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Development and Analysis of a Nutrient Trading Program for the James River Watershed

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DEVELOPMENT AND ANALYSIS OF A NUTRIENT TRADING PROGRAM FOR THE JAMES RIVER WATERSHED

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ABSTRACT

Academic literature indicates that implementing trading programs into regulatory policy can yield substantial cost savings. Additionally, existing trading programs report cost savings and improved efficiency. This project evaluates a nutrient trading program for the James River, and models its effects on the private cost of nutrient reduction.

Data for land cover, nonpoint source nitrogen loadings, point source sites and loads, best management practices and efficiencies, and cost per unit reduction were collected. The Chesapeake Bay Agreement forty percent reduction goal was used as a watershed nitrogen reduction goal. Data were input into Excel's Solver linear programming model in order to model the least-cost outcome under each scenario. Scenarios included single point sources purchasing credits in various increments as well as trades including all entities in the watershed. Transport coefficients were added to the model to account for the behavior of nitrogen along the waterway.

While the model results were confined by data limitations, results indicated cost savings from 38% with a single point source purchaser to nearly 90% savings when the entire watershed can sell and purchase credits. The James River has potential as a watershed for trading application, but further research is necessary to determine the specific parameters necessary in order to ensure water quality and economic sustainability.

DEVELOPMENT AND ANALYSIS OF A NUTRIENT TRADING PROGRAM FOR THE JAMES RIVER WATERSHED

PREFACE

"In response to President Clinton's *Reinventing Environmental Regulation* (March 1995), EPA is strongly promoting the use of watershed-based trading." This statement begins the EPA's May 1996 "Draft Framework for Watershed-Based Trading" which lays out a national plan for pollution trading and provides thorough evaluation of options. The rationale behind pollution trading schemes is that they apply economic principles to environmental problems in order to reduce costs. Although the EPA draft was not published until 1996, nutrient trading programs have been employed on a local level since the mid-1980s. There is still, however, only scattered academic literature on the subject. This study aims to evaluate the potential for implementation of a nutrient trading scheme in the James River watershed (VA), one of the major tributaries to lower Chesapeake Bay.

INTRODUCTION

The Clean Water Act (CWA) is the federal legislation that deals most directly with pollutant discharge into the nation's waterways. It presents numerous assessment methods, water quality standards, permit structures, and the penalties for noncompliance. Such "command and control" regulation provides clear direction and a rigid structure of standards and means of achieving specific water quality goals. While providing fairly predictable successes with respect to pollutant levels, command and control regulation often places heavy economic burdens on those companies forced to comply with the regulations. Compliance with pollution reduction programs can trigger outright unwillingness to comply, regional economic losses, or possibly bankruptcies.

Pollution trading presents an alternative market-based option wherein pollution reduction is viewed in the context of the entire watershed rather than discharger-by-discharger. The rationale behind pollution trading is best described by the following hypothetical example.

Two companies make up the entire pollutant discharging population on a waterway. Each discharges only nitrogen as a byproduct of its operation. The regional environmental agency finds excessive levels of nitrogen in the waterway. As a consequence, each producer is required to reduce its nitrogen input by 200 lbs/day. If Company One can achieve this reduction at $30/lb and Company Two can reduce at $10/lb, the corresponding costs, without trade, would be as follows:

	Company One	**Company Two**
Reduction Responsibility	200 lb/day	200 lb/day
Amount Reduced In-House	200 lb/day	200 lb/day
Unit Reduction Cost	$30/lb	$10/lb
TOTAL COST (without trade)	$6000/day	$2000/day

If a trading scheme were implemented, Company One would examine its high reduction cost and be willing to buy pollution credit units from Company Two for about $20 per unit. Company Two would then take on the responsibility of reducing its nitrogen output by the full 400lb/day and Company One would maintain its current level of emissions. The costs then change as follows:

	Company One	**Company Two**
Reduction Responsibility	200 lb/day	200 lb/day
Unit Reduction Cost	$30/lb	$10/lb
Amount Reduced In-House	0 lb/day	400 lb/day
In-House Control Cost	$0/day	$4000/day
Payment for Credits	$4000/day	$-4000/day
TOTAL COST (with trade)	$4000/day	$0/day
Savings from Trading	$2000/day	$2000/day

Therefore, there is a $4000/day savings from the trading program *while achieving the required 400lb/day reduction of nitrogen to the waterway.*

This simplified example does not account for other pollutants or producers, transaction costs, trading ratios, uncertainty, or feasibility of larger scale reductions, but it does illustrate the general character of benefits in a market-based solution. The entire basis of trading programs lies in the fact that firms will experience varying costs associated with pollution reduction. As long as the overall level of pollution reduction is achieved and water quality is improved, allocating the reduction to those entities that can reduce pollution at the least cost yields a more efficient outcome. Low-cost reducers can be compensated by high-cost reducers who can then maintain their current pollution emissions.

There are several possible categories of trading in a watershed-based system because of the number of pollutants entering waterways and various types of discharging entities. Each category deals with either point or nonpoint sources. Point sources "are direct dischargers that introduce pollutants into waters of the United States" (EPA 5-96) and include public-owned and private wastewater treatment plants, industrial dischargers, mining operations, aquaculture, and municipal stormwater outfalls. These point sources are required to comply with the National Pollutant Discharge Elimination System (NPDES) established in Section 402 of the Clean Water Act ("Draft Framework" 1996). The nonpoint source category describes sources "discharging" pollutants more indirectly through erosion, runoff, or snowmelt to the surface waters as well as seepage to groundwater with its possible recontamination of surface water. Typical nonpoint sources include agriculture, silviculture, urban development, construction, land disposal, and modification of flow or channel structure.

Although there is no explicit control of nonpoint sources described in the Clean Water Act, the 1987 Water Quality Act requires states to develop programs to assess and manage nonpoint source pollution with the help of the EPA (Malik 1993). Section 6217 of the Coastal Zone Act Reauthorization Amendments (CZARA), commonly referred to as the "Coastal Nonpoint Program," places a specific burden on coastal states and requires them to implement nonpoint source nutrient management for land uses adjacent to impaired or threatened coastal waters. In addition, Section 319(b)(4) of the 1987 Amendments to the Clean Water Act allows states to design nonpoint source management plans on a watershed-by-watershed basis. Congress allocated $143.75 million for such projects between FY90 and FY92; however, much of the cost is left up to states in addressing nonpoint source pollution (Letson 1992). Some states have addressed the problem in part by employing provisions for "best management practices" (BMPs) to control pollutants from nonpoint sources ("Draft" 1996); these are be outlined below. Hall and Howett (1996) state that "Both House and Senate versions of the Clean Water Act reauthorization bills for the last two years have contained provisions for a watershed approach to water quality improvement." Additionally, Virginia's 1995 Potomac Basin Tributary Strategy states that "[a] number of approaches . . . could be used . . . to minimized the costs of nutrient reductions. A useful example . . . is a system of nutrient trading" (Kerns and Stephenson 1996).

Considered in the watershed context, the options whereby point and nonpoint dischargers can interact to offset pollution loads are:

(1) Point/Point Source Trading: One point source, finding an excessive burden to reduce its discharges, contracts with another point source for greater-than-required emissions by the second in order to make up for the shortfall of the first.

(2) Intra-plant Trading: A single point source erects an imaginary "bubble" over all of its outfalls and ensures only that its total emissions comply rather than ensuring that each outfall complies independently.

(3) Point/Nonpoint Source Trading: A point source agrees with a nonpoint source for pollution reduction by the latter (usually lower cost) instead of costly upgrades of the effluent treatment by the former.

(4) Nonpoint/Nonpoint Source Trading: A nonpoint source arranges for reductions by another nonpoint source in lieu of upgrading or installing its own pollution prevention practice. Wetland mitigation projects are often considered under this category.

For the first three types of trading categories, for which at least one of the partners is required to have an NPDES permit, there exist two general trading frameworks. First, the total maximum daily load (TMDL) framework can guide trades. A TMDL describes the loading capacity of a particular watershed and identifies current sources and potential areas of reduction or remediation. A requirement for a TMDL is that a link be established between ambient water quality conditions and pollutant reductions on the watershed and local level. A TMDL framework is not possible in many situations, however, because many receiving waterways do not have a TMDL computed. Second, existing point source permits can be used, and trades can be arranged through the established permit process. The permittee is held accountable for achieving the required pollutant reductions, but could allocate its reduction burden to another entity within the watershed by offering payment. Additionally, public or private "banks" could facilitate trades by dealing in a pollution credit currency ("Draft Framework" 1996).

In general, resource managers prefer to treat a watershed as a unit when evaluating policies because of the interactions that take place along a waterway that are larger than established political units. The EPA developed a watershed screening process that would identify the basic characteristics needed for potentially successful trading. These steps are as follows:

(1) Are trades consistent with water quality and other environmental objectives?
Trading will be most attractive if sources already meeting requirements are looking for more cost-effective means to meet additional requirements, or numerous sources are being forced to comply with additional in-stream water quality requirements;

(2) Will either potential trading partner benefit from trading?
Success will be surer with a number of potential traders in both the point and nonpoint-source category, with varying treatment methods, and with different degrees of purity required; and

(3) Are administrative arrangements available to support trading?
Administrative coverage should be on the same scale as the trading area; participants' information needs must be met; existing institutional structure should be utilized; trades must be facilitated and documented; and monitoring, accountability, and enforcement tools must be in place ("Draft Framework"

1996).

Answers to these questions can serve to evaluate the three pillars of effluent control: water quality, economics, and administration.

EXAMPLES OF TRADING APPLICATIONS

Trading Under the Clean Air Act

The EPA applied a market-based strategy to air pollution control with mixed success. The Clean Air Act instituted a program for sulfur dioxide discharge in 1975, using bubbles, netting, offsets, and banking to facilitate reduction load reallocation. Bubbles are the cornerstone of the Emissions Trading Program and most closely represent the theoretical concept of free market pollution trading. In this scheme, an imaginary "bubble" is placed over a plant or region so that emissions are evaluated for the whole rather than pipe-by-pipe. This allows existing sources to transact internal (or external) trading in order to comply with emissions limits. Netting is similar to a bubble except that it occurs only within a single plant. A firm creating a new source of pollution will obtain permits from other areas of the plant through internal trading. Offsets involve trading between firms in areas that have not attained the ambient air quality standards. Prospective new effluent sources can purchase offsets from existing firms and may commence business where otherwise they would have been prohibited. Finally, banking adds a time component to trading. Through banking, entities may save permits beyond their normal time limits in order to redeem them at some future time ("Draft Framework" 1996).

A table from Hahn (1989) indicates a "probably insignificant" or "insignificant" environmental quality impact for each trading activity, and savings are estimated to be from "small" for banking to over $300 million for netting and bubbles over the life of the program. The researchers determined that companies tend to utilize internal transactions much more frequently than external agreements. This is partially because of the high transaction cost of inter-facility trading. As a result of its tremendous cost savings coupled with insignificant, if any, degradation in air quality, EPA Administrator Lee Thomas has described the air pollution trading program as "one of the EPA's most impressive accomplishments" (Hahn 1989).

However, Atkinson and Tietenberg (1991) find that the bubble policy has failed to be as successful in practice as it was predicted to be in theory. They find that while bubbles have resulted in cost savings, they have failed to achieve the most cost-effective allocation of pollution. The "trading process hypothesis" suggests that while trades are modeled as being open and with few constraints, the corporate trading atmosphere is characterized instead by sequential and bilateral trades. By creating an algorithm that models the actual dynamics of the trading process, the authors find that the bilateral trades which conform to EPA regulations yield less dramatic cost savings than those modeled by a mathematical programming equilibrium. Additionally, a restriction that trades cannot decrease air quality at any receptor site (the "constant-emissions rule") means that traders cannot take advantage of areas where pollution is already lower than legally required in order to gain cost savings. The Emissions Trading Program in the Clean Air Act demonstrates that when restrictions are imposed in an environment in which only limited information is available to traders, there is a tendency for for more internal, rather than external, trading and failure to fully realize the benefits of free market trading.

Lead Trading

The lead trading program contains the most free-market approach to trading in the natural resources context. Trading lead in gasoline was permitted beginning in 1982 and terminated in 1987 in response to a mandated reduction in gasoline lead levels. There was a very high volume of trades, with over half of the refineries participating. Hahn (1989) attributes the success of the lead trading program to two key features. First, the amount of lead in gasoline is readily measured and easily monitored. Second, the program was grounded in specific and already-established environmental goals.

Existing Watershed-Based Programs

The concept of applying trading programs dates from the mid-1980's. There are 26 programs currently in place or specifically proposed, with some reporting marked success. A leading example is in the Tar-Pamlico River, North Carolina, overseen by state Environmental Management Commission. In that watershed, a group of fourteen point source dischargers belonging to the Tar-Pamlico Basin Association are treated as a single unit for pollution accounting purposes. An annual loadings cap is established for the group as a whole rather than individual caps for each enterprise. The Association members can transact point source-point source trades amongst themselves at negotiated prices; or if exceeding the collective cap is necessary, they can purchase credits from nonpoint sources. The nonpoint source credits were originally paid for with a $29 per kilogram contribution to the "state agriculture cost share fund" which supports implementation of best management practices on agriculture lands. This amount was determined by multiplying the mid-range cost of anaerobic lagoon installation ($13/kg nitrogen reduced) by a safety factor of two, and adding a standard ten percent administrative cost (Tippett and Dodd 1995). The cost to buy a unit of pollution credit has increased to $56/kg (TMDL Case Study). This trading structure is particularly administration-intensive, requiring to weekly effluent monitoring for total nitrogen, total phosphorus, and flow.

This trading program in the Tar-Pamlico has been in existence since 1991 and has already exhibited success. Through operational improvements, the Association has reduced its nutrient discharges by 28% despite flow increase of 18%. So far, only point-point trades have occurred, but the Association predicts that nonpoint source credits will be purchased during the next phase of the program. In addition to the environmental benefits from the program, "without trading, the Association estimates it would cost its members an average of $7 million in plant upgrades to achieve a comparable level of nutrient reduction that a $1 million investment in nonpoint source controls provides" ("Draft Trading Update" 1996).

Three projects in Colorado use similar approaches to nutrient reduction. In the Lake Dillon reservoir project, officials credit the trading program with encouraging cooperative management and reducing phosphorus loads from 3748 kg/year to 529 kg/year (some of the highest removal capability in the nation) through improved operating efficiency at wastewater treatment plants. Towns also create credits when they convert individual septic systems to public sewers. The Lake Dillon program itself has changed focus and now primarily provides opportunity for new nonpoint sources to offset impacts by adding Best Management Practices (BMPs) to older nonpoint source sites.

In a similar project at Cherry Creek Basin (CO), the program has experienced no trades thus far. However, the Cherry Creek Basin Authority has established a phosphorus total maximum daily load (TMDL) and assigned wasteload allocations to the watershed's twelve wastewater treatment plants. The Authority will conduct nonpoint source water quality improvement projects to generate phosphorus credits that it can transfer to individual dischargers through a trade pool.

In the case of Boulder Creek, CO, the stream suffered from ammonia toxicity that could not be remedied simply through upgrades at Boulder's municipal wastewater treatment plant. This project implemented additional BMP's to restore the stream's integrity. Costs for the program have been $1.4 million, which reflect $3 to $7 million in capital cost savings by avoiding upgrade to full nitrification at Boulder's wastewater treatment plant. Most importantly, environmental improvements have been realized including balanced pH and temperature, decrease in non-ionized ammonia, and better habitat quality ("Draft Trading Update 1996).

ECONOMIC FUNDAMENTALS OF TRADING

Different economic analysis tools yield varying solutions for the appropriate level of pollution control. One could evaluate the overall benefit to society of water quality improvements and compare this to the costs of achieving certain nutrient standards. Such a large-scale evaluation would be labor intensive but could also fail to yield a justifiable solution. Lack of complete specification could indicate inaccurate ratios, of the social costs of pollution to landowners' (private) benefits from control installation (Milon 1987). However, as long as assumptions are clearly presented and results are qualified, economic models can yield important information about a system.

Cost-Benefit Analysis

Weimer and Vining (1989) describe the cost-benefit analysis process as having four steps: "1. identifying relevant impacts, 2. monetizing impacts, 3. discounting for time and risk, and 4. choosing among policies." This first step involves identification of *all* impacts, internal or external. In this systematic process, the costs and benefits are fully evaluated and compared on an equivalent basis. The authors note that "[the] appropriateness [of cost-benefit analysis] as a decision rule depends on whether efficiency is the only relevant value and the extent to which important impacts can be monetized." Cost-benefit analysis of water quality should address more than efficiency and has several components that are difficult to identify, much less monetize.

Hence, the strategy shifts from cost-benefit to cost-effectiveness – determining the least-cost solution to a pre-determined environmental goal. If the goal is to achieve a certain level of bottom water dissolved oxygen, then economic analysis focuses on determining the lowest cost to achieve it. Under a cost-effectiveness analysis, benefits are not analyzed categorically. One assumes instead that benefits from various approaches which achieve the same goal are essentially equal.

The cost of pollution reduction program is measured as cost to the producer of reducing units of emission by technology improvement, pretreatment, or avoidance. While cost per unit is usually measured as *average cost* – total cost divided by number of units, or *marginal cost* – cost of one additional unit of reduction, the EPA recommends a third type of accounting, *incremental cost,* as the most appropriate method of measuring costs associated with trades. Incremental cost is the average cost only of the additional reduction units. To measure this, one divides the total cost of remaining reductions by the number of units of additional reduction. This procedure avoids the problems associated with the aforementioned traditional cost measurements, as average cost assumes that preexisting and future reduction units are equal in cost, while marginal cost incorrectly assumes that pollution reduction could be approached in small units like a pound at a time. Producers will have an incentive to trade if they perceive a high incremental cost associated with further pollution reduction ("Draft" 1996).

Initial Allocation

Specifying the pattern of initial permit allocation is one of the fundamental preliminary determinations when designing a trading scheme. Several structures are available including an auction with a single clearing price, a Groves-type auction[1] where truthful disclosure is in the best interest of the companies, or free initial distribution of rights according to current discharge levels. Lyon's (1982) analysis of a simulation in the

1 A Groves mechanism is a "class of public-goods preference revelation mechanisms."

Lake Michigan basin indicates the importance of incentive-compatibility (eliciting information from companies regarding bids, costs, and loads, that has not been manipulated). An incentive-compatible program requires less government intervention and has more stable outcomes. However, after a complete analysis Lyon finds that despite the potential for misrepresentation in free initial allocation, this strategy yielded least-cost solutions and was closest to Pareto optimality[2].

Tietenburg (1989) also supports the allotment of future permits based on current discharges rather than auctions. He admits that allocating permits to existing firms and requiring new firms to bargain for pollution privileges seems at first biased. However, this tends to be a more politically palatable arrangement since existing sources "vote" while future ones do not.

Other authors do not agree that free allocation is the best solution, and claim instead that a permit is essentially a property right or permission to discharge. They find that companies should be forced to internalize the cost of the privilege, which is a valuable asset to the company (Hahn 1989). Additionally, Hahn argues that as regulatory limitations increase, the value of a permit to the holder increases as well. Hence, companies should view permits as investments for the future and be willing to purchase them at fair market price.

Market Dynamics

Another initial parameter is ensuring that enough dischargers would be willing to

2 Pareto optimality implies an equilibrium situation where no individual or company could be made better off without making another worse off.

participate in order to create a healthy and diversified market, since trading relies on the existence of a variety across marginal costs of pollution reduction. Often, polluters see a fine for non-compliance simply as a "production cost" which is easily internalized, so there is no incentive to experiment with a new system. For this reason, it may be necessary to change the fine structure so that trading is identified as the preferred option. Ideally, not only would the permit price be less than the fine, but nitrogen inputs would also be decreased which is environmentally preferable to the fine option when limits are still exceeded. Currently, the Virginia Department of Environmental Quality does not regularly issue fines for companies that exceed permit limits. Instead, they concentrate on injunctive relief and "behavior modification" by requiring retrofits (DEQ compliance officer, personal communication 9-17-98).

As stated previously, under uniform treatment regulations (command and control), marginal costs of reduction vary across dischargers, but each is required to accomplish equal percentages of reductions. Under a trading scheme, the reduction units are reallocated until marginal reduction costs are roughly equal. In this way, the first order condition for minimum aggregate treatment costs is satisfied (Lyons 1982).

WATER QUALITY CONSIDERATIONS

Nitrogen and Its Behavior in the Watershed

Total nitrogen (dissolved, particulate, organic, inorganic) is the most comprehensive measure of nitrogen loadings. The primary forms of nitrogen found in a waterway are nitrate (NO_3), ammonium (NH_4), degradable organic nitrogen (BOD), living organic nitrogen (plankton), and dead refractory organic nitrogen (ORN). Each nitrogen species has a different behavior pathway in the water column, and the transformation from one species to another is primarily microbially mediated. Ammonium is oxidized through nitrification by chemoautotrophic bacteria, resulting in nitrate. The nitrification rate is temperature dependent, and the process depends upon a supply of dissolved oxygen. The denitrification process results in a loss of nitrogen in the system when nitrate is reduced by facultative anaerobic bacteria that use NO_3 for respiration. The end product is primarily nitrogen gas. This nitrogen gas can be "fixed" by nitrogen-fixing bacteria which return it to a biologically available state (Libes 1992).

Dissolved ammonium can be adsorbed onto suspended sediment particles which then sink to the river bed. Dissolved NH_4 and NO_3 also provide nitrogen for algal growth. Phytoplankton advection and settling depend upon the flow rate and the concentration of organisms is taken up. Algal death transforms living matter to dead refractory nitrogen, phosphorus, carbon, and degradable organic matter. Hence nutrient transport in a system depends upon the nutrient form, length of transport, nutrient limitation, and presence of nutrient reservoirs (Watershed Model 1994).

Nutrient Limitation

In the Chesapeake Bay, nitrogen and phosphorus both fuel phytoplankton growth. When large quantities of excess phytoplankton die and degrade, the result is critically low bottom water dissolved oxygen (DO) and eutrophication. One goal of nutrient reduction strategies is to maintain sustainable bottom water DO throughout the year. In a waterway where the mass ratio of Dissolved Inorganic Nitrogen (DIN) to Dissolved Inorganic Phosphorus (DIP) is greater than about 7.2 (the Redfield ratio for the composition of marine algal cells), a phosphorus limited environment is indicated. In the northern three-quarters of the Bay, the system is considered phosphorus limited, meaning that phosphorus concentrations control the primary production of phytoplankton. The southern-most quarter is considered nitrogen limited throughout the year, and in fall, the nitrogen limited conditions creep about halfway up the Bay mainstem ("Response" 1994). When an area is nitrogen limited, phytoplankton nitrogen utilization rates are dependent on additional nitrogen inputs to the system. In some cases it is necessary to know the nutrient limitation situation of an area so that policy will provide the desired environmental effects.

The model of a Bay-wide, phosphorus-only restriction indicates benefit to the phosphorus limited upper Bay regions but increase in phytoplankton production in the lower Bay. As phosphorus loads are reduced (with constant nitrogen load), the excess nitrogen not taken up in phytoplankton biomass is transported through surface waters to the nitrogen-limited lower Bay. This excess nitrogen stimulates phytoplankton production which eventually settles and creates increased sediment oxygen demand downstream. Thus, while phosphorus removal is most beneficial in the upper Bay, nitrogen reduction is important throughout the Bay both for the direct improvements in the middle and lower regions as well as the indirect avoidance of excess nitrogen transport from the upper regions ("Response" 1994).

Nitrogen also has a direct impact on submerged aquatic vegetation (SAV) habitat. Since SAV provides nursery and spawning grounds for fish, food for marine organisms, and oxygenation to the water column, the health of SAV beds dictates the health of the entire system. These submerged plants thrive best when dissolved inorganic nitrogen (DIN) in mesohaline and polyhaline environments is less than 0.15 mg/l during the annual growth period. Additionally, there is an indirect impact when phytoplankton biomass decreases light penetration and limits shallow water plant growth. The light extinction coefficient used in Chesapeake Bay water quality modeling is directly proportional to phytoplankton biomass. The models of SAV response to nutrient reduction indicate a less dramatic benefit from phosphorus-only reductions than from equivalent nitrogen reductions ("Response" 1994).

Dissolved Oxygen

When bottom waters reach dissolved oxygen (DO) levels below 1 mg/L, the water condition is considered anoxic. During the summer, surface waters are often DO saturated by algal production while bottom waters are oxygen sinks because of the oxidation of dissolved organic carbon (DOC) and the chemical oxygen demand of reduced sediment resuspensions. Once again, reducing total nitrogen improves water column DO conditions more than equivalent reductions of phosphorus ("Response" 1994).

Estuarine Circulation

Estuarine circulation refers to the typical flow pattern of water in estuarine systems, which is driven by the interaction of fresh water and salt water. Since the higher salinity water has a greater density, it will tend to "sink" to the bottom of the water column. Meanwhile the lighter fresh water comes out in a seaward "wedge" to overlay the saline intrusion. A cross-sectional diagram of the estuary would indicate landward flow of higher salinity water in the bottom waters and seaward flow of fresher water nearer the surface. This circulation pattern and the degree of vertical stratification it imparts has implications for the oxygenation of the system.

The James River is described as a "partially-mixed estuary." This means that the vertical density differential is not strong enough to regularly limit vertical mixing, thereby indicating that hypoxia is not predicted to be an overwhelming problem. Additionally, gravitational circulation carries nutrients up the estuary, so when a bloom occurs the hypoxic region (due to phytoplankton degradation) will be just landward of the bloom location. In some systems, the water column is so stratified that oxygen will not diffuse down from the surface and a hypoxic system will go anoxic. This could happen when there is an increased freshwater flow which creates a stronger pycnocline and inhibits vertical exchange. Based on the model of gravitational circulation, hypoxia is possible, but not likely, in a partially-mixed estuary like the James River (Kuo and Nielson 1987).

Best Management Practices

A Best Management Practice (BMP) is a technology-based standard for nutrient reduction. Projects are designed to achieve certain environmental conditions, and efforts are focused on pre-project specifications rather than measuring only end results. The cost effectiveness of a BMP depends on the pre-existing nutrient control practice, the use intensity on the site, and sometimes the desired water quality. Descriptions of specific Best Management Plans for nonpoint sources follow in Table 1.

Table 1. Best Management Practices
Source: York River Tributary Strategy, 1998.

Shoreline Erosion Control	Structural (riprap, revetments) or nonstructural (marsh grass, vegetative buffer) components to reduce loss of sediment and nutrients into a waterway
Septic System Management	Regular pumping of systems, installation of denitrification components, or bypassing existing septic system and connecting to sanitary sewer
Urban Nutrient Management	Educational efforts to reduce lawn chemical use in residential areas
Retrofits for Urban Best Management Practices	Enhancing existing stormwater management systems to slow runoff, remove sediment and nutrients, and restore eroding stream channels
Erosion and Sediment Control	Practices such as silt fences, sediment basins, and check dams reduce not only sediment but also associated nutrient runoff
Grassed Filter Strips	Vegetative buffers adjacent to streams which filter runoff from surrounding lands
Cover Crops	Fall planting of crops such as rye, wheat, or barley without fertilizer in order to trap nitrogen left over in the soil from the planting season; also reduces winter-time erosion of soils
Grazing Land Protection	Rotational grazing practices which minimize effects of livestock on land
Agricultural Land Retirement	Ceasing to farm on highly erodible or sensitive lands – taking land out of production or grazing and planting instead with a permanent vegetative cover (grass, shrubs, or trees)
Nutrient Management Planning	Managing the timing, amount, and placement of fertilizer application to minimize nutrient loss potential
Farm Plans	Control practices to limit sediment runoff from land through comprehensive natural resource management plans

Conservation Tillage	Crop production method that leaves the maximum crop residue on the ground – can be done either by planting without tilling (no-till) or tilling in a manner or direction that limits nutrient and sediment runoff
Stream Protection from Livestock	Installing streambank stabilization equipment or fencing to exclude livestock from directly entering the stream

For point sources, the major nutrient management technologies are categorized as either biological nutrient removal (BNR) processes or non-biological nutrient removal processes. The biological processes are composed of a nitrification component whereby ammonium and organic nitrogen are converted to nitrate under aerobic conditions, and a denitrification component wherein these nitrates are converted to nitrogen gas under anoxic conditions. New technologies have been designed to remove both nitrogen and phosphorus, making them particularly cost-effective. In these processes, wastewater passes through tanks which are anaerobic, anoxic, and aerobic, in order to accelerate the microbially-mediated processes. These BNR systems are distributed under trade names including A/O and A^2O^{TM}, Bardenpho^{TM}, Biolac^{TM}, Phostrip^{TM}, and the University of Capetown process. On the other hand, the non-biological nutrient removal systems involve adding chemicals or other treatments to wastewater for nutrient removal. These include breakpoint chlorination, electrodialysis, electrochemical treatment, and distillation. These non-biological procedures have been used primarily for phosphorus removal ("Nutrient Reduction Strategy Reevaluation Report #8 1993).

POLITICS AND ADMINISTRATION

Social Benefits

Trading provides the opportunity to develop consensus-building efforts. By providing an integrated watershed approach, all of the "stakeholders" on the waterway are included in a collective project. For example, the Tar-Pamlico program was developed as a coordination effort of the Tar-Pamlico Association (point source entities in the basin), the Environmental Defense Fund (EDF), Pamlico-Tar River Foundation, and the North Carolina Division of Environmental Management (Hall 1996). The process then becomes a local-regional initiative, bringing regulatory measures down to a manageable scale. The goal is not only cost-effectiveness but also efficiency and inclusiveness.

Implementation Timeframe

The Tar-Pamlico project used a phased implementation with Phase I outlined as three years of nutrient information development, identifying point source upgrades, evaluating the nonpoint source program, creating infrastructure, and developing a specialized GIS watershed model of the estuary. The second phase would then enable nonpoint source trades and build management tools (TMDL Case Study). In general, programs which have gradual implementation time frames have the benefit of more stakeholder interaction, goals in line with actual conditions, and more willing participation since there is time to become familiar with a new concept.

Program Design

In designing a trading program, it is necessary to determine the optimum level along the spectrum from strict regulation to unrestricted free market. While strict regulation does provide more reliable outcomes, it may hinder the system from realizing maximal efficiency. For example, regulatory or organizational constraints on some discharging entities may not allow them to behave as competitive firms in a market (Tietenburg 1989). However, a free market system could reduce the regulatory oversight to the point that efficiency becomes unrestricted chaos. Additionally, a system which claims to be free-market, but is simply command and control disguised in trading language, can not fully realize the benefits of the free market. It is important for individual programs to determine a sustainable amount of oversight, along with free trade elements.

Legal Issues

There are numerous legal issues that could affect the selection of regulatory policy alternatives. Takings cases now require landowner compensation when legislated land decisions are equivalent to removing economically viable land uses. The legal and planning communities are also currently examining the option of Tradable Development Permits (TDP's) as a means of protecting some areas from concentrated development. Some of this information can be extrapolated and applied to the specific conditions of coastal lands.

Company participation is another legal issue. In most situations, participation in the trading program is voluntary, although most point source dischargers are expected to find the scheme an attractive option compared to more expensive fines. It may be necessary to codify the framework for trading in state law since industry may be hesitant to participate in the program that they could cease to be legal. For example, in the Pamlico-Tar River Foundation's 1996 comments of the *Draft Framework*, the membership indicated that although the program as a whole was exhibiting success, two shortfalls were the lack of inclusion into state law and no clear mandate. The Lake Dillon project report noted that part of its strength was codification of the 1984 Dillon control regulations adopted by the State (Colorado) Water Control Commission (Draft Trading Update 1996).

LITERATURE REVIEW

Two years before publication of the EPA draft, Crutchfield et al (1994) evaluated coastal watersheds for feasibility of point-nonpoint source trading programs. They used data from the National Coastal Pollutant Discharge Inventory (NCPDI) and the National Resources Inventory (NRI) for 350 USGS cataloging units, each covering all or part of a surface drainage basin or distinct hydrologic feature.

This study used three screening criteria to evaluate the potential for point-nonpoint trading and developed a cumulative screening process so that only those watersheds meeting the first criterion were tested for the second and third criteria. First, the watersheds needed to have a significant portion of total loadings from point source (PS) and agricultural nonpoint source (NPS), since "if either the agricultural NPS or the PS share of total loadings is small, then trading is unlikely to contribute much to water quality improvement." They determined the screening limit of 30% of loadings for each pollutant (nitrogen, phosphorus, and sediment) by both PS and NPS, and thirty-five watersheds met this initial requirement for at least one pollutant. The Virginia watersheds qualifying at this level were the Lower Rappahannock and the Chowan[3] (shared with NC). The James and York Rivers did not qualify under the pollution loading distribution criteria, but neither did the Tar-Pamlico where trading has met considerable success. Hence, this is an indication that the authors' first criteria may have been incorrectly specified.

The second screening level required that there be a few PS's of significant size, because numerous small sources would present intractable transaction costs. Of the thirty-five first-round qualifiers, this level identified those watersheds where the total loadings of the five largest PS's contribute at least 75% of each category. The third level selected those areas where the trading program would be able to reduce NPS pollution by converting to a less-polluting land use or installing new technologies. Thus, the screening program looked for areas where water quality enhancing practices were not already in place but where there was an identifiable need for them. Because levels two and three assessed the PS and NPS sides respectively, all thirty-five of the watersheds identified in the first round were assessed through steps two and three. Crutchfield's study found only one watershed where this particular screening process yielded a "High" potential for successful trading, and eight units were of "Medium" potential. This "High" potential was

3 The author misspelled this river as the "Ghowan" throughout the article. However, there is no river with that name, and he was clearly referring to the location of the Chowan.

found in Severn River, MD, and the Lower Rappahannock and Chowan received "Low" and "Medium" scores, respectively.

Analysis of the methods and results of this publication yields several lessons for this study. First, in their conclusion the authors did note that their intent to broadly identify coastal watersheds had required them "to forgo some detail for the sake of our national scope," and they recommended further research on a local level. Additionally, the first screening criterion may have been too restrictive, since it eliminated 90% of the watersheds, including some where successful trading programs have already been implemented.

Another study by Krupnick of Resources for the Future (1989) evaluated the potential of tradable nutrient permits in the more focused region of the Chesapeake Bay watershed. The author noted that the in the Chesapeake Bay Agreement (1987) the states of Maryland, Virginia, and Pennsylvania, and the District of Columbia committed to reduce nutrient loadings to the Bay by forty percent by the year 2000. A 40% reduction should increase dissolved oxygen (DO) levels to 1 mg/l in the bottom waters of the mainstem Bay. In the original plan, reductions would be allocated according to each state's share of baseline loads of "controllable" nitrogen and phosphorus, with each state required to reduce its loadings by 40%. Although the Agreement did not specifically mention trading as an option for compliance, Krupnick's model evaluated a "nutrient reduction credit (NRC)" system whereby permits were traded between states rather than between sources. Krupnick also mentioned some of the potential problems of permit programs including coordination difficulties, lack of baseline data, locational effects (reductions below the "fall line" have more effect at the mouth than those above it), and the imperfect substitutability between nitrogen and phosphorus. The author concluded that while a source-based incentive policy on this scale would be onerous if not impossible, there was some theoretical support for state trading. However, he did indicate that "gains in efficiency from state trading may be relatively modest if they are limited to those arising only from interstate trades."

Krupnick presented two options for the design of trades. The first was a "load based trading system . . . with some simple modifications for locational and source-type differences." While allowing for a simpler structure, this option incorporated some uncertainty regarding whether environmental goals would be met. On the other hand, policy-makers could hold environmental improvement as the ultimate measurement which would require models of nutrient flows above the fall line and their effect on the mainstem Bay, nutrient flux out of sediments, and nutrient "exhaustion," in order to fully understand the implications of specific trades ("The Bay Model"). A clear problem with the second approach is that the models are often based on uncertainty and cannot reliably predict effects.

The most obvious criticism of Krupnick's model is the small number of actors (four) and the large geographic scale. It appears that true efficiency improvements will only be achieved through intrastate trades where the states maximize the credits each can provide by concentrating on lower-cost pollution reducers. At such a large scale, it is quite possible that entire watersheds will be overlooked or deemed "pollution inflow" areas. Despite its unwieldy scale, Krupnick provides a very comprehensive economic analysis of the trading procedure that will be most helpful if adapted to a watershed level.

PROJECT DESCRIPTION

Problem

This project evaluates the feasibility of applying a pollution trading scheme to Virginia's James River Watershed. The James River's 450 mile reach runs through large areas of agricultural land. Portions of its reach have been identified as imperiled (particularly near its mouth in the Elizabeth River portion), and it has point source dischargers of considerable size in Richmond and in Hampton Roads. At first glance, the James River satisfies several criteria for trading.

Currently, the states in the Chesapeake Bay watershed are committed to nutrient reductions of 40% of 1985 levels by the year 2000 (1987 Chesapeake Bay Agreement) in the face of increasing population growth and intensification of agriculture and industry. The James provides the third largest nitrogen load to the Bay; the Susquehanna and the Potomac have the first and second highest discharges ("Response" 1994. In the case of the James River, the Virginia Department of Environmental Quality has committed to improving ambient water quality in the river itself rather than focusing primarily on interstate agreements to protect and improve the Bay estuary. While nutrient loadings from the James are significant, the river runoff is carried primarily out to the Atlantic, thereby influencing shelf processes. Hence, the James actually contributes little to mainstem Bay water quality due to its position near the ocean margin of the Bay ("Response" 1994). However, it is still in Virginia's interest to improve water quality within the river's reach and to contribute even small improvements to the Chesapeake waters.

In order to simplify the model, and since nitrogen and phosphorus are not perfect substitutes, only nitrogen will be described in this project. Nitrogen is currently the nutrient of concern; its reduction is crucial to the status of the entire Bay region. Additionally, the James River lies in the nitrogen limited region where elimination of additional discharges could prevent harmful algal blooms. Once future research establishes an appropriate ratio between nitrogen and phosphorus, then the region can implement an effective reduction strategy for the health of the entire Bay and address the two nutrients together.

Additionally, the Progress Report of the Baywide Nutrient Reduction Reevaluation (1992) indicates that 80% of the 43.7 million pounds of nitrogen is "controllable load," although this relies upon the determination that 99% of the point source load and 58% of nonpoint source load is controllable. In 1996, 64% of the nitrogen load in the river came from point sources, 21% from agriculture, 18% from urban, and 4% from septic (James River Tributary Strategy, 1998).

Table 2. Nitrogen Loadings in the James River Watershed (million pounds).
Source: "Achieving the Chesapeake Bay Nutrient Goals" (1994).

	Nitrogen	**Phosphorus**
1985 base year	43.7	6.18
1992 progress	39.7	4.26
2000 allocation cap	29.6	4.04
Remaining reduction	14.8	0.92
Tributary strategy	14.8	1.53

Table 2 provides nitrogen loading data for the James River Watershed. While the tributary strategy indicates that it can address the full shortfall of nitrogen reductions, this may be at a high cost due to the regulatory structure. The current reduction strategy is based on a "command and control" structure is be more straightforward but relies upon costly point source reduction of nutrients. Some policy analysts argue that only by taking advantage of the more cost effective nonpoint source reductions, even though they are more difficult to quantify, will the Bay states most efficiently reach the nutrient reduction goals. As the system nears the goal of nitrogen reduction, the marginal cost of each additional unit reduction will increase. This will make further progress increasingly expensive, and perhaps impossible[4].

Data

The identity of each point source discharger (wastewater treatment plants, industrial, manufacturing) was obtained through NPDES permits which are catalogued in EPA's Permit Compliance System. Additionally, data from the Virginia Department of Environmental Quality provided information regarding whether these sources had achieved Biological Nutrient Removal (BNR), which is considered the state of the art best management practice in the field. The specific nitrogen discharge quantities (pounds per year) for permits in the watershed were acquired through the Chesapeake Bay Program Office for each year from 1985 to 1996. Most researchers consider this point source pollution to be 100% controllable. While this may seem economically impractical, there is

4 In addition to point source and nonpoint sources of nitrogen, there is also atmospheric deposition. However, due to the uncertainties concerning quantity and behavior, this component was omitted from the current model.

no defensible background or in-between level at which a plant could operate. Hence this project will follow rationale that point sources are fully expendable. In economic terms this may be supported as well since a firm offered a very large compensation may be willing to go out of business or suspend operation for a particular period of time.

The cost per unit reduction for point sources came primarily from the Chesapeake Bay Program Office publication (Report #8 1993) which presented results from a 1989 CH2M Hill study. A disclaimer with the figure indicates that they are accurate within +50 percent to –30 percent, but they embody the best information currently available. This study report examined large wastewater treatment plants and provided Equivalent Annual Costs (EAC), annualized capital costs plus yearly operation and maintenance, using a 10% interest rate and an expected 20 year project life. These costs were given for the technology necessary to reach the water quality criteria similar to that which is projected with the 40 percent reduction. The standard of nutrient removal was a seasonal 10mg/l total nitrogen level, and total phosphorus 2.0 mg/l or less[5]. The technology used varied by plant, but mostly consisted of nitrification/denitrification with two anoxic zones or a nitrogen trickling filter with a denitrification filter.

Assuming a uniform regulation scenario (Lyon 1982), 40% of each company's 1985 loads was subtracted from 1989 loads in order to identify discharge reduction goals. The Chesapeake Bay Agreement does not specifically mandate that each point source must reduce 40% of its loads. An assumption of this project, however, is that under command and control the reductions would be allocated equally across all entities subject

5 A year-round TN of 10mg/l is expected to maintain an average annual performance effluent level of TN=7 mg/l.

to regulation (point sources). Reduction goals have not been identified specifically for the James but the "James River Tributary Strategy" (1998) states that, "Just like the forty percent reduction for the entire Bay, the nutrient and sediment goals [for the James] will be based on the results of sophisticated computer modeling . . .."

The following companies had already reduced discharges by 40% in 1989: Hoechst-Celanese, Fort Eustis STP, Allied Signal, Falling Creek (Chesterfield Co.) STP, South Central Wastewater Authority (Petersburg), and Babcock & Wilcox. These reductions resulted from production changes at Babcock & Wilcox and Allied Signal, installation of seasonal biological nutrient removal at Falling Creek, and upgrading and expanding to provide advanced secondary treatment in Petersburg. In addition, several other plants have implemented reduction technology. Lynchburg STP has replaced an Zimpro sludge heat treatment process which had contributed to process inefficiency, Henrico installed BNR capability, and the Virginia Initiative Plant installed BNR and patented a removal process which is being made available to other plants without royalty payment. In addition, the Richmond plant added nitrification capacity and is pilot testing methanol addition (James Tributary Strategy 1998).

In the next step, the Equivalent Annual Cost (EAC) was divided by the number of pounds still remaining to be reduced. It is important to note that the size of this cost per unit reduction figure has much to do with the number of pounds remaining rather than simply high cost. However, since cost was calculated relative to achieving the goal from 1989 levels, this provides at least a relative comparison of costs. For point sources not in this report, a $20 cost was extrapolated from estimates of BNR costs on the Potomac

River (Kerns 1996). The cost per unit reduction is shown in Appendix III.

The nonpoint source loading distributions were calculated from the 1996 EPA Region III Land Cover GIS Data Set which has multi-resolution land characteristics (MRLC). This was the most recent land use data available so it was considered to be the "current" distribution of land use and nonpoint source loadings. The James River watershed was clipped, using ArcInfo commands, from the Chesapeake Bay Watershed coverage. The original land use categories were re-combined as shown in Table 3.

Table 3. EPA MRLC Land Cover Categories Recombined.

Water	= Water
Urban	= Low intensity urban + High intensity urban
Hay/Pasture	= Hay/Pasture
Ag/Till	= Row Crop + Probably Row Crop
Forest	= Coniferous Forest + Mix Forest + Deciduous Forest
Wetlands	= Wooded Wetlands + Emergent Wetlands
Barren	= Barren Quarry + Barren Beach + Barren Coal + Barren Transitional

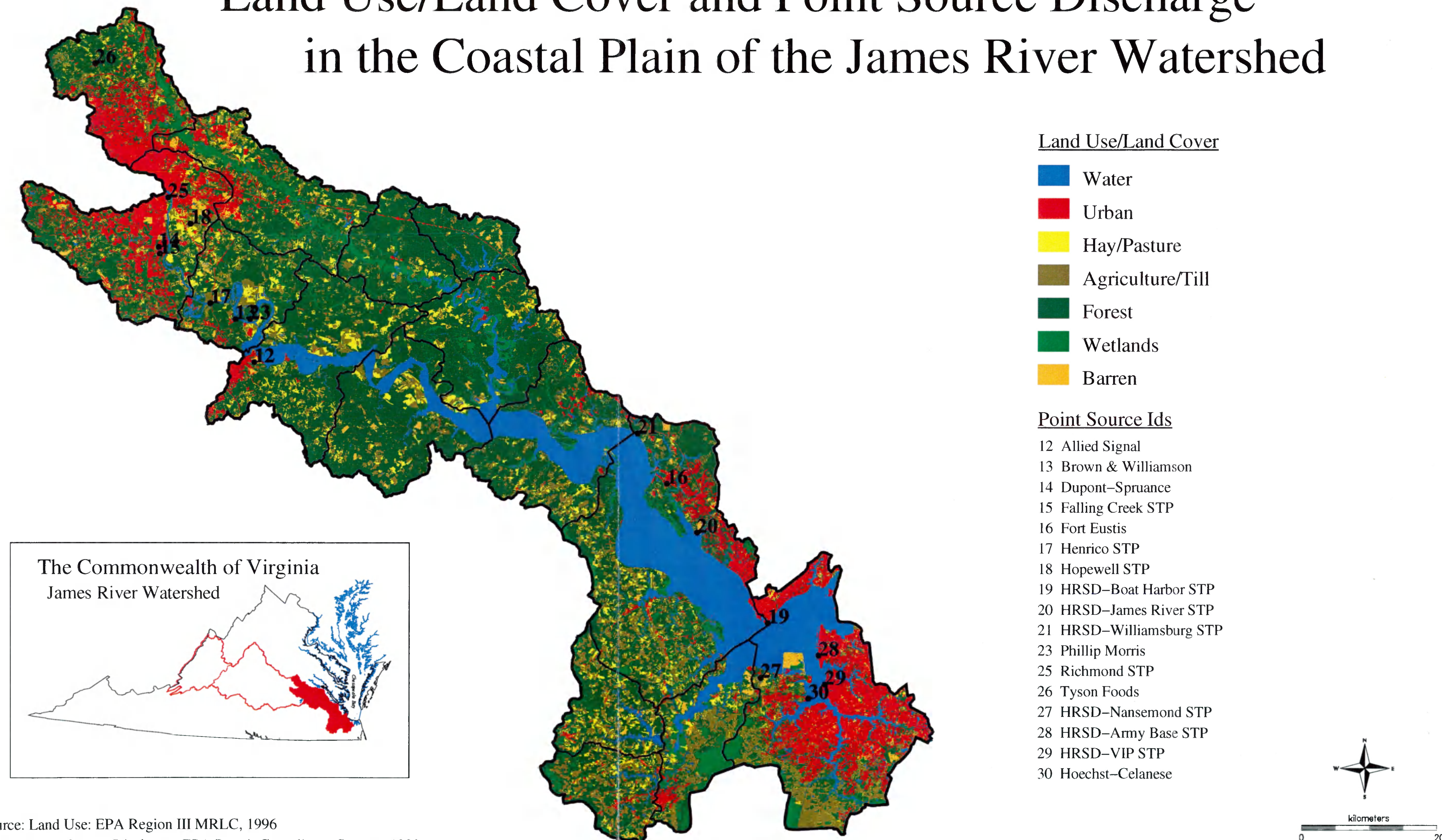
In this way, the fifteen EPA categories were condensed into the seven most useful for the project. Of these seven, water, forest, wetlands, and barren were eliminated from consideration since they are considered "background" or non-controllable sources of nitrogen loadings. Figures 1,2, and 3 show the land use coverages for each section of the watershed. A Chesapeake Bay Program table in the "Nutrient Reduction Strategy Reevaluation Report #8" (1993) provided "Edge-of-Stream Nitrogen Loading Factors by Land Use Category" from the Chesapeake Bay Watershed Model Base Case Scenario. In order to come up with a reasonable estimation of nitrogen loadings, only those hydrologic units directly adjacent to a stretch of the main channel were quantified. Loadings from more distant hydrologic units would need to be corrected for topographic features or soil types, and such factors were not available. Of the one hundred-nine total units in the watershed, twenty-nine of these were selected as adjacent. The selected hydrologic units are depicted on the watershed coverage in Figure 4. The GIS coverage units were transformed from meters squared to acres and then the number of acres of each land use in each hydrologic unit was multiplied by the loading factor. The loading factors are as follows:

Urban	= 8 lbs/acre/yr
Hay/Pasture	= 7 lbs/acre/yr
Till	= 19 lbs/acre/yr

As an additional reference point for these figures, the forested "background loadings" rate is 2.5 lbs/acre/year. Together, the estimates for loadings from these three sources in the designated hydrologic units total 8,921,971 lbs/yr, which reflects 22% of the Chesapeake Bay Program Model's estimated nitrogen loadings to the James River of 39.7 million pounds. Additionally, the percentage of each land use in the selected segments is roughly proportional to the published data for the whole watershed.

Figure 1. Land Use/Land Cover and Point Source Discharge in the Coastal Plain of the James River Watershed.

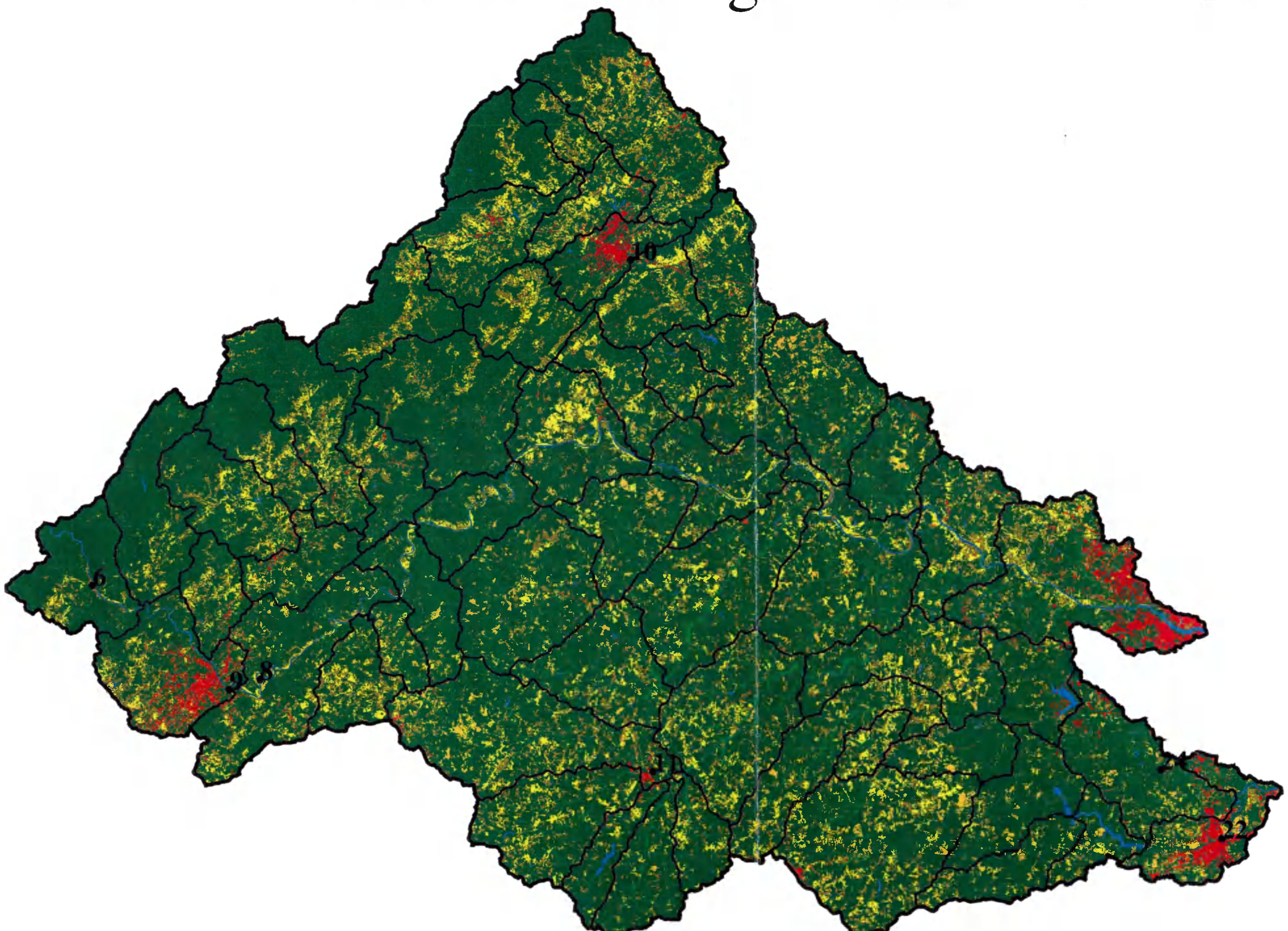
Land Use/Land Cover and Point Source Discharge in the Coastal Plain of the James River Watershed

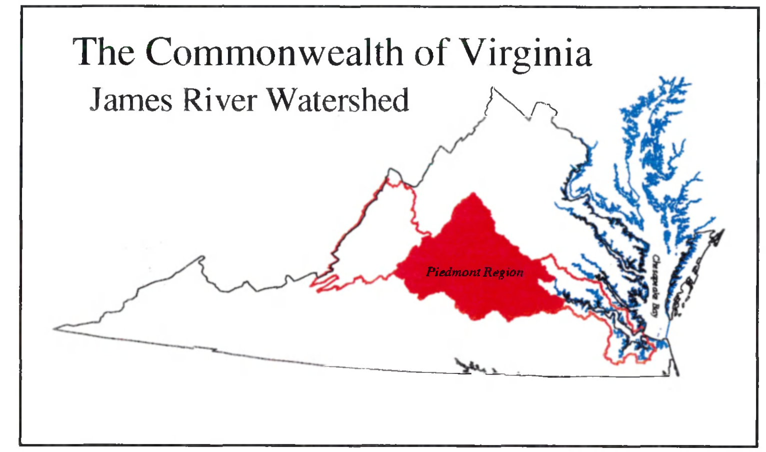


Source: Land Use: EPA Region III MRLC, 1996
Point Source Discharge: EPA Permit Compliance System, 1998

Figure 2. Land Use/Land Cover and Point Source Discharge in the Piedmont Region of the James River Watershed.

Land Use/Land Cover and Point Source Discharge in the Piedmont Region of the James River Watershed





<u>Land Use/Land Cover</u>

- Water
- Urban
- Hay/Pasture
- Agriculture/Till
- Forest
- Wetlands
- Barren

<u>Point Source Ids</u>

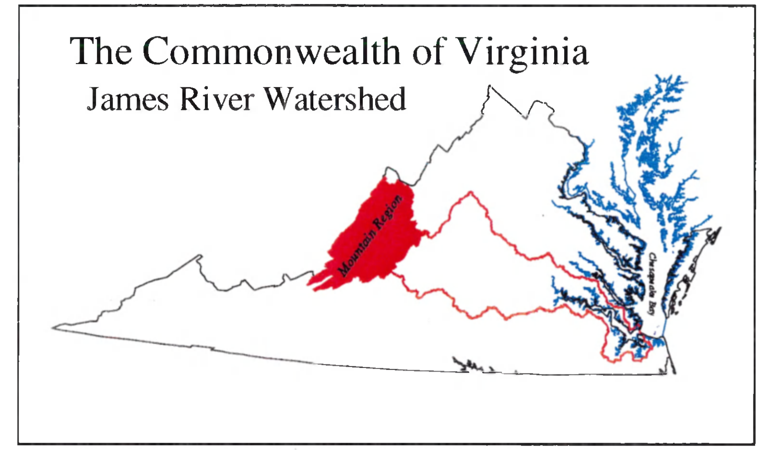
6 Georgia–Pacific
8 Lynchburg STP
9 Babcock & Wilcox
10 Moores Creek STP
11 Farmville STP
22 Petersburg STP
24 Proctors Creek

kilometers
0 20

Source: Land Use: EPA Region III MRLC, 1996
Point Source Discharge: EPA Permit Compliance System, 1998

Figure 3. Land Use/Land Cover and Point Source Discharge in the Mountain Region of the James River Watershed.

Land Use/Land Cover and Point Source Discharge in the Mountain Region of the James River Watershed

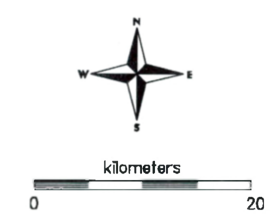


Land Use/Land Cover

- Water
- Urban
- Hay/Pasture
- Agriculture/Till
- Forest
- Wetlands
- Barren

Point Source Ids

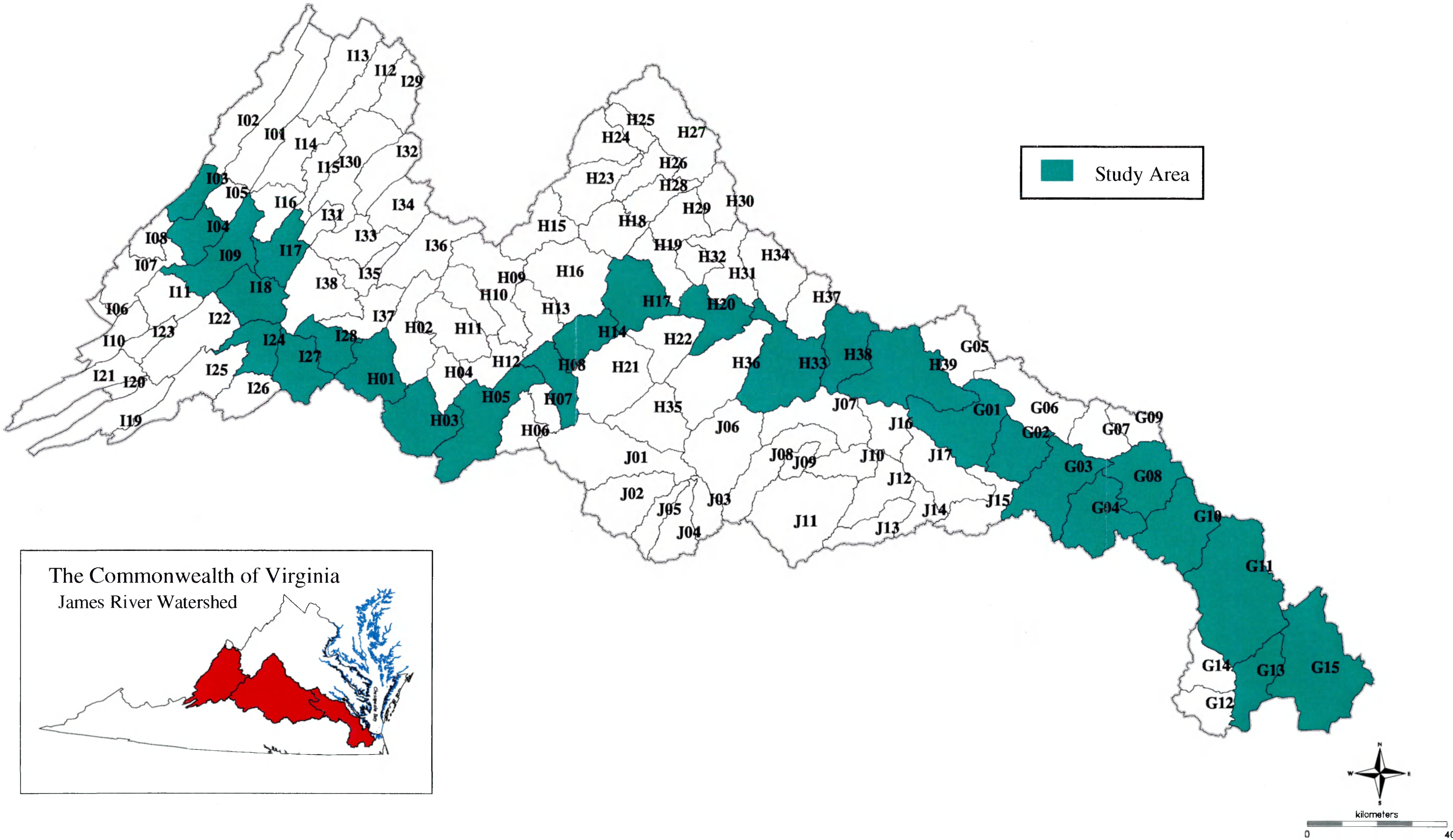
1 Lexington
2 Buena Vista STP
3 Clifton Forge STP
4 Covington STP
5 Lees Commercial Carpets
7 Westvaco



Source: Land Use: EPA Region III MRLC, 1996
Point Source Discharge: EPA Permit Compliance System, 1998

Figure 4. James River Hydrologic Units.

James River Watershed Hydrologic Units



The next step was to determine the "controllable" loads of each source. The York River Initial Tributary Nutrient Reduction Strategy (July 1998) listed BMP efficiencies from the Chesapeake Bay Watershed Model (Phase IV). The efficiencies for applicable practices under each land use category were averaged to determine efficiency estimates. The 33% efficiency for urban BMPs was an average from Erosion and Sediment Controls, Stormwater Management Retrofits (Extended Detention (dry), Pond-Wetland System (in series), Stormwater Wetland, Retention (wet), Conversion from dry to wet, and Sand Filters), Septic Systems (Septic Pumping, Septic Connections, Septic Denitrification), and Urban Nutrient Management. The 35% for Hay/Pasture was an average from Hay and Pasture Farm Plans, Grazing Land Protection, Nutrient Management, and Streambank Protection with and without fencing. Finally, the 21% nitrogen reduction for Till came from Agricultural Crop Farm Plans for conventional or conservation till, Nutrient Management, and Cover Crops.[6] Current nitrogen loads were multiplied by the corresponding efficiencies to determine the maximum controllable load in each hydrologic unit. The results indicated the maximum pounds of nitrogen available for purchase as BMP credit in each hydrologic unit.

Cost per unit reduction was derived for nonpoint source much in the way that efficiencies were determined. The "Nutrient Reduction Strategy Reevaluation, Report #8" (1993) outlined the cost per pound for various BMP technologies. These costs ranged from $2.40 for agricultural nutrient management to $103 for sediment retention and water control structures. The costs for BMP's for each land use type were averaged, and BMP

6 It is important to note that while BMPs are available and fairly effective for animal waste control, this land use feature was not identifiable through land use designations or permits. This could be another area of

costs per pound of reduction follows:

Urban	= $61.25
Hay/Pasture	= $5.43
Till	= $2.58

When compared to the point source estimate of $20 per pound, the data are at least proportional to other studies. The Tar-Pamlico Association estimates that one unit of nonpoint source control with Best Management Practices costs roughly one-tenth of the cost for one unit from a wastewater treatment plant (TMDL Case Study).

The Model

Once all of the background information had been collected, experimentation could begin evaluating trading applications. The options currently available to a firm facing violations (pay fine, retrofit, install ponds) were supplemented with a trading option. A firm could either purchase a reduction credit from another point source that had a lower cost per unit reduction, or they could pay into a fund which subsidizes non-point source reductions (riparian buffers, alternative tillage, wetland creation). Once the parameters of the trading scheme are established, it is necessary to allow the market to function freely. However, very close monitoring will be necessary, especially in the early stages when actual outcomes are unpredictable.

The method chosen to predict and evaluate the effects of trading was a linear programming model which comes from the field of operations research. In this context, programming means "planning" in the sense of predicting that a system will behave in a

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significant reduction in nitrogen loading.

certain way. The method requires that several alternative choices exist, solutions are measured according to attainment of specific objectives, optimization, and examination of interrelationships between components are involved. The first component of the model is the decision variables or "unknowns" (X_i). The second is the objective function which relates the decision variables in the form $\Sigma\ C_iX_i$, were C_i is the cost of X_i under the given circumstances. Finally, the constraints are linear equations or inequalities which govern the options for the objective function. The goal of linear programming is to optimize (maximize or minimize) a certain function by changing the decision variables within the bounds of the constraints. In many cases, the goal is to find the minimum cost of a particular tableau of options given known costs and constraints on the total number of units of different types of X (Feiring 1986).

The Solver function in Microsoft's Excel program is fitted to handle such linear programming exercises. The Excel Solver was developed by Frontline Systems for Microsoft. It uses spreadsheet formula language and solves by the "dense Simplex method" with bounds on the variables. It can handle up to 200 decision variables, which was adequate for this project (NEOS Guide). The benefit of this method is that it is readily available to policy analysts, straightforward, and inexpensive. The model is set up so that the user answers "minimize/maximize *what equation*, by changing *what cells*, according to *what constraints*?" The model can also be specified to "assume linear model" and be non-negative. The specific method used when running the model is shown in Appendix IX.

The linear programming technique has been used by several authors, including

O'Neil et al (1983), in a project evaluating the potential for trading in the Fox River, Wisconsin. Here the commodity unit was dissolved oxygen (DO) in the waterway, and linear approximation defined the relationship between effluent quantity of several components and water quality. Relations of impact coefficients with flow and temperature were estimated using ordinary least square regression. O'Neil et al. indicated that as long as the program accounted for daily fluctuations of environmental conditions, a least-cost solution at market equilibrium could be realized. The difference in the current study is that it evaluates a single parameter which has multiple effects in the watershed system. However, concentration on a single nutrient, nitrogen, will enable use of a linear equation and eliminate some of the uncertainty. Although this model is unable to account for all variations in environmental conditions, it does include a correction for nitrogen cycling along the waterway which will be explained under the "transport coefficient" section.

Milon (1987) noted that most studies of nonpoint source reduction costs used a deterministic optimization (linear programming) model which assumes steady-state conditions. However, with nonpoint source loads related to weather events, he believed that a stochastic optimization model might more appropriately represent the variable nature of discharges. A stochastic model was applied to Honey Creek in the Lake Erie basin, Ohio. From this research, Milon concluded that including reliability requirements adds to the cost of attaining pollution reduction objectives. Additionally, he found that a single pollutant reduction program could have consequences in other areas (e.g. reduction of total phosphorus can leave excess nitrogen after phytoplankton production decreases). Ideally a comprehensive reduction program will have a multiple-objectives approach. In this project, linear programming was chosen for straightforwardness, realizing its limitations in modeling a real-life system accurately[7].

Transport Coefficients

In its comments on the "Draft Framework" (1996), the Water Environment Federation claimed that "[o]ne consideration favoring trading even without a TMDL is that the water body would be no worse off with trading than without trading so long as the total load does not increase." While this may be true in part, it is also necessary to monitor the distribution of loadings so that a "dead zone" is not created in the river. This linear programming equation will incorporate control for water quality by using a transport factor for nitrogen.

The transport coefficient factor indicates the potential degradation of nitrogen along the waterway through biomass uptake, adsorption to particulates, nitrification, or denitrification. The transport factor can be linked to distance along the watershed, and each hydrologic unit is designated relative to its distance from the river's mouth. Reducing one unit of nitrogen at some point in the watershed may require more than one unit to be reduced upstream due to the natural riverine processes. One unit of pollution at an upstream point may only equal a fraction of one unit once it reaches a downstream point.

The transport factors for point sources were provided by the Virginia Department of Environmental Quality. They were extrapolated to apply to non-point sources as well,

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7 As a result of data constraints, this LP model was constructed for a steady-state condition. However, dynamic optimization models are available for situations which require modeling multiple nutrients or when an

according to hydrologic unit location. According to the data, one pound from the upper watershed would load 0.74 pounds of nitrogen at the mouth, and a pound of nitrogen in the piedmont region would load 0.89 pounds at the mouth[8]. East of the fall line, there is a unitary ratio between loadings at the source and loadings at the mouth. These ratios require multiplying pounds of nitrogen reduction required by 1.54 for the mountain region or 1.35 for the piedmont. Additionally, loadings from Farmville STP, due to its location on the Appomattox River (a James River tributary), were multiplied by 2.27 to account for additional nitrogen loss along that pathway. While Farmville was included in the evaluation since the specific loading factors was known, nonpoint loadings from that region were not.

For the purpose of deriving a straightforward model, initial restrictions will be placed on trading options so that a point source discharger in a permit-purchaser role would only be able to offset its excess discharge by compensations to upstream PS or NPS entities. The units of controllable nitrogen were multiplied by the cost per unit reduction for each land use type, and a total cost of reduction was obtained.

The objective function combines the costs per unit reduction for each type of land use for each hydrologic unit with the point source reductions and their associated cost. With the unknown variable being pounds of nitrogen reduced by each hydrologic unit, linear programming can solve for the minimum total cost, thereby determining the reduction distribution that minimizes the private cost of the program for a given point source increase. Assuming that the equation solution is constrained so that resulting

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assessment through time is desired.

8 The DEQ figures are similar to those in the literature for the Potomac River where "69 percent to 91 percent

reductions must equal the point source excess and the transport factor is incorporated, the water quality impacts should be mitigated in this model.

The point source maximum reductions were calculated so that each point source must be in compliance with the Chesapeake Bay Agreement themselves before they can sell credits to other entities. Otherwise they would be receiving compensation to undertake already-mandated reductions. Hence the "maximum reduction" model constraint has two options. If the company had already met the 40% reduction level, then the maximum available for purchase is its 1996 loading value (current loadings). If they are still not in compliance, then only the optimal discharge quantity was available for credit sale (60% of 1985 levels). While not built into the model, a legislative restriction would require compliance or plans to comply with the Agreement before a point source could sell credits.

MODEL RESULTS

Lynchburg STP

The first model run was for Lynchburg STP, located in the Piedmont region. Lynchburg's 1996 nitrogen discharge was 671,680 pounds/year or 2.42 times the 40% reduction goal of 276,983 pounds. Hence, under the Chesapeake Bay Agreement, Lynchburg STP would have to reduce 394,697 pounds by the year 2000. Since specific data were not available for this plant, it was estimated to cost $20 per pound to implement BNR technology (Kerns 1996). If Lynchburg installed in-house control technology, compliance

of the nitrogen . . . entering the Potomac above the fall line reached the Lower (tidal) Potomac" (Kerns).

would cost $7,893,940. To determine the cost under trading, the reduction goal was placed into the linear programming model with the objective function being the sum of cost-per-unit-reductions multiplied by each available reduction options. The equation used is shown in Figure 5.

Figure 5. Objective Function for Scenario with Lynchburg Held to 40% Reduction Level, Point Source and Nonpoint Source Trades, and with Transport Coefficients.

= (U optimal h03)*(cpurU) + (HP optimal h03)*(cpur HP) + (T optimal h03)*(cpurT) + (optimal BWX)*(cpur BWX) + 1.12*[(U optimal h01)*(cpur U)+ (HP optimal h01)*(cpurHP) + (T optimal h01)*(cpurT)] + 1.12*[SUM(U optimal i03 : U optimal i28)*(cpurU) + (SUM(HP optimal i03 : HP optimal i28)*(cpurHP) + (SUM(T optimal i03 : T optimal i28)*(cpurT)] + 1.12*[(optimal Lees)*(cpurLees) + (optimal Lexington)*(cpurLexington) + (optimal BuenaVista)*(cpurBuenaVista) + (optimal CliftonForge)*(cpurCliftonForge) + (optimal Covington)*(cpurCovington) + (optimal Westvaco)*(cpur Westvaco)]

U = Urban
HP = Hay/Pasture
T = Till

Optimal = quantity (pounds of nitrogen discharge) reduced at optimum/equilibrium
Model "unknowns" (decision variables) constrained as:
0 <= BWX optimal <= BWX maximum reduction

cpur = cost per unit reduction

The constraints mandated that the sum of units reduced equal the reduction goal, and reductions by each source could not exceed the maximum reductions described earlier. The model solution results (Appendix IV) indicated that in the optimal case, the 394,697 pounds/year credit would be acquired from Till farming in each hydrologic unit west of Lynchburg as well as from Babcock and Wilcox and Covington STP in order to achieve the least cost solution.

The cost per unit reduction for Till, $2.58/pound/year, was the least expensive option overall. However, the hydrologic units (HUs) had different transport factors, and these affected the cost per unit reduction. HU h03 was the least expensive, since the transport factor was one. Hence, Till load from this unit was the first purchased. Next, Hay/Pasture loads were purchased in the same pattern. All units to the west (h01 and i03-i28) had a loading factor of 0.89 pounds to the Lynchburg region of the river. For each pound of nitrogen input upstream of h03, only 0.89 pound is expected to reach that segment. Hence, any source upstream which wanted to sell credits would have to reduce 1.12 lbs of nitrogen for every pound that Lynchburg was granted to exceed. The cost would then be $2.86/lb instead of $2.58.

The credits selected after Till and Hay/Pasture were point sources. In this region, the $20 point source reduction cost is less than the $61.25 to reduce a pound of urban nonpoint source runoff. The model could have selected any of eight point sources west of Lynchburg and these two were chosen first by alphabet order. In the case of Lynchburg, the hypothetical trading example indicated a cost of $4,888,455 -- savings of $3,005,485, or 38%, from command and control costs.

Proctors Creek

The next trading scenario was Chesterfield/Proctors Creek STP. This plant was also exceeding its required reduction in 1996 and would need to reduce 110,445 pounds/year. Again the model was run with all available upstream nutrients (see Figure 6). From the objective function, the optimal solution was to purchase the full amount from Till farming in h33. Again, this could have been any segment from h33-h39 since all were specified in the same manner. The important feature is that the cheapest reduction ($284,831) was again found in Till, and in the segment just upstream, where the transport factor was not increasing cost per unit. The cost saving was approximately $2.07 million, or 88% of the command and control cost. This figure is in line with Tietenburg's estimate (1989 quoting 1985) that potential control costs could be reduced by more than ninety percent in some cases with marketable pollution permits. Even if Till was required to reduce two or three pounds per one pound of point source increase, the savings would still be considerable.

Figure 6. Objective Function for Scenario with Proctors Creek (Chesterfield) Held to 40% Reduction Level, Point Source and Nonpoint Source Trades, with Transport Coefficients and Upstream Credit Purchase Only.

= SUM(U optimal h33 : U optimal h39)*(cpur U) + SUM(U optimal h33 : U optimal h39)*(cpur U) + SUM(U optimal h33 : U optimal h39)*(cpur U) + 1.35*[SUM(U optimal h03 : U optimal h20)*(cpurU) + SUM(HP optimal h03 : HP optimal h20)*(cpur HP) + (T optimal h03 : T optimal h20)*(cpurT)] + 1.35*[(optimal BWX)*(cpur BWX) + (optimal Lynchburg)*(cpur Lynchburg)] + 1.54*[(U optimal h01)*(cpur U)+ (HP optimal h01)*(cpurHP) + (T optimal h01)*(cpurT)] + 1.54*[SUM(U optimal i03 – U optimal i28)*(cpurU) + (SUM(HP optimal i03 – HP optimal i28)*(cpurHP) + (SUM(T optimal i03 – T optimal i28)*(cpurT)] + 1.54*[(optimal Lees)*(cpurLees) + (optimal Lexington)*(cpurLexington) + (optimal BuenaVista)*(cpurBuenaVista) + (optimal CliftonForge)*(cpurCliftonForge) + (optimal Covington)*(cpurCovington) + (optimal Westvaco)*(cpur Westvaco)]

U = Urban
HP = Hay/Pasture
T = Till

Optimal = quantity (pounds of nitrogen discharge) reduced at optimum/equilibrium
Model "unknowns" (decision variables) constrained as,
0 <= BWX optimal <= BWX maximum reduction

cpur = cost per unit reduction

The model becomes more interesting when the restriction to upstream credit purchase and transport factors are removed (see Figure 7). Due to estuarine circulation and other factors, the transport factor is unitary east of h33. Essentially it could be assumed that pollution is as likely to go up as down the estuary at this point, so there is less need to account for one-directional flow. However, removing the transport factor from consideration in the whole watershed model could yield environmental inadequacies unless other measures are implemented. Allowing a wider trading opportunity takes advantage of the one point source that has a lower cost per unit reduction than Till farming, Richmond STP.[9] At $2.16 /pound, this would be the least expensive choice, and the total cost would be $238,561. Assume that Proctors Creek would be willing to pay up to $5.30 per pound reduced (its cost to do in-house reduction), and possibly more due to the all-or-nothing nature of BNR installation. If it were to pay this amount ($585,358 for 110,445 pounds at $5.30/pound), a significant portion of the $766,813 that Richmond would need to reduce its original 244,561 pounds excess would be offset. *Plus* it could reduce the 110,445 from Lynchburg, at its cost of $2.16/pound.

9 It is important to keep in mind that cost per unit reduction is as much a factor of pounds of reduction required as low cost of BNR installation. However, the example is good for hypothetical cost variability.

Figure 7. Objective Function for Scenario with Proctors Creek (Chesterfield) Held to 40% Reduction Levels, Point Source and Nonpoint Source Trades, with Transport Coefficient, and Removal of "Upstream Credit Purchase Only" Restriction.

= SUM(U optimal g1 : U optimal g15)*(cpurU) + (SUM(HP optimal g1 : HP optimal g15)*(cpurHP) + (SUM(T optimal g1 : T optimal g15)*(cpurT) + (SUM(U optimal h33 : U optimal h39)*(cpurU) + SUM(HP optimal h33 : HP optimal h39)*(cpurHP) + (SUM(T optimal h33 : T optimal h39)*(cpurT) + SUM(U optimal h03 : U optimal h20)*(cpurU) + SUM(HP optimal h03 : HP optimal h20)*(cpurHP) + SUM(T optimal h03 : T optimal h20)*(cpurT) + (U optimal h01)*(cpur U) + (HP optimal h01)*(cpur HP) + (T optimal h01)*(cpur h01) + (U optimal i03 – U optimal i28)*(cpur U) +(HP optimal i03 : HP optimal i28)*(cpur HP) + (T optimal i03 : T optimal i28)*(cpur T) + (optimal Allied)*(cpur Allied) + (optimal B&W)*(cpur B&W) + (optimal Dupont)*(cpur Dupont) + (optimal FallingCreek)*(cpur FallingCreek) + (optimal FtEustis)*(cpur FtEustis) + (optimal Henrico)*(cpur Henrico) + (optimal Hopewell)*(cpur Hopewell) + (optimal BoatHarbor)*(cpur BoatHarbor) + (optimal JamesRiverSTP)*(cpur JamesRiverSTP) + (optimal Williamsburg)*(cpur Williamburg) + (optimal PhillipMorris)*(cpur PhillipMorris) + (optimal Richmond)*(cpur Richmond) + (optimal Tyson)*(cpur Tyson) + (optimal Nansemond)*(cpur Nansemond) + (optimal Army)*(cpur Army) + (optimal VIP)*(cpur VIP) + (optimal Hoechst)*(cpur Hoechst) + (optimal Petersburg)*(cpur Petersburg) + (optimal Proctors)*(cpur Proctors) + 1.35*(optimal Moores)*(cpur Moores) + 2.27*(optimal Farmville)*(cpur Farmville) + 1.35*(optimal Lynchburg)*(cpur Lynchburg) + 1.35*(optimal BWX)*(cpur BWX) + 1.54*(optimal GP)*(cpur GP) + 1.54*(optimal Lees)*(cpur Lees) + 1.54*(optimal Lexington)*(cpur Lexington) + 1.54*(optimal CliftonForge)*(cpur CliftonForge) + 1.54*(optimal BuenaVista)*(cpur BuenaVista) + 1.54*(optimal Covington)*(cpur Covington) + 1.54*(optimal Westvaco)*(cpur Westvaco)

U = Urban
HP = Hay/Pasture
T = Till

Optimal = quantity (pounds of nitrogen discharge) reduced at optimum/equilibrium
Model "unknowns" (decision variables) constrained as,
0 <= BWX optimal <= BWX maximum reduction

cpur = cost per unit reduction

Repetition of this model would indicate the same essential results – purchase of the cheapest per-unit pounds, and then movement to the next cheapest until the credit is fulfilled. Additionally, most model runs would indicate significant cost savings over equivalent in-house reductions. In this case, low cost reducers have a financial incentive to further reduce their effluent, loads are redistibuted until roughly equivalent, and ideally, minimum marginal cost is realized.

Multilateral Trades

Finally, the trading arena model was opened up not only to bilateral trades but also to multilateral trades. Atkinson and Tietenburg (1991) find that "[w]hereas simultaneous, multilateral trades can instantaneously capitalize on all offsetting increases and decreases among surrounding sources subject to the ambient standards, bilateral sequential trades cannot." This set of model runs begins with the 5,065,784 pounds of point source nitrogen that must be removed from the system (from 1996 loadings) in order to have all point sources in compliance with the 40% reduction. This figure is the total of the "reduction needs" column which had been figured as 1996 loads minus .60*(1985 loads). One anomaly in this situation was Henrico STP which did not have an NPDES permit in 1985. Although loadings at this plant are quite high, the plant was considered only a potential seller and not factored into the reduction needs.

Under a purely command and control system, the total cost of reaching 40% reduction in point source loadings would be $70,911,551.03, calculated as "reductions needed" (in pounds) multiplied by the corresponding cost per pound at each of the treatment sites. If a trading system were implemented and only point sources only were able to sell credits, the optimal solution to the objective function in Figure 8 would be $17,402,990 and the permit sellers would be Richmond and Hopewell sewage treatment plants (see Appendix VI).[10] Since Richmond was the lowest cost, and point source pollution is considered 100% controllable, Richmond would cease operations (or completely eliminate nitrogen discharge) at the market equilibrium while Hopewell would eliminate about 86% of its 1996 loads. This ideal model assumes that excesses from the reduction mandate, (1996 loads - 0.6*(1985 load)), have been eliminated prior to the trade. However, if the cost of the prerequisite reduction were to be added to the total cost, then total cost would rise by about $2.5 million ($3.96 * 512,073 for Hopewell plus $2.16 * 244,561 for Richmond).

10 The incremental cost (average cost of reducing remaining units) was applied to all units produced at the plant, under the assumption that point source loads were 100% controllable. This was because no data was available for the increased MC as pounds remaining neared zero. Hence the total cost is probably greater than reflected here.

Figure 8. Objective Function for Scenario with All Point Sources Held to 40% Reduction Level, Only Point Sources Trades, and with Transport Coefficient.

= (optimal Allied)*(cpur Allied) + (optimal B&W)*(cpur B&W) + (optimal Dupont)*(cpur Dupont) + (optimal FallingCreek)*(cpur FallingCreek) + (optimal FtEustis)*(cpur FtEustis) + (optimal Henrico)*(cpur Henrico) + (optimal Hopewell)*(cpur Hopewell) + (optimal BoatHarbor)*(cpur BoatHarbor) + (optimal JamesRiverSTP)*(cpur JamesRiverSTP) + (optimal Williamsburg)*(cpur Williamburg) + (optimal PhillipMorris)*(cpur PhillipMorris) + (optimal Richmond)*(cpur Richmond) + (optimal Tyson)*(cpur Tyson) + (optimal Nansemond)*(cpur Nansemond) + (optimal Army)*(cpur Army) + (optimal VIP)*(cpur VIP) + (optimal Hoechst)*(cpur Hoechst) + (optimal Petersburg)*(cpur Petersburg) + (optimal Proctors)*(cpur Proctors) + 1.35*(optimal Moores)*(cpur Moores) + 2.27*(optimal Farmville)*(cpur Farmville) + 1.35*(optimal Lynchburg)*(cpur Lynchburg) + 1.35*(optimal BWX)*(cpur BWX) + 1.54*(optimal GP)*(cpur GP) +1.54* (optimal Lees)*(cpur Lees) + 1.54*(optimal Lexington)*(cpur Lexington) + 1.54*(optimal CliftonForge)*(cpur CliftonForge) + 1.54*(optimal BuenaVista)*(cpur BuenaVista) + 1.54*(optimal Covington)*(cpur Covington) + 1.54*(optimal Westvaco)*(cpur Westvaco)

U = Urban
HP = Hay/Pasture
T = Till

Optimal = quantity (pounds of nitrogen discharge) reduced at optimum/equilibrium
Model "unknowns" (decision variables) constrained as,
0 <= BWX optimal <= BWX maximum reduction

cpur = cost per unit reduction

When nonpoint sources are permitted to sell credits and the transport factors are maintained (as they were in the above example), the total cost is $16,635,277 (see Figure 9 for equation). Once again, the full amount from Richmond STP would be purchased. Next, the Till loadings are purchased from hydrologic units g01 to g15 and h33 to h39, each at $2.58 per pound. The transport factor of 1.35 in hydrologic units h03 to h20 causes the price per unit credit to rise to $3.48 per pound. The solution indicates that these should still be purchased as the next least cost option. However, then the transport factor of 1.54 west of hydrologic unit h01 raised the price per pound to $3.97, which is one cent more expensive than reductions at Hopewell STP ($3.96/pound). For this reason, the final 2,958,024 pounds are purchased from Hopewell instead of from Till farming in the mountain region. This option represents a seventy-eight percent (78%) savings when compared to the command and control option for the same reduction. The data for this run are shown in Appendix VII.

Figure 9. Objective Function for Scenario with All Point Sources Held to 40% Reduction Level, Point Source and Nonpoint Source Trades, and with Transport Coefficient.

= SUM(U optimal g1 : U optimal g15)*(cpurU) + (SUM(HP optimal g1 : HP optimal g15)*(cpurHP) + (SUM(T optimal g1 : T optimal g15)*(cpurT) + (SUM(U optimal h33 : U optimal h39)*(cpurU) + SUM(HP optimal h33 : HP optimal h39)*(cpurHP) + (SUM(T optimal h33 : T optimal h39)*(cpurT) + SUM(U optimal h03 : U optimal h20)*(cpurU) + SUM(HP optimal h03 : HP optimal h20)*(cpurHP) + SUM(T optimal h03 : T optimal h20)*(cpurT) + (U optimal h01)*(cpur U) + (HP optimal h01)*(cpur HP) + (T optimal h01)*(cpur h01) + (U optimal i03 : U optimal i28)*(cpur U) +(HP optimal i03 : HP optimal i28)*(cpur HP) + (T optimal i03 : T optimal i28)*(cpur T) + (optimal Allied)*(cpur Allied) + (optimal B&W)*(cpur B&W) + (optimal Dupont)*(cpur Dupont) + (optimal FallingCreek)*(cpur FallingCreek) + (optimal FtEustis)*(cpur FtEustis) + (optimal Henrico)*(cpur Henrico) + (optimal Hopewell)*(cpur Hopewell) + (optimal BoatHarbor)*(cpur BoatHarbor) + (optimal JamesRiverSTP)*(cpur JamesRiverSTP) + (optimal Williamsburg)*(cpur Williamburg) + (optimal PhillipMorris)*(cpur PhillipMorris) + (optimal Richmond)*(cpur Richmond) + (optimal Tyson)*(cpur Tyson) + (optimal Nansemond)*(cpur Nansemond) + (optimal Army)*(cpur Army) + (optimal VIP)*(cpur VIP) + (optimal Hoechst)*(cpur Hoechst) + (optimal Petersburg)*(cpur Petersburg) + (optimal Proctors)*(cpur Proctors) + 1.35*(optimal Moores)*(cpur Moores) + 2.27*(optimal Farmville)*(cpur Farmville) + 1.35*(optimal Lynchburg)*(cpur Lynchburg) + 1.35*(optimal BWX)*(cpur BWX) + 1.54*(optimal GP)*(cpur GP) + 1.54*(optimal Lees)*(cpur Lees) + 1.54*(optimal Lexington)*(cpur Lexington) + 1.54*(optimal CliftonForge)*(cpur CliftonForge) + 1.54*(optimal BuenaVista)*(cpur BuenaVista) + 1.54*(optimal Covington)*(cpur Covington) + 1.54*(optimal Westvaco)*(cpur Westvaco)

U = Urban
HP = Hay/Pasture
T = Till

Optimal = quantity (pounds of nitrogen discharge) reduced at optimum/equilibrium
Model "unknowns" (decision variables) constrained as,
0 <= BWX optimal <= BWX maximum reduction

cpur = cost per unit reduction

If the transport factor were omitted from this last example (see Figure 10) with all else held constant, then trading unrestricted by location would yield an equilibrium cost of $16,391,012, and the resulting distribution purchases all available Till and Richmond STP units and then a smaller portion of Hopewell STP's units. However, a one percent reduction in cost would have to be compared to the uncertainty of appropriate ratios without the transport coefficient.

Figure 10. Objective Function for Scenario with All Point Sources Held to 40% Reduction Level, Point Source and Non-Point Source Trades, and No Transport Coefficient.

= (SUM(U optimal g15 : U optimal i03)*(cpurU) + (SUM(HP optimal g15 : HP optimal i03)*(cpurHP) + (SUM(T optimal g15 : T optimal i03)*(cpurT) + (optimal Allied)*(cpur Allied) + (optimal B&W)*(cpur B&W) + (optimal Dupont)*(cpur Dupont) + (optimal FallingCreek)*(cpur FallingCreek) + (optimal FtEustis)*(cpur FtEustis) + (optimal Henrico)*(cpur Henrico) + (optimal Hopewell)*(cpur Hopewell) + (optimal BoatHarbor)*(cpur BoatHarbor) + (optimal JamesRiverSTP)*(cpur JamesRiverSTP) + (optimal Williamsburg)*(cpur Williamburg) + (optimal PhillipMorris)*(cpur PhillipMorris) + (optimal Richmond)*(cpur Richmond) + (optimal Tyson)*(cpur Tyson) + (optimal Nansemond)*(cpur Nansemond) + (optimal Army)*(cpur Army) + (optimal VIP)*(cpur VIP) + (optimal Hoechst)*(cpur Hoechst) + (optimal Petersburg)*(cpur Petersburg) + (optimal Proctors)*(cpur Proctors) + (optimal Moores)*(cpur Moores) + (optimal Farmville)*(cpur Farmville) + (optimal Lynchburg)*(cpur Lynchburg) + (optimal BWX)*(cpur BWX) + (optimal GP)*(cpur GP) + (optimal Lees)*(cpur Lees) + (optimal Lexington)*(cpur Lexington) + (optimal CliftonForge)*(cpur CliftonForge) + (optimal BuenaVista)*(cpur BuenaVista) + (optimal Covington)*(cpur Covington) + (optimal Westvaco)*(cpur Westvaco)

U = Urban
HP = Hay/Pasture
T = Till

Optimal = quantity (pounds of nitrogen discharge) reduced at optimum/equilibrium
Model "unknowns" (decision variables) constrained as,
0 <= BWX optimal <= BWX maximum reduction

cpur = cost per unit reduction

POLICY IMPLICATIONS

The results of this model are useful as an analysis of basic economic principles applied to a particular watershed. However, the most interesting facets are perhaps those which this model cannot indicate. Several of the assumptions were based on "best judgement," yet the model outcome would be significantly different if some of these were changed.

Point Source Constraints

In order to create a linear relationship between point source and nonpoint source loads, it was assumed that point sources could eliminate quantities as small as a pound of nitrogen. However, in reality, installing BNR is a very large-scale investment. As the CH2M Hill study indicates, capital outlays range from $104,000 to $73 million in capital costs alone for systems that would reduce nitrogen to sustainable levels. Therefore point sources may not actually trade in small units but rather in "chunks" of nitrogen amounts, correlated with the expected efficiencies of BNR systems.

This constraint may actually be an incentive to participate in trading. For example, if Company A only needs to reduce only 10,000 pounds, but its in-house BNR installation would be designed to reduce 20,000 pounds, then it will not see a benefit in paying to reduce double the requirement. Hence it would be willing to pay up to half the cost of the full BNR installation to purchase nitrogen credits rather than having to invest double that amount for in-house reductions.

Information Asymmetry

A trading model assumes that information regarding costs, loads, and reduction measures is exchanged freely and without cost. However, examination of any system in operation will indicate that this does not always hold true. Companies guard their cost data, and gathering and verifying load data is a costly endeavor. There is no central clearinghouse for information, and the permit market may not be as "thick" ("having easily arranged transactions at predictable prices") as the market for labor or raw materials that Hahn and Noll (1983) describe. Any analysis of a model must account for the additional cost (often publicly borne) of information exchange. In the Tar-Pamlico, this extra cost was accounted for in a 10% administration cost to cover the burdens on local agencies and monitoring expenses. However, this cost may not be so straightforward or easy to estimate, and the actual responsibility may be shared by companies for research, government for monitoring, and farm agencies to determine nonpoint source compliance. Because overcoming information asymmetry is not calculated into project costs, the cost per unit reductions in this project are significantly lower than those in documentation of existing programs.

Limitations on Market Interactions

One problem with trading and free market applications is the potential for abuse of the system. For example, there could be price collusion by several large corporations to lower the cost of a reduction credit below the market equilibrium price. One solution to this problem would be to set a minimum price per pound. This could be determined by taking an average of costs per unit reduction and adding a safety factor or administrative cost. Also, the nonpoint source credit sales could be handled through a single agency at a single price. For example, a government-linked farm cooperative could sell credit units for the average of nonpoint source reduction costs plus a safety factor.

In addition, some modeled permit markets would allow non-profit organizations or other groups to participate in the pollution market as "non-dischargers." They would buy allocations to discharge and then retire them in order to reduce the overall pollution level. In the trading market described herein, there is no central clearinghouse for point source trades or initial permit auction; non-dischargers would have to buy directly from individual point sources. This purchase could happen under the current regulatory system but does not, probably due to information asymmetry and lack of interest. However, if an agency were created to centralize nonpoint source projects, there may be more non-discharger participation. Units would probably be less costly and could be purchased in small increments. It does not appear that such an option has been attempted in any existing trading programs, but the idea does arise in theoretical literature on the subject.

Economist Ronald Coase asserts that as long as there is a "clear rule of entitlement" (like a right to pollute through possession of a permit), the optimal result will be reached without regard to the exact initial allocation. The Coase Theorem relies on assumptions of equal access to information and absence of transaction costs. A hypothetical example of the theorem is a smog-producing factory and a nearby village. The factory is "permitted" to have a certain level of air emissions. However, if this is unacceptable to the village, then citizens will be mobilized to determine a "price" that they would pay to decrease air effluents *or* a price that they would accept to put up with the current level of smog (if they threatened to boycott or harm the company in some way).

Economists argue that in this way the socially optimum distribution is achieved since externalities of pollution are compensated. They also argue that even if citizens were allocated "freedom from pollution" rights, there would be some price that the factory could pay to induce sale of rights and achieve the same (optimum) level of pollution as if the factory had initial allocation. However, the real-world market is limited by the hurdle of mobilizing a large enough group of people to counteract a powerful and organized point source discharger (Plater 1992).

Population Growth

Data constraints for this project required the assumption of a steady state condition. However, this is not an accurate representation, as the population in Hampton Roads, VA, is projected to increase significantly. Tied to this is the assumption that point source loads are 100% controllable. While private firms may have the incentive to reduce to zero if the compensation is great enough, municipal wastewater treatment plants have a mandate to provide sewage treatment to the locality. Current nitrogen reduction technology has efficiency limits beyond which it cannot reduce effluent nitrogen loads. In reality, wastewater treatment plant point sources have maximum reductions significantly less than the assumed 100%. Additionally, sewage treatment procedures are tied to the flow (usually measured in million gallons per day (mgd)) of sewage material that enters the plant.

The predicament of wastewater treatment plants becomes clear – a mandate to attain the 40% reduction goal in the face of increasing flow due to population increase. At some point the plant will reach its limit of technology and be unable to comply. At this point trading may provide significant benefit.

There is an unusual twist to this population and development model. As development increases, hay/pasture and till lands are converted to urban lands[11]. This development trend creates increased air pollution, loss of green space, and loss of habitat. However, in the nitrogen loadings realm, urban land loads 8 pounds/acre/year while hay/pasture and till load 7 and 19 pounds/acre/year, respectively. At least for till-to-urban conversion, the associated nitrogen load would actually decrease by 11 pounds/acre/year. Although this decreased load is theoretically beneficial to the system, it would eventually limit the options available for point sources wishing to purchase nitrogen credits. An example in Appendix X explains this concept.

Assessment of a model scenario 10% increase in urban development with land conversion from hay/pasture and till was attempted. However, the solver could not find a solution, since total available nonpoint source loads across the watershed was on the order of 1 million pounds while a 10% increase in point source discharge (corresponding to population increase) was over 7 million pounds. However, if this model had used all of the hydrologic units in the watershed rather than just those adjacent to the river, there would be more nonpoint source loadings reductions available. Therefore, one suggestion for future research would be to determine loading factors which account for distance and

11 Forest land is converted as well. However, since it was omitted from consideration earlier, it is not considered here either.

topography in order to be able to confidently include these parcels.

Trading Ratios

The need for appropriate trading ratios arises from to qualitative differences between sources, both with regards to enforcement costs and uncertainty of nonpoint source loading levels. Nonpoint discharges are more difficult to measure and are stochastic due to weather events such as rainfall. Malik et al (1993) indicate that equating marginal cost of abatement with stochastic loadings does not yield optimal results. He uses a Just and Zilberman (1988) model to assess the possibility of an appropriate trading ratio by deriving a relationship between expected loadings per acre and actual loadings and using a certainty equivalent of the farmer's wealth to estimate reduction cost. The farmer can change the ratio of expected to actual loadings by changing the number of acres on which new technology is applied. Using this ratio as well as enforcement costs, the model provides a benchmark optimum equation to minimize control costs while ensuring environmental quality.

Malik et al concluded that the trading ratio (accounting for loadings uncertainties and enforcement costs) should equal the relative environmental impacts of those loadings from the two sources. The authors find that "uncertainty does not imply *a priori* that the optimal trading ratio is greater than one." However, several existing programs have chosen to forego these intensive calculations in favor of implementation efficiency. The Lake Dillon project uses a NPS:PS ratio of 2:1, and the Tar Pamlico charges point sources double the cost of one nonpoint source BMP reduction unit (plus administrative costs) per pound. Milon (1987) also recommends "ample offset ratios (2:1 or 3:1) which reflect the inherent uncertainty in nonpoint controls as compared to point controls" as an alternative to expensive reliability requirements.

Banking

The biological process of nitrification is seasonally variable. Full nitrification takes place more slowly in winter due to more sluggish reactions at colder temperatures. Therefore, some regulations already account for this seasonal trend by limiting *average annual* nitrogen concentrations, assuming that they will be higher in winter and lower in summer. This variation can be incorporated into the trading process using the banking feature. If permits are traded monthly, credits can be generated in the summer by extra reductions and then could be redeemed during the less efficient winter months. This trading could be conducted either by a single discharger saving credits for itself or by a number of companies in bilateral or multilateral exchanges.

Like the point source arena, nonpoint sources also experience a seasonal variability. Agricultural runoff is most significant during the planting and harvesting months of April through October. However, urban runoff and animal feedlots are likely to have a more constant discharge across the seasonal cycle. In the early part of the planting cycle, high river flows are likely to dilute the nutrient enrichment effects. However, during the low flow, high input summer months, agricultural sources will contribute significant loadings to the waterway. This is a time when the nonpoint source BMP's will act to decrease these loads and ideally even out this peak to be more in line with the year-round runoff levels.

Economic Outcome

The introduction to this project described the difference between cost-benefit analysis and cost-effectiveness or least cost analysis. The latter was chosen in order to compare the costs of several alternatives – command and control and market-based scenarios – all aimed at reaching the same nitrogen reduction. The water quality benefits under each type of reduction were assumed to be equal. However, these benefits were never quantified since it was both difficult and costly to evaluate the benefits of improved water quality. These may include drinking water purity, recreation, swimming and bathing, fish health and abundance, improved stocks of harvestable bivalves, risk avoidance, wetlands functions (storm buffering, habitat) and existence value ("just knowing" that the water is cleaner).

Additionally the equation used accounts for only the private cost (to the company, farmer, or locality) of BMP installation. However, there may also be public costs even beyond government-funded administration. These could include higher sewer bills, more restrictions on drains, loss of access to streams lined with buffers, or reduced sales of fertilizer or heavy equipment. A true cost-benefit analysis would evaluate the net social surplus – the social benefits compared to the social costs under different project scenarios. The evaluation of only private cost was chosen because it enables comparison of the same component (private cost) of different projects and thereby provides an acceptable relative analysis of each. Since data for public costs are difficult to find and often unreliable, a full cost-benefit analysis should be reserved for further along in the policy adoption process when a region can support a thorough examination of a few options, both in terms of data collection and labor needed. The goal at the early stages would be a *qualitative* evaluation of the cost to producer versus the benefits to society and a *quantitative* analysis of costs under different scenarios.

CONCLUSIONS

The goal of this project was to determine the applicability of a trading program to the James River watershed. The James was identified as a candidate for such a scheme because of a need for nutrient reduction, significant nitrogen loads from both point and nonpoint sources, and varying marginal costs of nutrient reduction strategies. Additionally, the Chesapeake Bay Agreement provided a guide (40% reduction) to what might be sustainable loads in the year 2000, even if these were not specified for the James or mandated on a uniform reduction basis. Part of the challenge of nutrient regulation is addressing agricultural sources without a legislative mandate, but Letson (1992) finds that "it is easy to be pessimistic about the prospects for PS/NPS trading. On the other hand, no obvious alternative exists for achieving NPS control on a large scale."

A linear programming model was developed and solved to evaluate potential trading opportunities and the outcome that would minimize private cost. The shortcomings inherent in the model assumptions were also explained, and it was predicted that different assumptions could yield more costly outcomes. While the model indicated cost savings of forty to eighty percent compared to command and control, this may not be an instant signal to switch to the alternative system. Individual regulatory agencies must also consider regulatory oversight, administrative costs, and information availability. Hence, the model results presented herein are not designed to yield a clear determination for or against trading in the James. The goal was instead to provide information regarding potential application of a market-based solution to nitrogen reduction and then allow regulatory agencies to design more specialized evaluation models if the general idea indicates promise. Finally, trading may not become a widely used program until there is a foreseeable increase in the marginal costs of abatement as environmental statutes are tightened. Also, the "demonstration effect" may take hold as localities attempting the new program are having success, or at least encouraging results (Tietenburg 1989).

APPENDICES

Appendix I. Land Use Data and Nitrogen Loadings by Hydrologic Unit.
Source: Chesapeake Bay Program Office 1989 Land Use GIS Coverage,
"Chesapeake Bay Program Nutrient Reduction Strategy Reevaluation, Report #8" (1993).

Key:

Water ac = acres of Water land cover calculated from GIS coverage

Urban ac = acres of High Intensity Development + Low Intensity Development calculated from GIS coverage

HP acres = acres of Hay/Pasture land cover calculated from GIS coverage

Till acres = acres of Row Crop + Probable Row Crop calculated from GIS coverage

Forest ac = acres of Coniferous Forest + Mix Forest + Deciduous Forest calculated from GIS coverage

U/HP/T load = estimated nitrogen loadings by land use in each hydrologic unit, above acreage multiplied by corresponding streamside nitrogen loading factor

HU#	totacres	water ac	urban ac	U loading:	HP acres	HP load	till acres	T load	forest acr:	forst load
g01	103,386	1,770	39,072	312,578	8,034	56,238	9,132	173,514	41,162	102,905
g02	41,526	5,813	3,134	25,074	6,405	44,837	8,138	154,621	31,005	77,512
g03	155,768	10,063	4,314	34,513	9,999	69,992	9,632	183,017	58,718	146,794
g04	74,444	13,439	301	2,406	6,325	44,277	7,759	147,413	56,172	140,431
g08	62,272	8,392	931	7,449	5,646	39,525	5,053	96,003	46,518	116,294
g10	87,907	24,161	2,990	23,921	5,335	37,344	9,957	189,174	41,732	104,329
g11	133,419	67,669	17,930	143,437	11,361	79,530	22,816	433,510	63,462	158,655
g13	59,686	10,730	3,230	25,843	4,404	30,825	11,341	215,471	11,334	28,335
g15	220,023	26,362	42,332	338,655	3,815	26,707	12,566	238,749	7,269	18,173
h01	5,397	1,019	254	2,031	2,381	16,667	2,233	42,430	56,908	142,269
h03	58,378	1,445	13,474	107,792	7,497	52,479	6,806	129,321	48,463	121,157
h05	166,852	1,832	2,418	19,343	8,689	60,823	7,978	151,573	83,225	208,063
h08	64,395	620	55	439	1,885	13,196	1,512	28,728	39,099	97,746
h14	43,356	1,112	59	470	2,135	14,943	2,042	38,798	39,902	99,755
h17	51,870	1,573	798	6,382	10,376	72,631	6,889	130,892	53,054	132,634
h20	55,644	1,296	573	4,588	4,520	31,642	3,159	60,019	44,644	111,610
h33	107,522	2,347	320	2,557	9,793	68,552	8,326	158,185	87,441	218,603
h38	44,806	1,717	661	5,291	8,312	58,182	9,284	176,401	42,839	107,097
h39	124,681	3,896	21,729	173,828	11,517	80,620	15,515	294,779	72,005	180,013
i03	38,605	2,484	4	34	7	50	359	6,830	26,325	65,812
i04	43,376	359	738	5,904	1,827	12,791	3,876	73,636	33,756	84,390
i09	151,112	627	3,132	25,054	695	4,865	1,767	33,574	69,864	174,660
i17	46,345	253	379	3,033	779	5,454	1,184	22,503	46,328	115,821
i18	37,788	447	510	4,080	1,460	10,219	4,555	86,550	47,986	119,964
i24	41,021	710	341	2,729	3,364	23,549	5,759	109,424	31,961	79,903
i27	44,718	552	765	6,121	2,495	17,464	3,370	64,022	47,566	118,915
i28	47,877	399	693	5,547	2,704	18,928	2,677	50,861	31,481	78,703
27/109hu's										
SUM	2,112,174	191,086	161,137	1,289,098	141,762	992,331	183,684	3,489,996	1,260,218	3,150,545
loading factor(lbs/acre/year)			8		7		19		2.5	
total loadings(acres*load factor)			1,289,098		992,331		3,489,996		3,150,545	

Appendix II. Nonpoint Source Loading Data.
Source: Chesapeake Bay Program 1989 Land Use GIS Coverage,
York River Tributary Strategy (1998).

Key:

Load = nitrogen loadings calculated from GIS land use coverage

U/HP/T max = maximum nitrogen reduction possible with given Best Management Practices technology, above loadings multiplied by BMP efficiencies

HU#	**U load**	**HP load**	**till load**	**U max**	**HP max**	**T max**
g01	312,578	56,238	173,514	103,151	19,683	36,438
g02	25,074	44,837	154,621	8,274	15,693	32,470
g03	34,513	69,992	183,017	11,389	24,497	38,434
g04	2,406	44,277	147,413	794	15,497	30,957
g08	7,449	39,525	96,003	2,458	13,834	20,161
g10	23,921	37,344	189,174	7,894	13,071	39,727
g11	143,437	79,530	433,510	47,334	27,835	91,037
g13	25,843	30,825	215,471	8,528	10,789	45,249
g15	338,655	26,707	238,749	111,756	9,347	50,137
h01	2,031	16,667	42,430	670	5,834	8,910
h03	107,792	52,479	129,321	35,571	18,368	27,157
h05	19,343	60,823	151,573	6,383	21,288	31,830
h08	439	13,196	28,728	145	4,619	6,033
h14	470	14,943	38,798	155	5,230	8,148
h17	6,382	72,631	130,892	2,106	25,421	27,487
h20	4,588	31,642	60,019	1,514	11,075	12,604
h33	2,557	68,552	158,185	844	23,993	33,219
h38	5,291	58,182	176,401	1,746	20,364	37,044
h39	173,828	80,620	294,779	57,363	28,217	61,904
i03	34	50	6,830	11	18	1,434
i04	5,904	12,791	73,636	1,948	4,477	15,464
i09	25,054	4,865	33,574	8,268	1,703	7,050
i17	3,033	5,454	22,503	1,001	1,909	4,726
i18	4,080	10,219	86,550	1,347	3,576	18,176
i24	2,729	23,549	109,424	900	8,242	22,979
i27	6,121	17,464	64,022	2,020	6,113	13,445
i28	5,547	18,928	50,861	1,830	6,625	10,681
BMP effic	33%	35%	21%			

Appendix III. Point Source Loadings Data.

Source: Chesapeake Bay Program Office (1998), "Chesapeake Bay Program Nutrient Reduction Strategy Reevaluation, Report #8" (1993).

Key:

Nquant1996 =	1996 nitrogen loadings
w/ 40% red =	loadings reflecting attainment of 40% reduction goal, 1985 nitrogen loadings multiplied by 0.60
red needs =	reduction needed in 1996 to attain 40% reduction goal, 1996 loads with 40% reduction level subtracted
xMax =	maximum pounds available for sale, either remaining discharges (for companies already below 40% goal) or 1996 loads with reduction needs subtracted (for companies still having reduction needs)
cpur =	cost per unit reduction

Facility	Nquant1996	w/ 40% red	red needs	xMax	cpur
Hoechst Celanese	10,792	59,430		10,792	$20.00
HRSD-Virginia Initiative Plant	1,432,292	802,072	630,220	802,072	$12.94
HRSD-Army Base	824,403	464,076	360,327	464,076	$10.99
HRSD-Nansemond	727,638	305,477	422,161	305,477	$12.35
HRSD-Boat Harbor STP	1,067,511	646,440	421,071	646,440	$20.39
HRSD-James River STP	960,589	378,655	581,934	378,655	$5.94
Fort Eustis	52,915	56,355		52,915	$23.20
HRSD-Williamsburg STP	389,679	379,209	10,469	379,209	$282.09
Allied Signal	1,368,610	2,676,373		1,368,610	$20.00
Philip Morris	260,779	91,170	169,609	91,170	$20.00
Brown & Williamson	41,483	29,611	11,872	29,611	$20.00
Henrico County WWTP	2,015,704	0		2,015,704	$20.00
Falling Creek STP	366,990	460,712		366,990	$20.00
Dupont-Spruance	119,611	110,332	9,279	110,332	$20.00
Hopewell STP	4,172,711	3,660,638	512,073	3,660,638	$3.96
Richmond City STP	1,722,286	1,477,724	244,562	1,477,724	$2.16
Tyson Foods/Holly Farm	120,201	79,484	40,717	79,484	$20.00
Petersburg STP	299,115	307,910		299,115	$5.84
Chesterfield Co/Proctors Creek	216,426	105,972	110,454	105,972	$5.30
Farmville STP	65,503	10,589	54,914	10,589	$20.00
Moores Creek STP (C'ville)	448,750	173,185	275,565	173,185	$20.00
Lynchburg STP	671,681	276,984	394,697	276,984	$20.00
Babcock & Wilcox	194,772	436,947		194,772	$20.00
Georgia-Pacific	223,124	32,870	190,255	32,870	$20.00
Lexington STP	63,447	29,986	33,461	29,986	$20.00
Lees Commercial Carpet	78,317	14,627	63,690	14,627	$20.00
Buena Vista STP	124,381	64,197	60,184	64,197	$20.00
Clifton Forge STP	85,091	38,931	46,160	38,931	$20.00
Westvaco Corp-Covington Hall	701,787	332,890	368,897	332,890	$20.00
Covington STP	118,842	65,630	53,212	65,630	$20.00

Appendix IV. Model Output for Scenario with Lynchburg STP Achieving 40% Reduction Through Trading, Point Source and Nonpoint Source Trades, Transport Coefficient

Key:

U/HP/T max =	maximum nitrogen reduction possible with given Best Management Practices technology
U/HP/T optimal =	decision variable outcome, pounds of nitrogen reduced in an optimal (model output) scenario
xMax =	maximum pounds available for sale
cpur =	cost per unit reduction
optimal =	decision variable outcome, pounds of nitrogen from a point source reduced in an optimal (model output) scenario

HU#	U optimal	HP optimal	T optimal	U max	HP max	T max
g01				103,151	19,683	36,438
g02				8,274	15,693	32,470
g03				11,389	24,497	38,434
g04				794	15,497	30,957
g08				2,458	13,834	20,161
g10				7,894	13,071	39,727
g11				47,334	27,835	91,037
g13				8,528	10,789	45,249
g15				111,756	9,347	50,137
h01	0	5,834	8,910	670	5,834	8,910
h03	0	18,368	27,157	35,571	18,368	27,157
h08				145	4,619	6,033
h14				155	5,230	8,148
h17				2,106	25,421	27,487
h20				1,514	11,075	12,604
h33				844	23,993	33,219
h38				1,746	20,364	37,044
h39				57,363	28,217	61,904
i03	0	18	1,434	11	18	1,434
i04	0	4,477	15,464	1,948	4,477	15,464
i09	0	1,703	7,050	8,268	1,703	7,050
i17	0	1,909	4,726	1,001	1,909	4,726
i18	0	3,576	18,176	1,347	3,576	18,176
i24	0	8,242	22,979	900	8,242	22,979
i27	0	6,113	13,445	2,020	6,113	13,445
i28	0	6,625	10,681	1,830	6,625	10,681

objective function
$4,888,455
sum constraint
394,697 pounds

Facility	xMax	cpur	optimal
Hoechst Celanese	10,792		
HRSD-VA Initiative Plant	802,072	$12.94	
HRSD-Army Base	464,076	$10.99	
HRSD-Nansemond	305,477	$12.35	
HRSD-Boat Harbor STP	646,440	$20.39	
HRSD-James River STP	378,655	$5.94	
Fort Eustis	52,915	$23.20	
HRSD-Williamsburg STP	379,209	$282.09	
Allied Signal	1,368,610	$20	
Phillip Morris-Park 500	91,170	$20	
Brown & Williamson	29,611	$20	
Henrico County WWTP		$20	
Falling Creek STP	366,990	$20	
Dupont-Spruance	110,332	$20	
Hopewell	3,660,638	$3.96	
Richmond City	1,477,724	$2.16	
Tyson Foods/Holly Farms	79,484	$20	
S.Cent.WWTP Petersburg	299,115	$5.84	
Proctors Creek-Chesterfield	105,972	$5.30	
Farmville	10,589	$20	
Moores Creek-Charlottesville	173,185	$20	
Lynchburg	276,984	$20	
Babcock & Wilcox	194,772	$20	194772
Georgia-Pacific	32,870	$20	0
Lexington STP	29,986	$20	0
Lees Commercial Carpet	14,627	$20	0
Buena Vista	64,197	$20	0
Clifton Forge STP	38,931	$20	0
Westvaco Corp-Covington Hall	332,890	$20	0
Covington	65,630	$20	13040

Appendix V. Model Output for Scenario with Proctors Creek (Chesterfield) STP Achieving 40% Reduction Through Trading, Point Source and Nonpoint Source Trades, Transport Coefficient

Key:

U/HP/T max =	maximum nitrogen reduction possible with given Best Management Practices technology
U/HP/T optimal =	decision variable outcome, pounds of nitrogen reduced in an optimal (model output) scenario
xMax =	maximum pounds available for sale
cpur =	cost per unit reduction
optimal =	decision variable outcome, pounds of nitrogen from a point source reduced in an optimal (model output) scenario

HU#	U optimal	HP optimal	T optimal	U max	HP max	T max
g01				103,151	19,683	36,438
g02				8,274	15,693	32,470
g03				11,389	24,497	38,434
g04				794	15,497	30,957
g08				2,458	13,834	20,161
g10				7,894	13,071	39,727
g11				47,334	27,835	91,037
g13				8,528	10,789	45,249
g15				111,756	9,347	50,137
h01				670	5,834	8,910
h03				35,571	18,368	27,157
h08				145	4,619	6,033
h14				155	5,230	8,148
h17				2,106	25,421	27,487
h20				1,514	11,075	12,604
h33			110,445	844	23,993	33,219
h38				1,746	20,364	37,044
h39				57,363	28,217	61,904
i03				11	18	1,434
i04				1,948	4,477	15,464
i09				8,268	1,703	7,050
i17				1,001	1,909	4,726
i18				1,347	3,576	18,176
i24				900	8,242	22,979
i27				2,020	6,113	13,445
i28				1,830	6,625	10,681

objective function
$284,831
sum constraint
110,445 pounds

Facility	xMax	cpur	optimal
Hoechst Celanese	10,792		
HRSD-VA Initiative Plant	802,072	$12.94	
HRSD-Army Base	464,076	$10.99	
HRSD-Nansemond	305,477	$12.35	
HRSD-Boat Harbor STP	646,440	$20.39	
HRSD-James River STP	378,655	$5.94	
Fort Eustis	52,915	$23.20	
HRSD-Williamsburg STP	379,209	$282.09	
Allied Signal	1,368,610	$20	
Phillip Morris-Park 500	91,170	$20	
Brown & Williamson	29,611	$20	
Henrico County WWTP		$20	
Falling Creek STP	366,990	$20	
Dupont-Spruance	110,332	$20	
Hopewell	3,660,638	$3.96	
Richmond City	1,477,724	$2.16	
Tyson Foods/Holly Farms	79,484	$20	
S.Cent.WWTP Petersburg	299,115	$5.84	
Proctors Creek-Chesterfield	105,972	$5.30	
Farmville	10,589	$20	
Moores Creek-Charlottesville	173,185	$20	
Lynchburg	276,984	$20	
Babcock & Wilcox	194,772	$20	
Georgia-Pacific	32,870	$20	
Lexington STP	29,986	$20	
Lees Commercial Carpet	14,627	$20	
Buena Vista	64,197	$20	
Clifton Forge STP	38,931	$20	
Westvaco Corp-Covington Hall	332,890	$20	
Covington	65,630	$20	

Appendix VI. All Sources Achieving 40% Reduction Through Trading, Point Source Trades Only, Transport Coefficients

Key:

N load 1996 = 1996 nitrogen loadings

w/ 40% red = loadings reflecting attainment of 40% reduction goal, 1985 nitrogen loadings multiplied by 0.60

red needs = reduction needed in 1996 to attain 40% reduction goal, 1996 loads with 40% reduction level subtracted

xMax = maximum pounds available for sale, either remaining discharges (for companies already below 40% goal) or 1996 loads with reduction needs subtracted (for companies still having reduction needs)

cpur = cost per unit reduction

optimal = decision variable outcome, pounds of nitrogen from a point source reduced in an optimal (model output) scenario

Facility	N load 1996	w/ 40% red.	red. Needs	xMax	cpur	optimal
Hoechst Celanese	10,792	59,430		10,792	$20.00	0
HRSD-VA Initiative Plant	1,432,292	802,072	630,220	802,072	$12.94	0
HRSD-Army Base	824,403	464,076	360,327	464,076	$10.99	0
HRSD-Nansemond	727,638	305,477	422,161	305,477	$12.35	0
HRSD-Boat Harbor STP	1,067,511	646,440	421,071	646,440	$20.39	0
HRSD-James River STP	960,589	378,655	581,934	378,655	$5.94	0
Fort Eustis	52,915	56,355		52,915	$23.20	0
HRSD-Williamsburg STP	389,679	379,209	10,469	379,209	$282.09	0
Allied Signal	1,368,610	2,676,373		1,368,610	$20.00	0
Phillip Morris-Park 500	260,779	91,170	169,609	91,170	$20.00	0
Brown & Williamson	41,483	29,611	11,872	29,611	$20.00	0
Henrico County WWTP	2,015,704	0		2,015,704	$20.00	0
Falling Creek STP	366,990	460,712		366,990	$20.00	0
Dupont-Spruance	119,611	110,332	9,279	110,332	$20.00	0
Hopewell	4,172,711	3,660,638	512,073	3,660,638	$3.96	3,588,060
Richmond City	1,722,286	1,477,724	244,562	1,477,724	$2.16	1,477,724
Tyson Foods/Holly Farm	120,201	79,484	40,717	79,484	$20.00	0
S.Cent. WWTP Petersburg	299,115	307,910		299,115	$5.84	0
Proctors Creek-Chesterfield	216,426	105,972	110,454	105,972	$5.30	0
Farmville STP	65,503	10,589	54,914	10,589	$20.00	0
Moores Creek-Charlottesville	448,750	173,185	275,565	173,185	$20.00	0
Lynchburg STP	671,681	276,984	394,697	276,984	$20.00	0
Babcock & Wilcox	194,772	436,947		194,772	$20.00	0
Georgia-Pacific	223,124	32,870	190,255	32,870	$20.00	0
Lexington STP	63,447	29,986	33,461	29,986	$20.00	0
Lees Commercial Carpet	78,317	14,627	63,690	14,627	$20.00	0
Buena Vista	124,381	64,197	60,184	64,197	$20.00	0
Clifton Forge STP	85,091	38,931	46,160	38,931	$20.00	0
Westvaco	701,787	332,890	368,897	332,890	$20.00	0
Covington STP	118,842	65,630	53,212	65,630	$20.00	0

objective function
$17,402,990
sum constraint
5,065,784

Appendix VII. All Sources Achieving 40% Reduction Through Trading, Point and Nonpoint Source Trades, Transport Coefficients

Key:

N load 1996 = 1996 nitrogen loadings

w/ 40% red = loadings reflecting attainment of 40% reduction goal, 1985 nitrogen loadings multiplied by 0.60

red needs = reduction needed in 1996 to attain 40% reduction goal, 1996 loads with 40% reduction level subtracted

xMax = maximum pounds available for sale, either remaining discharges (for companies already below 40% goal) or 1996 loads with reduction needs subtracted (for companies still having reduction needs)

cpur = cost per unit reduction

optimal = decision variable outcome, pounds of nitrogen from a point source reduced in an optimal (model output) scenario

HU#	U optimal	HP optimal	T optimal	U max	HP max	T max
g01	0	0	36,438	103,151	19,683	36,438
g02	0	0	32,470	8,274	15,693	32,470
g03	0	0	38,434	11,389	24,497	38,434
g04	0	0	30,957	794	15,497	30,957
g08	0	0	20,161	2,458	13,834	20,161
g10	0	0	39,727	7,894	13,071	39,727
g11	0	0	91,037	47,334	27,835	91,037
g13	0	0	45,249	8,528	10,789	45,249
g15	0	0	50,137	111,756	9,347	50,137
h01	0	0	0	670	5,834	8,910
h03	0	0	27,157	35,571	18,368	27,157
h05	0	0	31,830	6,383	21,288	31,830
h08	0	0	6,033	145	4,619	6,033
h14	0	0	8,148	155	5,230	8,148
h17	0	0	27,487	2,106	25,421	27,487
h20	0	0	12,604	1,514	11,075	12,604
h33	0	0	33,219	844	23,993	33,219
h38	0	0	37,044	1,746	20,364	37,044
h39	0	0	61,904	57,363	28,217	61,904
i03	0	0	0	11	18	1,434
i04	0	0	0	1,948	4,477	15,464
i09	0	0	0	8,268	1,703	7,050
i17	0	0	0	1,001	1,909	4,726
i18	0	0	0	1,347	3,576	18,176
i24	0	0	0	900	8,242	22,979
i27	0	0	0	2,020	6,113	13,445
i28	0	0	0	1,830	6,625	10,681

objective function
$16,635,278
sum constraint
5,065,784 pounds

Facility	xMax	cpur	optimal
Hoechst Celanese	10,792	$20.00	0
HRSD-VA Initiative Plant	802,072	$12.94	0
HRSD-Army Base	464,076	$10.99	0
HRSD-Nansemond	305,477	$12.35	0
HRSD-Boat Harbor STP	646,440	$20.39	0
HRSD-James River STP	378,655	$5.94	0
Fort Eustis	52,915	$23.20	0
HRSD-Williamsburg STP	379,209	$282.09	0
Allied Signal	1,368,610	$20.00	0
Phillip Morris-Park 500	91,170	$20.00	0
Brown & Williamson	29,611	$20.00	0
Henrico County WWTP	2,015,704	$20.00	0
Falling Creek STP	366,990	$20.00	0
Dupont-Spruance	110,332	$20.00	0
Hopewell	3,660,638	$3.96	2,958,024
Richmond City	1,477,724	$2.16	1,477,724
Tyson Foods/Holly Farm	79,484	$20.00	0
S.Cent. WWTP Petersburg	299,115	$5.84	0
Proctors Creek-Chesterfield	105,972	$5.30	0
Farmville STP	10,589	$20.00	0
Moores Creek-Charlottesvill	173,185	$20.00	0
Lynchburg STP	276,984	$20.00	0
Babcock & Wilcox	194,772	$20.00	0
Georgia-Pacific	32,870	$20.00	0
Lexington STP	29,986	$20.00	0
Lees Commercial Carpet	14,627	$20.00	0
Buena Vista	64,197	$20.00	0
Clifton Forge STP	38,931	$20.00	0
Westvaco	332,890	$20.00	0
Covington STP	65,630	$20.00	0

Appendix VIII. All Sources Achieving 40% Reduction Through Trading, Point and Nonpoint Source Trades, No Transport Coefficients

Key:

N load 1996 = 1996 nitrogen loadings

w/ 40% red = loadings reflecting attainment of 40% reduction goal, 1985 nitrogen loadings multiplied by 0.60

red needs = reduction needed in 1996 to attain 40% reduction goal, 1996 loads with 40% reduction level subtracted

xMax = maximum pounds available for sale, either remaining discharges (for companies already below 40% goal) or 1996 loads with reduction needs subtracted (for companies still having reduction needs)

cpur = cost per unit reduction

optimal = decision variable outcome, pounds of nitrogen from a point source reduced in an optimal (model output) scenario

HU#	U optimal	HP optimal	Toptimal	U max	HP max	T max
g01	0	0	36438	103151	19683	36438
g02	0	0	32470	8274	15693	32470
g03	0	0	38434	11389	24497	38434
g04	0	0	30957	794	15497	30957
g08	0	0	20161	2458	13834	20161
g10	0	0	39727	7894	13071	39727
g11	0	0	91037	47334	27835	91037
g13	0	0	45249	8528	10789	45249
g15	0	0	50137	111756	9347	50137
h01	0	0	8910	670	5834	8910
h03	0	0	27157	35571	18368	27157
h05	0	0	31830	6383	21288	31830
h08	0	0	6033	145	4619	6033
h14	0	0	8148	155	5230	8148
h17	0	0	27487	2106	25421	27487
h20	0	0	12604	1514	11075	12604
h33	0	0	33219	844	23993	33219
h38	0	0	37044	1746	20364	37044
h39	0	0	61904	57363	28217	61904
i03	0	0	1434	11	18	1434
i04	0	0	15464	1948	4477	15464
i09	0	0	7050	8268	1703	7050
i17	0	0	4726	1001	1909	4726
i18	0	0	18176	1347	3576	18176
i24	0	0	22979	900	8242	22979
i27	0	0	13445	2020	6113	13445
i28	0	0	10681	1830	6625	10681

objective function

$16,391,013

sum constraint

5,065,784 pounds

Facility	xMax	cpur	optimal
Hoechst Celanese	10792	$20.00	0
HRSD-VA Initiative Plant	802072	$12.94	0
HRSD-Army Base	464076	$10.99	0
HRSD-Nansemond	305477	$12.35	0
HRSD-Boat Harbor STP	646440	$20.39	0
HRSD-James River STP	378655	$5.94	0
Fort Eustis	52915	$23.20	0
HRSD-Williamsburg STP	379209	$282.09	0
Allied Signal	1368610	$20.00	0
Phillip Morris-Park 500	91170	$20.00	0
Brown & Williamson	29611	$20.00	0
Henrico County WWTP	2015704	$20.00	0
Falling Creek STP	366990	$20.00	0
Dupont-Spruance	110332	$20.00	0
Hopewell	3660638	$3.96	2,855,160
Richmond City	1477724	$2.16	1,477,724
Tyson Foods/Holly Farm	79484	$20.00	0
S.Cent. WWTP Petersburg	299115	$5.84	0
Proctors Creek-Chesterfield	105972	$5.30	0
Farmville STP	10589	$20.00	0
Moores Creek-Charlottesville	173185	$20.00	0
Lynchburg STP	276984	$20.00	0
Babcock & Wilcox	194772	$20.00	0
Georgia-Pacific	32870	$20.00	0
Lexington STP	29986	$20.00	0
Lees Commercial Carpet	14627	$20.00	0
Buena Vista	64197	$20.00	0
Clifton Forge STP	38931	$20.00	0
Westvaco	332890	$20.00	0
Covington STP	65630	$20.00	0

Appendix IX. Method for Model Solutions.

Data were input into Microsoft Excel spreadsheets under the following column categories: hydrologic unit number, maximum pounds of nitrogen removal available, point source facility name, maximum point source nitrogen reduction available, and cost per unit reduction. Blank columns wre created for the decision variables and were titled "optimal". The objective function equation was entered into one cell, using Excel references to the other cells on the spreadsheet (see equations in text which accompany each model results section). The solution in this "objective function" cell would be the total private cost under a given scenario.

Once all the data were entered, the Solver function was specified. The "objective function" cell into the top cell with directions to minimize that equation by changing the cells which contained the corresponding "optimal" decision variables (at that point, blank cells). The constraints were that the "sum constraint" cell must equal another cell which contained the numerical value of pounds to be reduced in that scenario. "Optimal" cells were all constrained to be positive and less than the corresponding maximum reduction capacity. "Non-negative" and "assume linear" were selected under the options. The model was directed to run for no more than 100 iterations.

Appendix X. Example of Population Growth Scenario.

Assume that there is a system with only one point source that has fully exploited its in-house nutrient reduction capacities. It needs to purchase 250 pounds of nonpoint source credits. The surrounding land use is as follows:

Urban	**Hay/Pasture**	**Till**	
20 acres	30 acres	50 acres	

multiplied by the loading factors

20(8)	30(7)	50(19)	

equals pounds of nonpoint source nitrogen

160 lbs	210 lbs	950 lbs	=1320lbs in watershed.

Multiplying total pounds by the BMP efficiencies

160(.33)	210(.35)	950(.21)	

yields pounds available for trading

52.8 lbs	73.5 lbs	199.5 lbs	=325.8 lbs for trading.

The point source would buy the following credits

0	50.5	199.5	

at the price of

$61.25/lb	$5.43/lb	$2.58/lb	

for a total cost of

0	$274.22	$514.71	= total cost $788.93.

Now 10 acres are converted from till to urban land for development yielding new amounts of each land use

30 acres	30 acres	40 acres	

and new nitrogen loading quantities

240 lbs	210 lbs	760 lbs	=1210lbs in watershed

The pounds available for trading after conversion are

79.2 lbs	73.5 lbs	159.6 lbs	=312.3 lbs for trading.

Under this plan, the point source would buy the following credits,

16.9	73.5	159.6

and the cost per unit reduction would be the same,

$61.25	$5.43	$2.58

for a total cost of

$1035.13	$399.11	$411.77	= total cost $1846.

Under the population and development intensification scenario, with a 10 acre land conversion, there would be a decrease of 110 lbs of nitrogen loadings but an increase in trading cost of $1058. At some point, given the constraint on nitrogen loads, there will come a threshold where conversion of another acre to urban land use, with accompanying loading increase to point sources, will be economically infeasible due to lack of offsets.

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VITA

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