for ENR equipped WWTPs and 8 mg/l for BNR treatment plants (see Table 1).

TABLE 1. Nitrogen WLA and Concentration Requirements for Virginia Point Sources

Basin	WLA**	Nitrogen Concentration Limit for upgraded WWTPs
Potomac-Shenandoah		
<i>Tidal Waters-BFL*</i>	3 mg/l x design flow	3 mg/l for ENR plants 8 mg/l for BNR plants
<i>AFL*</i>	4 mg/l x design flow	4 mg/l for ENR plants 8 mg/l for BNR plants
Rappahannock	4 mg/l x design flow	4 mg/l for ENR plants 8 mg/l for BNR plants
York	6 mg/l x design flow	8 mg/l for BNR plants
Eastern Shore	4 mg/l x design flow	8 mg/l for BNR plants
James		
<i>AFL*</i>	6 mg/l x design flow	5,8 mg/l for ENR, BNR plants in
<i>Tidal Waters</i>	5 mg/l x design flow	
<i>Lower James</i>	12.7 mg/l x design flow	8 mg/l for BNR plants 8-12 mg/l for BNR plants

*AFL: Above Fall Line; BFL: Below Fall Line

**WLA is calculated by multiplying design flow (MGD) x reference concentration level (mg/l) x 365 (days per year) x 8.344 (imperial to metric conversion units)

Source: Virginia Watershed Implementation Plan (WIP) Phase I, Section 4.1

The binding WLA and non-uniform nutrient removal capabilities created possible compliance challenge for BNR and non-upgraded plants. Virginia plants expecting compliance challenges faced two options to achieve compliance in 2011 with their WLA: install a capital

upgrade to enhanced nutrient removal or purchase nutrient credits under the state's point source trading program. It is important to note that WWTPs may not trade to maintain compliance with their assigned concentration limit regardless of their compliance status with their WLA.

The Virginia Nutrient Credit Exchange Association, established through the Act, provides a means for non-upgraded and BNR WWTPs to maintain compliance in the face of strict individual annual WLAs and a means to smooth the sequencing of plant upgrades (Pomeroy et al, 2007). The program gives plants challenged with meeting nutrient WLA an alternative to undergoing a costly capital upgrade by providing a trading program that facilitates the buying of nitrogen and phosphorus credits. A nutrient credit is expressed in pounds of nitrogen or phosphorus per year delivered to the Chesapeake Bay and is calculated as the difference between a plant's individual WLA (allocated lbs per year of nitrogen or phosphorus delivered to the Chesapeake Bay) and annual discharge (actual lbs per year of nitrogen or phosphorus delivered to the Chesapeake Bay).

The Association coordinates the supply and demand of credits in each major Virginia tributary to the Chesapeake Bay (Potomac, Rappahannock, York, James, and Eastern Shore) (see Figure 4). Each year, the Association publishes a compliance report outlining planned individual plant compliance and basin wide cap achievement per year on a five-year time horizon. Members submit projected loads, based on estimated flows and nutrient concentrations, for each year of a five-year plan.

Plants that expect to exceed their WLA must buy credits (delivered lbs of nitrogen per year) to cover the deficit. The Association designates planned credit purchases as Class A credits and sets the price buyers pay on a five-year time horizon for each basin. To ensure stability and

the use of trades for compliance, buyer prices are set low and based on marginal cost of abatement estimated through operational and maintenance costs (Pomeroy et al, 2007). Buyer prices are established in advance on a 5 year planning horizon. Class A credit prices for buyers for 2013 are shown in Table 2. If plants experience unanticipated need for credits at the end of each compliance year, they must buy credits at 1.5 times the established Class A credit prices. The Association designates these unplanned credits as Class B credits. Class A buyers must buy the entire amount of projected Class A credits, regardless of what their actual load ends up being. Revenue from the credits is paid to the Association (see Figure 4).

The Association also oversees the planning and coordination of credit supply. Credit suppliers, typically plants with upgrades, must also submit credit projections. After estimating projected credits, point source sellers may choose to pledge a portion of those credits as Class A credits. Plants that choose to pledge Class A credits must supply these credits, regardless of their actual load at the end of the year. If a plant fails to generate enough credits through the difference in their WLA and their actual load, they must buy Class B credits to meet their pledge obligations. Plants expecting to over-comply with their individual WLA may choose not to pledge all expected credits as Class A. In this situation, the Association designates these non-pledged credits as Class B credits. Suppliers of Class B credits have no obligation to provide credits at the end of the compliance year.

The Association announces credit prices for the sellers at the end of each compliance year based on the total revenue received from credit sales. To determine the price received for Class A credit sellers, the Association divides 90% of the credit revenue by the total number of Class A credits supplied. To determine the price *received* for Class B credit sellers, the Association divides the remaining 10% of the credit revenue by the total number of Class B credits supplied.

Table 2 provides examples of Class A and Class B prices, by watershed, for 2013. Relative to Class A seller prices, Class B seller prices are very small, typically less than \$0.10 per nitrogen credit. Class A prices received by the seller are typically a fraction of the buyer price because of significant over-compliance with the tributary caps. In watersheds where all plants meet individual WLA, no buyers exist and no sales occur (Virginia Nutrient Credit Exchange Association Compliance Document, 2011, 2012, 2013).

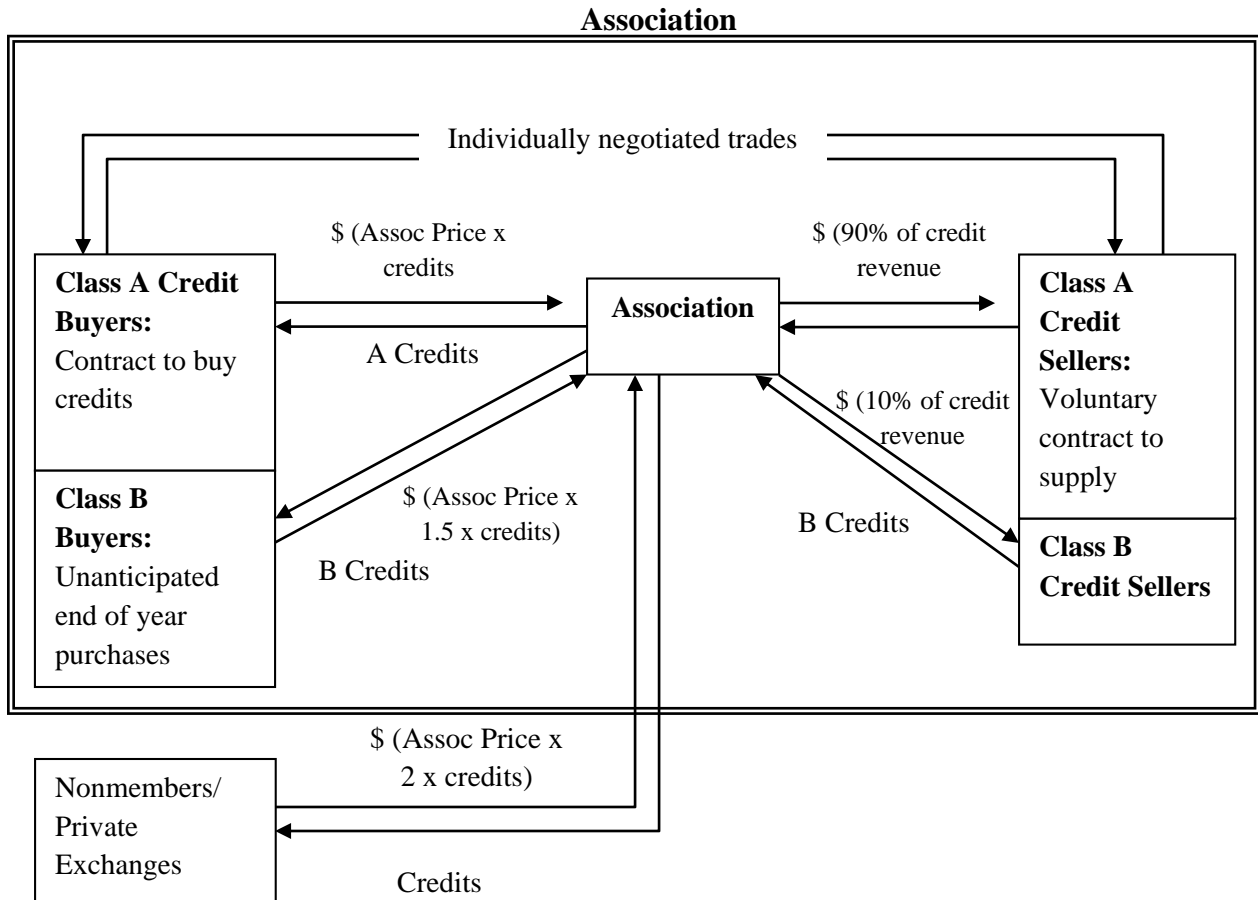
TABLE 2. 2011, 2012, and 2013 Nitrogen Credit Prices Established by the Virginia Nutrient Credit Exchange Association (\$/delivered lbs)

Watershed	Administered N Credit Buyer Price	Class A Seller	Class B Seller
Potomac			
2011	\$2.00	\$1.27	\$0.11
2012	\$2.00	\$1.29	\$0.13
2013	\$2.15	\$1.35	\$0.10
Rappahannock			
2011	\$2.00	\$0.38	\$0.04
2012	\$2.00	\$0.51	\$0.03
2013	\$2.15	\$0.39	\$0.02
Upper James			
2011	\$2.00	\$1.40	\$0.16
2012	\$2.00	\$1.10	\$0.14
2013	\$2.15	\$1.07	\$0.12
York			
2011	\$2.00	\$1.62	\$0.32
2012	\$2.00	\$0.90	\$0.02
2013	No Sale	No Sale	No Sale
Eastern Shore			
2011	\$2.00	No Sale	\$0.27
2012	\$2.00	No Sale	\$0.09
2013	\$2.15	No Sale	\$0.10

Dischargers also have other compliance options beyond those arranged by the Association. Plants operated by an aggregate waste authority within the same tributary may elect to consolidate all WLA into a single plant “bubble” to maintain compliance. Also, WWTPs may supply or buy credits through private exchanges outside of the Association as long as all trades

are recorded in the annual Association compliance report. The Association price setting mechanism is graphically described in Figure 4 and credit exchange options.

FIGURE 4. Virginia Nutrient Credit Exchange Association Credit Pricing System



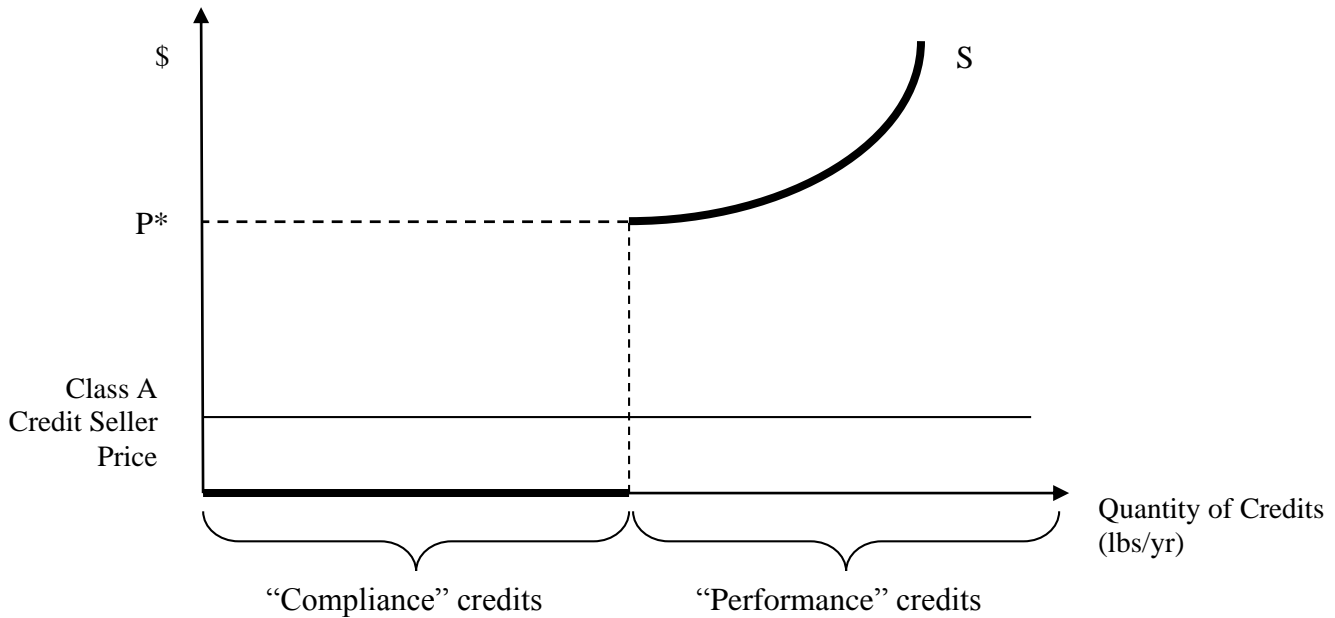
Virginia Plant Operator’s Nitrogen Control Decisions and Outcomes.

Conceptually, the decision to supply nitrogen credits for a point source with an ENR upgrade is based on the marginal abatement cost to reduce nitrogen, the nitrogen concentration limit, and excess flow design capacity (Poe, 2009). For most Virginia ENR plants, meeting the concentration limit will mean that the plant will automatically overcomply with their nitrogen load constraint (WLA). Since WWTPs typically operate below design flow, WWTPs will

generate credits when operating at or below their nutrient concentration limit. A WWTP's "constrained load" is defined here as its required nitrogen concentration limit and realized discharge flow. The difference in an ENR WWTP's WLA and their "constrained load" generates credits without any operational improvements in nitrogen removal capacity (called "compliance credits"). The binding nutrient concentration limit means that most ENR plants will supply compliance credits at zero credit price.

Figure 5 summarizes an ENR plant's Class A credit supply decision. The upper sloping portion of the supply curve, denoted as the "S" curve, is the marginal abatement cost of achieving load reductions beyond the "constrained load" by lowering concentration levels beyond regulatory limits. Price P^* represents the minimum expected price necessary for the WWTP to pledge Class A credits. If the Class A credit price is below the marginal abatement cost of achieving additional reductions in concentration levels, the WWTP will not pledge any credits beyond "compliance credits." "Performance" credits are generated when a plant pledges credits based on lowering their nitrogen concentration below regulatory requirements through operational improvements. Figure 5 shows the result when Class A credit prices are not set high enough to induce any incentives for "performance" credit generation. If prices were set at P^* on the graph, plants would begin to have incentives to supply "performance" credits.

FIGURE 5. Supply of Class A Nitrogen Credits for Virginia WWTPs



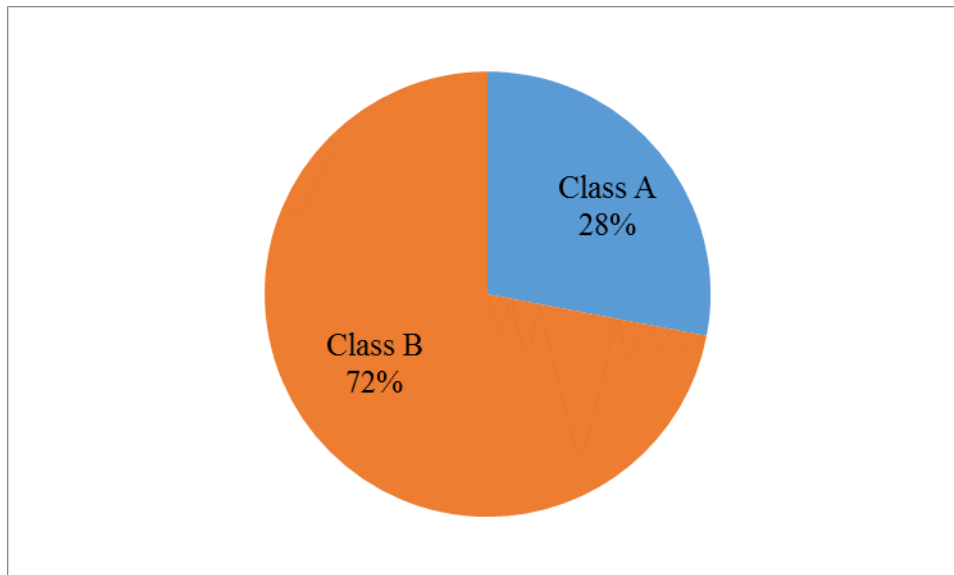
As an illustration of compliance credits, suppose an ENR plant in the Potomac basin with a design capacity of 10 MGD and an attenuation factor of 1 (one pound of nitrogen discharged is delivered to the Chesapeake Bay). Virginia DEQ assigns a nitrogen WLA based on 4 mg/l concentration standard operating at plant design capacity (10 MGD), producing an annual WLA of 121,822 lbs/yr.¹ The plant also faces an average annual concentration limit of 4 mg/l. In addition, most average annual flows for WWTPs range between 60 and 70% of design capacity. Thus, a plant that exactly matches the 4 mg/l concentration limit and discharges 65% of design flow would discharge 79,185 lbs/yr of nitrogen. This plant would supply 42,683 “compliance” credits without the presence of any price incentives, thus supplied at a zero price, as a direct result of a binding concentration limit. The WWTP operator would only pledge additional Class

¹ 10 MGD x 4mg/l x 365 x 8.344 (metric to English unit conversion factor)

A credits (beyond 42,682) if the prices were high enough to cover the incremental cost to achieve reductions in nitrogen concentrations below 4 mg/l.

To date, wastewater plant operator Class A credit pledging decisions are not based on achieving additional reduction in concentration levels. In Virginia, ENR plants face a nitrogen concentration limit between 3 and 5 mg/l, depending on individual plant location (see Table 1). Every Class A pledge in Virginia is based on the assumption of achieving (not exceeding) the regulatory concentration limit. Thus, all Class A pledges are compliance credits. Furthermore, ENR plants typically only pledge Class A for a portion (about 30%) of compliance credits generated by the difference in their WLA and their “constrained” load (Figure 6).

FIGURE 6. “Compliance Credits” Supplied by Virginia ENR WWTPs (lbs/yr), 2013



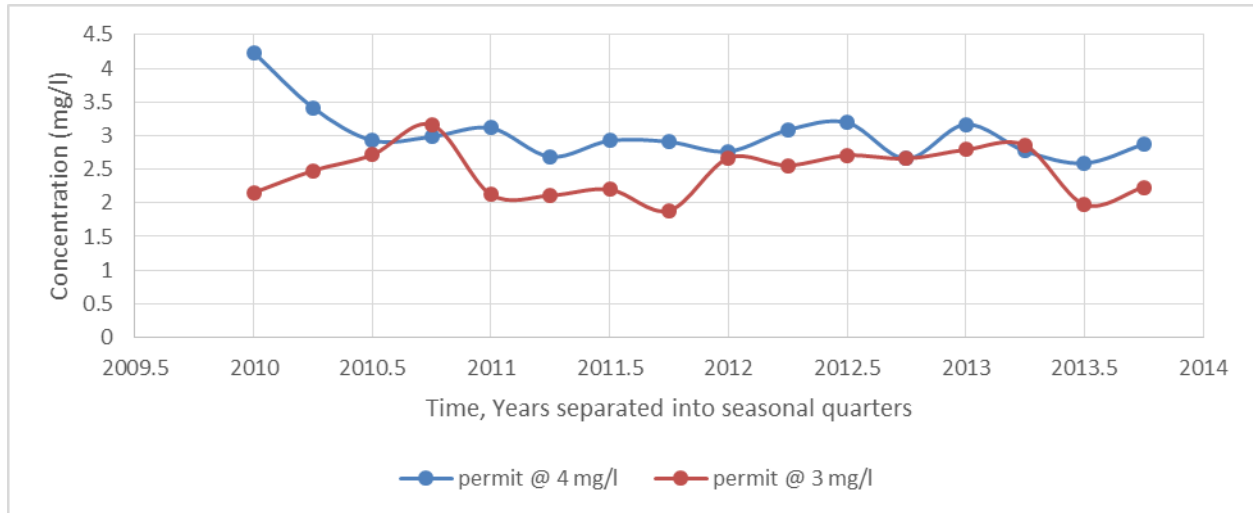
Because ENR plants in the Association do not pledge credits generated by projected concentrations below permit limits, they face Class B credit prices for any improvement to concentration levels below what they projected. Compared to Class A prices, Class B prices are

approaching \$0 per lb/year of nitrogen removed, providing very little price incentive for plants that over-perform.

Figure 7 shows flow weighted average nitrogen concentration, by seasonal quarters for Virginia WWTPs with a 3 and 4 mg/l concentration limit. The annual nitrogen concentrations between 2011 and 2013 averaged 2.78 mg/l for plants with 4 mg/l concentration limit and 1.93 mg/l for plants with a 3 mg/l concentration limit. These statistics show high levels of over-performance, but cannot be attributed to Association trading financial incentives.

Municipal WWTPs, on average, operate below their nitrogen concentration limit, but risk aversion appears to motivate this observed over performance. Risk aversion in effluent control performance at municipal WWTPs has been noted in other regulatory programs and contexts (Hamstead and BenDor, 2010). Since nitrogen effluent concentrations exhibit natural variation through the year, plant operators must operate with a margin of safety to ensure they do not violate their average annual concentration permit limit at the end of the year. (Personal communication Chris Pomeroy, 2015).

FIGURE 7. Virginia ENR WWTPs Flow Weighted Average Annual Nitrogen Concentrations, 2010-2013



The compliance decision faced by Virginia BNR WWTPs depends on the initial WLA and plant effluent flow relative to design capacity. BNR plants in Virginia face a WLA level that they are not designed to meet at their current BNR technology. BNR plants, once upgraded, must meet a concentration limit consistent with the operational design performance (typically of 8 mg/l nitrogen). If a plant's actual flow is well below its design flow, the plant could be a supplier of "compliance credits" without any reduction in concentrations below the regulatory concentration limit. For example, in watersheds, such as the James, VADEQ sets WLAs based on a concentration standard of 6 mg/l of nitrogen. Thus, the WLA is based on a concentration standard that is 25% less than the required 8 mg/l concentration limit. A 10 MGD BNR plant in the Upper James basin, with a WLA of 182,734 lbs/yr nitrogen would discharge only 134,005 lbs/yr if operating at 65% design flow capacity while just meeting an 8 mg/l concentration limit. In this example, the 10 MGD BNR plant is not designed to meet the reference WLA

concentration, but still generates 48,729 credits, because of a small flow relative to design flow and a WLA set based on a 6 mg/l concentration standard.

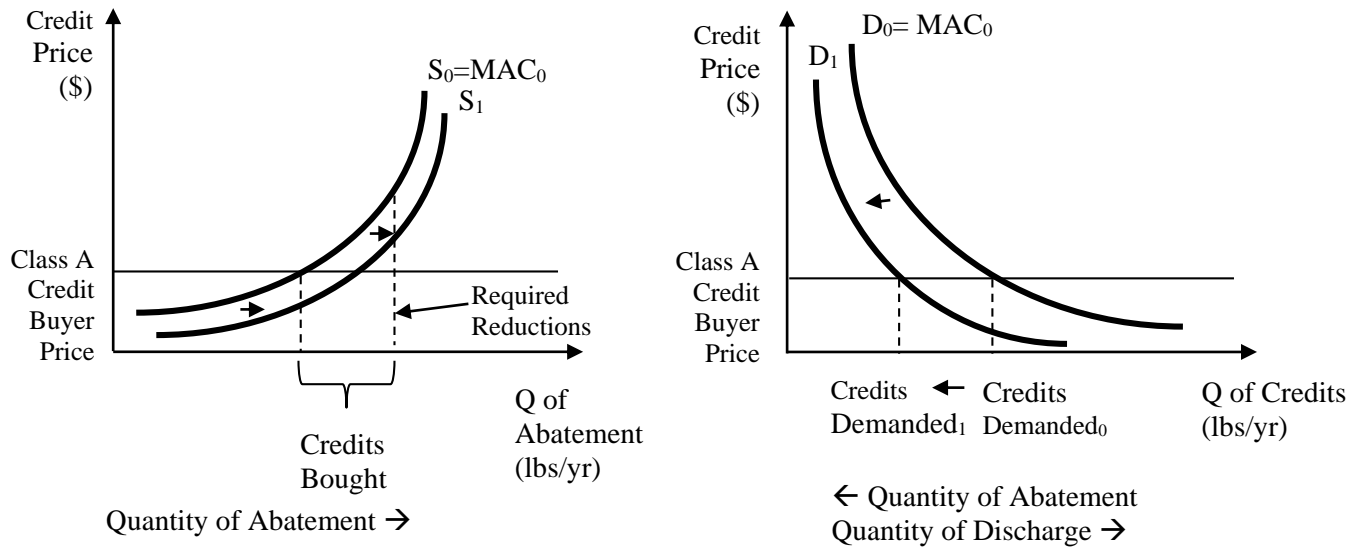
Furthermore, WWTPs with an 8 mg/l nitrogen concentration limit typically discharge an average of 7-7.5 mg/l, representing another operating factor that contributes to BNR WLA compliance. In some watersheds, BNR plants are credit suppliers because their flows relative to their design flows are low. As with ENR plants, these BNR WWTPs credit suppliers do not supply Class A credits based on projected concentration levels lower than concentration limits. The only Class A credits pledged by BNR plants to supply each year are compliance credits. They face the same supply decisions as ENR plants, illustrated in Figure 5.

Other BNR plants, however, cannot rely on excess flow capacity to help meet their WLA. For instance, WWTPs located in the watersheds with WLAs based on nitrogen concentration standards of 3 or 4 mg/l do not have sufficient excess flow capacity to compensate for the difference between plant concentration limit (8 mg/l) and the WLA concentration standard (4 mg/l). For plants that do face compliance challenges, if the marginal abatement cost of reducing one more unit of nitrogen is greater than Class A buyer credit prices established by the Association, then the plant will purchase credits. The derivation of credit demand is shown in Figure 8. A WWTP's abatement supply curve is shown on the left, denoted as the "S₀" curve. A plant must supply nitrogen reduction until they meet their WLA. Under the trading program, a plant will buy reductions to meet their WLA once plant abatement costs exceed the Class A credit price established by the Association. The abatement supply curve is upward sloping because as you increase abatement supplied, costs increase.

In Figure 8, the abatement supply curve on the left mirrors the credit demand curve on the right. The right hand graph shows increasing marginal costs increasing with additional levels of abatement. As a WWTP supplies more abatement, less credits are demanded. If the marginal cost of required reductions exceeds Class A prices, the discharger will reduce abatement (increase discharge) until marginal abatement costs (MAC_0) equal the credit price.

The WWTPs supply curve for credits can also be expressed as a downward sloping demand curve for credits, illustrated by the D_0 curve (right side graph, Figure 8). The WWTPs abatement cost curve can be shown as downward sloping (by convention) because the horizontal axis is reversed with abatement decreasing out from the origin (right side graph, Figure 8). If a Class A buyer makes operational improvements or refinements to attain compliance and decrease their demand for credits needed to comply, they are shifting their underlying production function for nitrogen removal, illustrated as the shift to the marginal abatement cost curve D_1 in Figure 8. This is also shown as a shift in the abatement supply curve (S_0 to S_1) as a plant can now supply the same level of abatement at a lower cost.

FIGURE 8. Supply of Nitrogen Abatement and Demand of Nitrogen Credits by Compliance Challenged BNR and Non-upgraded Virginia WWTPs



Finally, non-upgraded WWTPs in Virginia constitute a final group of potential credit buyers. Non-upgraded point sources face a WLA based on concentration standards typically well below what each plant can achieve with only secondary treatment. Nitrogen concentrations for a non-upgraded municipal WWTP typically range between 15 and 20 mg/l annual average. Similar to BNR WWTP credit buyers, non-upgraded plant operators will buy credits from the Association as long as their marginal cost of nitrogen abatement is greater than the established credit buyer price, also illustrated in Figure 8. While each plant is constrained by the lack of capital upgrades for significant nutrient removal, they may find ways to reduce nutrient loads to minimize necessary credit purchases, shifting their D_0 curve left to D_1 . Further analysis will show if there is evidence of operational over performance at BNR and non-upgraded municipal WWTPs in Virginia because of the presence of financial incentives from the nutrient credit trading program.

*Maryland Incentive Payments Program***Design.**

Maryland imposes nitrogen WLA based on a uniform nitrogen concentration standard of 4 mg/l multiplied by plant design flows (Personal communication, Elaine Dietz, MDE 2014). Plants must meet the WLA only after receiving an ENR upgrade. Maryland government pays 100% of the capital costs for ENR upgrades at municipal WWTPs and the ENR upgrades are designed to achieve 3 mg/l of nitrogen. In addition, the state requires all upgraded ENR plants to meet a 4 mg/l average annual concentration limit. MDE does not impose WLA compliance requirements on BNR plants and non-upgraded Maryland municipal WWTPs. BNR plants, however, must still meet an 8 mg/l concentration limit.

To induce extra reductions beyond regulatory requirements, Maryland provides operational grants to WWTPs with ENR technology to operate their upgrade at an annual nitrogen concentration of 3 mg/l or lower (Personal communication, Walid Saffouri, MDE 2015). Plants able and willing to reduce concentrations to this level or lower receive a fixed annual payment of \$18,000 per MGD design flow (capped at \$216,000) for the years 2008 and 2011 and \$30,000 per MGD (capped at \$300,000) from 2012 to present. Immediately after an ENR upgrade, WWTPs automatically receive operational grant funds for a year following the completion of upgrade construction, regardless of the level of nitrogen removal achieved. These phase-in grants allow plants the opportunity to optimize their upgrade technologies and still receive grant support for operational costs as they transition. Once this “transitioning” year concludes, plants must achieve a 3 mg/l nitrogen annual average to receive operational grants.

MDE did not offer operational grants in the years of 2009 and 2010, due to insufficient funding. BNR plants are not provided any financial incentives for improving operational performance.

Maryland Plant Operator's Nitrogen Control Decisions.

A Maryland ENR plant operator's decision to reduce nitrogen concentrations in effluent to participate in the operation grant program, or "supply" nitrogen abatement from 4 to 3 mg/l, is dependent upon the individual WWTPs per pound average cost of abatement between 4 and 3 mg/l and the per pound lump sum of the grant.

At the current rate of \$30,000 per MGD of design flow, Maryland is paying approximately \$15.15/lb per year assuming nitrogen concentrations are reduced from 4 mg/l to 3 mg/l an attenuation ratio of 1 and 0.65 MGD annual flows². Conceptually, low abatement cost (LAC) plants, or plants illustrated as the $WWTP_{LAC}$ curve in Figure 9, would operate at 3 mg/l if the grant amount was as low as P^{**}_{LAC} of nitrogen (the minimum cost the reduction could be provided at). The plants' average abatement costs from 4 mg/l to 3 mg/l per pound of nitrogen are lower than the \$15.15 per pound lump sum of the operational grant. Decisions are made based on average cost between 4 and 3 mg/l because the operational grants are allotted in lump sums for performance at 3 mg/l annual average nitrogen concentrations. High abatement costs (HAC) plants, illustrated as the AC_{HAC} curve in Figure 9, cannot operate at 3 mg/l for less than \$15.15/lb per MGD of design flow. These plants will not participate in the program as the financial incentive is not high enough to offset the average total abatement costs of achieving 3 mg/l nitrogen concentration.

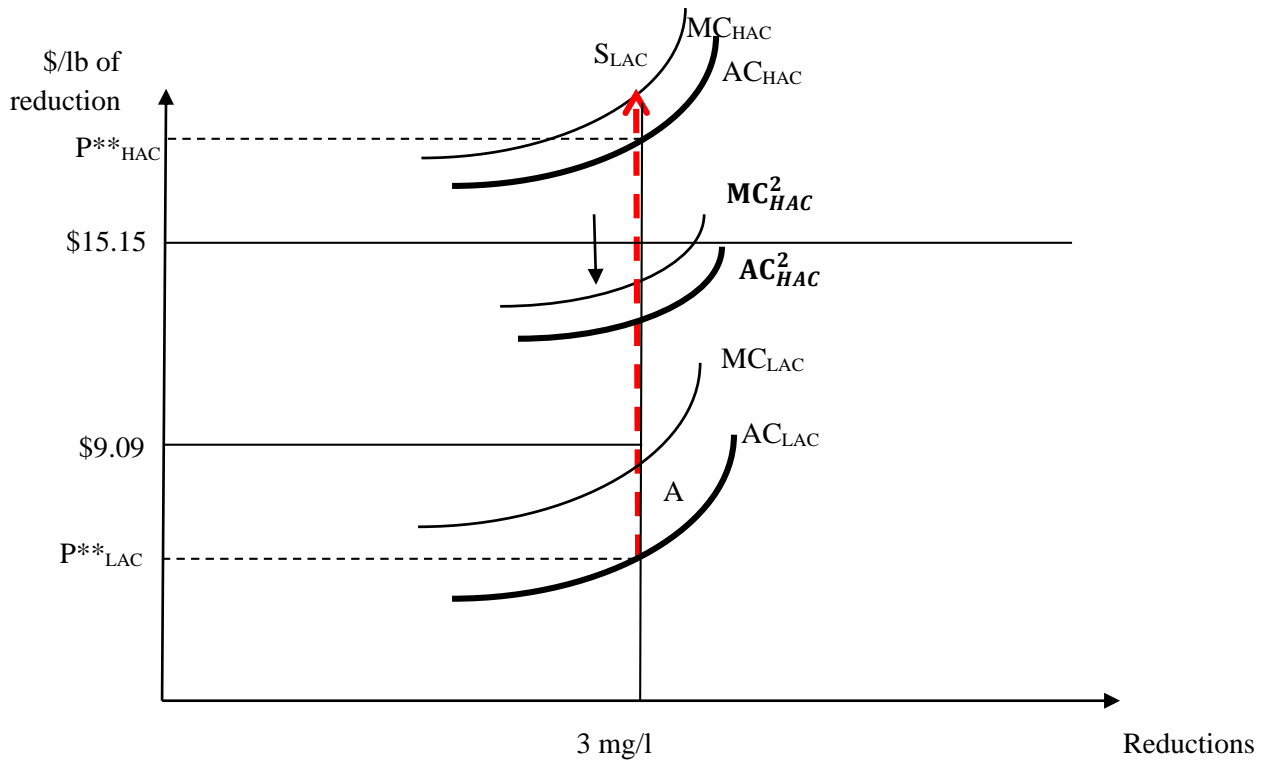
² 1 mg/l concentration reduction x 0.65 MGD (average flow relative to 1 MGD design flow) x 8.344 x 365 x 1 = 1,980 lbs/yr; \$30,000/1,980 lbs = \$15.15/lb

At the previous rate of \$18,000 per MGD, Maryland was paying approximately \$9.09/lb nitrogen (assuming .65 annual average flows and attenuation ratio of 1). The increase to \$30,000 per MGD (\$15.15/lb) could have induced more participation in the program from higher average abatement cost plants depending on the average nitrogen abatement costs between 4 and 3 mg/l.

For example, an ENR WWTP with a 1 MGD design flow and low average abatement costs of achieving 3 mg/l operates at the curve AC_{LAC} in Figure 9. This plant will participate in the program and achieve 3 mg/l nitrogen concentrations because it can do so at a lower cost than the per pound financial incentive presented by the program ($P^{**}_{LAC} < 15.15/\text{lb}$). It's important to note that once an ENR plant reaches 3 mg/l nitrogen concentrations, the plant has no incentive to further decrease concentration as operational grants are awarded as a lump sum. They do not recognize further reductions below 3 mg/l with more grant money so the “abatement supply curve” becomes perfectly inelastic at that point “A” in Figure 9, illustrated by the red dashed line (in Figure 9, the supply curve for the low cost abatement plant starts at P^{**}_{LAC}).

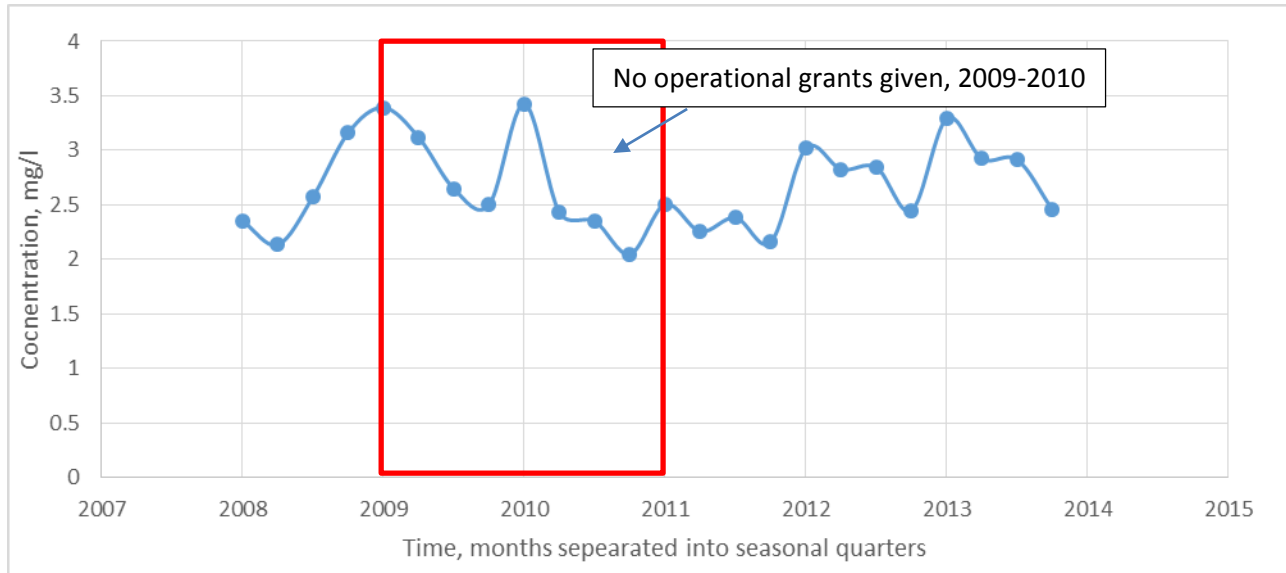
Higher abatement average cost plants may, over time, discover operational improvements to meet the 3 mg/l requirement to receive an operational grant, illustrated by the shift of the AC_{HAC} curve to AC^2_{HAC} in Figure 9. Financial incentives from these operational grants could be inducing innovation in operational performance over time.

FIGURE 9. Maryland ENR WWTPs Decision to Participate in the Grant Program (1 MGD)



Preliminary analysis of average nitrogen concentrations among Maryland municipal WWTPs operating with ENR technology shows that ENR WWTPs, on average, are operating at 3 mg/l nitrogen concentrations from 2008 to 2013 (Figure 10). As of 2013, Maryland has upgraded 33 municipal WWTPs to ENR technology. The operational grant program pays ENR WWTPs over \$1 million a year to encourage plants to achieve 3 mg/l, but ENR plants, designed to achieve 3 mg/l, may operate at this level regardless of the financial incentive program to ensure compliance with the concentration standard, with a margin of safety.

FIGURE 10. Maryland ENR WWTPs Flow Weighted Average Nitrogen Concentrations, 2008-2013*



*Only includes ENR plants after one year of operation

In the first year since restarting the program (2011), every ENR plant received an operational grant. In 2012, despite the grant increase from \$18,000 to \$30,000 per MGD, seven newly upgraded WWTPs could not achieve 3 mg/l to remain in the program past their transitioning year. There is no observable behavioral change in plant performance eligibility as a result of the increase in operational grant rates. Table 3 describes operational grant recipients in the years following their first year of operation (referred to as a transitioning year).

TABLE 3. Maryland ENR WWTP Performance Eligibility in Non-Transitioning Years

Year	No. of ENR plants operating under the program	No. of Performance Eligible Plants
2008	4	4
2009	0	0
2010	0	0
2011	10	10
2012*	20	13
2013*	21	15

* Indicates rate increase to \$30,000 MGD

Virginia ENR WWTPs also have observed over-compliance without any significant financial incentive. Chapter 4 will examine the extent to which the Maryland operational grant program induces additional nutrient reductions through operational improvements at ENR plants. Maryland could be paying plants to operate at a concentration level they would achieve without the opportunity to receive operational grants, undermining the concept of “additionality.” The requirement of additionality is fulfilled when nitrogen reductions occur that would not have taken place without the presence of the program. Incentive programs should aim to increase additionality to ensure that incremental improvements occur (Claassen, Horowitz, Duquette, Udea 2014).

CHAPTER 4: EXPLANATORY MODEL FOR ENR WWTPs OPERATIONAL PERFORMANCE UNDER THE MARYLAND GRANT PROGRAM

Virginia's and Maryland's municipal wastewater treatment plants with ENR technology face different incentives for operational over-performance. Based on credit pledging evidence from the Virginia Nutrient Credit Exchange Association, Virginia ENR plants are not responding to Class A credit prices to achieve higher levels of nitrogen removal through operational improvements (see Chapter 3). Maryland, however, provides grant money to plants with ENR level technology to reduce nitrogen concentrations from 4 mg/l to 3 mg/l. To identify the extent to which Maryland's incentive program leads to operational over-performance, an explanatory model is constructed to isolate the effect of this program using Maryland ENR WWTPs during the years the program was discontinued (2009-2010) and Virginia ENR WWTPs as a control group. Through careful trading behavior analysis of Association documents, Virginia ENR plants do not respond to the financial incentives of credit prices. WWTPs in Virginia do not pledge credits as a result of lower concentration performance.

Conceptual Model

While there is a vast literature on the engineering aspects of BNR and ENR technology at WWTPs, less work has been done on empirical investigations of plant operators' nutrient control behavior response to different policies. Conceptually, the supply of nutrient reductions by an ENR plant (mg/l) is a function of the credit prices, treatment technologies/plant characteristics, ownership structure and behavior, input prices, enforcement penalties, and other factors that might influence a plant operator's decision-making. To determine which variables affected WWTP plant performance, in terms of nitrogen discharge concentrations, an individual plant's

nitrogen reduction “supply” function had to be understood. Statistical studies analyzing the effects of factors other than price incentives that influence discharger performance were used to inform the construction of the reduction supply functions used as the explanatory models in this paper.

A case study, conducted in Suzhou City, China, used discharge performance analysis to measure the impact of changing industrial wastewater plant ownership on environmental performance (Yuan, Jang, Bi, 2010). The authors found that ownership structure, in terms of centralization of management among plants, affects operational cost and discharger performance, an important variable in a plant’s reduction supply function.

Sancho and Garrido (2009) assessed the potential for desalination in Spanish wastewater plants, analyzing plant operational performance in terms of the impacts that variables such as energy cost, labor cost, maintenance and management costs had on the amount of contaminants removed. The authors concluded that larger plants ran more cost effectively, in terms of less inputs needed for a given level of contaminant removal, than smaller plants. This led to the inclusion of plant size in a plant’s reduction supply function.

Other authors analyzed the effects of community and regulatory pressure on WWTPs incentives to over-comply, specifically with BOD effluent standards (Horowitz and Bandyopadhyay, 2006; Earnhardt, 2004). Earnhardt controls for community characteristics, such as income per capita, flow capacity, treatment technology level, permit structure, and seasonal fluctuations to isolate the effect of regulatory enforcement actions on plant discharges.

Horowitz and Bandyopadhyay (2006) found that dischargers who experienced high flow variability displayed more over-compliance with regulatory limits than plants that experienced a

fairly stable flow, labeled the “safety margin” effect. They further analyzed a wide array of community characteristics and their effects on discharger performance and found that plants in poorer, nonwhite communities exhibit elevated violation rates. Shimshack and Ward (2007) used self-reported discharge data to examine the effect of enforcement on over-compliance. The authors also found evidence of a “safety margin” effect in plants that faced regulatory punishment for violations, while controlling for seasonal fluctuations, abatement technology, and idiosyncratic, plant characteristics (Shimshack and Ward, 2008).

No analysis has been conducted regarding the effect of financial incentives on pollution prevention behavior, in terms of nutrient reductions, but these studies informed the construction of this paper’s explanatory models. The nitrogen reduction supply curve used for the following explanatory models is a function of abatement technology, community and geographic characteristics, ownership structure, regulatory enforcement, energy input costs, flow variability, seasonal fluctuations, and, most importantly for this paper, the presence of an operational grant program that provides lump sum grants for discharger over performance.

Empirical Model

An econometric model is constructed to determine whether the financial incentives presented through Maryland’s operational grant program induce more pollution prevention behavior, in the form of lower nitrogen concentrations, when controlling for other factors. The model assesses WWTP nitrogen concentration performance from January 2008 to December 2013, as this is when the grant program was established in Maryland and when the first wave of Maryland WWTPs completed their upgrade to ENR technology. Furthermore, only discharge performance from Virginia and Maryland ENR upgraded plants are included in the time series.

This model represents an individual WWTP “*i*” at time “*t*” in months (Equation 1). Each variables is described in Table 4.

$$\begin{aligned} \ln(TNmgl)_{it} = & \beta_0 + \beta_1 PerfElig_{it} + \beta_2 NoGrant_{it} + \beta_3 Time_{it} \\ & + \beta_4 \ln(PrecentCapacity)_{it} + \beta_5 MethanolPrice_t + \beta_6 Temp_{it} \\ & + \beta_7 LagTemp_{it} + a_i + \varepsilon_{it}, \quad t = 1, 2, \dots, 72 \end{aligned} \quad (1)$$

The natural log of average monthly nitrogen discharge concentrations, in milligrams per liter, is the dependent variable for this model. It is logged in this model because it creates the correct functional form to maintain model that is linear in parameters. Only plants upgraded to ENR technology were included. Once a plant completes its ENR upgraded, its discharge performance data is added to the model making this time series panel unbalanced.

The key explanatory variables in this model concern the financial incentives presented by Maryland’s operational grant program. The effects of the operational grant program are separated into two dummy variables: “performance eligible” and “no grant received.” If a Maryland ENR WWTP is eligible for an operational grant for a given year that the program is in effect, meaning they have annual nitrogen concentrations at or below 3 mg/l for the years 2008, 2011, 2012, or 2013, they are identified with a 1 for the “*PerfElig*” variable. If a plant could receive a grant, meaning they are operating with ENR technology in 2008, 2011, 2012, or 2013, but did not receive one, they are given a 1 for the “*NoGrant*” variable. This isolates the effects of the operational grant program on Maryland ENR plants that receive grants based on performance, which, theoretically, means the financial incentive (per unit of reduction) is greater than an individual plant’s average cost of abatement to 3 mg/l nitrogen concentration. The *NoGrant* variable illustrates the differences in reduction behavior amongst the presumed higher average cost abatement Maryland plants.

These variables capture any effect that financial incentives in Maryland have had on ENR plant performance. For the years 2008, 2011, 2012, and 2013, Maryland ENR WWTTPs have an additional financial incentive to over-perform compared to Virginia plants (who have no significant financial incentive). For the years 2009 and 2010, both Maryland and Virginia ENR WWTTPs operate with no financial incentives to increase nutrient removal beyond regulatory compliance. The *PerfElig* variable is expected to have a negative coefficient supporting the hypothesis that Maryland's financial incentives encourage incremental nitrogen abatement beyond what would be observed without the grant. The *NoGrant* variable could be either positive or negative. It captures the increased concentrations for plants with assumed higher abatement costs, due to their lack of participation in the program but also may capture lower concentration trends as a result of efforts to achieve 3 mg/l and receive an operational grant.

Both Maryland and Virginia allow ENR WWTTPs to refine plant operations after completion of upgrade construction, as each plant must learn to incorporate unfamiliar technologies into their wastewater treatment process. This effect is captured by the "*Time*" variable, which denotes the number of months a plant has been operating ENR technology. For example, plant managers may learn to use nutrient removal technologies more effectively and efficiently or discover process changes. Virginia and Maryland ENR WWTTPs are not required to meet their concentration limits for a year following completion of the upgraded. The *Time* variable is expected to have a negative coefficient estimate as plant managers learn and optimize ENR technologies. The dependent variable, nitrogen concentration, is logged, so the continuous time variable has a diminishing effect on concentrations as most learning occurs in the first year of operating the ENR upgrade.

The “*PercentCapacity*” variable is calculated as an individual WWTPs actual flow (in MGD) divided by its design flow (in MGD) multiplied by 100. Plants that operate close to their design flow have less room in settlement tanks and aeration basins to perform nitrogen removal in response to influent fluctuations (DC Water, 2015; Horowitz and Bandyopadhyay, 2006). Also, this variable is common in the literature and is argued to be a reflection of treatment capacity as more room in settlement tanks aids in more efficient nitrification and denitrification processes (Sedlak, et. al. 1991). This variable is expected to have a positive effect on nitrogen concentrations, and therefore a positive estimated coefficient. As the percentage of a WWTPs capacity increases, operators are less able to remove nitrogen.

A variable representing methanol prices, “*MethanolPrice*,” obtained from Methanex’s posted regional monthly contract prices, is also included in this model to control for input costs as WWTPs typically use methanol as the added carbon source in ENR treatment (Saffouri, 2005; Sancho and Garrido, 2009). This variable is expected to have a positive coefficient. As prices increase for methanol, it becomes more expensive to achieve the same level of nutrient removal.

Temperature variables, “*Temp*” and “*LagTemp*,” are included in this model as ENR technology is sensitive to seasonal fluctuations, specifically temperature changes (DC Water, 2015). Average mean monthly temperature data, in degrees Fahrenheit, was collected from the Southeast Regional Climate Center CLIMOD system. Each WWTP was located geographically to ascertain the closest weather station with available temperature data. Distances between individual WWTPs and weather stations range from 0 to 15 miles. A one month lagged temperature variable was also included. WWTPs that experience colder temperatures in one month experience a decrease in nutrient removal for up to three months after (DC Water, 2015). Temperature coefficient estimates are expected to be negative. As temperature increases,

nitrogen concentrations should decrease as the bacteria used in this technology are better able to perform biological nutrient removal functions. Temperature is expected to have diminishing effects on nitrogen concentrations (due to the logged dependent variable).

The idiosyncratic error term includes all other factors that are not controlled for in this model. The term a_i represents the fixed effects, containing all individual factors that do not vary across time and are unobserved. This term may include any time constant aspects of ownership structure, demographic information, management aspects, and influent characteristics, which, according to literature research, are correlated with variables such as the time trend, flow, and capacity (Horowitz and Bandyopadhyay, 2006; Earnhardt, 2004; Yuan, Jang, Bi, 2010). For example, a plant with storm water collection will have higher flows and different influent characteristics than one without, but data is not available to make this distinction. Also, if a plant is managed by a more technology driven, motivated group of people, they are more likely to learn and induce innovation over time. If pooled OLS were to be used for estimation, the coefficient estimates would be biased, as the unobserved fixed effects term would be in the error term, and therefore correlated with the explanatory variables. A random effects estimator would be less appropriate than the fixed effect estimator because the unobserved time invariant error is correlated with the explanatory variables. Due to these assumptions, each variable was demeaned:

$$\begin{aligned}
& [\ln(TNmgl)_{it} - \overline{\ln(TNmgl)_i}] \\
& = (\beta_0 - \overline{\beta_0}) + \beta_1(PerfElig_{it} - \overline{PerfElig}_i) \\
& + \beta_2(NoGrant_{it} - \overline{NoGrant}_i) + \beta_3(Time_{it} - \overline{Time}_i) \\
& + \beta_4(\ln(PercentCapacity)_{it} - \overline{\ln(PercentCapacity)_i}) \\
& + \beta_5(MethanolPrice_{it} - \overline{MethanolPrice}_i) + \beta_6(Temp_{it} - \overline{Temp}_i) \\
& + \beta_7(LagTemp_{it} - \overline{LagTemp}_i) + (a_i - \overline{a_i}) + (\varepsilon_{it} - \overline{\varepsilon}_i), \\
& t = 1, 2, \dots, 72
\end{aligned} \tag{2}$$

to derive the fixed estimator to run the model:

$$\begin{aligned}
\ln(TNmgl)_i = & \beta_1 PerfElig_i + \beta_2 NoGrant_i + \beta_3 Time_i + \beta_4 \ln(PercentCapacity)_i \\
& + \beta_5 MethanolPrice_i + \beta_6 Temp_i + \beta_7 LagTemp_i + \varepsilon_i, t = 1, 2, \dots, 72
\end{aligned} \tag{3}$$

Variable descriptions are presented in Table 4.

TABLE 4. ENR Model Variable Descriptions

Variable	Description
PerfElig	=1 if a Maryland ENR WWTP operates at or below an annual average of 3 mg/l nitrogen concentrations, 0 otherwise
NoGrant	=1 if a Maryland ENR WWTP is operating in a year the operational grant program is in effect, but does not receive a grant, 0 otherwise
Time	Time period since upgrade, measured in months
Percent Capacity	The ratio of monthly average flow divided by design flow x 100
MethanolPrice	Established monthly price of Methanol, provided in \$/gal
Temp	Average mean monthly temperature, °F
LagTemp	1 month lagged average mean monthly temperature, °F

Data

All data was obtained from Virginia Department of Environmental Quality (VADEQ), Maryland Department of the Environment (MDE), and the Environmental Protection Agency from 1986 to 2013. Average monthly nitrogen concentration discharge data was obtained for all wastewater treatment plants in each state in milligrams per liter. Daily flow data was averaged over each month as flow is measured in millions of gallons per day. Design flow was included, also measured in millions of gallons per day. Capacity, measured in percentages, was obtained by dividing actual average daily flow by design flow and multiplying by 100. Upgrade information for Virginia plants was obtained from the Virginia Water Quality Improvement Fund (WQIF) database. Maryland upgrade and operational grant program information was obtained from Elaine Dietz and Walid Saffouri of the MDE. Table 5 provides summary statistics for the variables included in this model.

TABLE 5. Summary Statistics for ENR Model Variables, n=2127

Variable	Mean	Std. Dev.	Min	Max
TN (mg/l)	2.817	1.809	0.14	19.1
PerfElig	0.225	0.418	0	1.0
NoGrant	0.175	0.380	0	1.0
Time	23.086	15.367	1	72.0
Flow	3.067	6.360	0	56.5
Design Flow	5.709	11.615	1	75.0
PercentCapacity	54.562	20.255	0	189.3
MethanolPrice	1.376	0.236	1	2.5
Temp	56.893	15.289	24	85.9
LagTemp	57.316	15.231	23.6	85.9

Of the 55 ENR WWTPs used in this model, 36 (65%) are Virginia plants and the remaining 19 (35%) are Maryland WWTPs. As of January 2014, Virginia has upgraded 37 of its 75 municipal WWTPs (50%) to ENR technology with a total of 396 MGD of design flow, constituting 50% of total design flow (794 MGD) in the state. One WWTP, King George-Dahlgren (1 MGD design flow), was left out of the ENR study group because of operating problems that caused much higher than average nitrogen concentrations. Maryland has upgraded 33 of its 64 municipal WWTPs to ENR technology with a total of 143 MGD of design flow, constituting 26% of total design flow (546 MGD) in the state. Of these 33 plants, 14 were removed from analysis because they upgraded after 2011 and did not have enough variation in key explanatory variables.

The operational grant program aims to induce plants to maintain discharges at below 3 mg/l annual average nitrogen concentrations. It is important to note that this explanatory model describes Maryland ENR WWTP operational behavior under the operational grant program, but the model does not capture the decision to participate in the operational grant program. Observed plant behavior under this program suggests that the grant rate (at \$18,000 and \$30,000 per MGD) is high enough to induce all early ENR plants (updated prior to 2011) to participate based on performance eligibility. What is of interest in this paper is to what extent Maryland would achieve incremental reductions without ENR operational grants.

Table 6 describes summary statistics for *PerfElig* plants. Plants in this group had a slightly lower mean nitrogen concentration than the entire study sample. They also had smaller design flows, while operating at slightly higher capacities. Maryland's upgrade scheduling could be driving these discrepancies as the state upgraded smaller plants to ENR first. The last wave of

Maryland BNR upgrades set to be completed in 2008 were switched to ENR. These plants were last on the list for BNR technology typically because of their smaller design flows.

TABLE 6. Summary Statistics for Performance Eligible WWTPs

Variable	Mean	Std. Dev.	Min	Max
TN (mg/l)	2.25	1.04	0.40	11.30
Time	37.31	17.33	1.00	72.00
Flow	1.10	0.70	0.22	3.08
Design Flow	1.78	1.12	0.50	4.00
Methanol-Price	1.45	0.19	1.00	2.50
Percent-Capacity	62.93	21.62	15.57	189.33
Temp	56.84	15.24	23.60	82.40

Table 7 describes summary statistics for plants classified by the *NoGrant* variable. These plants have a higher mean nitrogen concentration than performance eligible plants, which was expected. These Maryland WWTPs, that fail to meet 3 mg/l and receive an operational grant, have had an upgrade in place, on average, for 18 months less than the performance eligible WWTPs.

TABLE 7. Summary Statistics for “No Grant Received” ENR WWTPs

Variable	Mean	Std. Dev.	Min	Max
TN (mg/l)	3.51	2.15	0.50	19.10
Time	19.04	10.96	1.00	45.00
Flow	1.00	0.72	0.22	4.26
Design Flow	1.68	1.05	0.50	4.00
Methanol-Price	1.16	0.31	0.60	1.90
Percent-Capacity	0.61	0.20	0.16	1.46
Temp	56.74	15.84	25.10	81.90

Results

Table 8 summarizes the coefficient estimates from the fixed effects model results along with standard errors, t-values, and significance levels. Robust standard errors were used as a diagnostic test indicated the presence of heteroskedasticity. To test for correct functional form, the fixed effects estimator was performed “by hand” and a Ramsey RESET test was conducted. The test failed to reject the hypothesis that the model’s functional form was incorrect, suggesting the correct functional form was used.

TABLE 8. Fixed Effects Estimation. Dependent Variable: logged nitrogen concentration (mg/l), n=2127

Variable	Coef.	Std. Error	Robust Std. Error	t (robust)	P-value (robust)	Significance
Perfelig	-0.270	0.069	0.096	-2.81	0.007	***
Nogrant	-0.016	0.060	0.058	-0.27	0.788	
Time	-0.002	0.001	0.001	-1.17	0.246	
Ln(Percent-Capacity)	0.119	0.050	0.073	1.62	0.111	
Methanol-Price	0.036	0.075	0.114	0.32	0.751	
Temp	-0.005	0.001	0.001	-3.12	0.003	***
Lagtemp	-0.0003	0.001	0.002	-0.20	0.846	
Constant	0.747	0.227	0.347	2.15	0.036	

R²= 0.042

Ramsey RESET: F(3, 2116)=1.56; p-value= 0.1962

*, **, *** indicate a significance level of 0.10, 0.05, 0.01, respectively

The model was also estimated using pooled OLS and random effects estimators. Fixed effects was deemed most appropriate for this study. Coefficient estimates from the three models are listed, along with their significance levels, in Table 9.

TABLE 9. Comparison of Fixed Effects, Random Effects, and Pooled OLS Coefficient

Estimates

Variable	Fixed Effects		Random Effects		Pooled OLS	
	Estimate	Significance	Estimate	Significance	Estimate	Significance
Perfelig	-0.270	***	-0.222	***	-0.059	*
Nogrant	-0.016		0.033		0.338	***
Time	-0.002		-0.003		-0.006	***
Ln(Percent-Capacity)	0.119		0.118	*	0.011	
Methanol-Price	0.036		0.052		0.364	***
Temp	-0.005	***	-0.004	***	-0.003	
Lagtemp	-0.0003		-0.0003		-0.001	**
Constant	0.747	***	0.725	***	0.641	***

*, **, *** indicate a significance level of 0.10, 0.05, 0.01, respectively

In the fixed effects model, the key explanatory variables, *PerfElig* and *NoGrant*, have coefficient estimates of -0.27 and -0.016, respectively. The -0.27 on the performance eligible variable means that Maryland ENR plants have 23.66% lower nitrogen concentrations than the base group (Virginia plants and Maryland plants operating in 2009 and 2010), holding all else constant. This particular variable is significant at the 99% level. According to model estimates, performance eligible plants will discharge 1.94 mg/l nitrogen concentration with grant incentives and 2.55 mg/l without the grant incentives. This reduction represents a 24%, or 0.60 mg/l decrease in discharger nitrogen concentration, calculated at the sample means. This supports the hypothesis that Maryland's operational grants for ENR WWTP performance induce lower concentrations when a plant's average abatement cost is low enough to respond to the financial incentive.

The *NoGrant* variable attempts to capture the behavior of the presumed higher abatement cost WWTPs that do not receive operational grants. This variable is not significant. Plants in this group may be working towards achieving 3 mg/l nitrogen concentrations to receive a grant, and

achieving lower concentrations than base group WWTPs without the operational grant program in place in the process. Some plants in this group, however, may have high enough abatement costs to choose not to change operational behavior in response to the grant program, at the current \$30,000 per MGD rate.

The coefficient estimates for the *Temp* variable, significant at the 99% level, indicates that as temperature increases by 1 degree Fahrenheit, nitrogen concentrations decrease by 0.5%. A one-degree change in temperature yields a relatively small change in nitrogen concentrations, however, a 60-degree change would yield a 30% decrease in nitrogen concentrations. This is a key variable in effective nitrogen removal at these ENR plants.

Time, *PercentCapacity*, *MethanolPrice* and *LagTemp* all have the expected signs but not at a significant level. The coefficient estimate on the time variable indicates that an ENR WWTP decreases nitrogen concentrations by 0.2% for every month they are operating the technology. The coefficient estimate on the logged percent capacity variable means as the percent capacity increases by 1%, nitrogen concentrations increase by 0.11%. According to the coefficient estimate for methanol price, if the price per gallon increases by \$1, nitrogen concentrations increase 4%. For lagged temperature, as the previous month's temperature increases by 1 degree Fahrenheit, nitrogen concentrations in the subsequent month decrease by less than 0.03%.

Discussion

In 2013, Maryland paid 15 performance eligible ENR WWTPs, totaling 44.92 MGD of design flow, \$1.2 million in operational grants. This does not include grants given to WWTPs if they were in their transitioning year. According to the model, these plants reduced approximately 0.60 mg/l in response to the grant program. This reduction in concentration across plants equates

to approximately 41,370 lbs/yr of delivered nitrogen removed, assuming an average flow of 28.30 MGD and a 0.80 average attenuation ratio (average 63% capacity of design flow among performance eligible plants, Table 6). On a per pound basis, the state is paying these plants \$29.00/lb of nitrogen removal.

Could Maryland spend \$1.2 million per year more cost effectively to obtain nitrogen reductions from other sources? Or, could Maryland spend \$1.2 million per year more cost effectively within the point source operational grant program? For comparison, urban projects to reduce nutrient runoff to the Bay, such as rain gardens/bio-retention ponds and tree planting, cost anywhere from \$250-500/lb of nitrogen (Busch, 2013). Nutrient reduction projects to reduce agricultural run-off (cover crops, no-till, reduced fertilizer application, etc.) are less expensive than urban and cost, on average, \$14-236/lb per year (Wainger et al, 2013). At the lower end of cost estimates on agricultural reduction projects, Maryland could be achieving per pound reductions at a much lower cost than they do with their point source operational grant program.

However, the lump sum structure of the operational grants could be preventing Maryland from achieving further reductions for \$1.2 million in grants. Once plants achieve 3 mg/l and receive an operational grant, there is no additional incentive to go further. If the state were to use a per pound grant award rather than a lump sum, it would incentivize further reductions. A fixed performance standard would be set, such as a level below individual WLAs and plants that achieved that would then be eligible for per pound grants as they continued to go beyond that fixed performance level.

The state could also look to other methods for allocating the annual \$1.2 million to achieve more nitrogen reductions. Reverse auctions have been used in Pennsylvania to achieve

reductions in non-point source agricultural activities. Farmers in the Conestoga watershed bid for a chance to achieve reductions and funds were awarded to the lowest bidders (Greenhalgh, 2010). This same program could be adapted for ENR WWTPs in Maryland. Plant operators could bid to receive grant funds, offering reductions in exchange for a per pound grant award. They would then bid each other down closer to their marginal costs of abatement as each operator would attempt to undercut the other to receive grant money. This method would allow the state to maximize reductions for a given amount of annual operational grant funds, as it would allow each plant to bid towards their individual marginal abatement cost per pound of nitrogen removal.

While the estimated model indicates that Maryland's operational grant program incentivizes plant over performance, at a statistically and economically significant level, there may be some omitted variables missing in analysis. Methanol consumption data, along with more accurate prices for methanol, would aid in clarifying the methanol price variable. WWTPs may receive special bulk contract prices or be less responsive to price changes due to low consumption of methanol in the nitrogen removal process at an individual plant. In addition, temperature proved to be significant in this model, but including a variable to capture storm events would capture variances in concentration due to approaching or exceeding design capacity from higher storm flows.

Time variable characteristics in influent are also missing from this model. These upgrades are measured in percentage of nitrogen removed. Plants barely hitting 4 mg/l may be experiencing periods of high nitrogen concentrations in their influent. For example, an upgrade that usually removes 90% of nitrogen concentrations from influent, and therefore achieves 3.5 mg/l in effluent, may experience a spike in influent nitrogen. Now, removing 90% will not put

them at the 3.5 mg/l in their effluent but at a higher concentration. Time constant influent characteristics were captured by the fixed effects model but there still could be time variable characteristics that were missed in analysis. The model could also be missing the long-term effects of increasing the operational grant to \$30,000 per MGD. The plants that fail to meet the performance requirement to receive an operational grant may be working towards achieving it in response to this rate increase but may need more than two years to achieve an annual average of 3 mg/l nitrogen concentration.

CHAPTER 5: BNR AND NON-UPGRADED WWTPs OPERATIONAL PERFORMANCE

The Virginia point source program provides incentives for Virginia plants to reduce nitrogen concentrations for BNR and non-upgraded WWTPs. BNR and non-upgraded municipal WWTPs face both regulatory concentration and mass load limits. The plants that cannot meet their WLA with excess flow capacity face two options: reduce nitrogen concentrations to comply or purchase nutrient credits at prices established by the Association. BNR and non-upgraded plants in Maryland face no mass load limits nor financial incentives to reduce discharge below a permit concentration limit. However, both Maryland and Virginia impose a nitrogen concentration limit of 8 mg/l on BNR WWTPs.

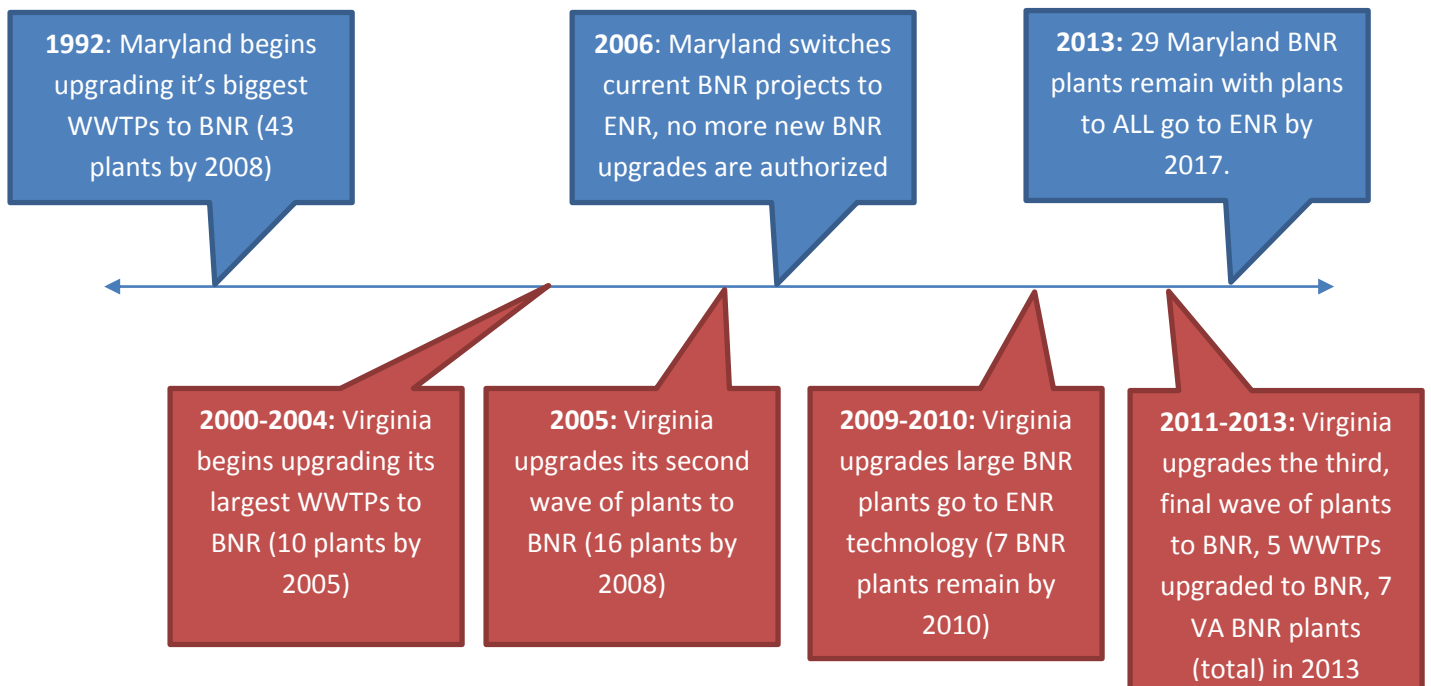
This chapter will examine empirical evidence to assess the extent to which Virginia's nutrient trading program incentives induce operational improvements in nitrogen concentration BNR and non-upgraded WWTPs. A regression estimator using nitrogen discharge panel data cannot be used for BNR performance analysis because of a lack of Virginia WWTPs that operate at BNR both before and after implementation of the 2011 nutrient trading program. Non-upgraded analysis is also limited, as Maryland only has a handful of non-upgraded plants that do not provide for effective comparison. Although the data do not lend themselves to rigorous statistical tests of causation, a variety of quantitative and qualitative evidence is assembled to evaluate the evidence of operational improvements in Virginia and Maryland. Annual averages for a cross section of BNR plants in Maryland and Virginia will be compared in 2004 and 2013 to determine if there is a significant difference in annual averages between the states before and after the establishment of the Association. Also, non-upgraded plants in Virginia will be analyzed on an individual, case-by-case basis to identify any downward trends in nitrogen concentrations because of Virginia's trading program.

BNR Operational Performance in Virginia and Maryland

Virginia completed BNR upgrades of the first wave of municipal wastewater treatment plants in the early 2000s (2001-2003). These 10 plants were typically larger plants, with an average individual design flow of 13 MGD. All but two of these plants upgraded to ENR technology before the new WLAs went into effect in 2011. Virginia WWTPs that upgraded to BNR technology in the second wave of upgrades (2005-2008) were all upgraded to ENR technology by 2012. Post-2010, six plants were upgraded to BNR technology in the third and most recent wave of upgrades.

Maryland, however, began upgrading municipal WWTPs to BNR in the early 1990s and into the mid-2000s. They upgraded smaller, non-upgraded plants to ENR technology from 2008-2010, so 29 plants continued to operate at BNR technology until 2013. Figure 11 provides a graphical representation of this upgrade scheduling between the two states.

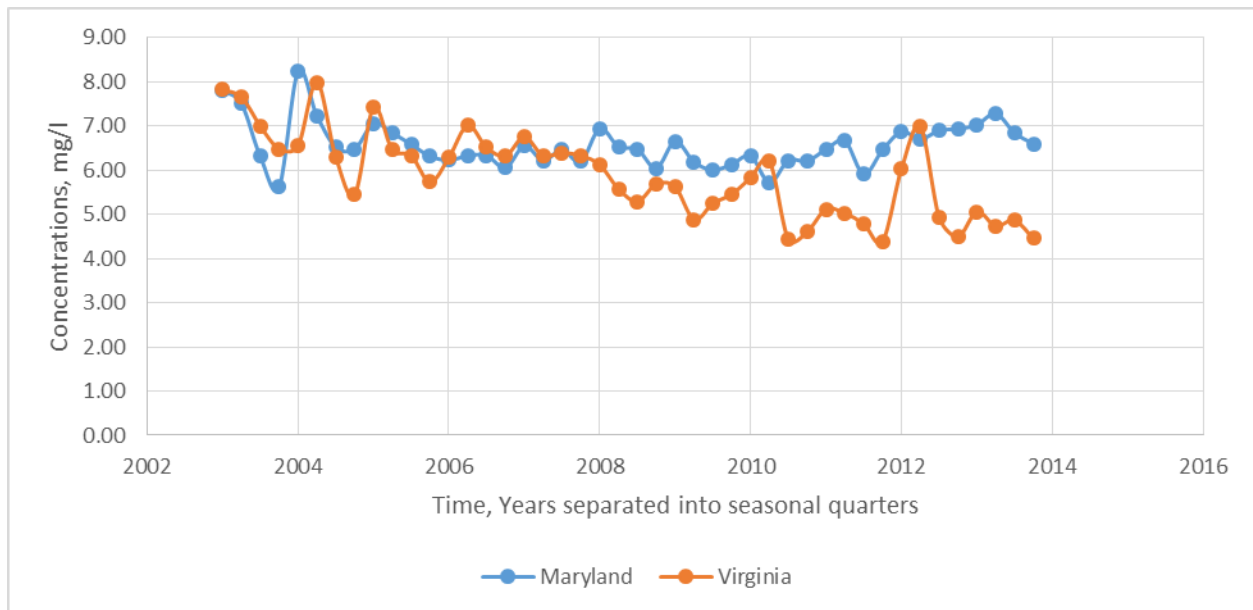
FIGURE 11. Maryland and Virginia BNR Upgrade Timeline, 1992-2013



BNR performance analysis was limited by a lack of continuously BNR designated plants in Virginia spanning the years before and after the establishment of the trading program. The state upgraded all but two BNR plants to ENR plants prior to 2012 whereas Maryland has a continuous group of BNR WWTPs both before and after 2011 for comparison. The lack of continuous time series discharge data for individual Virginia BNR WWTPs precludes the use of a panel data model for comparative analysis.

Average, flow weighted nitrogen concentrations were calculated for BNR plants in Maryland and Virginia from 2003 to 2013 to examine if any difference in averages between the two states begins in 2011. Figure 12 illustrates the gap in flow weighted average concentrations between the two states that begins around 2010. This analysis was done using discharge data from plants that were allowed to come out of and into the study group, or a “dynamic” study sample. For example, if a plant upgraded to ENR technology in 2009, their discharge data from 2006 to 2008 was used to calculate flow weighted BNR nitrogen concentration averages. If a plant received a BNR upgrade in 2010, their discharge data from 2010 to 2013 is used to calculate flow weighted averages. Due to this lack in continuity, the gap between Maryland and Virginia could be driven by a number of possible factors including differences in the size and types of BNR technologies of the more recent BNR WWTPs. Virginia plants post-2010 are mostly two to three years old whereas Maryland has plants that have been operating BNR technology since 1992. However, the gap could also be the result of incentives from Virginia’s trading program.

FIGURE 12. Maryland and Virginia BNR municipal WWTPs Flow Weighted Average Nitrogen Concentrations (dynamic), 2003-2013



Maryland and Virginia BNR plant mean annual averages of nitrogen concentration were computed for 2004 and 2013 for comparison (Table 10 and Table 11). The year 2004 is prior to the Virginia nutrient trading law that began the process of establishing binding WLA and created the trading program. At the time, Maryland and Virginia BNR plants only faced nitrogen concentration limits, all centered around 8 mg/l. Table 10 shows very similar mean annual average concentrations with a sample means test indicating no significant difference between the two states BNR plant performance. However, in 2013, the averages differ between the two states (Table 11). Virginia BNR plants have an average nitrogen concentration of approximately 4.94 mg/l whereas Maryland has an average of 5.99 mg/l. This difference was expected based on the presence of both a non-uniform, binding WLA and the newly established Association. When a sample means test was conducted, the difference between these means, the null hypothesis, could

not be rejected at a 95% level. However, assuming a one tailed t-test, the difference in means between the two states is significant at a 90% level.

TABLE 10. Mean Annual Averages in Nitrogen Concentrations (mg/l) at Virginia and Maryland BNR WWTPs, 2004, n=49

	Obs.	Mean	Std. Err.	Std. Dev.	95% Conf. Interval	
Maryland	39	5.759	0.385	2.404	4.980	6.538
Virginia	10	5.845	0.404	1.279	4.931	6.760

TABLE 11. Mean Annual Average in Nitrogen Concentrations (mg/l) at Virginia and Maryland BNR WWTPs, 2013, n=33

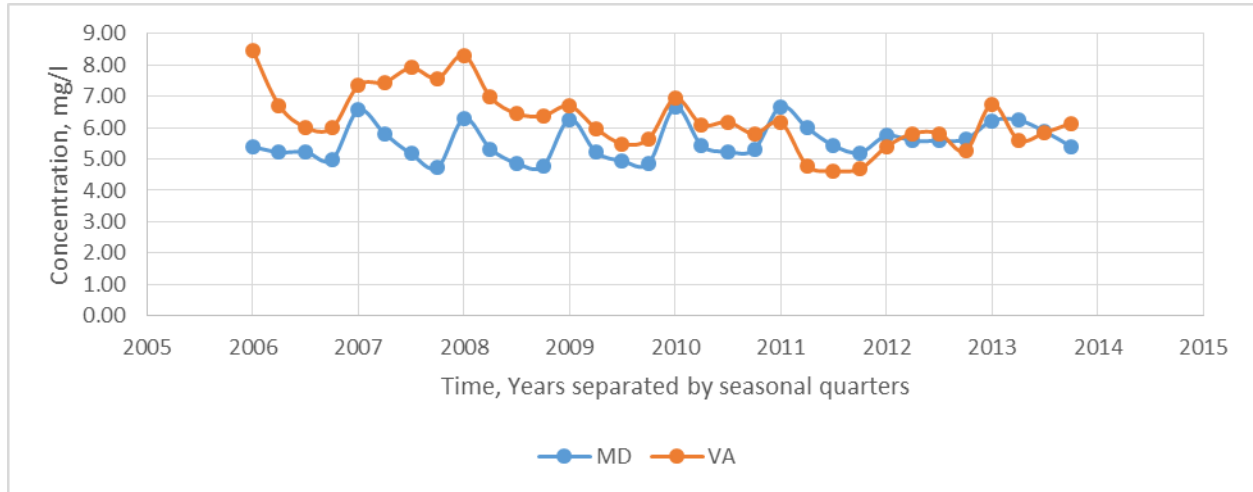
	Obs.	Mean	Std. Err.	Std. Dev.	95% Conf. Interval	
Maryland	25	5.994	0.577	2.884	4.804	7.185
Virginia	8	4.939	0.542	1.534	3.657	6.222

The difference in average nitrogen concentrations in 2013 between the two states could be attributed to differences in BNR technology or installation methods over time. Also, specific plant characteristics, such as those variables controlled for in Chapter 4 (excess capacity, economies of scale, time constant plant heterogeneity), could be driving this difference.

Other insights may be gained by examining performance over time for the few Virginia BNR plants that operated across policy regimes. Flow weighted averages using a consistent, or “static,” group of Virginia and Maryland BNR plants from 2006 to 2013 are illustrated in Figure 13. Nitrogen concentrations differ between the two states as there is a downward trend in average nitrogen concentrations of the only two Virginia plants included in the calculations: Leesburg

and FMC WWTPs. These two plants were analyzed more closely for any possible evidence of operational improvements.

FIGURE 13. Maryland and Virginia BNR municipal WWTPs Flow Weighted Average Nitrogen Concentrations (static), 2006-2013



Figures 14 and 15 illustrate individual nitrogen discharge averages for these two plants. The downward trend in Virginia is driven by the discharge behavior at the Leesburg WWTP. This downward trend in nitrogen concentrations, was caused by the Leesburg WWTP's decision to use methanol in the BNR nitrogen removal process. The option to add supplemental carbon to the wastewater treatment process was installed at the time of Leesburg's BNR upgrade in 2000, but was not used until 2010. Plant operators did not have sufficient incentives to pay the input costs of using methanol for additional nitrogen abatement until faced with the binding WLA. In 2010, the plant operator decided to use methanol to lower nitrogen concentrations in anticipation of the new 2011 WLA and the establishment of the Association. In contrast, Maryland BNR plants, on an individual and aggregate level, did not exhibit any significant downward trends over time.

Leesburg was given a delivered nitrogen WLA of 101,113 that became binding in 2011. At average 2013 flows of 4.40 MGD and an average of 6.42 mg/l nitrogen concentration before the addition of methanol, the plant would have maintained compliance and discharged a delivered nitrogen load of 71,405 lbs/yr.³ Through the addition of methanol, Leesburg reduced their delivered nitrogen load by an estimated additional 16,127 lbs/year as nitrogen concentrations to 4.97 mg/l.⁴ However, the WWTP did not have to incur increased methanol input costs to maintain compliance.

In 2013, Leesburg supplied Class B credits to the Association generated by both excess capacity (compliance credits) and lower concentration levels compared to the 8 mg/l limit applied to the plant (performance credits) (Personal Communication with Brian Bailey, Leesburg WWTP Operator, 2015). Due to a lower design flow than what the Leesburg WWTP was rated at in 2013, the plant could only pledge 17,000 of the approximately 42,000 expected credits in 2013. The plant received approximately \$1,700 for the 17,000 B credits supplied at a B credit price of \$0.10.

³ 6.42 mg/l x 4.40 MGD x 0.83 attenuation ratio x 365 x 8.344

⁴ (6.42 mg/l-4.97 mg/l) x 4.40 MGD x 0.83 attenuation ratio x 365 x 8.344

FIGURE 14. FMC WWTP Nitrogen Concentrations with BNR Technology, 2002-2013

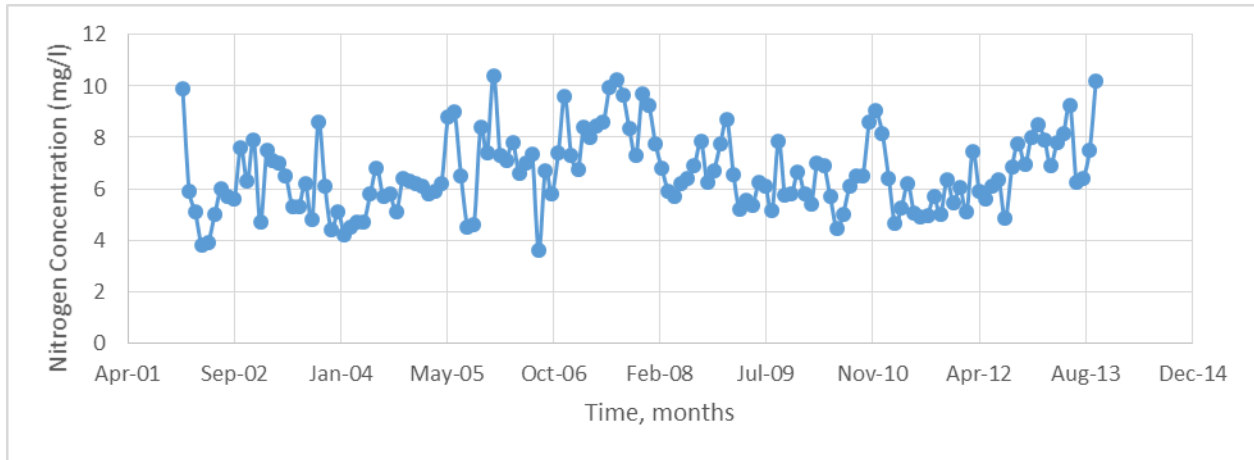
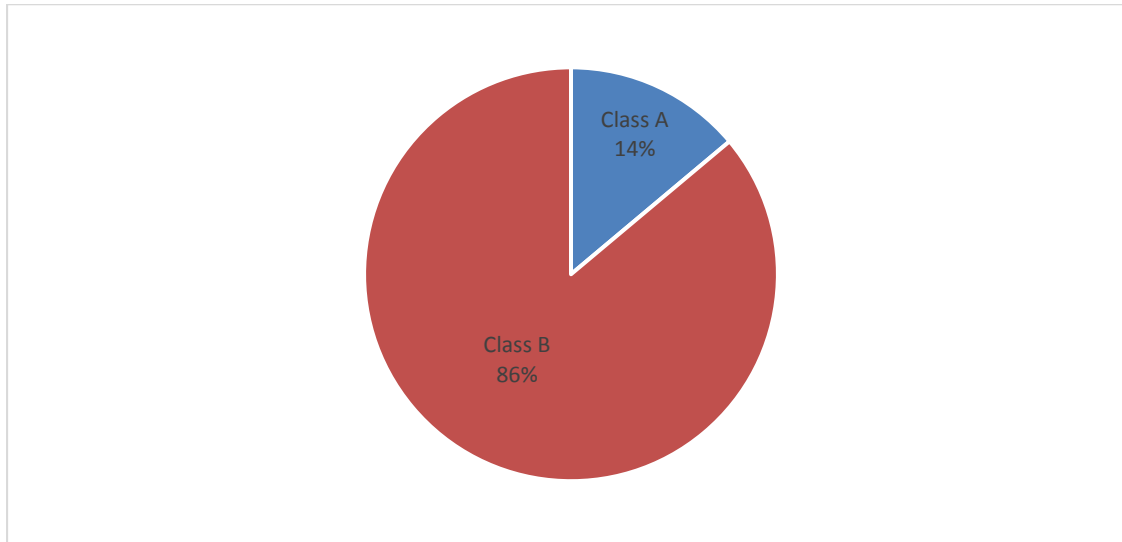


FIGURE 15. Leesburg WWTP Nitrogen Concentrations with BNR Technology, 2006-2013



Looking at 2013 trading data from the Association compliance plan, *all* seven BNR Virginia plants were credit suppliers rather than buyers. Similar to ENR plants in Virginia, BNR plants only supplied compliance credits in 2013, with 14% pledged as Class A credits (Figure 16).

FIGURE 16. “Compliance Credits” Supplied by Virginia BNR WWTPs (lbs/yr), 2013



Information gathered from Leesburg and the sample means tests (Tables 11 and 12) provide some tentative evidence of operational improvements in response to Virginia’s 2011 WLA and the Association’s trading program. More continuous time series data would be needed for a definitive conclusion.

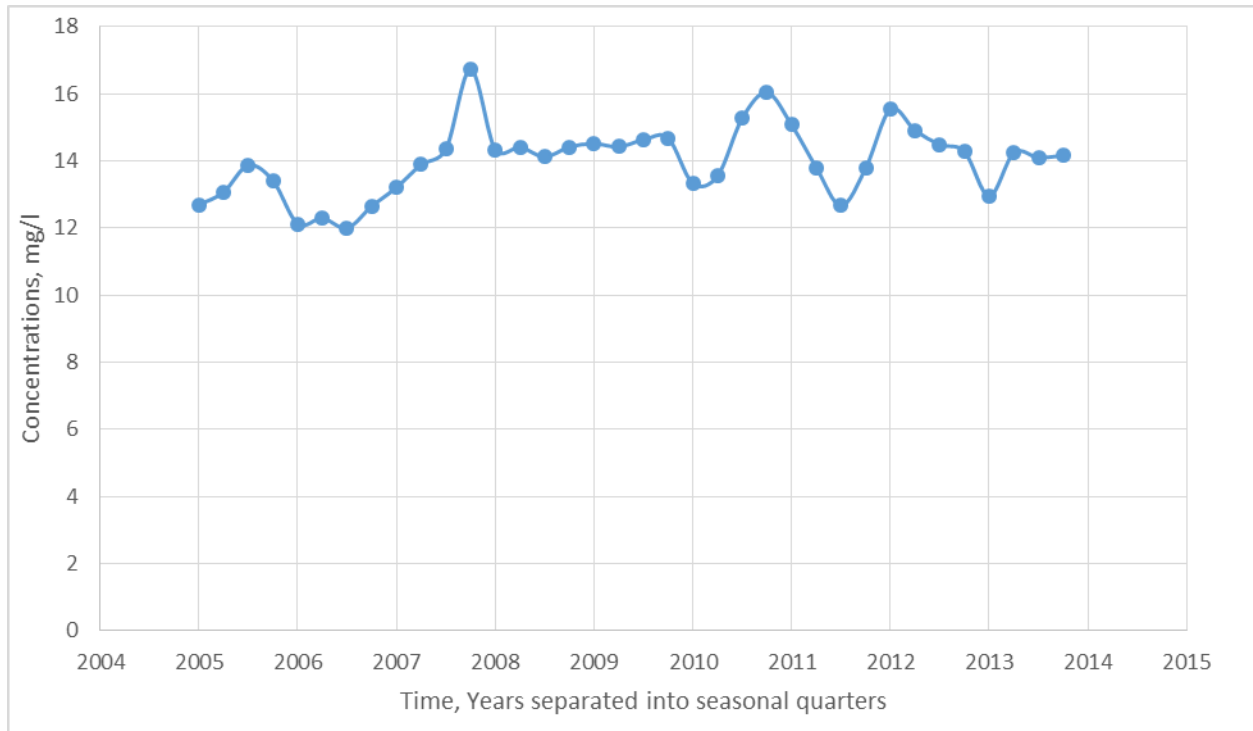
Non-Upgraded Analysis

From 2000 to 2013, all but 26 Virginia WWTPs and four Maryland WWTPs were upgraded to either BNR or ENR technologies. Virginia non-upgraded WWTPs averaged 6.24 MGD, whereas Maryland non-upgraded WWTPs averaged 18.74 MGD driven by one large plant that remained non-upgraded (Patapsco, 73 MGD).

Only discharge data from the Virginia plants that remained non-upgraded from 2000-2013 are used for this analysis. Maryland non-upgraded WWTPs were not included in this analysis as these plants remained non-upgraded because of difficult construction logistics (Patapsco) or very low design flows. Each non-upgraded plant was analyzed for any noticeable

downward trends in nitrogen concentration over time. There is a very slight downward trend in concentration averages of non-upgraded plants, beginning in 2011, as illustrated by Figure 17.

FIGURE 17. Virginia Non-Upgraded Flow Weighted Average Nitrogen Concentrations, 2000-2013



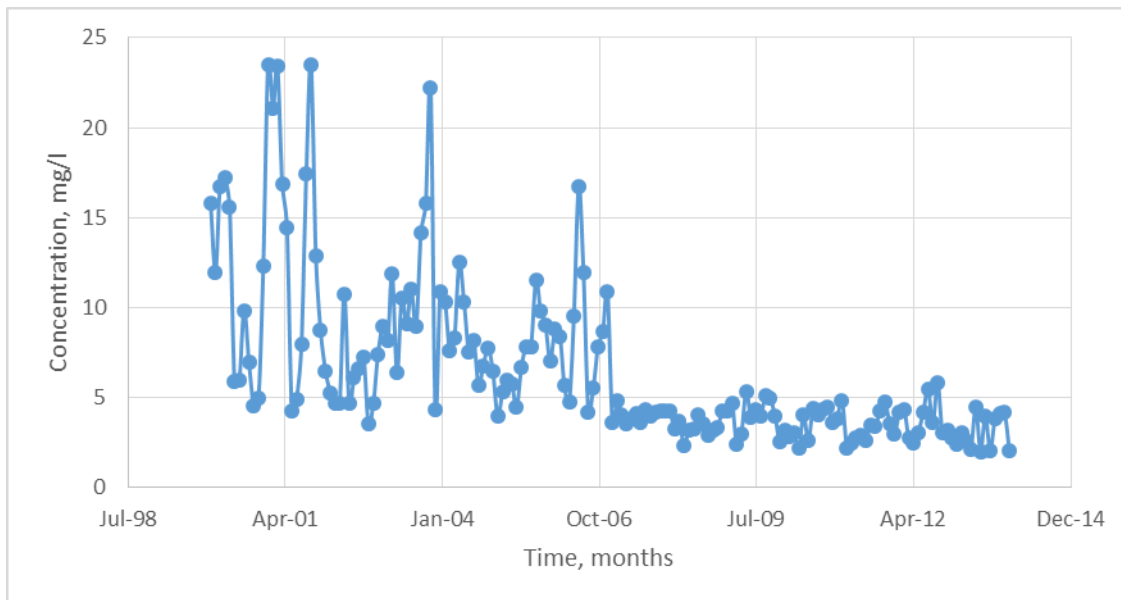
With respect to trading behavior, 11 of these plants are consistent credit buyers, while 13 either rely on low flows relative to design flows to maintain compliance with their WLA. Three plants depended on within-bubble transfers (transfers among plants owned and operated by the same group) to achieve compliance. If any credits were supplied by these plants, they were compliance credits as no downward trends in concentration can be determined from examining individual discharge data and projection estimates provided by plants to the Association, with an exception of one WWTP. The Crewe WWTP is a consistent performance credit supplier, with clear evidence that this supply of credits was the result of process refinements.

Crewe WWTP Case Study.

Crewe is a 0.5 MGD plant that serves 2,400 people in the James River basin. When the 2011 WLAs were set in 2005, Crewe WWTP operators recognized the need for nitrogen concentration reductions for compliance. Consulting engineers estimated that an enhanced nutrient removal capital upgrade would cost the small town \$250,000 to achieve concentration reductions and comply with the 2011 WLA. Instead, plant operators found innovative methods to mimic these upgrades. These process refinements reduced loads by more than 50% from 2004 (Rulseh, 2009).

The plant went from an average nitrogen concentration of 9.51 mg/l (2001-2005) to an average of 4.23 mg/l (2006-2013), a 5.28 mg/l reduction. Figure 18 illustrates the nitrogen concentrations discharged by Crewe from 2000 to 2013. A significant drop in concentration occurs in late 2006, which coincides with the operational refinements made at the WWTP.

FIGURE 18. Crewe WWTP Nitrogen Concentrations, 2000-2013



To achieve this significant drop in nitrogen concentrations, Crewe plant operators began to add lime to adjust alkalinity to aid in nitrification and dried molasses as a carbon source to aid in denitrification. This was done daily during spring, summer, and fall months, at an estimated annual cost of \$15,637.50. Crewe plant operators also designed and installed aeration ditches themselves to keep DO in the effluent at appropriate levels for both denitrification and nitrification. This required a system of timers to adjust to nitrogen removal needs throughout each day. This ditch network cost the plant \$6,000 to install (VADEQ, 2008).

At the time of the improvements, plant operators expected to earn approximately \$20,000 a year by supplying excess credits to the Association (Rulseh, 2009). Once the trading program began operating in 2011, Crewe generally received approximately \$2,000 a year in credit sales (the plant consistently pledges 1,736 Class A credits).

Discussion

On average, the Virginia BNR and non-upgraded plants are doing better than their Maryland counterparts, in terms of nitrogen concentrations. Virginia BNR plants designed for 8 mg/l have lower nitrogen concentrations than Maryland plants, on average. The reason for these differences cannot be definitively attributed to the Virginia point source trading program but there are case studies of Virginia plant operators, at BNR and non-upgraded WWTPs, who find operational improvements at their plants to respond to the Association's trading program and 2011 WLA.

There is some evidence of a select number of Virginia BNR and non-upgraded plants lowering their discharge levels below what would occur in the absence of the imposition of

binding WLA and trading program. Due to data limitations, however, no statistical tests could be done on observed behaviors to bring more certainty about the cause of this outcome.

Two case studies, Crewe and Leesburg, provide evidence that Virginia operators made reductions in nitrogen concentrations that they would not likely have made under a Maryland style BNR and non-upgraded program. Plant operators at these facilities attributed the motivation behind these operational changes as both the impending 2011 WLA and the financial incentives provided by the Association's trading program (Rusleh, 2009; Personal Communication with Brian Bradley, Leesburg WWTP operator, 2015). However, the magnitude of the financial incentives from nutrient credit prices appears small relative to the cost of the operational improvements.

In the case of Crewe, operational changes achieved nutrient reductions at a cost considerably lower than what would have been achieved with a capital upgrade. In 2013, Crewe had annual average flows of 0.27 MGD and an annual nitrogen concentration of 3.07 mg/l. Prior to operational improvements, the plant was discharging an average nitrogen concentration of 9.5 mg/l (2001-2005). Crewe achieved 6.43 mg/l in nitrogen concentration reductions at an annual total cost of \$17,679.60 in (2013 dollars; Rusleh, 2009). With a nitrogen wasteload allocation of 3,472 lbs/yr, the plant discharged 917 lbs of nitrogen to the Chesapeake Bay, thus generating 2,555 nitrogen credits (VADEQ, 2014). Crewe pledged 1,736 Class A credits for 2013, earning \$1.07 per credit totaling \$1,857.52. The remaining 819 credits were supplied as B credits at approximately \$0.12/credit, totaling \$98.28. Credit revenue for Crewe combined to lower the annual net cost of reductions to \$15,683.26.

Assuming the operational changes reduced nitrogen concentrations 6.43 mg/l, 0.27 MGD annual average flows, and 0.38 attenuation ratio, Crewe removed 2,009 lbs/year of nitrogen (compared to 2001-2004 averages) with the plant operational modifications at a per pound cost of \$7.81.

Crewe faced two alternatives to operational changes: a capital upgrade or purchasing credits from the Association. The capital upgrade, at a total cost of \$282,638.90 (2013 dollars; Rusleh, 2009), would have achieved similar concentration levels as the operational changes with an annualized capital cost of \$18,386.06 (assumed 30 year upgrade life and 5% interest rate) as well as annual input costs similar to what is now being incurred, or \$17,679.06 (2013 dollars; Rusleh, 2009). They would have also received the same combined credit revenue from the Association to partially offset annual costs (\$1,955.80). Crewe would have paid \$34,109.32 per year for nitrogen reductions, at a per pound cost of \$16.98.

Crewe could also choose to forgo the operational improvements. If Crewe had forgone *any* operational improvements, the plant could have purchase credits from the Association to maintain compliance. This option appears to be less costly than the operational improvements currently being achieved. Future and projected nitrogen credit prices range between \$2.00 and \$3.83 per credit. Given that the plant is operating well below design flows, the plant may not even need to buy credits. For instance, if the plant operates at a 9.5 mg/l nitrogen concentration and with an annual average flow of 0.27 MGD, the plant would discharge less than 3,000 lbs of nitrogen a year, about 500 lbs below their wasteload allocation. No credit purchases would have been necessary due to the excess design capacity.

Like Crewe, Leesburg pursued operational improvements that significantly lowered overall nitrogen concentrations. Leesburg increased variable costs (methanol) to lower nitrogen concentrations while only receiving modest revenue (less than \$2,000) from the sale of surplus credits. Similar to Crewe, Leesburg could forgo these operational changes and still maintain compliance with their WLA without purchasing credits. At an average nitrogen concentration of 6.42 mg/l and an average flow of 4.2 MGD (design flow of 10 MGD) from 2006 to 2009, Leesburg discharged approximately 68,117 lbs/yr to the Chesapeake Bay (0.83 attenuation ratio). Leesburg's WLA (delivered load) is 101,113 lbs/yr nitrogen.

In both Crewe and Leesburg cases, the price incentives received from operational improvements appear small relative to the cost of achieving these improvements. The motivation for the continued maintenance of these operational changes is unclear. Operational decision-making at Leesburg and Crewe could be a result of regulatory uncertainty (regulators may prevent "back sliding" once a performance level is achieved), plant operator risk aversion, or professional obligations rather than solely based on financial realities. In terms of risk aversion, plant operators are usually worried about possible growth in flows as they consistently overestimate flow projections in Exchange Compliance Plans. There could also be transaction costs associated with the trading program that can be avoided by intra-plant reductions, in the case of Crewe. More research could be done on the reluctance of some Virginia WWTPs to rely on Association credit purchases to maintain compliance.

REFERENCES

- Bailey, Brian. "Leesburg WWTP." Personal Communication. 10 June. 2015.
- Bandyopadhyay, Sushenjit, and John Horowitz. "Do plants overcomply with water pollution regulations? The role of discharge variability." *Topics of Economic Analysis & Policy*. 6:1 (January 2006): 1-30.
- Brown, William, and Peter Atherton. "Wastewater Nutrient Removal: An Overview of Phosphorus and Nitrogen Removal Strategies." New Hampshire Department of Environmental Services, 2009. Web.
- Busch, Greg. "Cost Efficiency and Other Factors in Urban Stormwater BMP Selection." WIP Local Technical Meeting Series. Maryland Department of the Environment., Nov. 2013. Lecture.
- Claassen, Roger, John Horowitz, Eric Duquette, and Koehi Ueda. "Additionality in U.S. Agriculture Conservation and Regulatory Offset Programs." Economic Research Service. United States Department of Agriculture, 1 July 2014. Web.
- "Chesapeake Bay Watershed Agreement." Chesapeake Bay Program. Chesapeake Bay Program, 6 June 2014. Web.
- Constantine, Tim. "An Overview of Ammonia and Nitrogen Removal in Wastewater Treatment." Water Environment Association of Ontario. Ch2m Hill Canada, 19 Feb. 2008. Web.
- Earnhart, Dietrich. "Regulatory Factors Shaping Environmental Performance at Publicly-owned Treatment Plants." *Journal of Environmental Economics and Management* 48.1 (2004): 655-81. ScienceDirect. Web.

- Dietz, Elaine. "ENR Grant Upgrade Information." Personal Communication. 15 Aug. 2014.
- Freed, Tony. "Wastewater Industry Moving Toward Enhanced Nutrient Removal Standards." *WaterWorld* 1 Mar. 2007. Web.
- Greenhalgh, Suzie. "Conestoga Reverse Auction Project, Pennsylvania, USA." *The Economics of Ecosystems and Biodiversity*. 1 Oct. 2010. Web.
- Grote, Bill. "Biological Nutrient Removal (BNR) in New and Upgraded WWTPs." *SkillsTech Australia*, 22 June 2010. Web.
- Hamstead, Zoe, and Todd BenDor. "Overcompliance in Water Quality Trading Programs: Findings from a Qualitative Case Study in North Carolina." *Environment and Planning* 28 (2009): 1-17. Web.
- Howarth, Robert W. "Coastal Nitrogen Pollution: A Review of Sources and Trends Globally and Regionally." *Harmful Algae* 7.5 (2008): 14-20. Web.
- Howarth, Rort, Donald Anderson, James Cloern, Chris Elfring, Charles Hopkinson, Brian Lapointe, Tom Malone, Nancy Marcus, Karen McGlathery, Andrew Sharpley, and Dan Walker. "Nutrient Pollution of Coastal Rivers, Bays, and Seas." *Issues in Ecology* 7 (2000): n. pag. Ecological Society of America. Web.
- Malik, Omar. "Primary vs. Secondary: Types of Wastewater Treatment." *Environmental Performance Index*. Yale University, 22 Jan. 2014. Web.
- "National Summary of Impaired Waters and TMDL Information." 2015 Watershed Assessment, Tracking & Environmental Results. U.S. Environmental Protection Agency. Web.

"Nutrient Pollution- The Problem." U.S. Environmental Protection Agency. U.S. Environmental Protection Agency, 3 Feb. 2015. Web.

"Nutrient Reduction Technology Cost Estimates for Point Sources in the Chesapeake Bay Watershed." Chesapeake Bay Program, 1 Nov. 2002. Web.

"Plant Optimization Strategy for Nitrogen Removal Town of Crewe Wastewater Treatment Facility." Virginia Department of Environmental Quality. Web.

Pomeroy, Chris, Glen Harvey, Mark Haley, Cy Jones, and Cody Stanger. "The Virginia Nutrient Credit Trading Program- How Program Structure and Price Affects the Willingness to Participate and the Ability to Develop Optimal Compliance Plans Through Trading." The Water Quality Event, 2007. Web.

Pomeroy, Chris. "Plant Operator Risk Aversion." Personal Communication. 2 April. 2015.

"Primer for Municipal Wastewater Treatment Systems." (n.d.): n. pag. U.S. Environmental Protection Agency, Sept. 2004. Web.

Randall, Clifford. "A "LOT" for Less: Innovative Economical and Technological Implementation of Limit of Technology (LOT) Strategies for the Nutrient Removal Chesapeake Bay Watershed in the." Chesapeake Bay Foundation, 1 May 2004. Web.

Rulseh, Ted. "Top Performer - Plant: A Little Creativity." Treatment Plant Operator 1 Sept. 2009. Web.

Saffouri, Walid. "Maryland Operational Grant Program." Personal Communication. 25 March. 2015.

- Saffouri, Walid. "Maryland Goes Beyond Other States in Enhanced Nutrient Removal (ENR)." Maryland Department of the Environment. 1 Nov. 2005. Web.
- Sancho, Francesc, and Ramon Garrido. "Technical Efficiency and Cost Analysis in Wastewater Treatment Processes: A DEA Approach." *Desalination* 249.1 (2009): 230-34. ScienceDirect. Web.
- Sedlak, Richard. "Phosphorus and Nitrogen Removal from Municipal Wastewater: Principles and Practice." N.p., 1991. Web.
- Shimshack, Jay, and Michael Ward. "Enforcement and Over-compliance." *Journal of Economic Economics and Management* 55.1 (2008): 90-105. ScienceDirect. Web.
- Van Houtven, George, Ross Loomis, Justin Baker, Robert Beach, and Sara Casey. "Nutrient Credit Trading for the Chesapeake Bay: An Economic Study." (2012). Chesapeake Bay Commission. Web.
- Wainger, Lisa, George Van Houtven, Ross Loomis, Jay Messer, Robert Beach, and Marion Deerhake. "Tradeoffs among Ecosystem Services, Performance Certainty, and Cost-efficiency in Implementation of the Chesapeake Bay Total Maximum Daily Load." *Agricultural and Resource Economics Review* 42.1 (2013): 196-224. AgEcon Search. Web.
- Yuan, Zengwei, Ling Zhang, and Jun Bi. "Which Is More Cost-effective? A Comparison of Two Wastewater Treatment Models in China–Singapore Suzhou Industrial Park, China." *Journal of Cleaner Production* (2010): 1-6. ScienceDirect. Web.

APPENDIX A: DO-FILE COMMANDS

```

clear all

use F:\enranalysis.dta
xtset id Time

tsset id Time
ssc install acetest

gen lnTNmgl= ln(TNmgl)
gen Capacityp= PercCap*100
gen lncap= ln(Capacityp)
by id: gen lagtemp= temp[_n-1]

regress lnTNmgl Perfelig Nogrant Time lncap methprice lagtemp temp
ovtest

xtreg lnTNmgl Perfelig Nogrant Time lncap methprice lagtemp temp, fe

xtreg lnTNmgl Perfelig Nogrant Time lncap methprice temp lagtemp, fe robust

xtreg lnTNmgl Perfelig Nogrant Time lncap temp methprice lagtemp, re

xtreg lnTNmgl Perfelig Nogrant Time lncap methprice temp lagtemp, re robust

sort id

by id: egen mtnmgl= mean(TNmgl)
gen dmtnmgl= TNmgl-mtnmgl
by id: egen mlnmgl= mean(lnTNmgl)
gen dmlnmgl= lnTNmgl-mlnmgl
by id: egen mtime= mean(Time)
gen dmtime= Time-mtime
by id: egen mcap= mean(Capacityp)
gen dmcap= Capacityp-mcap
by id: egen mlncap= mean(lncap)
gen dmlncap= lncap-mlncap
by id: egen mmeth= mean(methprice)
gen dmmeth= methprice-mmeth
by id: egen mtemp= mean(temp)
gen dmtemp= temp-mtemp
by id: egen mlagtemp= mean(lagtemp)
gen dmlagtemp= lagtemp-mlagtemp
by id: egen mPerfelig= mean(Perfelig)
gen dmPerfelig= Perfelig-mPerfelig

```

```
by id: egen nNogrant= mean(Nogrant)  
gen dmNogrant= Nogrant-mNogrant
```

```
regress dmlntn dmtime dmlncap dmmeth dmtemp dmlagtemp dmPerfelig dmNogrant  
ovtest
```

```
xtserial dmlntn dmtime dmlncap dmmeth dmtemp dmlagtemp dmPerfelig dmNogrant
```