Multipurpose Approaches to Regional Goals: Chapters in Environmental and Development Economics

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(ABSTRACT)

This dissertation presents three chapters of contemporary research in environmental and development economics. Each chapter echoes a common theme, in that achievement of regional goals constitute 'Wicked Problems' and that the approaches that parties may take to address these specific regional goals may have complex interactions with other regional goals. Decision-making, cost analysis, and multipurpose efficacy of the approaches that regional parties may take to achieve goals are evaluated in environmental and development contexts and implications for program analysis and policy design are discussed.

The first chapter of this dissertation seeks to understand how regulated parties, i.e. Municipal Separate Storm Sewer Systems (MS4s), choose from the strategies at their disposal to achieve compliance with their Chesapeake Bay Total Maximum Daily Load (TMDL) obligations. To address declining Chesapeake Bay water quality, the United States Environmental Protection Agency (EPA) set extensive nutrient and sediment reduction goals under the 2010 Chesapeake Bay TMDL. Virginia has responded by passing along explicit nutrient and sediment reduction requirements to its MS4s, which can choose from a variety of urban stormwater, land use change, source control, and restoration practices to achieve reductions toward these requirements. MS4s in Virginia have also been granted flexibility to achieve reduction requirements through purchase of nutrient and sediment credits toward requirements through trade. In spite of the cost-savings that these credits provide, MS4s' interest in trading for these credits has been low. MS4s instead generally engage in onsite nutrient and sediment reduction themselves, in spite of the high costs of doing so. In response to low interest in trade, case analysis of MS4s' Bay TMDL compliance behavior and semi-structured interviews are conducted to better understand the role of trade in compliance strategy and the reasons for its non-use. Findings reveal that the Virginia MS4s studied typically choose to implement onsite urban stormwater practices, source control practices, and restoration practices in order to generate long-lasting local benefits, like erosion control, flood risk reduction, and progress toward local TMDL obligations, alongside reductions toward the Bay TMDL. MS4s refrain from term credit purchases out of concern over future availability and refrain from perpetual credit purchases because they have been able to use funding sources to achieve reductions from long-lasting onsite practices at similar per-pound costs, while also receiving local benefits. Implications are that supply-side efforts to support trade markets may not generate the level of activity expected, given that would-be buyers have generally limited interest in trade as a compliance strategy.

The second chapter studies the degree to which the practices used to meet local TMDL water quality obligations contribute to Bay TMDL compliance for the Loudoun County MS4. Linear programming is used to estimate the minimal cost of achieving Bay compliance in addition to local obligations through representative nutrient and sediment reduction strategies.

The model estimates that Loudoun County MS4 faces substantial costs just to meet local water quality goals ($11 million/yr). Since many of the actions taken to meet local water quality goals also generate pollutant reductions to the Chesapeake Bay, adding Bay TMDL obligations adds 0.2%, 3%, and 32.9% to these costs, depending on the water quality trading used to reach Bay TMDL compliance. Findings shed additional light on Chapter 1's goal of investigating the role of trade by explaining low interest in trade as stemming from heavy local water quality needs. Implications are that the burden imposed by the Bay TMDL may not be as high as generally thought.

The third chapter shifts focus to the Opioid Crisis to evaluate the efficacy of Syringe Exchange Programs, best known for their efforts to prevent bloodborne illness transmission, at achieving their secondary intervention goal of preventing opioid overdose. While research has established that Syringe Exchange Programs, or SEPs, are effective at preventing bloodborne illness, little focus has been given to their ability to prevent fatal overdose, which they aim to do by engaging in intervention practices like naloxone and fentanyl test strip distribution. In response for need for understanding of Syringe Exchange Programming's impact on overdose, fixed effects analysis is used to empirically study the impact of county-level SEP in North Carolina following the state's 2016 SEP legalization. Need-based programming complicates analysis and likely biases findings of the impact of SEP on overdose upward. Regardless, findings consistently fail to find that SEP has a significant effect on fatal overdose from four categories of opioids, which should reduce concerns in recent literature that they may increase overdose death. Implications are that, since SEPs have a richly documented history of saving lives through the prevention of bloodborne illness and do not appear to increase overdose, contrary to findings in other work, policy makers should continue to incorporate SEP into their portfolio of strategies used to address the Opioid Crisis.

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(GENERAL AUDIENCE ABSTRACT)

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Dedication

This work is dedicated to my family and friends who have supported me throughout my time at Virginia Tech. Though there are truly too many individuals to list, I would like to begin by thanking my family, James, Jennifer, and Lauren Ferris. I would like to thank the faculty of Virginia Tech's Department of Agricultural and Applied Economics for their support throughout my time at Virginia Tech. In particular, I would like to thank my advisor, Dr. Kurt Stephenson, and my committee members, Dr. Bradford Mills, Dr. Zachary Easton, and Dr. Darrell Bosch. I would also like to thank Dr. Wen You, Dr. Susan Chen, Dr. Kelly Cobourn, Dr. Sarah Lyon-Hill, Dr. Mary Kasarda, and Normand Adams for support throughout my Ph.D. journey. I would also like to thank Amanda Hodes, Stephen Walsh, JoAnna Platzer, Claire Gleason, Samir Chethan, Elyce Buell, Kory Wait, Ange Kakpo, Konstantinos Syrengelas, Jinyang Yang, Alexis Villacis, and Roger and Leslie Slusher.

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List of Abbreviations

BMP	Best Management Practice
CBP	Chesapeake Bay Program
CDC	Centers for Disease Control and Prevention
CWA	Clean Water Act
DEQ	Virginia Department of Environmental Quality
EPA	Environmental Protection Agency
ERS	United States Department of Agriculture's Economic Research Service
FE	'Fixed Effects', as in a 'fixed effects model'.
HUC	Hydrologic Unit Code
Imp.	Impervious, as in 'Impervious Land'
MS4	Municipal Separate Storm Sewer System
MSM	Men Who Have Sex With Men
N	Nitrogen
NCDHHS	North Carolina Department of Health and Human Services
NIMBY	Not In My Backyard
NPS	Nonpoint source

O&M	Operations and Maintenance
Opp.	Opportunity Costs, as in ‘Land Opportunity Costs’
P	Phosphorus
Perv.	Pervious, as in ‘Pervious Land’
PS	Point Source
Reqs.	Requirements, as in ‘Bay TMDL Requirements’
Rest.	Restoration, as in ‘Stream Restoration’
SEP	Syringe Exchange Program
SLAF	Stormwater Local Assistance Fund
TMDL	Total Maximum Daily Load
TSS	Total Suspended Solids; analogous to ‘Sediment’
USDA	United States Department of Agriculture
WLA	Wasteload Allocation
WQT	Water Quality Trade/Trading/Trades
WWTP	Wastewater Treatment Plant

Chapter 1

The Role of Nutrient Credit Trading for Chesapeake Bay TMDL Compliance: Evidence from Virginia's MS4s

1.1 Abstract

Water quality credit trading has been advanced as a cost-effective means of achieving regulatory compliance. However, the volume of trading activity in operational programs is typically less than estimated by empirical analysis. The compliance compliance behavior of Virginia Municipal Separate Storm Sewer Systems (MS4s) is studied in response to the Chesapeake Bay Total Maximum Daily Load (TMDL) to understand the circumstances in which trading is adopted, the extent to which trading is adopted, and the factors contributing to trading's use or non-use. Findings suggest that MS4s prefer to implement onsite practices, especially urban stormwater BMPs, source control practices and restoration practices, to generate reductions toward the Bay TMDL and reserve trade as a backup option to be exercised, if need be, to ensure compliance can be achieved. MS4s prefer onsite options to term credits out of concern for term credit availability in the future, even though these credits offer cost-savings. MS4s prefer onsite options to perpetual credits because, in addition to reductions toward Bay TMDL requirements, onsite options provide a number of local benefits, such as erosion control, infrastructure protection, and reductions toward local TMDL obligations, over long horizons. MS4s have been able to support onsite practice implementation through use of public land and leverage of grant funding. Findings may explain low interest in trade as stemming from demand-side considerations and set expectations for future trading markets.

1.2 Introduction

Water quality trading (WQT) has been proposed as a way for regulated parties with pollution control obligations to lower the costs of regulatory compliance. In water quality trading, a regulated party subject to pollution reduction requirements contracts another party to engage in pollutant reduction on the regulated party's behalf. The resulting reductions are then credited toward the regulated party's compliance requirements. The regulated party has incentive to purchase pollutant reduction credits if credit providers can supply the necessary pollution abatement at marginal costs lower than those the regulated party is able to otherwise achieve.

Empirical research into pollution abatement costs consistently demonstrates water quality trading's potential to provide regulated parties with substantial cost savings in a variety of trade settings (Van Houtven et al., 2012; Wainger et al., 2013; McManus et al., 2019; Wieland et al., 2009; Fang & Easter, 2003; Tao et al., 2000; Hung & Shaw, n.d.; Farrow et al., 2005). In addition, government agencies and industry groups have dedicated significant effort to supporting water quality trading programs (USDA OCE, n.d.; ACWA & Willamette Partnership, 2016; EPA, 2022d). The Environmental Protection Agency (EPA) has produced a series of guidance documents since 1996 to support water quality trading (EPA, 1996, 2022c). The United States Department of Agriculture (USDA) has encouraged trade because agricultural entities represent a potential low-cost supplier of credits and because water quality trading is seen as a potential revenue stream for farmers (USDA OCE., n.d.; Davis, 2013; Mills, 2017; Zook, 2014). Furthermore, trading has seen support under the Clinton, Bush, Obama, Trump, and Biden administrations (EPA OW, 1994; The White House, n.d.; Steinzor et al., 2012; USDA Press, 2018; EPA, 2022c).

In spite of regulatory support for trade program development, water quality trading often fails to generate the level of trading activity suggested by empirical research (Fisher-Vanden & Olmstead, 2013; Stephenson & Shabman, 2017c; Hoag et al., 2017; Ribaudo & Nickerson, 2009). Policy analysts advance numerous possible explanations for limited trading. Sizeable research interest focuses on the credit supply from nonpoint sources, which are primarily from agricultural sources, and on the factors that may discourage nonpoint source credit producers from entering water quality trade (WQT) credit markets. Factors that could limit the supply of nonpoint source credits include transaction costs, perceived risks of participating in trade with regulatory sources, and regulatory rules that drive up the price of nonpoint source credits (trading ratios, credit baseline definitions, verification requirements, etc.), all of which may increase seller costs and reduce seller willingness to participate in trade (Nguyen & Shortle, 2006; DeBoe & Stephenson, 2016; Motallebi et al., 2017; O'Connell et al., 2017; Ribaudo & Gottlieb, 2011; Ribaudo et al., 2014).

Less research has focused on potential demand-side barriers to water quality trade. Researchers have pointed out that discharges regulated under the U.S. Clean Water Act (CWA) permitting programs face a number of institutional impediments that may reduce their ability or incentive to trade (Shabman & Stephenson, 2007; Stephenson & Shabman, 2017a, 2017c; Fisher-Vanden & Olmstead, 2013). For example, the existence of technology-based permit requirements, mandatory requirements to meet minimum effluent concentration standards, trade ratios requiring greater nonpoint source reductions, and sequencing rules prioritizing onsite treatment may limit the ability of regulated point source discharges to trade (Stephenson & Shabman, 2017a, 2017b; Fisher-Vanden & Olmstead, 2013).

Other demand-side factors that may limit buyer willingness to engage in trade include buyers abilities to generate regulatory and non-regulatory co-benefits with onsite treatment technologies, buyers' regulatory risks incurred in the event of seller noncompliance, and buyers' senses of ethical responsibility to manage pollutants themselves (Kuwayama et al., 2018; O'Hara et al., 2012; Berck & Helfand, 2005; Virginia DEQ, n.d.d). Behavioral economics research suggests that the lumpy, long-lived investments characteristic of regulated parties' capital-intensive point source upgrades could limit their willingness to engage in trades, as well (Suter et al., 2013).

This study adds to this present understanding of water quality credit demand by examining the compliance choices of Municipal Separate Storm Sewer Systems (MS4s) to meet the nutrient and sediment control goals for the Chesapeake Bay under the Chesapeake Bay TMDL (Total Maximum Daily Load). MS4s are responsible for managing urban stormwater discharge not connected to sanitary sewer systems, which includes maintaining infrastructure necessary to control, transport, and treat urban stormwater runoff.

Historically, MS4s have faced largely narrative permit requirements, but under efforts to achieve water quality standards established under the Chesapeake Bay TMDL, several states, including Virginia, have assigned annual numeric nitrogen, phosphorus and sediment control effluent load limits to MS4 permits (MDE, 2022; PA DEP Bureau of Clean Water, 2022; Davenport, 2021). In Virginia, MS4s' compliance choices under Chesapeake Bay requirements offer a number of new opportunities to gain insights into regulated parties' willingness to engage in trade. Virginia MS4s appear to have both the incentive and flexibility to use water quality trading. Research suggests that MS4s stand to achieve significant cost savings from trading because MS4 nutrient abatement costs are estimated to be at least an order of magnitude higher than those from other sources (Price et al., 2021; Van Houtven et al., 2012). Furthermore, MS4s have expressed concerns about Chesapeake Bay Program pollutant control requirements' costs and feasibility (Hibbard, 2017; Mandelbaum, 2019; Maryland Courts, n.d.).

Virginia MS4s' nutrient requirements provide an opportunity to investigate why potential buyers may or may not make use of trading as a compliance option. The objectives of this study are to 1) identify the nutrient and sediment control strategies, including nutrient trading, that Virginia MS4s utilize to achieve Bay nutrient control obligations; 2) estimate the extent and magnitude of any cost premium MS4s are willing to pay for onsite control options above nutrient credit costs; and 3) identify how MS4s evaluate the stormwater management options at their disposal to achieve the Bay Total Maximum Daily Load, as well as identify the reasons for MS4s' compliance choices. To address these objectives, the compliance choices and behavior of 17 Virginia MS4 permittees, including both general and individual permittees, are examined. Observed compliance choices and costs are collected from primary sources. Findings are coupled with semi-structured interviews to understand whether and how trading opportunities are evaluated in complying with Chesapeake Bay nutrient reduction requirements.

1.3 MS4 Chesapeake Bay Permit Requirements and Compliance Options

The federal Clean Water Act (CWA) establishes permitting requirements for MS4s. MS4s are designated by size as being either Phase 1 or Phase 2 MS4s. Phase 1 MS4s are those that are "operators of large and medium systems (serving populations of greater than 100,000 people per the 1990 decennial census)", whereas Phase 2 MS4s are those that are "small MS4s in 'urbanized areas' (as defined by the latest decennial census)" (Virginia DEQ, n.d.c).[1] Phase 1 MS4s generally operate under individual permits that include more specific permit conditions than those of Phase 2 MS4s, which operate under general permits. After the TMDL, Virginia added new MS4 permit conditions designed to meet EPA's Chesapeake Bay nitrogen, phosphorus and sediment (total suspended solids) reduction targets for the Bay (EPA, 2010; Davenport, 2021; Virginia DEQ, 2018). The permit conditions require MS4s to reduce total nutrient (nitrogen and phosphorus) and sediment mass load (lb/yr)

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[1] Per EPA, "'Urbanized areas,' as defined by the Census Bureau when the Phase II regulations were issued, comprise areas 'that together have a minimum population of 50,000 people."' (U.S. Census Bureau, as quoted in EPA, 2022a and referenced in EPA, 1999). EPA is revising Phase 2 classification criteria, in response to changes in the U.S. Census Bureau's reporting practices regarding 'urbanized' areas. Further guidance from EPA for MS4 permit writing, regarding implications of shifting designations of 'urbanized' and 'urban' areas is forthcoming (EPA, 2022a).

within the MS4 boundaries from a 2009 baseline. Per acre nutrient and sediment loads (lbs/ac/yr) for broad land uses (ex. forest, pervious lawn, impervious cover) are calculated by Virginia's Department of Environmental Quality (DEQ)-based per acre pollutant loading estimates from the Chesapeake Bay Program (CBP) watershed model. Per acre loading rates are multiplied by land use acreage existing within the MS4 boundaries in 2009 to create an estimate of total MS4 annual N, P, and S loads in 2009. Total mass load reductions permit requirements are:

- 6% and 9% reductions in nitrogen loads from regulated pervious and impervious areas,
- 7.25% and 16% reductions in phosphorus loads from regulated pervious and impervious areas, and
- 8.75% and 20% reductions in sediment loads from regulated pervious and impervious areas, respectively.

These reduction requirements are phased in under three 5-year permit cycles. Specifically, MS4s must achieve 5%, 40%, and 100% of numeric requirements by the end of each of the three permit cycles. Most General Permittee (Phase 2) MS4s currently operate under the second permitting cycle's requirements (40%), while many Individual Permittee (Phase 1) MS4s still operate under the first permitting cycle's requirement (5%).[2]

To achieve nutrient and sediment reductions creditable towards the Bay TMDL, MS4s may choose from an EPA- and DEQ- approved list of best management practices (BMPs) and strategies (Virginia DEQ, n.d.d; Davenport, 2021; EPA, 2022b). General options include treatment of stormwater runoff via best management practices (BMPs), changing land use (ex. lawn to forest), source reduction (e.g. retiring individual septic systems by connecting

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[2] See Virginia DEQ, 2018 for information on small MS4s' approval of plans to achieve the first cycle of the Bay TMDL's requirements.

to central sewer), or restoration activities (e.g. wetland and stream restoration). These practices are considered to be 'onsite', given their local implementation occurs within MS4 boundaries.

MS4s are also granted broad discretion by the state of Virginia to meet Bay nutrient compliance requirements through water quality trading. MS4s may purchase credits from both point and nonpoint sources within major Chesapeake Bay tributaries (Potomac, Rappahannock, York, James). Nutrient and sediment credits are denominated in terms of pounds delivered to the Chesapeake Bay annually ("edge of stream" loads are multiplied by delivery ratios to estimate pounds delivered to the Bay). MS4s may trade with both point and nonpoint sources on a 1:1 ratio. Under Virginia law 9VAC25-900-90, the state also retires 5% of all credits in a credit trade, as a way of generating a small public benefit from trade.[3]

Virginia rules define two types of credits: "term" and "perpetual" (9VAC25-900-10). Term credits have a finite duration based on the lifespan of the credit-generating technology and are defined as "nutrient reduction activities that generate credits for a determined and finite period of at least one year but no greater than five years" (9VAC25-900-10). Term credits can be generated from either point sources or nonpoint sources (e.g. BMPs implemented on working agricultural lands such as cover crop planting).

To date, term credits are almost exclusively point source (wastewater treatment plant) credits (Stephenson & Shabman, 2017b, 2017c). Point source discharges can create credits by reducing discharge below an annual mass load of nitrogen and phosphorus, called a Wasteload Allocation (WLA), as specified in a 5 year permit (9VAC25-890-40). Point sources generate hundreds of thousands of nutrient credits each year. For example, Virginia wastewater treatment plants (WWTPs) in the Potomac watershed generated 34,000 P

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[3] For instance, for 100 lbs N traded, the state would effectively require 5 additional lbs of N to be achieved and taken off the market.

credits and 563,000 N credits in 2022 (Virginia Nutrient Credit Exchange Association, Inc., 2021). Generally, point sources exchange credits with other WWTPs within a point source association but can and do extend credit sales to MS4s.

In addition to term credits, Virginia MS4s may also purchase "perpetual" credits from nutrient banks (§ 62.1-44.19:21). Perpetual credits never expire and provide the owner with a permanent stream of annual reduction credits (9VAC25-900-10; 9VAC25-900-90). Nonpoint source perpetual credits typically occur through permanent land use change (eg. agricultural lands are permanently converted to a less nutrient intensive use, typically forest). Active markets exist for these credits to meet the compliance needs of a regulatory program to offset pollutant impacts from urban development/land conversion (Stephenson & Shabman, 2017a, 2017c).

MS4s have multiple management objectives in addition to Bay nutrient and sediment requirements. MS4s manage and maintain municipal stormwater conveyance infrastructure and manage local flooding issues and risks (MPCA, 2023a; Eskin et al., 2021). MS4s must also meet pollutant control responsibilities and obligations assigned in response to locally impaired waters' local TMDLs. Bacteria and excess sediment are common causes of local urban water quality impairments in Virginia (Virginia DEQ, n.d.b).

In choosing how to comply with Bay TMDL nutrient requirements, MS4s must choose among compliance technologies and trading alternatives with multiple attributes. Many practices approved for nutrient reductions also generate a number of other cobenefits that support and help achieve other MS4 objectives (Wong & Eadie, n.d.; Muthukrishnan et al., 2004; MPCA, 2019). For example, many stormwater BMPs approved by DEQ to meet the Chesapeake Bay permit requirements also provide local flood risk reduction and bacteria and sediment reductions to local waters. Table 1.1 summarizes certain cobenefits associated with different Bay compliance strategies.

Table 1.1: Description of Compliance Options Available to MS4s

Chesapeake Bay Compliance Options	**Local Water Quality Cobenefits**	**Flood Risk Reduction**	**Amenity/ Aesthetic Value**
Bioretention	Bacteria, Sediment	Yes	Yes
Extended Detention Ponds	Bacteria, Sediment	Yes	Yes
Stormwater Filtering Practices	Bacteria, Sediment	No	No
Stormwater Wet Ponds	Bacteria, Sediment	Maybe	No
Septic	Bacteria	No	No
Nutrient Management Plans	Bacteria	No	No
LUC/Reforestation	Bacteria, Sediment	Yes	Yes
Wet Pond/Pond Enhancement	Bacteria, Sediment	No	Yes
Wetland	Bacteria, Sediment	No	Yes
Stream Restoration	Sediment	No	Yes
Nutrient Credit - NPS, Perpetual	None	No	No
Nutrient Credits - PS, Term	None	No	No

Sources: Parajuli et al., 2019; EPA OW, 2021a, 2021b; Lavelle et al., 2021; Muthukrishnan et al., 2004; Town of Wolfboro & Wentworth Watershed Association, n.d.; Virginia Stormwater BMP Clearinghouse, 2011; BMP screening tool at MPCA, 2023b; Virginia DEQ, 2017a; Richkus et al., 2016; Timmons Group, 2020; NWRM, n.d.; Fairfax County, Virginia, 2017a; Stormwater Manager's Resource Center, n.d.; Berland et al., 2017; MPCA, 2000, 2022, 2023a, 2023c; State of Michigan, n.d.; Jefferson County, Missouri, Stormwater Management Office, n.d.

1.4 Methods

Case study analyses were conducted on the Chesapeake Bay TMDL action plans of a sample of Virginia's municipal MS4s to evaluate MS4 compliance choices for the Bay TMDL. Focus was given to municipal MS4s, as opposed to MS4s that may serve government, military, or higher-educational institutions, as municipal MS4s are the most broadly representative class of MS4 throughout the state. Virginia has 44 municipal MS4s in the Chesapeake Bay watershed; 33 are Phase 2, General permittees, while 11 are Phase 1, individual permittees, per Virginia DEQ (n.d.a). A sample of Virginia's municipal MS4s was selected to evaluate compliance choices for the Bay TMDL.

The MS4s included in the sample were chosen based on a number of factors, including the availability of compliance choice data, MS4 size, and MS4 location. MS4s are responsible for publishing Chesapeake Bay TMDL action plans detailing the methods they use or intend to use to achieve Bay TMDL compliance. The level of detail in these compliance plans is heterogeneous, with regard to facility-scale cost and reduction information, as well as with regard to overall reporting, so focus was given to MS4s with sufficient information on compliance practice and cost information for study. A sample of MS4s operating under both phase 1 (5%) and phase 2 (40%) of the general permit Bay TMDL requirements was selected, with an emphasis on MS4s operating under the more stringent phase 2 permit. Sampling includes MS4s from the southeastern portion of the state, as a regional wastewater treatment authority, the Hampton Roads Sanitation District (HRSD), has offered to cover MS4 Bay nutrient permit compliance requirements by supplying point source term credits for free (Nylen, 2021; NACWA, 2018). Overall, the MS4s in the sample include 12 general permittee and 5 individual permittee MS4s. Four MS4s in the sample operate under phase 1 plans and thirteen MS4s in the sample operate under phase 2 plans to achieve Bay permit requirements. The MS4s selected, their MS4 permittee status, the phase of Bay TMDL requirements they are currently in, and their overall reduction requirements are detailed in Table 1.2.

Table 1.2: MS4 Characteristics and Reduction Requirements

Locality	**Total Chesapeake Bay TMDL Pollutant Reduction Requirement (lbs/year)**		
	N	**P**	**TSS**
Individual Permittees			
Fairfax County[1]	59,188	6,469	5,277,311
Prince William County[2]	20,043	2,209	1,806,701
Chesterfield County[1]	19,631	3,086	1,196,867
Henrico County[1]	19,341	4,631	2,075,807
Arlington County[1]	11,565	1,529	1,311,982
General Permittees			
Loudoun County[2]	20,230	2,072	1,656,944
City of Alexandria[2]	7,597	1,004	861,937
City of Lynchburg[2]	5,477	1,308	585,775
York County[2]	5,293	522	122,393
Albemarle County[2]	3,842	741	311,811
Hanover County[2]	3,124	915	367,027
Augusta County[2]	2,108	260	219,375
City of Suffolk[2]	1,805	356	150,905
City of Williamsburg[2]	1,190	288	118,733
Fauquier County[2]	679	42	27,806
James City County[2]	625	120	50,132
Stafford County[2]	619	92	40,464

[1] *MS4 in Phase 1 (5% of total pollutant reduction requirements) of Bay TMDL.*

[2] *MS4 in Phase 2 (40% of total pollutant reduction requirements) of Bay TMDL.*

Requirements based on data shared by DEQ's J. Selengut, supplemented by action plan data for James City County, Augusta and Fauquier due to data availability constraints. Information on Individual vs. General Permittee status from Virginia DEQ (n.d.a) and from individual MS4 permits, as referenced.

MS4s' compliance choices and costs reported in their Bay TMDL action plans were used to compare nutrient and sediment abatement costs across compliance options. All reductions claimed, whether complete or planned, were considered. Installation costs were annualized and reported as cost per unit of pollutant reduction per year. Since localities typically do not track or report operations and maintenance costs in the action plans, annual operations and maintenance (O&M), as well as land opportunity, costs were estimated separately. Practices were organized by type. Practice lifespans, discount rate (5%), O&M, and land opportunity costs were assigned based on statewide CBP estimates (CBP, n.d.a, n.d.b). Annualized installation costs were reported as low-estimates of costs and annualized installation plus annualized land opportunity and O&M costs were reported as high-estimates of costs.

Resulting annualized costs were divided by MS4-assigned nitrogen (N), phosphorus (P), and total suspended solids (TSS) reductions for each strategy to determine estimated annualized per-pound reduction costs for each facility/practice. Costs per pound were calculated independently, meaning each facility's costs were separately divided by N reductions, by P reductions, and by TSS reductions, for comparison.

Given the lack of trade-specific price information in MS4s' action plans, term point source credit prices were based on observed trades and on credit prices as reported by the Virginia Nutrient Credit Exchange Association, Inc., which focuses on point source trade (Virginia Nutrient Credit Exchange Association, Inc., 2021). Credit prices for nonpoint source perpetual trades were based on specific prices reported in the region (Albemarle County, 2015b, 2017, 2019; Prince William County School Board, 2019, 2020; Augusta County, VA, 2021). Perpetual credit prices were annualized at the same CAST-standard 5% discount rate as before. Since most perpetual credit prices are reported in terms of P, perpetual credit prices in terms of N were determined by dividing per-pound P costs by N:P retirement ratios reported in trades.

Semi-structured interviews with MS4 managers and subsequent qualitative content analysis were used to identify explanations for observed choices and to provide insight into what factors influence MS4s' compliance decisions. Semi-structured interviews provided opportunity for interviewees to give unanticipated responses and to provide elaboration into the rationales of compliance choices. The goal was to understand the rationale for the choices, with the overriding goal of avoiding leading questions. The main flow guiding semi-structured interviews is presented below:

- Compliance choices: Practices used for Bay TMDL compliance were verified and MS4s were asked how and why the MS4 decided to use these options. Managers were also asked about the practices they might use in the future.
- Water quality trading: Use, or lack thereof, of nutrient credit purchases as a means of achieving Bay TMDL compliance in the past and future was verified. Respondents were specifically asked to comment on their evaluation of point source term and nonpoint perpetual credits as means of meeting Bay TMDL requirements.
- MS4 financing and funding: MS4 officials were asked how their MS4s' organizational models (stormwater utility or public works department) influenced compliance choices. Officials were also asked about the role of Stormwater Local Assistance Fund (SLAF) funding in determining selection of compliance practices.

Conversations with MS4 officials were recorded and transcribed. Manifest information ('what' was said in responses) from interviews was coded based on content. The coding process noted content related to the factors anticipated to influence MS4 decision-making (i.e. cost-effectiveness, local TMDLs, maintenance, etc.), while also allowing for coding of new categories of content to accommodate unforeseen insight into MS4 decision-making.

1.5 Results

To date, the majority of MS4s studied have not made extensive use of water quality trading to comply with Bay TMDL requirements. Only 5 MS4s, Williamsburg, James City County, Loudoun, Augusta, and Hanover, claim reductions from trade toward the Bay TMDL. The majority of these MS4s use, or plan to use, trade in a limited manner. All five localities are in the second phase of Bay permit compliance (40% of total nutrient and sediment reduction goals). The role of trade is lower for MS4s unaffiliated with HRSD, i.e. Loudoun, Augusta, and Hanover, and higher for MS4s affiliated with HRSD, i.e. Williamsburg and James City County (Table 1.3).

Table 1.3: MS4s' Claimed Reductions from Trade

MS4	**Claimed Reductions from Trade**		
	N	**P**	**TSS**
Williamsburg	46%	95%	96%
James City County	40%	15%	20%
Loudoun	19%	15%	11%
Augusta	2%	3%	4%
Hanover	2%	-	-

Augusta's credits are purchased from a nutrient bank and are generated through stream restoration. Hanover's credit purchases are not finalized, though the semi-structured interview with the MS4 suggests these credits will likely be term PS credits. Loudoun's credits will be purchased over time; insight from semi-structured interviews suggests the MS4 leans strongly towards perpetual credits. Both Williamsburg and James City County's credits are affiliated with HRSD, and thus represent point source term credits.

To date, MS4s' Bay TMDL compliance relies primarily on a few types of practices: stream restoration, wet ponds and constructed wetland. For MS4s that have progressed to the Phase 2 of Bay-related permit requirements, these practices are responsible for 49%, 70%, and 67%

of N, P, and TSS reductions, on average. Figure 1.1 shows practices accounting for 5% or more of estimated N, P and/or TSS reductions, as well as perpetual nonpoint source (NPS) trade.

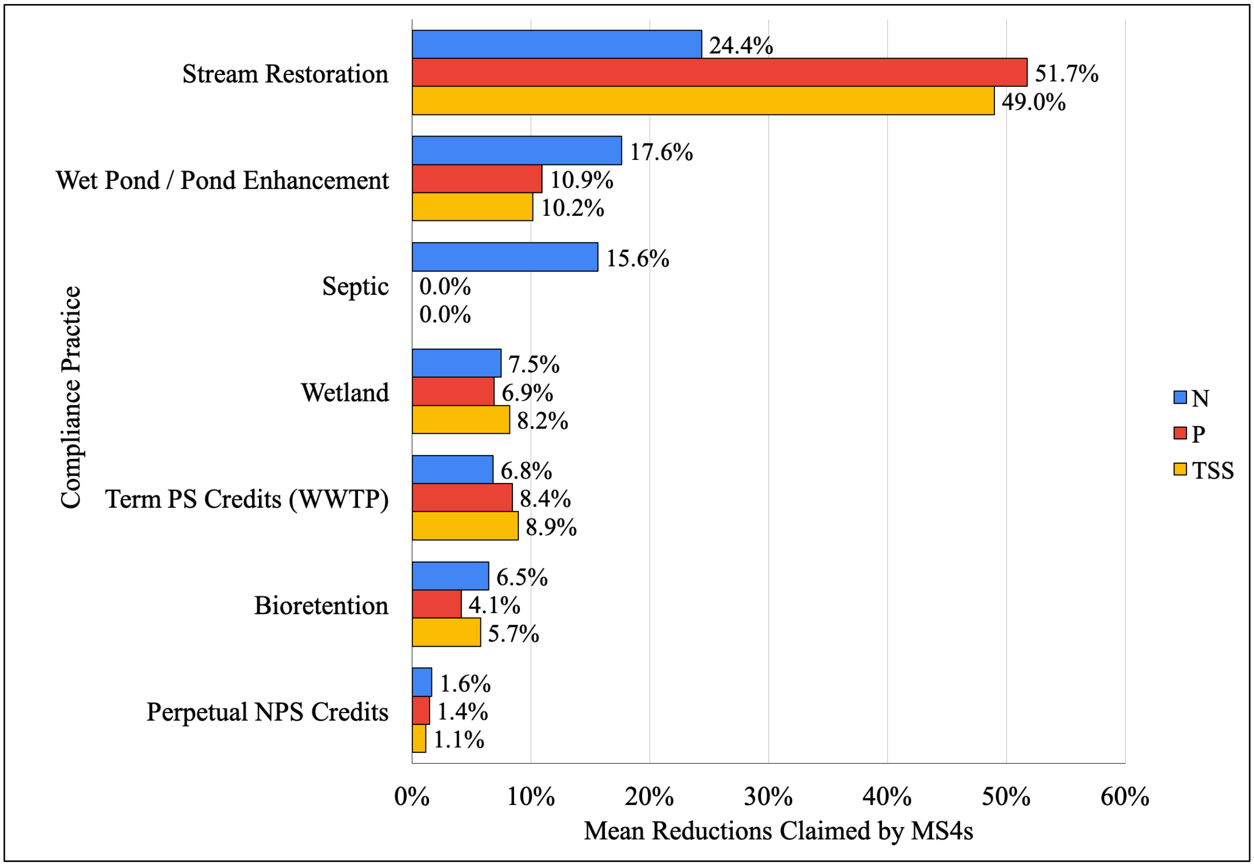

Figure 1.1: Mean Reductions from Major Practices and Trade Claimed by MS4s in Phase 2 of Chesapeake Bay TMDL Compliance

Sources: MS4 Chesapeake Bay TMDL action plans

MS4s were observed to use onsite BMPs and restoration practices, even though these practices generally had higher per unit pollutant control costs than trade alternatives. The estimated nitrogen and phosphorus annualized per pound abatement costs for the main compliance practices are shown in Tables 1.4 and 1.5.

The total per-pound cost of stream restoration projects ranged widely, from approximately \$1,022 to \$2,378/lb/yr for N, \$1,212 to \$2,991/yr for P, and \$3 to \$9/lb/yr for TSS. Wet pond and wetland practices were able to achieve N and TSS reductions at per-pound costs that were lower than those of other practices, though wetland and wet pond practices' per-pound P reduction costs were greater than those of stream restoration.

Observed perpetual P credit purchase prices throughout the state generally ranged from \$9,500 to \$17,000/lb. Annualizing these prices at a 5% discount rate yielded annualized prices of \$475 to \$850/lb/yr for P and implied prices of \$54 to \$142/lb/yr for N. Perpetual per-pound credit costs were generally lower than the annualized upfront and ongoing costs of stormwater BMPs and restoration practices, with the limited exceptions of stream restoration's annualized upfront costs per pound P and the annualized upfront costs per pound N of certain wet pond/pond enhancement and wetland facilities on the lower end of the cost spectrum. Point source credits, on the other hand, were available for \$0/lb/yr for both N and P to eligible MS4s within the HRSD service area and for \$5 to \$6 per pound P per year and \$3 to \$4 per pound N per year for all others, which represents a huge difference in nutrient control costs, relative to all other compliance options.

Comparison of compliance practices' costs to median trade prices shows that MS4s are willing to incur price premiums to achieve reductions onsite. The price premiums MS4s attach to onsite activity over trade are higher for P reductions than for N reductions and are higher for PS term trade than for NPS perpetual trade (1.6 and 1.7).

Table 1.4: Overall Cost Estimates for Phase 2 MS4s' Top 5 Sources of Reported Nitrogen Reductions, Plus Perpetual Trade

Strategy	**Quartile**	**N Reduction Costs ($/lb/yr)**	
		Annualized Capital Costs	**Annualized Capital + O&M + Opportunity Costs**
Stream Restoration	Q2:	$654	$1,673
	Q1-Q3:	$407-$930	$1,022-$2,378
Wet Pond / Pond Enhancement	Q2:	$160	$271
	Q1-Q3	$85-$348	$151-$589
Septic	Q2:	$303	$372
	Q1-Q3	-	-
Wetland	Q2:	$173	$293
	Q1-Q3:	$94-$360	$160-$596
		Annualized Purchase Price	
Term PS Credits	Representative Cost	$0-$4	
Perpetual NPS Credits	Representative Cost	$54-142	

Note: Septic costs are based on a singular observation, which explains lack of variability.

Table 1.5: Overall Cost Estimates for Phase 2 MS4s' Top 5 Sources of Reported Phosphorus Reductions, Plus Perpetual Trade

Strategy	**Quartile**	**P Reduction Costs ($/lb/yr)** **Annualized Capital Costs**	 **Annualized Capital + O&M + Opportunity Costs**
Stream Restoration	Q2: Q1-Q3:	$693 $474-$1,169	$1,771 $1,212-$2,991
Wet Pond / Pond Enhancement	Q2: Q1-Q3	$1,507 $915-$1,907	$2,546 $1,546-$3,221
Wetland	Q2: Q1-Q3	$1,325 $740-$2,557	$2,238 $1,251-$4,321
Bioretention	Q2: Q1-Q3:	$4,960 $2,903-$17,007	$7,631 $4,635-$26,165
		Annualized Purchase Price	
Term PS Credits	Representative Cost	$0-$6	
Perpetual NPS Credits	Representative Cost	$475-$850	

Table 1.6: Cost Premiums of Top Sources over Trade (N)

Compliance Options	**Premiums Over PS Term Credits, Based on:** Annualized Capital Costs	 Annualized Total Costs
Stream Restoration	$403 - $926	$1,019 - $2,374
Wet Pond / Pond Enhancement	**$81** - $345	$147 - $585
Septic	$299	$368
Wetland	**$91** - $356	$156 - $592
Compliance Options	**Premiums Over NPS Perpetual Credits, Based on:** Annualized Capital Costs	 Annualized Total Costs
Stream Restoration	$271 - $793	$886 - $2,241
Wet Pond / Pond Enhancement	**$0*** - $212	**$15** - $452
Septic	$166	$235
Wetland	**$0*** - $223	**$23** - $459

Note: 0* denotes no cost premium, given associated practices may be lower-cost than trade options.

Table 1.7: Cost Premiums of Top Sources over Trade (P)

Compliance Options	**Premiums Over PS Term Credits, Based on:**	
	Annualized Capital Costs	Annualized Total Costs
Stream Restoration	\$468 - \$1,164	\$1,206 - \$2,985
Wet Pond / Pond Enhancement	\$909 - \$1,901	\$1,540 - \$3,215
Wetland	\$734 - \$2,552	\$1,245 - \$4,315
Bioretention	\$2,897 - \$17,001	\$4,629 - \$26,159
Compliance Options	**Premiums Over NPS Perpetual Credits, Based on:**	
	Annualized Capital Costs	Annualized Total Costs
Stream Restoration	**\$0*** - \$532	\$574 - \$2,354
Wet Pond / Pond Enhancement	\$277 - \$1,269	\$908 - \$2,584
Wetland	**\$103** - \$1,920	\$613 - \$3,683
Bioretention	\$2,266 - \$16,369	\$3,997 - \$25,527

Note: 0* denotes no cost premium, given associated practices may be lower-cost than trade options.

Price premiums for onsite activity over PS term credits begin at \$81 per pound N (from wet pond and pond enhancement's annualized capital costs, and can exceed \$2,000 per pound N (from stream restoration's overall annualized costs), depending on whether the MS4 considers just capital, or all costs. Price premiums for onsite activity over PS term credits, in terms of P, are also substantial, beginning at \$468 per pound P (from stream restoration's annualized capital costs) and exceeding \$25,000 per pound P (from bioretention's overall annualized costs).

Price premiums for onsite activity over NPS perpetual credits are lower than those relative to PS term trade, in terms of both N and P. In some cases, annualized capital costs of onsite compliance choices, like wet pond and pond enhancement and wetland practices, are lower than those of NPS perpetual credits, on a per pound N basis. Similarly the annualized capital costs of stream restoration can be lower than those of NSP perpetual credits on a per-pound P basis. Price premiums for onsite activity over NPS perpetual credits are generally \$100 lower or more, per pound N, relative to price premiums for onsite activity over PS term credits. Differences between price premiums over NPS perpetual trade and PS term trade, on a per pound P basis are generally greater, with per-pound P price premiums $600 lower (such as those comparing all annualized costs of bioretention and wet pond and pond enhancement to the different trade options).

Findings suggest a greater price premium for onsite activity over PS term options than over NPS perpetual options, which suggests that MS4s choosing onsite compliance over trade my view onsite options as more favorable to trade, in general, and relatively more favorable to PS term options than to NPS perpetual options.

Interviews with MS4s shed light on the rationale for observed compliance behavior. Of the 17 MS4s in the sample, 14 agreed to interviews. Interviews were conducted virtually in the summer of 2022 and generally included a single stormwater official from each MS4, though two interviews included 2 MS4 officials. Interviews ranged from approximately 22 minutes to 2 hours. Median interview time was approximately 41 minutes. Table 1.8 summarizes MS4 managers' responses to questions about the reasons for projects and compliance actions taken to meet Bay TMDL permit requirements.

Table 1.8: MS4 Respondents' Explanation of Chesapeake Bay TMDL Compliance Strategy

Factors Considered in Compliance	**Prevalence in Responses (n=14)**
Local Impact - Overall	**100.00%**
Erosion, infrastructure, and community needs	93%
Amenities, aesthetics, ecology, and related considerations	71%
Flood control	43%
Moral duty to address onsite	36%
Local TMDLs and Impairments	29%
Cost/Availability - Overall	**100.0%**
Cost-effectiveness and budgetary considerations	100%
Easements (cost and hassle), access, and availability	93%
Consideration of SLAF to secure project funding	86%
Pre-Chesapeake Bay TMDL activity and guidance	79%
Consideration of practice maintenance obligations	64%
Role of Trading in MS4 Compliance	**Prevalence in Responses (n=14)**
Factors Cited for Use of Credit Trading - Overall	**79%**
Credits serve as a backstop.	71%
Credits are cost-effective	43%
Credits save on transaction or maintenance costs	14%
Factors Limiting Use of Trading - Overall	**100%**
Desire for local benefits and control as an impediment to trade	64%
Credit risk, term nature/ availability	57%
Credits are not cost-effective.	21%
Use of Water Quality Trading	**MS4s' Role of Trade (n=14)**
Present use based on action plan and conversations	6*
No current use, but mentions option if needed/potential future use.	7
No current use and no role in present or future mentioned.	1

Note: *Discrepancy between present use reported or observed and prior reported trade activity stems from Chesterfield's discussion of trading that was not observed to be claimed toward Bay TMDL requirements.

Though attentive to costs, MS4s voiced a strong preference for Bay TMDL compliance options that also generated local benefits and helped meet other MS4 objectives. MS4s correspondingly framed the selection of projects to meet the Chesapeake Bay TMDL as a way to generate these local benefits and to address these local needs. Arlington's compliance official echoed a common sentiment in the following rhetorical question illustrating compliance choice evaluation: "Where's the low hanging fruit that... not just gets us to compliance, but also stacks other benefits?".

The type of benefit mentioned differed across respondents and situations. Thirteen MS4 managers acknowledged the utility of Bay TMDL projects in addressing erosion management and/or infrastructure protection goals. For example, stream restoration was noted to be one way to reduce stream bank erosion and to protect adjacent infrastructure (water/sewer lines, roads, etc). Arlington, Virginia's compliance official provided insight into this, stating that "dealing with those projects gets you a lot of credit and you're protecting infrastructure; kind of creating resiliency is what we're really after, while getting the credits".

Similarly, six respondents noted that the practices they considered provided flood control and ten MS4s expressed complex consideration of benefits like amenity values, aesthetics, ecology, and environmental education. For instance, Hanover explicitly mentioned leveraging Bay TMDL funding to repair local infrastructure and mentioned upgrading a lake that would otherwise be lost to the community.

Insight from interviews suggested that MS4s' obligations to address local water quality impairments impacted their Bay TMDL compliance behavior. MS4s in our sample are subject to local TMDLs; in response, fifteen MS4s in our sample have published bacteria TMDL action plans, five have published sediment/benthic TMDL action plans, and four have published PCB TMDL action plans. During interviews, four MS4s discussed the local impairments underlying local TMDLs as influencing Bay TMDL compliance behavior. Two

MS4s reported intent to focus on local impairments and TMDLs in Phase 3 of the Bay TMDL. These observations imply that MS4s will likely continue to choose onsite compliance over offsite trades as a way of generating local water quality and other improvements, in addition to Bay TMDL reductions.

Though MS4s may elect to implement onsite BMPs and restoration activity, the expenses of which are generally higher than those of trade, MS4s do remain cognizant of cost, with all fourteen interviewed noting consideration of cost-effectiveness when evaluating compliance options. Thirteen MS4s noted preference for placing practices on public land; MS4s explained that this was due to this land being available at no cost and without need to secure access easements. Cost-effectiveness considerations motivated stream restoration, in particular. Arlington's stormwater manager, for instance, stated that, "dealing with eroding streams is still the most cost effective credit in terms of the Bay TMDL".

Hanover County, an MS4 that generates nearly 50% of its P reductions and nearly 90% of its TSS reductions from stream restoration, also noted that it has "been able to do projects more cost effective than" credits "on the open market" and mentioned use of reasonably cost-effective stream-restoration projects when deciding how to leverage funds for maximum effect.

The relative cost effectiveness of on-site compliance options is improved by the existence of state cost-share grant programs, specifically Virginia's Stormwater Local Assistance Fund program (SLAF). SLAF funds are generally equivalent to half of the installation expenses of the project for which they are awarded, but can be higher with demonstrated need (Morris 2023). Twelve respondents provided insight suggesting consideration or receipt of SLAF to fund reductions toward the Bay TMDL. MS4s' implementation of stream restoration was further enhanced by Virginia's Stormwater Local Assistance Fund (SLAF) grant program; these practices were perceived by MS4s to be strong candidates for SLAF and comprised one-third of all projects documented in action plans as having secured SLAF.

1.5.1 The Role of Water Quality Trading in MS4 Chesapeake Bay Compliance Choices.

Interviews with MS4s suggest that trade serves as a ‘backup’ compliance option to be exercised in the event that reductions are unable to be achieved onsite. Nine MS4s mention that they would consider credits as a backstop “in a pinch” to cover unforeseen problems with other compliance options. These MS4s included four presently trading and five not presently trading. James City County’s official describes the thinking as: “If we were, for some reason, unable... to meet the goals through our own actions, we have the ability to buy whatever outstanding credits we need through SWIFT, otherwise”.[4]

But, heavy term credit use by two MS4s, Williamsburg and James City County, suggests that trade can play a role beyond a ‘backup’ compliance choice. Williamsburg explains that it uses point source credits to avoid the hassle of tracking numerous onsite reduction projects.

Two MS4s relied on perpetual credits for a portion of their Bay compliance. Interview content suggests the permanence and lack of requisite maintenance of perpetual credits are important attributes valued by MS4s. Augusta’s stormwater manager cites direction from the board of supervisors to refrain from engaging in any term reductions. Loudoun’s compliance official more explicitly mentions the attractiveness of perpetual credits: “If I buy credits, you know, I buy my 30lbs of phosphorus... we don’t have to come back to it anymore... Those credits are locked; we don’t... have to maintain them...”.

Though term credits are a very low-cost compliance option, observed use of term cred-

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[4] ‘SWIFT’ refers to the wastewater treatment program used by HRSD to generate free credits for partnering MS4s; credits are available at no cost and use of the term ‘buy’ is conversational, rater than technical.

its is limited. Insight from eight respondents reveals that MS4s may refrain from point source term credits because of concerns about permanence and future availability. Growth in wastewater flows are projected to reduce the current surplus of PS credits in certain basins (VNCEA, 2021). MS4 Bay nutrient and sediment permit requirements, on the other hand, are permanent, and so term credit shortages would require MS4s to reevaluate compliance strategy.

Correspondingly, Prince William county mentioned that they do not engage in trade, particularly wastewater trade, as this would expose the MS4 to potential availability risks in the future. Loudoun's compliance official provides very clear insight into why MS4s may refrain from purchasing term credits, stating that, "The problem with those is they're annual. So every year you kind of have to go back and reassess them, and sooner or later...they will run out... And we did not want to... basically kick the can down the road".

Sentiments that expand upon MS4s' consideration of local benefits further explain lack of trade: nine of the fourteen MS4s mention that they prefer to implement strategies that can generate local benefits instead of purchasing credits to achieve compliance. Albemarle's stormwater compliance official explains, for instance, that there is "...direction from our Board of Supervisors to do capital projects to improve the quality of our local streams and lakes" and "...with that mentality it just doesn't make sense for [the MS4] to purchase credits that are generated somewhere else outside of [the] county".

1.6 Conclusion

Overall, results suggest that MS4s' use of onsite strategies instead of trade to achieve Bay TMDL compliance can be explained by three findings: MS4s' preferences for practices that generate local benefits that trade cannot, MS4s' concerns over future point source trade availability, and MS4s' ability to use grant funding to implement onsite activity that generates long-term benefits at per-pound reduction prices approaching those of perpetual trade.

The reasons MS4 gave for not relying on very low cost term credits are relevant and instructive for establishing expectations for other trading programs. Many water quality trading programs are designed around what Virginia calls 'term credits'. Point-nonpoint source trading programs, for example, are often designed around agricultural nonpoint practices with limited duration (cover crops, tillage practices, etc). MS4s managers interviewed for this study expressed desire for long-term solutions to permanent regulatory obligations, as well as expressed that they avoid term credits due to uncertainty around future credit availability. This means that expectations for MS4s' demand for term credits from agricultural nonpoint practices should be tempered. This may explain why research finds that the most active trading program in Virginia involves permanent, rather than term, transfers of nutrient control obligations between buyer and seller (Stephenson and Shabman, 2017c).

When evaluating credit markets, policy analysts also need to consider that the decisions MS4s must make regarding stormwater compliance choices are more complex than ones of simple cost-minimization, which affects their demand for water quality credit trades. MS4s face many local goals and utilize compliance technologies with multiple attributes. Local objectives and priorities, such as erosion control, infrastructure protection, local TMDL satisfaction, and amenity improvements, figure prominently in MS4 Bay compliance choices. Correspondingly, MS4s in the study are observed to have fairly lexicographic preferences, first prioritizing onsite reductions and then turning to cost-minimization as a goal. Theoretical analysis into trade program design and efficiency may consider this new information, regarding MS4s' preferences.

In finding ways to achieve simultaneous objectives, MS4s remain responsible stewards of taxpayer dollars, even if they refrain from lower-cost offsite credit activity. Within the scope of onsite compliance, MS4s generally take steps to reduce realized compliance costs, such as making use of public land and securing SLAF funding, which may reduce the effective cost to the permittee. Being more sensitive to these considerations will lead to better understanding of the demand for credits in different regulatory settings, which will establish more realistic estimates of trading volume and magnitude and will clarify economic and policy analysis of trading outcomes.

Future research might focus on the strategies that MS4s in other parts of the Chesapeake Bay watershed take to achieve Chesapeake Bay compliance. MS4s in Pennsylvania, for instance, have not achieved the degree of Bay cleanup in other areas, and insight into compliance perspectives in this state may explain observed Bay cleanup reductions in the state.[5] Economists might consider that one reason for noncompliance with Bay TMDL obligations in areas farther from the bay may be that parties farther from the Bay likely choose to focus heavily on local obligations, given their proximal relevance. Any low-trade activity in these areas may be thus explained by concern with mainly local goals.

Further research might engage in a more quantitative evaluation of the trade-offs that MS4 operators make across multiple objectives, as well as make a quantitative assessment of trading attributes, either of which may be achieved through choice experiments.

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[5] See Ortiz, n.d.

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Chapter 2

The Cost of Meeting the Chesapeake Bay TMDL in the Presence of Local Water Quality Obligations: Cost Analysis of Municipal Stormwater in Loudoun County, Virginia

2.1 Abstract

In 2010, EPA implemented the Chesapeake Bay TMDL, which set nutrient and sediment reduction goals designed to address Bay eutrophication and hypoxia. Achievement of the Bay TMDL's nutrient and sediment reduction goals is estimated to be costly, particularly for regulated urban stormwater sources. However sediment and nutrient control practices also produce local water quality improvements. Many urban areas have local water quality impairments and efforts to achieve local water quality goals will produce ancillary benefits to meeting the Bay TMDL. This paper estimates the cost of achieving the Chesapeake Bay TMDL as an incremental cost incurred after local water quality obligations have been met. This analysis frames the contribution of local water quality cobenefits toward achievement of the Bay TMDL for a municipal stormwater permittee, the Loudoun County, Virginia, MS4.

The model estimates that Loudoun County MS4 faces substantial costs just to meet local water quality goals ($11 million/yr). Since many of the actions taken to meet local water quality goals also generate pollutant reductions to the Chesapeake Bay, adding Bay TMDL obligations adds 0.2%, 3%, and 32.9% to these costs, depending on the water quality trading used to reach Bay TMDL compliance. Findings suggest that strategies implemented to achieve local water quality obligations could account for the majority of MS4s' overall water quality spending and that there is a close alignment between achievement of local water quality goals and downstream water quality goals for some urban areas.

2.2 Introduction

EPA established the Chesapeake Bay Total Maximum Daily Load (TMDL) in 2010 in response to impaired Chesapeake Bay water quality (EPA, 2021). The TMDL established annual mass load total nitrogen (N), phosphorus (P), and sediment (total suspended solids, i.e. TSS) reduction targets aimed at improving Bay water quality (EPA, 2021). The state of Virginia has chosen to set explicit nutrient and sediment reductions for its publicly-operated urbanized stormwater conveyances, termed Municipal Separate Storm Sewer Systems (MS4s), as a way of achieving its Bay water quality goals. Virginia MS4s must achieve Chesapeake Bay TMDL nitrogen, phosphorus, and total suspended solids (sediment) reduction requirements based on land types and quantities within their regulated areas. Reduction requirements must be achieved in three phases, which become more stringent with time: MS4s must achieve 5%, 40%, and 100% of their nutrient and sediment reduction requirements in Phases 1, 2, and 3 of the Bay TMDL.

To achieve Bay TMDL compliance, MS4s may implement urban stormwater BMPs, convert land to less-intensive (i.e. less pervious) uses, engage in source control practices, or conduct restoration practices (CBP, 2022; VA DEQ 2022). Virginia MS4s may also purchase "term" point and source credits and "perpetual" permanent nutrient credits to meet TMDL requirements (9VAC25-900-10; § 62.1-44.19:12-21; VA DEQ, n.d.b). Term credits may be generated by point source discharges, such as when wastewater treatment plants exceed their own reduction requirements, or can be generated by nonpoint source discharges, such as agricultural parties' implementation of working agricultural BMPs (Stephenson et al., 2022). Perpetual credits are generated through agricultural land retirement by nonpoint source discharges (Commonwealth of Virginia, 2021c).

The urban stormwater practices at MS4s' disposal generally achieve nutrient reductions at higher per-pound costs than those associated with point and agricultural nonpoint sources. For instance, nitrogen reduction costs can range from $37 to $106/lb/yr for urban stormwater BMP wet ponds and $105 to $211/lb/yr for detention basins, whereas cover crop BMPs, for example, can achieve nitrogen reductions in the range of approximately $1 to $39/lb/yr

(Wieland et al., 2009). Comparable wastewater reductions can achieve nitrogen reductions at $47/lb/yr (Jones et al. 2010).

Use of costly urban stormwater is therefore one driver of the high-costs of Bay TMDL compliance. Illustrating the high cost of urban stormwater compliance in aggregate is that Maryland, another state in the Bay watershed, anticipates that urban stormwater management will comprise nearly 33% of total annual watershed cleanup costs, but achieve only 2% of N and P and 4% of TSS reductions towards the third phase of its Bay improvement goals; agricultural practices, on the other hand, will achieve 48% of N, 41% of P, and 25% of TSS, while accounting for only 20% of anticipated annual costs (MDE et al., 2019). Estimated total costs to achieve Bay cleanup goals for the state of Virginia can top $15 billion (Nelson et al., 2012). Meanwhile, cost estimates for the entire watershed are placed at roughly $50 billion, translating to annual costs of $3.3 billion, though higher annual cost estimates of $5 billion have been suggested (Nelson et al., 2012; CBF, 2014).

A strongly motivating reason that MS4s may choose to use costly urban stormwater practices, in spite of their comparatively high costs, is that these urban stormwater practices and other Bay TMDL compliance strategies can provide local co-benefits towards MS4s' other water quality obligations and objectives, including local impairments, such as aquatic life impairments (typically due to excess sediment) and bacteria impairments. But, current cost estimates for the Bay TMDL do not consider that Bay TMDL requirements are one part of an overall set of water quality obligations faced by MS4s. As such, existing cost analyses that attribute full compliance costs to the Bay TMDL may overstate the costs to regulated parties for achieving compliance with the Chesapeake Bay TMDL.

The research objective of this paper is to estimate the incremental cost that the Chesapeake Bay TMDL imposes on MS4s subject to other water quality objectives, namely local TMDLs. Doing so will provide greater clarity on the burden that the Bay TMDL imposes on regulated parties. To achieve this research objective, this paper conducts a linear programming analysis to determine a Virginia MS4's incremental cost of achieving nutrient and sediment goals necessary to achieve Chesapeake Bay TMDL compliance, in addition to local water quality objectives. The regulated party in question is specifically Loudoun County MS4. Sub-objectives of this paper are as follows:

- To estimate the minimum cost to achieve local water quality objectives in isolation from Chesapeake Bay obligations.

- To estimate the minimum incremental costs incurred to achieve Chesapeake Bay TMDL compliance in addition to local water quality objectives.

- To estimate the minimum cost to achieve Chesapeake Bay TMDL compliance in isolation from other water quality objectives.

This analysis provides quantitative estimates of the contribution that achievement of local water quality objectives makes toward Bay TMDL requirements. Results may provide evidence to address concerns regarding the costs to residents from the Bay TMDL. Implications of findings extend beyond Bay TMDL evaluation to evaluation of other programs that see local water quality management goals overlap with broader regional efforts by shedding light on the contributions that local water quality management efforts make toward regional goals, and the costs incurred in the process.

2.3 Methods and Data

2.3.1 Overview of Incremental Costs, Compliance Evaluation, and Adopted Linear Programming Approach

Incremental cost analysis as a way of evaluating environmental program costs has a rich history in the evaluation of pollution management. The U.S. Army Corps of Engineers has recognized the importance of incremental cost analysis in compliance evaluation (Robinson, et al., 1995). A number of works have used incremental cost methods to study air pollution reduction, a topic relevant to the present work, given air pollution's point-nonpoint nature and the discharge limits and credit markets established to address it (Nikopoulou, 2017; Biermann, 1996; King & Munasinghe, 1991; EPA, 2022a, 2022b). In the more directly relevant context of water quality analysis and management, Orth et al. describe the merits of using incremental cost analysis to optimize costly environmental improvements that can be implemented across one or more sites (Orth et al., 1998). Assaf and Saadeh apply incremental cost analysis to evaluate the cost of, and choose from, different wastewater discharge management plans in Lebanon's Upper Litani Basin (Assaf & Saadeh, 2008). Schleich and White use linear programming methods to determine "the incremental cost associated with a shift from current practices to more intensive best management practices" implemented to reduce phosphorus and sediment in a regulated watershed and find evidence suggesting that controlling agricultural sources may be the most cost-effective way to do so (Schleich & White, 1997).

When evaluating stormwater management costs, review of literature identifies a number of 'best practice' considerations that should be made, for accuracy and generalizability. For instance, when evaluating stormwater management costs, opportunity and maintenance costs from stormwater compliance options are relevant for consideration (Thurston, 2006; Boatwright et al., 2014, Hunt et al., 2005, and Taylor, 2005). Land and stream constraints must also be considered when evaluating potential environmental cleanup solutions, as restrictions on land and stream availability can meaningfully impact Bay cleanup strategy (Giuffria, et al., 2017). Literature identifies that feasible implementation of stormwater management practices may depend on the public and private nature of land, as well as the pervious and impervious nature of land (Anderson, et al., 2008, VSM Handbook, 2013a, and MPCA, 2022). Literature also establishes that environmental compliance cost analyses should incorporate sensitivity analyses as a matter of ‘best practices’, when testing how stormwater management research’s findings change under different assumptions (Xu et al., 2017; Giuffria, et al., 2017; Jia et al., 2012).

To achieve the present research objectives of evaluating the incremental cost of the Bay TMDL, GAMS software is used to conduct a linear programming optimization designed to calculate the least cost combination of pollutant control practices necessary for Loudoun County MS4 to achieve compliance with its Bay and local water quality obligations. Results are used to calculate the incremental costs associated with Chesapeake Bay TMDL compliance in addition to local TMDL compliance as a way of framing the costs of achieving obligations in the presence of other water quality obligations.

To build a model representative of Loudoun County MS4’s compliance obligations, Loudoun County MS4’s Bay and local water quality objectives are first established. A choice set of representative compliance practices is chosen based on observed MS4 compliance behavior. Unit reductions and costs for stormwater compliance practices and trade are estimated and refined to account for differences in costs that may stem from placement on pervious and impervious, as well as on public and private land. Land use and stream restoration constraints are established using information from the MS4’s Bay and local TMDL action plans and from GIS resources. Linear programming is conducted via GAMS modeling software to determine the least-cost way to achieve compliance goals. Results are analyzed and sensitivity of results is tested under different assumptions. Findings are discussed.

2.4 Loudoun County MS4 and Compliance Obligations

Loudoun County MS4 is a municipal MS4 in northern Virginia within the Potomac tributary of the Chesapeake Bay.[1] As a Virginia MS4 in the Chesapeake Bay, Loudoun County MS4 is held to explicit Chesapeake Bay TMDL nutrient and sediment reduction permit requirements (Davenport, 2021). Like other Virginia MS4s, Loudoun County MS4 is also required to address local water quality impairments in response to local TMDLs (VA DEQ, n.d.a). Within the Loudoun County MS4, portions of Goose Creek, Bull Run, and Sugarland Run fail to meet state water quality standards and are subject to local TMDLs (Figure 2.1) (Stone & Loudoun County DGS, 2021).

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[1] See Phase II Action Plan update (Loudoun County DGS & WEIS, 2022) and Loudoun County, Virginia n.d.

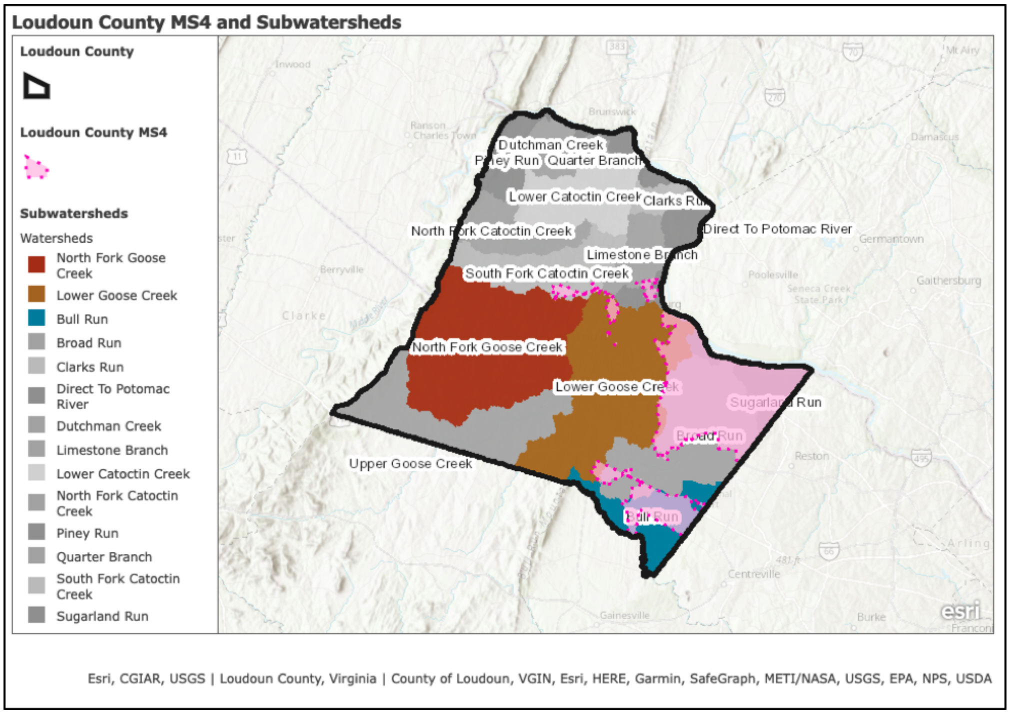

Figure 2.1: Loudoun County MS4 and Subwatersheds

Sources: Loudoun County 2017a and 2016; Ward 2020; map generated in ARCGIS Online using default topographic and hillshade layers.

In response to these TMDLs, Loudoun County MS4 has developed a combined local TMDL action plan to address the following[2]:

- A sediment TMDL in Goose Creek
- A sediment TMDL and a bacteria TMDL in Bull Run
- A bacteria TMDL in Sugarland Run

Loudoun County MS4 explains in its combined local TMDL action plan that "Sediment is a major cause of stream degradation nationally and has been identified as the primary stressor associated with the decline of benthic aquatic habitats in the Goose Creek and Bull

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[2] See combined local TMDL action plan (Stone & Loudoun County DGS, 2021).

Run watersheds" and that, "Bacteria contamination is one of the most common causes of water quality impairment in Virginia streams" and can harm those recreating or consuming products from associated waters (Stone & Loudoun County DGS, 2021).

Observations of Loudoun County MS4's combined local TMDL action plan and Bay TMDL action plan show only minor overlap between practices implemented in response to bacteria reduction obligations and practices implemented in response to Bay TMDL obligations, as opposed to the substantial overlap between the practices implemented in response to sediment reduction obligations and the practices implemented in response to Bay TMDL obligations.[3] In response, incremental cost analysis focuses on the cost of achieving Bay TMDL obligations in addition to sediment obligations. Given lack of overlap between strategies implemented in the MS4's Phase II Bay TMDL action plan to address Bay and strategies implemented in the MS4's combined local TMDL action plan to address bacteria obligations, omission of bacteria obligations from modeling will not meaningfully impact incremental cost analysis of Bay obligations.

Loudoun County MS4 must achieve annual reductions of 15,536 lbs of nitrogen, 1,808 lbs of phosphorus, and 1,501,815 lbs of sediment to achieve 100% Bay TMDL compliance, based on the 40% reduction requirements listed in its Phase 2 Chesapeake Bay TMDL Action Plan under DEQ (Loudoun County DGS & WEIS, 2022). Loudoun County MS4 must also achieve annual sediment reductions of 63,200 lbs/year in its portion of the Goose Creek subwatershed and 1,436,800 lbs/year in its portion of the Bull Run subwatershed in response to its local TMDL obligations (Table 2.1) (Stone & Loudoun County DGS, 2021).

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[3] See Phase II Bay TMDL action plan (Loudoun County DGS & WEIS, 2022) and combined local TMDL action plan (Stone & Loudoun County DGS, 2021).

Table 2.1: Loudoun County MS4's Chesapeake Bay TMDL and Sediment TMDL Obligations

Total Reduction Requirements	**Nitrogen**	**Phosphorus**	**Sediment**
Chesapeake Bay TMDL (100%)	15,536 lbs/yr	1,808 lbs/yr	1,501,815 lbs/yr
Goose Creek Sediment TMDL	–	–	63,200 lbs/yr
Bull Run Sediment TMDL	–	–	1,436,800 lbs/yr

2.4.1 Stormwater Management Practices for Local and Regional Water Quality

The choice set of strategies that the MS4 may use to achieve Bay and local objectives is restricted to major practices observed in the MS4's Phase 2 Bay TMDL action plan.[4] These practices include any practice determined to be responsible for at least 2.5% of planned N, P, or TSS reductions documented in Loudoun County MS4's Phase 2 Bay TMDL Action Plan (Table 2.2).

Table 2.2: Loudoun County MS4's Top Sources of Chesapeake Bay TMDL Reductions

Stormwater Practice	**Share of MS4's Claimed Reductions Toward 40% Reduction Requirements**		
	Nitrogen	**Phosphorus**	**Sediment**
Wetland	26.7%	20.2%	18.8%
Nutrient Credits (Perpetual NPS)	19.0%	15.3%	11.2%
Stream restoration	17.3%	37.6%	27.4%
Bioretention	16.2%	3.1%	12.0%
Wet Pond & Pond Enhancement	6.9%	9.0%	11.4%

Source: Loudoun County DGS & WEIS, 2019. Loudoun County MS4's Bay TMDL action plan reports wetland practices separately from wet pond & pond enhancement practices, but DEQ resources consider them in-tandem. See Davenport, 2021 for information on DEQ reporting.

The strategies adopted overlap with the sediment control practices listed under the local

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[4] See Loudoun County DGS & WEIS, 2019.

sediment TMDLs. Both the Bull Run and Goose Creek TMDLs, for instance, suggest use of "streambank protection and stabilization, and wetland development or enhancement".[5]

The MS4s' overall choice set is expanded beyond wet pond/wetland BMPs (categorized together by DEQ), bioretention, stream restoration, and nonpoint source perpetual credits to include point source term credits, to more fully investigate implications of trade for Bay compliance, given literature's current focus on the role of trade in achieving Bay cleanup obligations (Farrow et al., 2005; Van Houtven et al., 2012; Stephenson & Shabman, 2017a, 2017b, 2017c).[6] Point source trades, i.e. trades from wastewater, in Virginia generally do not provide sediment reductions (WRI & USDA OEM, n.d.). Virginia law 9VAC25-900-90 allows nitrogen and phosphorus to be traded separately. In response, distinct options for nitrogen and phosphorus, but not sediment, trade are incorporated into the choice set.

Subsets of the adopted overall choice set preclude use of PS term trade, as well as both PS term trade and NPS perpetual trade. These represent 'limited trade' and 'no trade' scenarios.[7] All choice sets include 'onsite' compliance options, i.e. stream restoration and BMPs. The reason for limited and no-trade scenarios in analyses is because the MS4 is not observed to use PS term trade in current Bay TMDL compliance strategy and because MS4s, in general, exhibit low interest in trade.[8] Incorporating Chapter 1's findings on MS4s' varying preferences for trade provides generalizable insight into MS4s' compliance costs under different preferences. Comparison of how costs change as trading options vary will also contribute to present literature focusing on the cost-implications of trade for Bay TMDL compliance (Farrow et al., 2005; Van Houtven et al., 2012; Stephenson & Shabman, 2017a, 2017b, 2017c).

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[5] See VA DEQ, VA DCR, & ICPRB, 2004 and VA DEQ & LBG, 2006.

[6] See Davenport, 2021 for DEQ's joint wetland and wet pond categorization.

[7] For reference, 'full trade' scenarios allow PS term credit purchases and NPS perpetual credit purchases.

[8] See Section 1.5.

2.4.2 Nutrient and Sediment Reductions From Strategies in the Choice Set

Urban stormwater and stream restoration practices in the choice set provide N, P, and TSS reductions toward Bay TMDL obligations and sediment reductions toward to local TMDL obligations. To determine the reductions provided toward Bay and local obligations by the urban stormwater BMPs in the MS4's choice set (i.e. bioretention and wetland and wet pond practices), reduction efficiencies for N, P, and TSS for bioretention and for wet pond and wetland practices are multiplied by per-acre nutrient and sediment loading rates for both impervious and pervious lands; reduction efficiencies and loading rates are sourced from DEQ's Chesapeake Bay TMDL Special Condition Guidance Memo (Table B.1) (Davenport, 2021). Wetland and wet pond efficiencies are the same as those reported in CAST, though bioretention efficiencies vary, given DEQ's reporting of a singular representative rate is simpler than CAST's reporting of rates for the various types of bioretention facilities (i.e. on A/B soils with and without underdrains and on C/D soils with underdrains) (CBP, 2023).

DEQ identifies 'edge of stream' total nitrogen (TN), total phosphorus (TP), and total suspended solids (TSS) loads that the MS4 must meet to be compliant with the Bay TMDL (Loudoun County DGS & WEIS, 2022 and Davenport, 2021). As such, the same loading rates are also used to estimate sediment reductions toward local TMDL obligations. The resulting rates represent per-pound reduction rates for acres of pervious and impervious land treated.

To determine the reductions provided by stream restoration toward Bay and local obligations, stream restoration N, P, and TSS removal rates, on a per-foot basis, are adopted from default revised rates made by recent Chesapeake Bay Program expert panel judgment regarding updated stream restoration nutrient and sediment removal capacity (Schueler et al., 2014; Swann, 2016.). As with the BMP efficiencies adopted, reductions from stream restoration are ‘edge of stream’, and so stream restoration’s sediment reduction rates toward Bay obligations are also applied toward local TMDLs (Scheuler et al., 2014).

To determine reductions from perpetual credits that Loudoun County MS4 may purchase from nutrient banks, ArcGIS was first used to determine the HUC8s and HUC12s in which the MS4 lies (Table B.2) (NVRC & Wagner, 2022; Ward, 2020). The U.S. Army Corps of Engineers’ RIBITS database was then used to source information on credits released from banks within these HUCs.[9] The mean ratio of N:P:TSS credits released was then adopted as the per-unit reductions from perpetual credit purchases (Table B.3). Reductions from point source trade were assumed to be achievable on a per-pound basis, per review of trades throughout the state (VNCEA, 2021). Credits provide reductions toward only Bay TMDL obligations, since Stephenson et al. 2022 report no active credit markets for local TMDL compliance in the state. Nutrient banks from which the MS4 may purchase nutrient credits tend to be located in rural areas, so any sediment credits are assumed to not apply to the urbanized portion of Goose Creek’s TMDL requirements to which the MS4 is held.

Reductions provided by all strategies are presented in Table B.4.

2.4.3 Compliance Activity Costs

Initial cost estimates for urban stormwater practices and stream restoration were based on CAST cost data for urban stormwater BMPs and stream restoration(CBP, n.d.a; Devereux, 2020). Installation costs were annualized over respective project lifespans reported in CAST and land opportunity costs are annualized in perpetuity at a 5% discount rate, per CAST standards (CBP, n.d.a). Annual O&M costs were based on annual estimates from the same

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[9] See U.S. Army Corps of Engineers, n.d.a-ae.

CAST data. The numerous types of bioretention in CAST cost data were jointly considered, to facilitate adoption of representative characteristics for bioretention facilities, meaning the average facility lifespan, and unit capital, O&M, and opportunity costs from the different types of bioretention facilities documented in CAST (bioretention on A/B soils w/ underdrain, on A/B soils w/out underdrain, and on C/D soils w/ underdrain) were adopted.

Urban stormwater and restoration costs were subsequently adjusted from initial estimates, depending on whether practices treat impervious and pervious land and whether they treat public or private land, to reflect changes in cost associated with placement on different land types. All adjustments to costs based on land perviousness and ownership are summarized in Table B.5. Corresponding changes to capital, opportunity, and O&M costs are detailed in Table B.6.

Capital costs of practices on impervious land were increased, since retrofit facilities, which are more indicative of activity in more developed areas, are costlier than new facility construction, which might occur in less-developed areas (King & Hagan, 2011). Retrofit facility costs were estimated to be 130% higher for wet pond and wetland practices and 250% higher for bioretention practices, relative to new facility costs (2011). These cost premiums are applied to corresponding capital costs for BMPs on impervious land.

O&M costs were not assumed to vary between pervious and impervious land, in accordance with both CAST's and King and Hagan's assumptions regarding O&M costs of retrofit and newly-constructed facilities (King & Hagan, 2011; CBP, n.d.b). O&M expenses on private land were, however, assumed to be 125% of those on public land, due to easements and challenges with disposing waste sediment from private land (Township of Ferguson, n.d; VSM Handbook, 2013b; NVRC, 2007).

Land opportunity costs on impervious land were increased by 25% over default costs, in accordance with recent real estate data on price premiums for urban, as opposed to suburban, homes (Fuller, 2016). Use of home sales price differences as proxies for impervious and pervious land value differences is supported by findings that underlying land value does have greater influence on real estate values in urban areas (Davis & Palumbo, 2006; Zhang & Hou, 2015).

Land opportunity costs were assumed to be zero for projects placed on public lands, in accordance with findings that MS4s generally do not consider public land to have land opportunity costs (Section 1.5). The opportunity costs on private lands were increased by 25% from default CAST estimates, since easements increase access costs to private land (Section 1.5).

Estimates of perpetual trade costs were sourced from observed nutrient credit prices throughout the state (Albemarle County, 2015, 2017, 2019; Augusta County, Virginia, 2021; Prince William County School Board, 2019, 2020). Perpetual credit prices were annualized at the same 5% discount rate used for annualizing costs associated with other compliance practices. The representative credit price that resulted was $12,750/lb P, which translated to an annualized cost of $637.50/lb/yr P. Term credit prices were adopted after review of available credits through Virginia's Nutrient Credit Exchange finds that annual N and P credits trade at a representative per-pound cost of $3.78 and $5.70 per pound per year (VNCEA, 2021). Annualized cost differences between perpetual and term trades are substantial, though perpetual credits simultaneously provide N, P, and TSS, rather than just N or P that term credits provide; furthermore, perpetual credits, once purchased, do not require the MS4 to rely on continual availability or to continually purchase credits, as is the case with term credits.

Unit costs and corresponding per-pound reduction costs for all resulting strategies in the choice set may be found in Tables B.7 and B.8.

2.4.4 Land Constraints for Urban Stormwater Management

Land availability constraints in each subwatershed limit bioretention and wet pond/wetland implementation. To determine these constraints, pervious and impervious land acreage for the entire Loudoun County MS4 was sourced from Loudoun County MS4's Bay TMDL Action Plan. Pervious and impervious regulated land acreage in the Bull Run and Goose Creek subwatersheds was sourced from Loudoun County's Local TMDL action plan (Table 2.3).

Table 2.3: Regulated Impervious and Pervious Land Throughout Loudoun County MS4

Subwatershed	**Regulated Acreage**		
	Perv.	**Imp.**	**Total**
Rest of MS4	8,991	4,812	13,804
Goose Creek Portion of MS4	689	283	972
Bull Run Portion of MS4	1,832	559	2,391

Sources: Loudoun County DGS & WEIS, 2022 and Stone & Loudoun County DGS, 2021. The MS4 does not consider forest land in its Phase 2 Bay TMDL Action Plan land determination.

Land cover constraints were refined to accommodate consideration of publicly and privately-owned land in each subwatershed using GIS data on public landholdings. GIS data was used to calculate public and private landholdings within the MS4 and its subwatersheds (Table 2.4).

Table 2.4: Distribution of Public and Private Land in Loudoun County MS4

Subwatershed	**Public Land**	**Private Land**
Rest of MS4	6%	94%
Goose Creek Portion of MS4	6%	94%
Bull Run Portion of MS4	4%	96%

Sources: Loudoun County, 2016, 2017, 2020; Ward, 2020. Private land and land in the Rest of MS4 were calculated by subtraction of GIS-measured components of public land in the entire MS4 and in the MS4's Bull Run and Goose Creek subwatersheds. Public area includes area owned or leased by Loudoun County.

Pervious and impervious acreage in the MS4 and in each subwatershed was multiplied by proportions of publicly and privately-owned land to generate estimates of public-pervious, public-impervious, private-pervious, and private-impervious MS4 land in the Bull Run and Goose Creek portions of the MS4 and in the remaining portions of the MS4, i.e. 'Rest of MS4' (Table 2.5).

Table 2.5: Land Use Constraints for Model

Subwatershed	**Pervious (ac)**		**Impervious (ac)**	
	Public	**Private**	**Public**	**Private**
Rest of MS4	540	8,452	289	4,524
Goose Creek Portion of MS4	41	648	17	267
Bull Run Portion of MS4	77	1,755	24	536

Note: Reported acreage represents rounded constraints.

2.4.5 Stream Length Constraints for Implementation of Stream Restoration Activity

The model establishes limits on stream restoration activity for use in each subwatershed, as well. Total stream length within subwatersheds, measured using layers available at ArcGIS, is 76,296 feet in Goose Creek, 52,579 feet in Bull Run, and 632,247 feet in the entire MS4 (Ward, 2020; TKniskern, 2022). But Loudoun County MS4 (and other MS4s) may only achieve reductions from restoration of degraded streams (Wood et al., n.d.; Virginia DCR et. al, n.d.; Kuo, n.d.; Davenport, 2021).[10]

The largely point-based county GIS resources available on degraded segments are insufficient to effectively measure these lengths of degraded streams.[11] So, establishment of a maximum level of stream restoration activity to be used to achieve Phase 3 Bay and lo-

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[10] English units are adopted for consistency with reporting practices pertaining to unit costs, unit reductions, and units implemented in both CAST and Loudoun County's Bay and local TMDL action plans. See Devereux, 2020; Stone, C., & Loudoun County DGS, 2021; and Loudoun County DGS & WEIS, 2022.

[11] See Daveward, 2022 and Ward, 2020.

cal TMDL requirements relies instead on extrapolation from restoration activity currently claimed by the MS4 toward Bay and local obligations.

The observations of stream restoration activity in each subwatershed in the MS4's Phase 2 (40%) Bay TMDL action plan update, and in the MS4's recent combined local TMDL action plans were first documented.[12] Documented activity in these Bay and local TMDL action plans was then scaled by a factor of 2.5, to predict what may be observed by the end of the third phase of the Bay TMDL, since Bay TMDL requirements will scale by a factor of 2.5 from the second to third phases of the Bay TMDL. This assumed that present stream restoration implemented in local subwatersheds will scale at the same rate as do Bay TMDL obligations, which is supported by the fact that current local compliance activity will need to increase to achieve goals and the fact that the MS4 is observed to claim reductions toward both Bay and local goals from the same stream restoration activity.[13]

The estimates of what stream restoration activity may be anticipated in the third phase of the Bay TMDL were then increased by 50% to yield absolute maximum constraints on stream restoration activity that may realistically occur (Table 2.6). Adopted maximum constraints represent 7% of total stream length in Goose Creek, 32% in Bull Run, and 3% of total stream length in the MS4, as calculated with GIS data; these constraints are thus not only achievable, but also conservative, relative to limited findings from historic stream assessment data (Ward, 2020; TKniskern, 2022; Loudoun County, 2009).

The proportions of what stream activity may occur in each subwatershed adjacent to public and private land are determined by the assumption that degraded streams adjacent to public and private land in each subwatershed are found in the same proportions as the

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[12] See Loudoun County DGS & WEIS, 2022 and Stone & Loudoun County DGS, 2021 for action plans considered.

[13] See Loudoun County DGS & WEIS, 2019, 2022 and Stone & Loudoun County DGS, 2021 for instances of overlapping stream restoration projects.

Table 2.6: Establishment of Maximum Feasible Stream Restoration Constraints

Subwatershed	**Observed Phase 2 Stream Rest.**	**Estimates of Phase 3 Stream Rest.**	**Estimate of Max. Feasible Stream Rest.**
Entire MS4	5,300 ft	13,250 ft	19,875 ft
Goose Creek Portion of MS4	1,350 ft	3,375 ft	5,062 ft
Bull Run Portion of MS4	4,500 ft	11,250 feet	16,875 ft

Note: Observed activity of 5,284 feet of activity in the entire MS4 is rounded to 5,300 feet, for simplicity.

proportions of public to private land in each subwatershed. Final adopted constraints on stream restoration are presented in Table 2.7:

Table 2.7: Adopted Modeling Constraints on Stream Restoration Activity

Subwatershed	**Estimate of Max. Feasible Stream Rest.**	**Adopted Modeling Constraint**	
		Public-Adj.	**Private-Adj.**
Entire MS4	19,875 ft	1,136 ft	18,739 ft
Goose Creek Portion of MS4	5,062 ft	297 ft	4,765 ft
Bull Run Portion of MS4	16,875 ft	709 ft	16,166 ft

The use of the 'Entire MS4' as a watershed, instead of the 'Rest of the MS4' adopted in land use constraint development is acknowledged and is a necessary result of use of observed activity throughout the MS4 to establish a maximal stream restoration constraint.

2.4.6 Linear Programming Model

The linear programming model seeks to minimize the cost of meeting water quality compliance obligations through use of urban stormwater practices, restoration practices, and trade, subject to land and stream constraints.

The linear programming model allows for urban stormwater (bioretention and wetpond/wetland) and restoration (stream restoration) practices to be implemented in non-negative quantities on the acreage and streams in each of the three subwatersheds in the model, i.e. the

Goose Creek subwatershed in Loudoun County regulated by the local TMDL, the Bull Run subwatershed in Loudoun County regulated by the local TMDL, and the MS4 outside these regulated portions of the Goose Creek and Bull Run subwatersheds in the MS4 (i.e. the 'Rest of the MS4').

The linear programming model's objective function is to minimize the total cost of decision variables used to achieve compliance,

$$MinC = \sum_{i=1}^{n} c_i x_i \qquad i = 1, ..., 33 \tag{2.1}$$

where , x_i, for $i = 1, ..., 33$, represents how many units of each compliance practice of type i are implemented and c_i represents the unit cost of stormwater compliance practice of type i. C represents the total cost of Loudoun County MS4's stormwater management compliance. Units of compliance are 'acres treated' for urban stormwater BMPs and 'feet' for stream restoration, per DEQ and CBP (Davenport, 2021; Devereux, 2020). Units for credits are 'credits purchased'. The 33 compliance practices are detailed in Table B.9.

The linear programming model represents Bay N, P, and TSS and Goose Creek and Bull Run sediment water quality objectives as inequality constraints to be met or surpassed,

$$\sum_{i=1}^{n} b_{qi} x_i \geq Q_i \qquad q = 1, ..., 5 \tag{2.2}$$

where b_{qi} represents the reductions of nutrient q, for $q = 1, 2, 3, 4, 5$, which represent nitrogen, phosphorus, and sediment reductions toward the Bay TMDL and sediment reductions toward each of the Bull Run and Goose Creek TMDLs, from each unit of compliance practice i, for $i = 1, ..., 33$.

The linear programming model incorporates land use constraints, for land that compliance practices can treat, that cannot be exceeded by BMP treatment,

$$\sum_{i=1}^{n} l_{kpti} x_i \leq L_{kpt} \qquad k = 1,2,3; \;\; p = 1,2; \;\; t = 1,2 \tag{2.3}$$

where l_{kpti} represents the unit acreage used by practice i, for $i = 1, ..., 33$, in watershed k, for $k = 1,2,3$, on land ownership-type p, for $p = 1,2$, on land type t, for $t = 1,2$. The subwatersheds are Bull Run, Goose Creek, and 'Rest of MS4', and the two land ownership types are public and private. The two land types are pervious and impervious land. In the equation, L_{kpt} represents the constraint for land in each subwatershed, of public or private ownership, and previous or impervious nature.

The linear programming model also incorporates constraints on stream lengths in each subwatershed adjacent to public and private lands that cannot be exceeded by stream restoration activity,

$$\sum_{i=1}^{n} r_{wpi} x_i \leq R_{wp} \qquad w = 1,2,3; \;\; p = 1,2 \tag{2.4}$$

where r_{wpi} represents the feet of stream that compliance practice i, for $i = 1, ..., 33$, utilizes in stream watershed w, for $w = 1,2,3$ (for Bull Run, Goose Creek, and the 'Entire MS4'), that is adjacent to land of ownership p, for $p = 1,2$ (for public and private land). R_{wp} representing the overall constraint on stream restoration in watershed w adjacent to land with ownership p.[14]

The linear programming model also incorporates non-negativity constraints on the decision variables, to ensure no compliance practice is implemented in a negative quantity,

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[14] Given that stream restoration has no opportunity cost, its costs only vary by public and private land designation, so its incorporation to the model does not specify the perviousness of adjacent land.

$$x_i \geq 0 \qquad i = 1, ..., 33 \tag{2.5}$$

where $i = 1, ..., 33$ represent each compliance choice within the vector of decision variables. Limited- and no-trade scenarios also restrict values of PS trade options to 'zero' in both limited- and no-trade scenarios and of NPS trade options to zero in no-trade scenarios. Term credit trade options represent x_i, for $i = 31, 32$ and perpetual credits represent x_i, for $i = 33$.

To achieve the first objective, which is to estimate the minimum cost to achieve local water quality objectives in isolation from Chesapeake Bay obligations for Loudoun County MS4, linear programming analyses are run to determine the cost-minimizing portfolio of compliance activity that achieves local sediment requirements in the Goose Creek and Bull Run subwatersheds.

To achieve the second objective, which is to estimate the minimum incremental costs incurred to achieve Chesapeake Bay TMDL compliance in addition to local water quality objectives, analyses are re-run to determine the cost-minimizing portfolio of compliance activity that achieves local sediment requirements in the Goose Creek and Bull Run subwatersheds, as well as the requirements of achieving the N, P, and TSS reductions necessary under the Bay TMDL. Minimum costs of achieving local objectives are subtracted from minimum costs of achieving Bay and local objectives to determine the incremental cost of Bay TMDL compliance.

To achieve the third objective, which is to estimate the minimum cost to achieve Chesapeake Bay TMDL compliance in isolation of other water quality objectives, linear programming analyses are run to determine the cost-minimizing portfolio of achieving Bay TMDL requirements.

The above compliance costs are determined in scenarios allowing and precluding term credit purchases.

2.5 Results and Discussion

The estimated costs, strategies implemented, and land and streams utilized to achieve compliance with local obligations, Bay and local obligations, incremental compliance with Bay obligations, and compliance with just Bay obligations are presented in Table 2.8. Associated results detailing the practices utilized to meet each objective may be found in the appendix in Tables B.10 through B.15.

Table 2.8: Annualized Costs to Achieve TMDL Compliance, With Full, Limited and No Trade

Water Quality Objective	**Annualized Costs of Compliance ($/yr)**		
	Full Trade	*Limited Trade*	*No Trade*
Local TMDLs	$11,137,248	$11,137,248	$ 11,137,248
Ches. Bay & Local TMDLs	$11,160,954	$11,468,061	$14,797,252
Ches. Bay TMDL	$4,186,398	$4,186,398	$11,990,373
Incremental Cost of Bay TMDL	$23,706	$330,813	$3,660,005

Note: Full-trade scenarios allow NPS perpetual and PS term credits. Limited-trade scenarios allow NPS perpetual credits. No-trade scenarios do not allow trade of either form.

The cost for the MS4 to achieve local obligations is $11,137,248. If local water quality goals are considered along with Bay TMDL goals, then the additional annualized cost to meet the Bay TMDL is $23,706 when both PS term trade and NPS perpetual credits can be purchased, $330,813 when NPS perpetual credits can be purchased, and $3,660,005 when the MS4 cannot purchase credits to achieve compliance. These incremental costs represent additional costs of 0.2%, 3.0%, and 32.9% to the MS4, respectively. These incremental costs are substantially lower than the cost estimates to meet just Bay TMDL obligations, which are $4,186,398 in full- and limited-trade scenarios and $11,990,373 in no-trade scenarios.

Overall, the reason that the incremental cost of Bay TMDL compliance is so low is that many of the MS4's Bay obligations are already achieved through activities designed to meet local obligations. Relative to Bay TMDL obligations, the activities implemented to meet local obligations provide 66.3%, 120.7%, and 99.9% of the N, P, and TSS obligations under the Bay TMDL (Table 2.9). Nitrogen is the only constituent that requires additional effort to meet Bay compliance.

Table 2.9: Nutrient Reductions Generated by Strategies Selected to Achieve Compliance with Only Local Objectives

Practice	**Land Type**	**Reductions (lbs/year)**		
		N	**P**	**TSS**
Practices in Goose Creek Portion of MS4				
Stream Restoration	Public-Adj.	22.3	20.2	13,342.8
Stream Restoration	Private-Adj.	83.3	75.5	49,857.2
Practices in Bull Run Portion of MS4				
Bioretention	Imp. Public	277.3	28.6	22,020.8
Wet pond and Wetland	Imp. Private	540.8	116.9	112,720.1
Bioretention	Imp. Private	4,427.1	455.8	351,500.0
Wet Pond and Wetland	Perv. Public	154.9	14.2	8,111.4
Wet Pond and Wetland	Perv. Private	3,534.2	323.8	185,096.3
Stream Restoration	Public-Adj.,	53.2	48.2	31,824.4
Stream Restoration	Private-Adj.	1,212.4	1,099.3	725,525.6
Total Reductions from Local Activity:		10,305.5	2,182.4	1,499,998.7
Total Bay Requirements:		15,536.2	1,808.0	1,501,814.9
Remaining Bay Requirements:		5,230.6	0; reqs. achieved	1,816.2
Portion of Bay Reqs. from Local Activity:		66.3%	120.7%	99.9%
Portion of Remaining Bay Requirements:		33.7%	0%	0.1%

To achieve the remaining N and TSS compliance, the MS4 uses low-cost term trade and a minor amount of stream restoration or perpetual trade to achieve remaining requirements in a cost-effective manner, in scenarios with full trade and limited trade (Seen in Tables B.11

and B.12, relative to Table B.10). When trade is precluded, the MS4 substitutes stream restoration in Goose Creek subwatershed for wet pond and wetland practices. Practice use in Bull Run are adjusted, as well, with some bioretention on impervious private land replaced by wet pond and wetland practices (Table B.13). Findings suggest that, when trade is precluded (i.e. in 'no trade' scenarios), the MS4 may implement a more diverse portfolio of compliance activity, as a way of ensuring N and P reductions are also provided by the practices generating TSS reductions toward local and Bay obligations.

Incremental costs of Bay TMDL compliance can be substantially reduced through trade. The addition of perpetual NPS trade to the choice set of compliance strategies otherwise precluding trade reduces the MS4's incremental cost of Bay TMDL compliance by more than $3 million; the incremental addition of PS term trade to the choice set in addition to NPS perpetual trade and other strategies reduces the MS4's costs by approximately $300,000. If the MS4 can purchase NPS perpetual credits, its incremental costs decline by approximately 91% from those needed to achieve Bay TMDL compliance without trade; allowing PS term trades, in addition to NPS perpetual trades leads to decline by an additional 93%, relative to costs when just NPS trades are allowed. In tandem, the incremental cost of Bay TMDL compliance is 99% lower when all trades are allowed than when trades are precluded. Effectively, expansion of the choice set leads to sizeable, albeit, diminishing incremental cost savings.

2.6 Sensitivity Analysis

Sensitivity analyeses are conducted to test the degree to which findings may change under assumptions other than those adopted. Seven sensitivity analyses adjust assumptions regarding capital, opportunity, and O&M costs. Two sensitivity analyses reflect changes to the incremental cost of Bay compliance, under different land and stream constraints. These nine sensitivity analyses are described below:

- *Sensitivity Analysis 1:* Adjustments to wet pond and wetland and to bioretention capital costs on impervious land are scaled back to 100% of CAST's adopted estimates, from the higher estimates of 230% and 350% based on King & Hagan 2011. This models a scenario where BMPs on impervious land are newly constructed, rather than retrofit facilities, and so are the same costs as the CAST-baseline estimate. All other assumptions are unchanged, relative to initial analyses.
- *Sensitivity Analysis 2:* Adjustments to wet pond and wetland and to bioretention capital costs on impervious land are increased to 300% and 400%, rather than 230% and 350%, respectively, which represents a rounding of adjustment factors up to the nearest 100%. All other assumptions are unchanged, relative to initial analyses.
- *Sensitivity Analysis 3:* Opportunity costs on public land are fully realized, at 100% of CAST's anticipated opportunity costs. This reflects a change in the previously adopted assumption that there are no opportunity costs for practice placement on public land, in response to MS4 perspectives that such land has no value. This models a scenario in which the MS4 considers the value of public land in its decision-making. All other assumptions are unchanged, relative to initial analyses.
- *Sensitivity Analysis 4:* Opportunity costs on private land are increased to 150%, from the 125% of CAST's cost estimates initially adopted. This adjustment is adopted by the researchers to model a scenario in which initial access easements are more costly than necessary. All other assumptions are unchanged, relative to initial analyses.
- *Sensitivity Analysis 5:* Opportunity costs on impervious land are scaled back to 100% and on both public and private are scaled to 100%. This represents a scenario in which

easements do not increase land opportunity cost and the MS4 considers land value; it reflects use of baseline cost assumptions for land value in CAST. All other assumptions are unchanged, relative to initial analyses.

- *Sensitivity Analysis 6:* O&M costs on private land are scaled back to 100%, to reflect a scenario where maintenance on private land presents no added difficulty, relative to maintenance on public land. All other assumptions are unchanged, relative to initial analyses.

- *Sensitivity Analysis 7:* O&M costs on private land are scaled up to 150% to reflect a scenario where maintenance on private land is more difficult than expected. All other assumptions are unchanged, relative to initial analyses.

- *Sensitivity Analysis 8:* Land and stream availability are half those initially adopted. All other assumptions are unchanged, relative to initial analyses.

- *Sensitivity Analysis 9:* Stream restoration availability constraints in Table 2.7 are relaxed by doubling initial availability (e.g. private-adjacent stream restoration in the 'Rest of MS4' increases from 18,739 ft to 37,477 ft).

Results in sensitivity analysis scenarios with adjusted practice costs generally do not lead to conclusions differing from those made after initial modeling. The incremental costs to achieve Bay TMDL compliance, relative to total water quality spending, determined in sensitivity analyses are similar to those under baseline calculations, within given conditions of trade availability (i.e. Full-trade, limited trade, and no-trade) (Figures 2.2 through 2.4).

Results are more complicated, when land and stream constraints are adjusted. When land and stream availability constraints are halved in Scenario 8, results find that achievement of obligations for local TMDLs is infeasible, though Bay TMDL costs are similar to those exhibited in other scenarios. Implications are that the degree of BMP and restoration activity observed in initial scenarios is likely to be rigid, if local requirements are to occur. When constraints on stream availability are relaxed in Scenario 9, costs to achieve Bay and local, as well as local, TMDL compliance are reduced. The incremental cost of the Bay TMDL still represents a minor portion of the MS4's overall water quality spending, though the model makes use of only stream restoration and trade, when all forms of trade are allowed and when just NPS perpetual trade is allowed, which is unrepresentative of the key compliance choices made in the MS4's action plans.[15]

When trade is precluded from use in Sensitivity Analysis 9, wet pond and wetland practices are incorporated into compliance, likely out of consideration for the N and P reductions they provide toward the Bay TMDL, as evidenced in the exclusive use of these practices toward Bay-only obligations (Table B.22). This deviation from stream-restoration-heavy compliance practices in other scenarios implies that N and P may be driving forces behind use of wet pond and wetland practices, when trade is otherwise restricted.

Regardless, findings from the nine sensitivity analyses show that the incremental cost of Bay TMDL compliance, as a portion of total water quality spending, remains similar, under full trade, limited trade, and no-trade scenarios. The incremental costs of Bay cleanup, as well as the total costs of achieving Bay and local, local, and Bay water quality obligations in initial analysis, as well as in sensitivity analyeses, may be found in Tables B.16 through B.20.

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[15] See Tables B.21 and B.22 for heavy use of stream restoration, Stone & Loudoun County DGS, 2021, Loudoun County DGS & WEIS, 2019 and 2022.

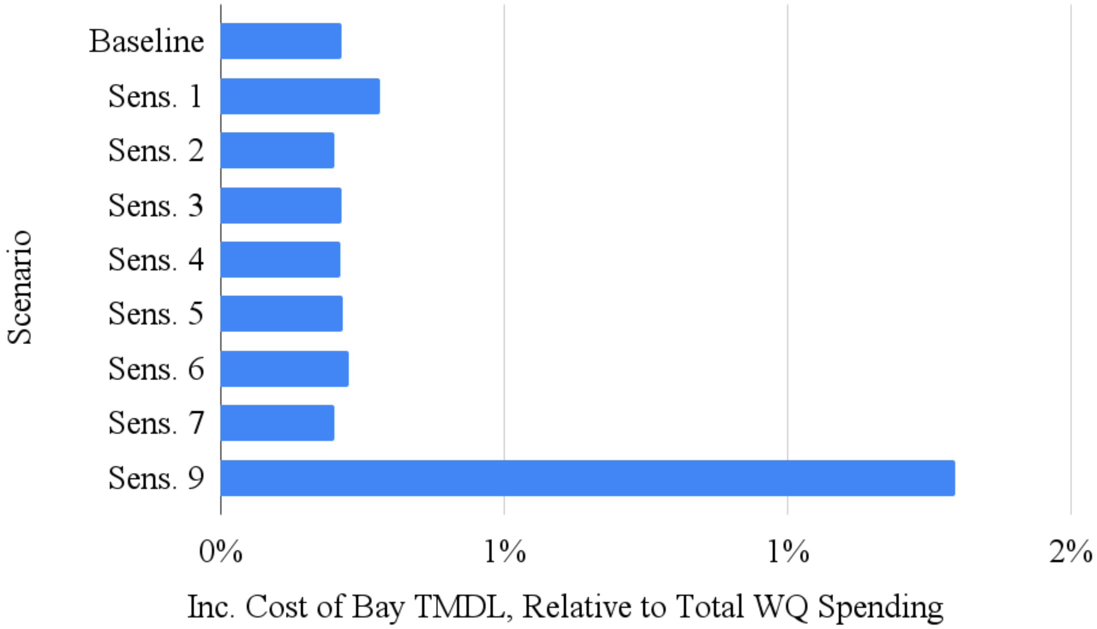

Figure 2.2: Incremental Cost of Bay TMDL Compliance, Relative to Total WQ Spending, Full Trade

Sens. 1: New facilities on imp. land.
Sens. 2: Retrofits costlier than anticipated.
Sens. 3: Public land has value.
Sens. 4: Private land easements costlier than expected.
Sens. 5: Public land has value; no easements for private land.
Sens. 6: O&M on private land is same as on public land.
Sens. 7: Costlier O&M on private land than anticipated.
Sens. 9: Stream constraints expanded.
Sensitivity Analysis 8 precluded from chart due to infeasible Bay and local obligation achievement.

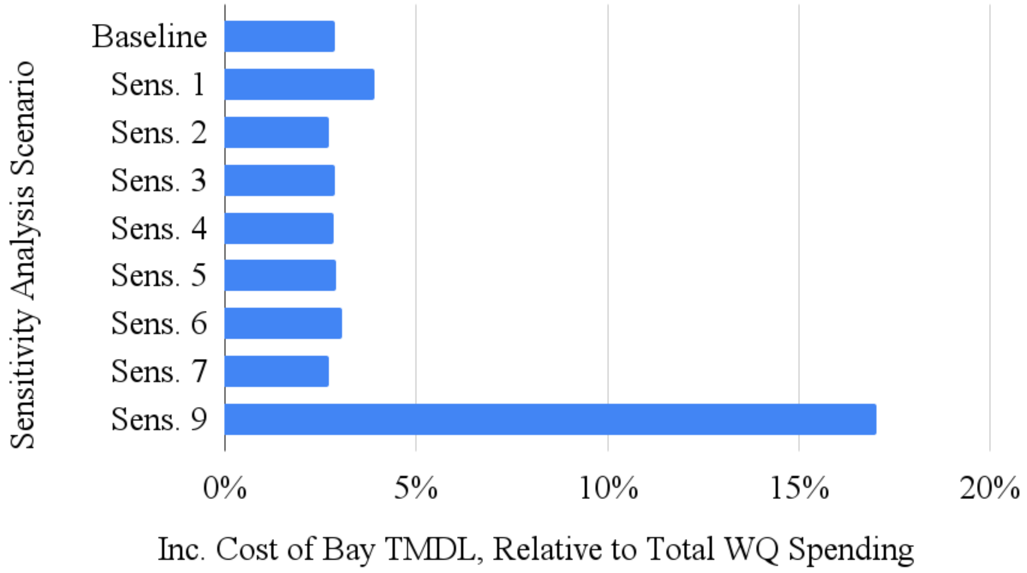

Figure 2.3: Incremental Cost of Bay TMDL Compliance, Relative to Total WQ Spending, Limited Trade

Sens. 1: New facilities on imp. land.
Sens. 2: Retrofits costlier than anticipated.
Sens. 3: Public land has value.
Sens. 4: Private land easements costlier than expected.
Sens. 5: Public land has value; no easements for private land.
Sens. 6: O&M on private land is same as on public land.
Sens. 7: Costlier O&M on private land than anticipated.
Sens. 9: Stream constraints expanded.
Sensitivity Analysis 8 precluded from chart due to infeasible Bay and local obligation achievement.

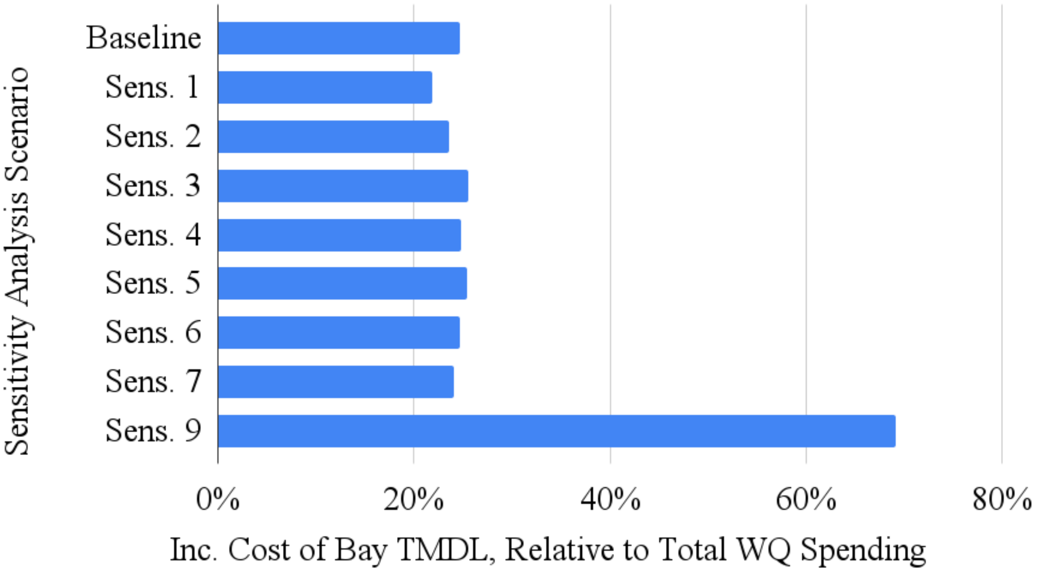

Figure 2.4: Incremental Cost of Bay TMDL Compliance, Relative to Total WQ Spending, No Trade

Sens. 1: New facilities on imp. land.
Sens. 2: Retrofits costlier than anticipated.
Sens. 3: Public land has value.
Sens. 4: Private land easements costlier than expected.
Sens. 5: Public land has value; no easements for private land.
Sens. 6: O&M on private land is same as on public land.
Sens. 7: Costlier O&M on private land than anticipated.
Sens. 9: Stream constraints expanded.
Sensitivity Analysis 8 precluded from chart due to infeasible Bay and local obligation achievement.

2.7 Conclusion

Results from this paper suggest that Bay TMDL compliance may be less costly to achieve, if considered to be an incremental burden by regulated parties prioritizing local water quality cleanup costs and obligations, relative to what the Bay TMDL compliance may otherwise cost to achieve on its own or if all costs of practices generating credits toward the Bay's cleanup were solely attributed to Bay TMDL compliance. Results from Loudoun County MS4 suggest that the practices necessary to achieve local TMDL obligations can make a substantial contribution to meeting the Bay TMDL. Once local obligations have been satisfied, Loudoun County MS4 may only need to increase costs by less than 1% when the MS4 can trade freely, by less than 3% when the MS4 can only purchase NPS perpetual credits, and by less than 33% when the MS4 cannot trade in any capacity.

Findings suggest that costs can be lowered through use of low-cost, term PS trade and through perpetual NPS trade. But, since trade does not address local obligations, the MS4 must heavily use urban stormwater and restoration practices to achieve water quality obligations. With urban stormwater and restoration practices generating reductions toward both the Bay TMDL and local TMDLs, MS4s have only a limited need for additional compliance behavior, including trade, once local water quality obligations have been met.

MS4s concerned over the high cost of Bay TMDL compliance, while also hesitant to trade, may consider that incrementally incorporating NPS perpetual trades into their compliance choices choices will provide almost as many cost-savings as incorporating both PS term and NPS perpetual trades, without exposing the MS4 to risks associated with future PS term trade availability.

Findings regarding the extent to which local TMDL compliance activity reduces the incremental obligations and costs of the Bay TMDL may address regulated parties' concerns regarding the burden of Bay TMDL. Findings regarding the limited need for Bay TMDL reductions once local obligations have been met may also be extended to the objectives of the first chapter, by explaining generally-sparse use of trade throughout the state as stemming from lower-than-expected potential needs of regulated parties for reductions from trade or other sources.

The adopted model has limits, in that it does not allow for diminishing marginal productivity from compliance practices. Refined land constraints with more specific land types data may allow for differing productivities of practices implemented throughout the MS4, which would allow for diminishing marginal productivity, as land use constraints become exhausted. However, Virginia DEQ has aggregated land uses for MS4s in Virginia into just three types of land, ‘pervious’, ‘impervious’, and ‘forest’ land, for determination of reduction requirements, rather than adopting disaggregated land uses underlying more specific land use modeling by the Bay Program. The present model considers pervious and impervious land types. No consideration for forest land is made in the model, because the MS4 does not report forest acreage in its establishment of Phase 2 Bay TMDL compliance obligations (Loudoun County DGS & WEIS, 2022). This means that modeling limitations, with regard to accomodating diminishing marginal productivity, may be difficult to overcome, given DEQ’s simplified assumptions regarding regulated land types used to calculate compliance obligations.

Further study may expand focus to the incremental costs needed to achieve Bay TMDL compliance at a broader scale, such as throughout the entire state of Virginia. Research may also shift focus to determining the incremental cost of local TMDL compliance in addition to Chesapeake Bay TMDL requirements for regulated parties, as a way of providing insight into the obligations that anticipated local impairments may impose on parties subject to existing water quality obligations. Further study may also expand modeling assumptions to allow for overlapping placement of BMPs on treated land, i.e. stacking BMPs on treated land, though results are unlikely to meaningfully change, given the marginal utility of placement on already-treated land is likely not enough to forgo placement on untreated land.

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Chapter 3

Overdose Outcomes and Syringe Exchanges: Empirical Evidence from North Carolina

3.1 Abstract

Little focus has been given to evaluating the impact of Syringe Exchange Programs on drug overdose, even though these programs regularly engage in activity designed to do so. In response, the impact of North Carolina Syringe Exchange Programs on fatal overdose at the county scale is studied using county fixed effects. Nonrandom service placement complicates analysis by potentially positively biasing findings of SEP impact on overdose. Regardless, findings suggest that SEP has no significant effect on overdose, which contrasts with present literature's limited findings that their impact may be positive. Implications are that, since SEPs are effective tools to prevent bloodborne illness and do not increase overdose mortality, they may continue to be implemented as effective intervention practices to achieve public health goals.

3.2 Introduction

The United States Opioid Epidemic is costly in terms of both human life and economic losses. American drug overdose mortality surpassed 100,000 in 2021, contributing to well over 600,000 overdoses from 1999 to 2021 (CDC, 2021a; CDC WONDER, as referenced in CDC, 2022b). The opioid crisis also contributes to extensive bloodborne illness transmission (Hodder et al., 2021; Lerner & Fauci, 2019). Annual federal funding to address the crisis has exceeded $7.4 billion and the total annual cost of the United States opioid crisis is estimated to be approximately $504 billion when health consequences from fatal and nonfatal overdoses are considered, though other calculations that include economic costs generate estimates of more than $1 trillion (BPC, 2019; Ryan, 2018; Florence et al., 2021).

Syringe Exchange Programming is one approach that has been implemented to combat the opioid crisis. Syringe Exchange Programs (SEPs) are typically known for their namesake activity, i.e. needle exchange, in which they "provide free sterile syringes and collect used syringes from injection-drug users... to reduce transmission of bloodborne pathogens" (Guardino et al., 2010). These pathogens include HIV and Hepatitis C, both of which contribute to the tremendous economic and social costs of the crisis (Mark et al., 2001). Research finds sterile needle exchange to be effective at preventing the spread of HIV among users and to those with whom users interact (Braine et al., 2004; Cloud et al., 2018). However, SEPs have another operational goal besides reducing bloodborne illness transmission: preventing opioid overdose. SEPs engage in a number of intervention strategies to achieve this goal (CDC, 2019; Peiper et al., 2019). As such, they may be viewed as intervention service centers that are part of a suite of intervention approaches implemented in response to the opioid crisis.

The main way SEPs aim to reduce overdose is by distributing naloxone to drug users or by referring users to naloxone distributors, in the absence of onsite distribution (CDC, 2019; NCGA, n.d.a; Piper et al., 2008; Bennett et al., 2018). Naloxone is a very safe medication that may be administered to a user to reverse the effects of an opioid overdose (NCDHHS, n.d.b; NIDA, 2022). Some research notes that naloxone distribution may incentivize users to engage in riskier drug use through the moral hazard that results from having a 'safety net' (Erfanian et al., 2019; Doleac & Mukherjee, 2019; Crowell, 2019). However, research generally finds naloxone distribution to be an effective means of reducing opioid overdoses that is met with enthusiasm by opioid users (Bennett et al., 2011; Bennett et al., 2018; Walley et al., 2013; Chimbar & Moleta, 2018; Rowe et al., 2015; Lagu et al., 2006; Clark et al., 2014; Bennett & Holloway, 2012; Piper et al., 2008).

SEPs also aim to reduce overdose by providing "education about overdose prevention and safer injection practices" (CDC, 2019). Examples of safer drug use practices include engaging in moderated use, non-intravenous routes of consumption, avoidance of polydrug use, and not consuming drugs while alone (Preston & Derricott, n.d.; The DOPE Project, n.d.). But, efficacy may be complicated by the fact that new synthetic opioids, like fentanyl, are orders of magnitude stronger than classic opioids, like heroin and morphine, and are thus difficult to safely 'pace' during consumption (Lufkin, 2021; McGowan et al., 2018). Correspondingly, SEPs additionally aim to reduce overdose by distributing fentanyl test strips to users (Park, et al., 2021). In recent years, fentanyl has entered the market as an opioid that can be consumed alone in a variety of forms, or may be mixed, potentially unbeknownst to users, in heroin (CDC, n.d.a). If test strips alert users to the presence of fentanyl or one of its analogs in their drugs, they may reduce risk by not consuming the drugs or by doing so in safer manners (Peiper et al., 2019; CDC, 2022a; LAPPA, 2021). But, fentanyl test strips' ability to prevent overdose may be complicated by potential preferences for fentanyl and the fact that use of fentanyl test strips has been observed alongside fentanyl-seeking behavior (Ciccarone et al., n.d.; Tilhou et al., 2022).

SEPs also work to reduce overdose by linking users to addiction treatment services (CDC, 2019). Like other interventions approaches, addiction treatment service as a means to reduce overdose is not without complication: relapse is common, at around 30%, which is problematic because, after periods of abstinence, users may be more susceptible to overdose due to loss of previous tolerance (Kassani et al., 2015; Tagliaro et al., 1998; Harding-Pink & Fryc, 1988).

In spite of the complexities surrounding SEPs' overdose-prevention intervention practices, only one paper, Packham's 2022 study of county-level SEP on various crisis-related health outcomes, focuses directly on how SEPs comprehensively affect overdose mortality. Packham utilizes a differences in difference (DID) model to test the impact of SEP presence on bloodborne illness transmission, hospitalization, and overdose at the county level in the year following opening of a syringe exchange, making use of nationwide self-reported exchange data in response to the challenges of documenting SEP activity (2022). Packham's work focuses on treatment from 2013 to 2016 and finds counties with SEPs experience reduced bloodborne illness transmission, but increased opioid overdose mortality, relative to similar control counties (2022). Packham's work suggests SEPs may increase overdose rates among users by decreasing the cost of drug use and by increasing access to the synthetic opioid fentanyl (2022).[1]

The current scale of and controversy surrounding SEP further motivate research into their impact on overdose. There are over 400 SEPs in 43 states across the U.S., each incurring annual operating expenses in the general range of \$400,000 to \$1.9 million of public and private funding (KFF, n.d.; Teshale et al., 2019). In spite of their prevalence throughout the United States, SEPs remain controversial, due to fears that SEP activity will increase drug abuse, related crime, and hazardous waste (Villarreal & Fogg, 2006; Ksobiech, 2004; Sharma, 2019; Schumaker, 2021). Corresponding political opposition and NIMBYism have fueled recent pushback against SEPs in West Virginia, Indiana, and New Jersey (McClain, 2021). A more comprehensive understanding of how Syringe Exchange Programs impact opioid users will help determine if Syringe Exchange Programs should remain in operation, and if so, will evaluate the impact that SEPs achieve with their available resources.

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[1] Fentanyl can be injected or consumed other ways (CDC, n.d.a).

3.3 Research Objective, Advantages of Study, and Contribution of Work

3.3.1 Research Objective

In response to the need for greater understanding of how SEPs affect overdose, this work studies the association between SEP rollout and overdose rates in North Carolina, a state that recently legalized SEP. North Carolina legalized syringe exchange in 2016, allowing SEP to take place alongside other intervention practices throughout the state, to address significant harm from the opioid crisis throughout the state (NCDHHS, n.d.e, 2020b; NCGA, n.d.a). North Carolina's legalization was motivated by strong need for Opioid Crisis intervention: the state saw a 1,119% rise in heroin-related deaths in the six years prior to SEP legalization (2010-2016) (Miller & Winecker, 2018). In recent years, heroin and prescription opioids have been used by approximately $^1/_{300}$ and $^1/_{30}$ of the state population aged 12 and older, respectively (SAMHSA, 2020). Within three years of legalization, North Carolina SEP coverage had expanded to 81 counties (NCDHHS, 2020a). Widespread SEP activity following a recent policy shift in a state that has been heavily affected by the opioid crisis thus provides an important opportunity for greater understanding of how SEPs affect overdose. In response, this work aims to achieve the following research objective: To identify whether legal North Carolina SEP activity reduces overdose at the county level.

3.3.2 Advantages of Location of Study

The circumstances surrounding North Carolina Exchanges' operations make the state's SEP logical for study for a number of reasons. A major advantage of choosing North Carolina SEPs for study is that the state's universally-legal, flexible operating environment and mandated annual reporting mean North Carolina SEPs are unlikely to remain underground.[2] This means that North Carolina SEP data is likely to be more complete and less biased than incorporation of voluntarily-reported data on illegal SEP activity, as was done in Packham 2022.

An additional reason to study North Carolina SEP is that the legal guidelines established for North Carolina SEP operation mean the intervention strategies SEPs provide throughout the state are likely to be not only very consistent, but also representative of activity in other settings. North Carolina exchanges are required to engage in a number of harm reduction practices beyond needle exchange, including distributing naloxone or referring users to naloxone, assisting users seeking treatment or mental health care, and educating users on topics related to the health consequences of drug use and abuse (NCDHHS, 2020b). These services are similar in scope to those provided by exchanges across the country (Des Jarlais et al., 2009).

A final reason to study North Carolina SEP is because the impact of legal NC SEP activity on overdose is unlikely to be affected substantially by analogous out-of-state activity, given that North Carolina SEPs operate in what may be termed a 'policy island'. North Carolina was the first of any state in its surroundings to legalize SEP and by June 2022, reported exchange activity in surrounding states remained sparse, with 3 locations in Georgia, 4 locations in South Carolina, 8 locations in Tennessee, and 7 locations in Virginia, which is characteristic of the slow acceptance of SEP in the southern United States (NCGA, n.d.a; AP/WABE, 2019; O'Connor, 2018; Dickerson et al., 2017; SCGA, 2020; KFF, n.d.).

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[2] See NCGA n.d.a for SEP operational and reporting requirements.

3.3.3 Research Contribution of Work

Study of North Carolina SEP activity will expand on present research in a few key ways. By focusing on Syringe Exchange in a universally-legal, homogeneous policy environment, this work controls for the complications of underground, illegal service on reporting, as well as controls for potential inconsistencies in the scope of services provided by different SEPs. Second, by focusing on SEP in a recent time frame, this work sheds new light on the ever-changing nature of the opioid crisis. Third, by acknowledging the complex pathways that exist between SEPs' intervention approaches and user impacts, this work will expand on present literature's first efforts to establish how SEPs' multi-faceted overdose intervention strategies may act in aggregate. Overall, this work will establish a benchmark for what program coordinators and governments in and beyond North Carolina may expect to achieve through SEP programming. Doing so will guide SEP implementation to ensure SEP has an appropriate role in opioid crisis intervention.

3.4 Empirical Approach

3.4.1 Model Specification: Empirical Analysis of North Carolina SEP on Overdose

The empirical approach uses a fixed effects (FE) panel analysis to determine the effect SEPs have on overdose. Fixed effects models are of a linear form that states the outcome variable as being a function of a linear independent variable and control variables, which include explicitly specified time- and unit-variant controls, as well as implicitly include all time- and/or unit- invariant controls.[3].

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[3] See Greene, 2012

The fixed effects nature of this analysis is incorporated to account for county- and year-fixed effects that may impact the degree to which the opioid crisis contributes to overdose. The broad structure of the empirical model is presented in Equation 3.1:

$$y_{ct} = \beta SEP_{ct} + \theta \mathbf{x_{ct}} + Year_t + County_c + u_{ct} \qquad t = 1, 2, 3; \;\; c = 1, ...n \tag{3.1}$$

- y_{ct} represents the fatal unintentional opioid overdose rate, per million residents, in county c in time period t, where $t = 1, 2, 3$ to represent the 3 years since North Carolina's SEP legalization. The number of counties represented by c varies, depending on whether analysis focuses on all counties or on a rural or urban subset of counties.[4]

- SEP_{ct} represents the independent variable; the variable is a binary indicator variable for SEP program coverage in county c in time period t.

- $\mathbf{x_{ct}}$ represents a vector, denoted in bold, of value of time- and unit-variant controls that may affect the overdose rate in county c in time period t.

- $Year_t$ represents time-fixed effects affecting all counties in time period t.

- $County_c$ represents unit-fixed effects affecting an individual county c consistently over time.

- u_{ct} represents the error term for estimation of overdose in county c in time period t.

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[4] Per NCDHHS, n.d.c, there are 100 counties in all of North Carolina, of which 54 are rural and 46 are urban, though data censoring causes final subset counts to vary.

3.4.2 Discussion of Model

Analysis is conducted on all counties, as well as on just rural and just urban county subsets to study whether SEPs' impacts on overdose vary across the urban/rural divide. This is because literature suggests opioid mortality may vary between urban and rural counties (Monnat, 2019; Lerner & Fauci, 2019). Packham 2022 focused on in-county service, but the NCDHHS reports that residents in NC counties are also served by NC SEPs outside their home counties (Packham, 2022; NCDHHS, n.d.d, 2019, 2020a). So, analysis is conducted to determine the impact of how SEP service originating from within a given county or from other NC counties affects overdose in a particular county in a given year. The combinations of the three county subsets and two types of SEP coverage lead to six broad classes of specifications (Table 3.1).

Table 3.1: Broad Specification Classes Used in Modeling

Specification Class	**Counties Included**	**SEP Coverage**
1	All	Primary
2	All	Any
3	Rural	Primary
4	Rural	Any
5	Urban	Primary
6	Urban	Any

Within each of the six specification classes, there are four sub-specifications, in which the impact of SEP is determined on overdose rates from four classes of opioids: any opioids, heroin, prescription opioids, and synthetic opioids. Study of SEP on heroin is assumed to be most relevant to the research objective and to detail the most significant impact, given SEP generally targets injection drug users with the needle distribution aimed at achieving their primary goal of reducing bloodborne illness needle and given that heroin is an injection drug. The model focuses on impacts on other forms of overdose, in addition to heroin, because

SEP clientele use multiple illicit substances and because users may use different substances in response to drug supply shifts (Heimer, 1998; Compton, 2016).

The model notably specifies unit- and time-fixed effects because its fixed-effects structure of the model inherently controls for time-invariant characteristics, such as urban-rural status, year-specific shocks and historic underlying cultural sentiment that may affect attitudes toward SEP and/or drug abuse, as well as unit-invariant characteristics, such as statewide trends in crisis manifestation like broad changes in drug supply and changes in relevant federal and state legislation and intervention.

The reason that the model also incorporates a matrix of control variables is because the fixed-effects model's county and year fixed effects do not inherently control for variables of time- and unit-variable natures.

Controls for annual county unemployment and for SNAP food stamp distribution are incorporated into the model because literature finds that economic hardship, specifically unemployment and poverty is associated with greater risk of drug abuse and overdose (Wang et al., 2013; Pear et al., 2019).

Controls for drug supply in a county in a given year are incorporated because literature finds that prescription drug abuse contributes to heroin abuse; furthermore, illicit drug users may also use prescription drugs, and more opioid prescriptions in an area are associated with higher odds of being a high-risk county (Shah et al., 2007; Compton et al., 2016; Kolodny et al., 2015; Haffajee et al., n.d.). Additionally, legal use of prescription opioids may still cause unintentional prescription opioid overdose, so controlling for legal drug supplies is also important. One control for drug supply is a control variable for legal opioid prescriptions dispensed per 100 people. Another seeks to control for overall illicit drug activity in an area through annual county felony rates. These controls, in tandem, work to control for differences in overall drug supply, which is otherwise difficult to measure, given the underground, blackmarket nature of drug use and sales.

A control variable for healthcare shortage, i.e. the percent of the population lacking health insurance, is incorporated into the model. This is because literature finds that a lack of health insurance may preclude users from seeking the mental health or addiction treatment care they might otherwise need and may lead to self-medication with opioids (Orgera & Tolbert, 2019; Cruden & Karmali, 2021).

3.4.3 Discussion of Threats to Empirical Approach: Nonrandom Program Placement

Studying the impact of intervention programs in any setting may be complicated by nonrandom service provision. Health intervention literature acknowledges the role of purposive program placement, or targeted intervention, in the context of health intervention (Angeles et al., 1998; Frankenberg et al., 2007). Present study of the impact of SEP is complicated by nonrandom program placement, since North Carolina SEP activity is reported to follow need (Harney, 2022). Need-based program placement has the potential to lead to an erroneous finding that SEPs may increase overdose, given SEPs may be drawn to enter areas with the highest levels of illicit activity. Controlling for the influence of 'need' is complicated by the underground, blackmarket nature of drug abuse and by the fact that proxies for drug abuse, such as bloodborne illness transmission, may be affected by factors other than the opioid crisis.

Efforts to control for need-based service placement are further complicated by pre-legal, underground syringe exchange service. Some exchanges operated illegally in North Carolina prior to the state's 2016 legalization of SEP (Lewis, 2016; McGee, 2020). The 'underground' nature of illegal SEP is difficult to track, given incentives that SEPs have to maintain a low profile, which complicates efforts to identify and control for nonrandom, need-based program placement prior to 2016. Need-based placement will bias impact positively, regardless of whether SEP's true impact on overdose is negative, neutral, or positive. Underground pre-legal service may affect starting conditions in counties during the window of observation by reducing perceived magnitude of impact of SEP, given already-achieved impact will not be attributed to legal SEP, but need-based placement will universally bias SEP impact on overdose positively. The model's focus on a period of time in which SEP is legal (i.e. 2016 and beyond) should largely rule out the presence of underground SEP in the data, though the potential impacts of pre-legal activity and need-based placement should be kept in mind, when interpreting results.

A key demographic factor closely relating to need may further complicate analysis by steering SEP placement: research suggests that areas with MSM populations and existing HIV/AIDS outreach activity are associated with SEP presence, likely stemming from the fact that HIV/AIDS is a threat to drug users and MSM populations alike (Tempalski et al., 2007). But, lack of time-variant data on MSM populations precludes ability to control for this variable.[5] However, to the extent that an area's demographic trends may be unit-fixed over the horizon of the study, the FE model should reasonably control for the impact of MSM populations on SEP placement.

Literature suggests that SEP placement may also be affected by politics. Conservative areas in the United States tend to "[prioritize] punitive sanctions over public health responses to drug use"; these areas are more resistant to harm reduction policy and their elected officials are often more hesitant to budget for SEPs (Cloud et al., 2018). Efforts to control for the impact of political leanings through incorporation of voting records is difficult because North

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[5] The most appropriate source available, The Williams Institute, n.d., provides estimates for a single year.

Carolina county lines do not correspond directly with electoral districts (NCGA, n.d.b, 2022). However, with political climate considerations likely being largely fixed in an area over the horizon of the study, the fixed effects model will inherently incorporate such considerations via its consideration of unit-fixed effects.

A minor threat to identification is that determination of whether an overdose is intentional or unintentional may be difficult (Hoover, 2018). Misidentification of the intentionality of death may introduce statistical noise into the model. But, intentional heroin overdose is uncommon, relative to unintentional heroin overdose (Vingoe et al., 1999). This reduces concern that misclassification will affect study of SEP on the most relevant form of overdose, i.e. heroin overdose.

3.5 Data

Data for the independent variables in each of the specifications, i.e. SEP coverage in each county during each year of study, is determined using annual SEP activity reports from the NCDHHS (n.d.d, 2019, 2020a). SEP coverage is identified to be 'primary' if it originates from within a county and to be 'any' if it stems from any NC county. 'Any' coverage is thus defined as occurring if either 'primary' or 'secondary' coverage occurs in a county, with 'secondary' coverage occurring if a county's residents are served by an exchange outside the county's borders, based on NCDHHS reporting practices in annual SEP activity reports.[6] NCDHHS reporting conventions preclude separate study of just 'secondary', or 'out-of-county', service, given that reporting suggests in-county activity overshadows out-of-county activity. A relatively large base of activity in the initial reporting period suggests SEPs may have quickly initiated service in response to built-up demand or may have imme-

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[6] See NCDHHS, n.d.d, for instance.

diately come above-ground following SEP legalization (Table 3.2).

Table 3.2: Counties Served by Syringe Exchange Programs In Each Year

Year	**Counties With Service**		
	Primary	**Secondary**	**Any**
2017	28	24	52
2018	34	35	69
2019	42	39	81

Sources: NCDHHS, n.d.d; 2019; 2020a.

Data on county rural/urban status, which is used to establish subsets for analyses, is sourced from the North Carolina Department of Health and Human Services (n.d.c). Of 100 counties in the state, 54 are rural and 46 are urban (n.d.c). Urban counties account for the majority of in-county service, whereas rural counties account for the majority of counties served by 'secondary' coverage (Table C.1).

Data for dependent variables in each specification rely on county-level unintentional fatal overdose of NC residents for heroin, any opioids, prescription, i.e. non-injection, opioids, and synthetic opioids from the North Carolina Department of Health and Human Services and annual county population data from USDA's Economic Research Service (NCDHHS, n.d.f; Cromartie, 2020). Analysis adopts intentionality as-reported by the NCDHHS (n.d.f). Rates are calculated by dividing annual overdoses in each county by annual county population estimates.

Median heroin and synthetic overdose rates are on the rise, while overall and prescription overdose rates are declining (Table 3.3 and Figure C.1). Summary statistics show that heroin, the class of drug most closely related to SEP is not a dominant cause of overdose, relative to other drugs; instead, synthetic opioids represent the dominant class of overdose from a single substance (Tables 3.3, Tables C.2 to C.4, and Figures C.2 to C.5). On the whole, that median overdose rates are generally lower than mean overdose rates suggests that program ‘need’ may be concentrated in a relatively small number of counties, as certain counties may be hit harder than others.

Table 3.3: Median County Overdose Rates, Per Million, in Each Year, for Different Classes of Overdose

Dependent Variable	**Median Annual Overdose, Per M**		
	2017	**2018**	**2019**
Fatal Opioid (All) Overdoses, Per M	161	160	154
Fatal Heroin Overdoses, Per M	45	48	50
Fatal Prescription Overdoses, Per M	66	43	38
Fatal Synthetic Overdoses, Per M	103	108	121

Note: The NCDHHS may attribute one death to multiple substances. Sources: NCDHHS, n.d.f; Cromartie, 2020.

County-level, annual control variables come from a number of sources. Control variable data for economic hardship, i.e. unemployment and SNAP distribution rates, come from unemployment data from the NC Department of Commerce and from annual SNAP distribution counts in each county from the U.S. Census Bureau divided by annual county population data from ERS (U.S. Census Bureau, n.d.; NC Department of Commerce, n.d.a, n.d.b, n.d.c; Cromartie, 2020). Data for the control variable for healthcare shortage, i.e. county healthcare shortage rates in each year, is sourced from the U.S. Census (2020). Control variable data for the drug-supply control of the number of opioid prescriptions dispensed per 100 people comes from the CDC (n.d.b, c, d, 2021b). Control variable data for the drug-supply control of felonies per person comes from North Carolina Judicial Branch caseload data divided by ERS county population data (North Carolina Judicial Branch, n.d.; Cromartie, 2020). Summary statistics statistics for control variables are presented in the appendix (Table C.6).

Stata 17 is used to conduct subsequent fixed effects analysis.

3.6 Results

Results are organized across six specification classes, which vary with regard to whether in-county or any- SEP constitute SEP intervention in a county in a given year, as well as with regard to whether the sample constitutes all counties in North Carolina, just urban counties in North Carolina, or just rural counties in North Carolina (Table 3.4).

The models underlying study of SEP on heroin overdose all achieve significance. Given that heroin is the class of opioid most relevant to SEP, due to the incentives that clean needles provide injection drug users to visit SEPs, this suggests the modeling framework is generally appropriate for the main focus of studying SEP on overdose. Mixed significance regarding the impact of SEP on other forms of overdose is observed.

Results universally fail to find that the coefficient of SEP coverage on overdose rates is significant, regardless of the type of coverage or county subset studied. Findings do not document any differences in SEP impact across the urban and rural divide or differences in impact between in-county, vs any-county service. Findings that SEP activity fails to impact overdose contrasts with Packham's findings, which held that SEP generally increases overdose rates (2022).

Table 3.4: SEP Service on Fatal Overdose Mortality in North Carolina Counties: Fixed Effects Results

Specification Class	**(1)**	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**
SEP Coverage	Primary	Any	Primary	Any	Primary	Any
County Sample	All	All	Rural	Rural	Urban	Urban
Impact on Dependent Variables						
Fatal Unintentional Any Opioids Overdose Per Million						
SEP Coefficient	2.232	-6.585	-6.553	1.375	32.887	-14.677
Std. Error	17.970	14.801	25.823	20.816	24.732	21.510
P value - Coefficient	0.901	0.657	0.800	0.947	0.187	0.497
P value - Model	0.052*	0.049**	0.090*	0.092*	0.132	0.203
# observations	298	298	161	161	137	137
Fatal Unintentional Heroin Overdose Per Million						
SEP Coefficient	-6.740	-6.219	-4.492	-6.943	-11.404	-2.850
Std. Error	9.776	8.053	15.349	12.355	11.494	9.974
P value - Coefficient	0.491	0.441	0.770	0.575	0.324	0.776
P value - Model	0.001***	0.000***	0.035**	0.032**	0.054*	0.074*
# observations	298	298	161	161	137	137
Fatal Unintentional Prescription Overdose Per Million						
SEP Coefficient	12.676	-1.295	19.153	8.479	11.904	-9.230
Std. Error	10.894	9.008	16.037	12.987	14.288	12.343
P value - Coefficient	0.246	0.886	0.235	0.515	0.407	0.457
P value - Model	0.055*	0.089*	0.404	0.523	0.007***	0.008***
# observations	298	298	161	161	137	137
Fatal Unintentional Synthetic Overdose Per Million						
SEP Coefficient	-5.769	-13.011	-20.205	-10.024	30.468	-11.501
Std. Error	16.850	13.857	26.050	21.032	19.369	16.914
P value - Coefficient	0.732	0.349	0.440	0.635	0.119	0.498
P value - Model	0.110	0.085*	0.087*	0.100*	0.496	0.763
# observations	298	298	161	161	137	137

Note: Significance is conveyed via the following: *: P<0.1; **: P<0.05; ***:P<0.01.

3.7 Robustness of Findings

Potential breakdown of the model's predictive ability toward the origin may occur, due to use of a linear model to study censored outcome variable data (i.e. non-negative overdose rates). But, literature accepts use of a linear model in a panel-data context to study SEP on overdose (Packham, 2022). Furthermore, alternative modeling frameworks and approaches are not without complication. Use of a Tobit model to estimate impact of SEP on the censored outcome variable would forego the time- and unit-fixed effects control advantages of the fixed effects specification, given the random-effects nature of Tobit analyses.[7] Restricting focus to only a subset of outcome variables in the middle to upper range of the observed overdose rates, to avoid modeling difficulty as overdose rates approach zero, introduces complications by not only reducing the sample size, but also magnifying the relative influence of need-based placement through increases to the relative weight of the hardest-hit counties in the sample. Use of piece-wise regression to conduct regression over discrete ranges of outcome variables would similarly be affected by small sample size and influence of need.

With potential use of different modeling approaches complicated by potential loss of the model's ability to control for unforeseen characteristics and by potential aggravation of the issues stemming from need-based placement, analyses involving transformation of outcome variables are conducted as a way of shedding new light on SEP's effect on outcomes in counties whose overdose rates are on the lower end of the spectrum. Analyses are run using natural logarithm transformations of overdose rates, which study the relative change in overdose rates, rather than the absolute change in overdose rates, as dependent variables. These analyses determine the relative, rather than absolute, change in overdose rates in a county that stem from SEP, and so corresponding analyses may provide greater emphasis on counties with starting overdose rates closer to zero. This will allow for consideration that

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[7] See Stata, n.d.

marginal impact of SEP may decrease as overdose rates become lower and lower. Though certain overall models in the robustness check achieve significance, estimates of the coefficient of SEP on overdose remain insignificant, and so these checks fail to find significant impact of SEP on overdose (Table C.7).

To test the degree to which findings may be contingent on assumptions made regarding what constitutes 'SEP coverage', analyses are conducted, in which the identification of 'service' in a county is re-defined, to accommodate impacts of intervention that may persist, even in times of program closure. SEPs are observed to open and close throughout time (NCDHHS, n.d.d, 2019, 2020a). But, naloxone, i.e. their main form of impact, may not be used completely in a given year of service (Uyei et al., 2021). In response, analysis is repeated with a variable for 'sticky' coverage, which is determined to occur in any county in its period of first treatment by an in- or out-of-county exchange and all periods beyond. This accounts for 'spillover' naloxone from prior periods on current overdose, even if SEPs are not actively operating. This 'sticky' coverage is notably analogous to how Packham's DID analysis considers 'SEP coverage' to occur in all periods after initial opening (2022). Sticky coverage occurred in 52 counties by the end of the first reporting period, 74 counties by the end of the second reporting period, and 87 counties by the end of the third reporting period (NCDHHS, n.d.d, 2019, 2020a). No significant coefficients for the impact of SEP on overdose are found when analyses are repeated with 'sticky' SEP coverage (Table C.8). Robustness checks therefore support the conclusion that SEP coverage has yet to significantly affect overdose in North Carolina counties.

3.8 Conclusion

The opioid crisis remains a multifaceted issue in the United States, carrying immense social costs in the form of bloodborne illness transmission, lost productivity, and overdose. Empirical methods are used to study the impact of Syringe Exchange Programs' activities, which encompass key intervention strategies, on opioid overdose mortality. A fixed-effects panel analysis is used to study the relationship between county-scale SEP programming and overdose mortality in North Carolina in the years following the state's legalization of SEPs. In spite of the tendency for need-based service provision to bias results positively, findings do not indicate that SEPs' activities have affected overdose mortality at the county-scale since legalization, which contrasts with recent research's conclusion that they may increase overdose in areas served.

As more time elapses and subsequent research is conducted on SEP, understanding of the role of SEP in addressing the Opioid Crisis may be continually refined. Correspondingly, future research should take steps to improve upon model specification, namely by expanding upon efforts to control for non-random service placement and may also consider evaluating impacts at a community-level, rather than county-level, scale. Research should be conducted to determine if and how SEPs' interventions affect overdose over medium- and long-term horizons.

Further research may also take steps to separate effects from each causal pathway by which SEP impacts overdose. The different causal pathways by which SEP may impact overdose are complicated, and findings that SEP has no impact on overdose may be due to the impact of an ineffective intervention strategy canceling out the impact of another effective strategy. The present reduced-form model does not allow for insight into the degree to which this may occur.

Though analysis is complicated by non-random SEP activity and results may change over a longer horizon of study as county coverage grows and SEPs are given more time to effect change, the conclusion from the observed lack of impact on overdose should not be interpreted to mean that SEPs do not have a role in Opioid Crisis intervention. Rather, given their demonstrated efficacy at achieving their primary goal of preventing the spread of bloodborne illness, SEPs, as a whole, can be reasonably concluded to lead to overall declines in mortality. Policymakers should therefore view this work's findings as an evaluation of the degree to which SEPs may achieve secondary objectives, rather than a criticism of their efficacy at achieving intervention, and should continue to offer Syringe Exchange Programming to address other harms.

3.9 References

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Appendices

Appendix A

First Appendix: The Role of Nutrient Credit Trading for Chesapeake Bay TMDL Compliance: Evidence from Virginia's MS4s

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Appendix B

Second Appendix: The Cost of Meeting the Chesapeake Bay TMDL in the Presence of Local Water Quality Obligations: Cost Analysis of Municipal Stormwater in Loudoun County, Virginia

Table B.1: Loading Rates for Regulated Urban Pervious and Impervious Land

Land Cover	**Loading Rate (lbs/ac/yr)**		
	N	**P**	**TSS**
Impervious	16.9	1.6	1,171.3
Pervious	10.1	0.4	175.8

Source: Davenport, 2021. Loading rates are “Edge of stream” and are “based on the Chesapeake Bay Watershed Model Progress Run 5.3.2”, per Davenport, 2021. Loudoun County MS4’s Bay TMDL reduction requirements are also based on these loading rates (Loudoun County DGS & WEIS, 2022).

Table B.2: Hydrologic Unit Codes (HUCs) of Loudoun County

HUC8	**HUC12**	**Acres**
02070008	20700080301	760
	20700080403	1,110
	20700080602	18
	20700080701	472
	20700080702	979
	20700080703	243
	20700080704	4,372
	20700080901	4,911
	20700080902	2,321
	20700080903	17,643
	20700080904	5,312
	20700080905	5,732
	20700081005	41
HUC 8 Total:		43,914
20700100	20700100701	1,781
	20700100704	4,860
HUC 8 Total:		6,642

Sources: See NVRC & Wagner, 2022 and Ward, 2020.

Table B.3: Nutrient Credits Released by Banks in Loudoun County MS4 HUCs

Nutrient Bank	**HUC**	**Released N (lbs)**	**Released P (lbs)**	**Released TSS (lbs)**
Elk Run	2070010	1,551.0	115.2	–
Elk Run Farm	2070010	306.0	22.7	–
Midland	2070010	2,245.0	168.0	–
Owl Run	2070010	557.0	51.0	–
Red Hill Farm	2070008	1,635.7	121.4	–
Windright Run	2070010	1,100.6	81.7	–
Glenowen Farm	2070008	191.4	20.1	–
Bristerburg	2070010	172.9	12.8	–
Licking Run	2070010	165.2	14.4	–
Edgecliff	2070008	2,405.4	324.0	–
Grace Hill	2070008	212.8	28.7	–
Virginia Oaks	2070010	658.2	75.0	–
Great Meadow	2070010	103.5	13.9	–
Two Song	2070010	289.0	34.3	2,138.7
Somerville	2070010	286.9	36.8	1,000.0
Crossroads Farm	2070010	109.4	15.2	875.0
Spytek	2070008	569.1	42.3	9,913.0
Town of Purcellville	2070008	1,036.7	77.0	70,081.0
Brookdale Farm	2070008	953.4	74.1	63,044.0
Bull Run Farm	2070010	68.6	8.4	218.0
Circleville Farm	2070008	166.3	25.1	2,689.0
O'Brien	2070008	0.0	0.0	-
Wood Glen	2070010	482.6	44.3	16,349.0
Whispering Hills	2070008	513.1	189.8	238,682.8
Gilberts Corner	20700080701	163.0	12.6	1,356.0
Ohana	20700080701	42.3	3.3	352.0
Leesburg	20700080403	136.4	24.1	23,201.0
Ohana	20700100701	23.0	4.4	127.0
Piscataway Crossing	20700080403	274.1	48.4	46,619.0
Crooked Run	20700080602	0.0	0.0	0.0
Mean Ratio of Credits Released:		*10*	*1*	*217*

Source: U.S. Army Corps of Engineers, n.d.a-ad

Table B.4: Nutrient and Sediment Reductions Provided by Compliance Strategies

Urban Stormwater BMPs	**Nutrient**	**Reduction Efficiency**	**Loading Rates (lbs/ac/yr)**		**Reductions (lbs/ac/yr)**	
			Perv.	**Imp.**	**Perv.**	**Imp.**
Wetland & Wet Pond	Nitrogen	20%	10.1	16.9	2.0	3.4
	Phosphorus	45%	0.4	1.6	0.2	0.7
	Sediment	60%	175.8	1,171.3	105.5	702.8
Bioretention	Nitrogen	70%	10.1	16.9	7.0	11.8
	Phosphorus	75%	0.4	1.6	0.3	1.2
	Sediment	80%	175.8	1,171.3	140.6	937.1
Restoration Practices	**Nutrient**				**Reductions (lbs/ft/yr)**	
Stream restoration	Nitrogen	-	-	-	0.1	
	Phosphorus	-	-	-	0.1	
	Sediment	-	-	-	44.9	
Nutrient Credit Purchases	**Nutrient**				**Reductions (lbs/credit/yr)**	
PS Term N	Nitrogen	-	-	-	1	
PS Term P	Phosphorus	-	-	-	1	
NPS Perpetual Credits	Nitrogen	-	-	-	9.9	
	Phosphorus	-	-	-	1.0	
	Sediment	-	-	-	216.9	

Note: All practices contribute stated reductions toward the Bay TMDL. Urban stormwater and restoration practices contribute sediment toward respective local sediment/benthic TMDLs, if implemented in the MS4's Goose Creek and Bull Run subwatersheds.

Table B.5: Cost Adjustments to CAST Cost Data

Costs Adjusted	**Land Type**			
	Pervious	**Impervious**	**Public**	**Private**
Capital Costs				
Wet pond wetland	100%	230%	100%	100%
Bioretention	100%	350%	100%	100%
Stream Restoration	N/A	N/A	100%	100%
Opportunity Costs				
Wet pond wetland	100%	125%	0%	125%
Bioretention	100%	125%	0%	125%
Stream Restoration	N/A	N/A	0%	125%
O&M Costs				
Wet pond wetland	100%	100%	100%	125%
Bioretention	100%	100%	100%	125%
Stream Restoration	N/A	N/A	100%	125%

Note: Adjustments to stream restoration costs refer to streams are based on adjacent lands; given lack of adjustment to stream restoration costs based on lands' pervious and impervious nature, stream restoration costs are affected only by public/private land costs, and so are designated only as being public- and private-adjacent.

Table B.6: Baseline and Adjusted Annualized Capital, Opportunity, and O&M Unit Costs of BMPs and Restoration

Strategy	**Land Type**	**Baseline Annualized Unit Costs**			**Adjusted Annualized Unit Costs**		
		Capital	**Opp.**	**O&M**	**Capital**	**Opp.**	**O&M**
Urban Stormwater BMPs							
Wet Pond/Wetland	Imp. Pub.	$847.78	$163.65	$420.99	$1,949.89	$0.00	$420.99
Bioretention	Imp. Pub.	$3,121.24	$245.47	$2,294.82	$10,924.33	$0.00	$2,294.82
Wet Pond/Wetland	Imp. Priv.	$847.78	$163.65	$420.99	$1,949.89	$255.70	$526.24
Bioretention	Imp. Priv.	$3,121.24	$245.47	$2,294.82	$10,924.33	$383.55	$2,868.53
Wet Pond/Wetland	Perv. Pub.	$847.78	$163.65	$420.99	$847.78	$0.00	$420.99
Bioretention	Perv. Pub.	$3,121.24	$245.47	$2,294.82	$3,121.24	$0.00	$2,294.82
Wet Pond/Wetland	Perv. Priv.	$847.78	$163.65	$420.99	$847.78	$204.56	$526.24
Bioretention	Perv. Priv.	$3,121.24	$245.47	$2,294.82	$3,121.24	$306.84	$2,868.53
Restoration							
Stream Restoration	Public-Adj.	$41.18	$0.00	$64.16	$41.18	$0.00	$64.16
Stream Restoration	Private-Adj.	$41.18	$0.00	$64.16	$41.18	$0.00	$80.20

Note: Units are 'acres treated' for wet pond & wetland and bioretention practices. Units are 'feet' for stream restoration. Bioretention characteristics adopted represent the average lifespans and cost estimates for bioretention/raingardens - A/B soils, underdrain & bioretention/raingardens - C/D soils, underdrain, given multiple practice types documented in CAST. Costs discounted at 5%, per CAST standards. Costs are reported in 2018 dollars.

Table B.7: Total Annualized Unit Costs

Compliance Strategy	**Land Type**	**Adjusted Annualized Unit Cost**
Urban Stormwater BMPs		
Wet Pond Wetland	Imp. Public	\$2,370.88
Bioretention	Imp. Public	\$13,219.15
Wet Pond Wetland	Imp. Private	\$2,731.83
Bioretention	Imp. Private	\$14,176.40
Wet Pond Wetland	Perv. Public	\$1,268.77
Bioretention	Perv. Public	\$5,416.06
Wet Pond Wetland	Perv. Private	\$1,578.57
Bioretention	Perv. Private	\$6,296.60
Restoration		
Stream Restoration	Public-Adj.	\$105.34
Stream Restoration	Private-Adj.	\$121.38
Nutrient Credits		
PS Term N Credits	-	\$3.78
PS Term P Credits	-	\$5.70
NPS Perpetual Credits	-	\$637.50

Note: Units are ‘acres treated’ for wet pond & wetland and bioretention practices. Units are ‘feet’ for stream restoration. Units are ‘credits’ for credit purchases.

Table B.8: Per Pound Annualized Reduction Costs by Strategies in Choice Sets

Compliance Strategy	**Land Type**	**N ($/lb/yr)**	**P ($/lb/yr)**	**TSS ($/lb/yr)**
Urban Stormwater BMPs				
Wet Pond Wetland	Imp. Public	$703.11	$3,252.24	$3.37
Bioretention	Imp. Public	$1,120.08	$10,879.96	$14.11
Wet Pond/Wetland	Imp. Private	$810.15	$3,747.36	$3.89
Bioretention	Imp. Private	$1,201.19	$11,667.82	$15.13
Wet Pond/Wetland	Perv. Public	$629.97	$6,876.80	$12.03
Bioretention	Per. Public	$768.34	$17,613.19	$38.51
Wet Pond/Wetland	Perv. Private	$783.80	$8,555.96	$14.97
Bioretention	Perv. Private	$893.26	$20,476.74	$44.77
Restoration				
Stream Restoration	Public Adj.	$1,404.58	$1,549.17	$2.35
Stream Restoration	Private Adj.	$1,618.45	$1,785.05	$2.70
Nutrient Credit Purchases				
Term N		$3.78	-	-
Term P		-	$5.70	-
Perpetual		$64.28	$637.50	$2.94

Note: TSS corresponds to sediment provision toward local TMDLs in applicable subwatersheds. Nutrient credit purchases do not provide credit toward local TMDLs. Units for reductions and costs are ‘acres treated’ for wet pond & wetland and bioretention practices and ‘feet’ for stream restoration (Davenport, 2021 and Devereux, 2020).

Table B.9: Strategies Eligible for Incorporation in Model

Practice Number	**Strategy**	**Land Type**	
		Perv./Imp.	**Ownership**
Practices in Rest of MS4			
Practice 1	Wet Pond Wetland	Impervious	Public
Practice 2	Bioretention	Impervious	Public
Practice 3	Wet Pond Wetland	Impervious	Private
Practice 4	Bioretention	Impervious	Private
Practice 5	Wet Pond Wetland	Pervious	Public
Practice 6	Bioretention	Pervious	Public
Practice 7	Wet Pond Wetland	Pervious	Private
Practice 8	Bioretention	Pervious	Private
Practice 9	Stream Restoration	-	Public-Adj.
Practice 10	Stream Restoration	-	Private-Adj.
Practices in Goose Creek Portion of MS4			
Practice 11	Wet Pond Wetland	Impervious	Public
Practice 12	Bioretention	Impervious	Public
Practice 13	Wet Pond Wetland	Impervious	Private
Practice 14	Bioretention	Impervious	Private
Practice 15	Wet Pond Wetland	Pervious	Public
Practice 16	Bioretention	Pervious	Public
Practice 17	Wet Pond Wetland	Pervious	Private
Practice 18	Bioretention	Pervious	Private
Practice 19	Stream Restoration	-	Public-Adj.
Practice 20	Stream Restoration	-	Private-Adj.
Practices in Bull Run Portion of MS4			
Practice 21	Wet Pond Wetland	Impervious	Public
Practice 22	Bioretention	Impervious	Public
Practice 23	Wet Pond Wetland	Impervious	Private
Practice 24	Bioretention	Impervious	Private
Practice 25	Wet Pond Wetland	Pervious	Public
Practice 26	Bioretention	Pervious	Public
Practice 27	Wet Pond Wetland	Pervious	Private
Practice 28	Bioretention	Pervious	Private
Practice 29	Stream Restoration	-	Public-Adj.
Practice 30	Stream Restoration	-	Private-Adj.
Nutrient Credit Purchases			
Practice 31	PS Term N	-	-
Practice 32	PS Term P	-	-
Practice 33	NPS Perpetual	-	-

Table B.10: Costs and Strategies Used to Achieve Local TMDLs, Full, Limited, & No Trade

Water Quality Objective(s): Local TMDLs		
Trade: Full Trade, Limited Trade, & No Trade		
Total Annualized Cost: $11,137,248		
Compliance Strategy:		**Quantity**
Goose Creek Portion of MS4:		
	Stream Restoration, Public-Adj.	297.3 ft
	Stream Restoration, Private-Adj.	1,110.9 ft
Bull Run Portion of MS4:		
	Bioretention; Imp. Public	23.5 acres
	Wet Pond Wetland; Imp. Private	160.4 acres
	Bioretention; Impervious Private	375.1 acres
	Wet Pond Wetland; Perv. Public	76.9 acres
	Wet Pond Wetland; Perv. Private	1,754.8 acres
	Stream Restoration; Public-Adj.	709.1 feet
	Stream Restoration; Private-Adj.	16,165.9 feet

Note: Results are identical, regardless of whether trade is allowed, limited, or precluded, given trade's irrelevance to local compliance obligations under present modeling assumptions.

Table B.11: Costs and Strategies Used to Achieve Chesapeake Bay and Local TMDLs, Full Trade

Water Quality Objective(s): Chesapeake Bay and Local TMDLs
Trade: Full Trade
Total Annualized Cost: $11,160,954

Compliance Strategy:		**Quantity**
Rest of MS4:		
	Stream Restoration, Public-Adj.	40.4 ft
Goose Creek Portion of MS4:		
	Stream Restoration, Public-Adj.	297.3 ft
	Stream Restoration, Private-Adj.	1,110.9 ft
Bull Run Portion of MS4:		
	Bioretention; Imp. Public	23.5 acres
	Wet Pond Wetland; Imp. Private	160.4 acres
	Bioretention; Impervious Private	375.1 acres
	Wet Pond Wetland; Perv. Public	76.9 acres
	Wet Pond Wetland; Perv. Private	1,754.8 acres
	Stream Restoration; Public-Adj.	709.1 feet
	Stream Restoration; Private-Adj.	16,165.9 feet
Nutrient Credit Purchases		
	PS Term Nitrogen Credits	5,144.5 credits

Note: The fungible nature of reductions toward the Bay TMDL from any watershed make watershed-specific placement of activity incurred in response to Bay TMDL obligations potentially arbitrary. Findings related to overall costs, as well as the role of specific compliance practices in MS4s' overall behavior are not impacted by fungibility concerns.

Table B.12: Costs and Strategies Used to Achieve Chesapeake Bay and Local TMDLs, Limited Trade

Water Quality Objective(s):	Chesapeake Bay and Local TMDLs	
Trade:	Limited Trade	
Total Annualized Cost:	$11,468,061	
Compliance Strategy:		**Quantity**
Goose Creek Portion of MS4:		
	Stream Restoration, Public-Adj.	297.3 ft
	Stream Restoration, Private-Adj.	1,110.9 ft
Bull Run Portion of MS4:		
	Bioretention; Imp. Public	23.5 acres
	Wet Pond Wetland; Imp. Private	160.4 acres
	Bioretention; Impervious Private	375.1 acres
	Wet Pond Wetland; Perv. Public	76.9 acres
	Wet Pond Wetland; Perv. Private	1,754.8 acres
	Stream Restoration; Public-Adj.	709.1 feet
	Stream Restoration; Private-Adj.	16,165.9 feet
Nutrient Credit Purchases		
	NPS Perpetual Credits	518.9 credits

Note: The fungible nature of reductions toward the Bay TMDL from any watershed make watershed-specific placement of activity incurred in response to Bay TMDL obligations potentially arbitrary. Findings related to overall costs, as well as the role of specific compliance practices in MS4s' overall behavior are not impacted by fungibility concerns.

Table B.13: Costs and Strategies Used to Achieve Chesapeake Bay and Local TMDLs, No Trade

Water Quality Objective(s):	Chesapeake Bay and Local TMDLs	
Trade:	No Trade	
Total Annualized Cost:	$14,797,252	
Compliance Strategy:		**Quantity**
Rest of MS4:		
	Wet Pond Wetland; Imp. Public	288.7 acres
	Wet Pond Wetland; Perv. Public	539.5 acres
	Wet Pond Wetland; Perv. Private	732.137 acres
Goose Creek Portion of MS4:		
	Wet Pond Wetland; Imp. Public	16.7 acres
	Wet Pond Wetland; Perv. Public	40.7 acres
	Wet Pond Wetland; Perv. Private	648.3 acres
Bull Run Portion of MS4:		
	Bioretention; Imp. Public	23.5 acres
	Wet Pond Wetland; Imp. Private	171.93 acres
	Bioretention; Imp. Private	363.57 acres
	Bioretention; Perv. Public	76.9 acres
	Wet Pond Wetland; Perv. Private	1,754.8 acres
	Stream Restoration; Public-Adj.	709.1 feet
	Stream Restoration; Private-Adj.	16,165.9 feet

Note: The fungible nature of reductions toward the Bay TMDL from any watershed make watershed-specific placement of activity incurred in response to Bay TMDL obligations potentially arbitrary. Findings related to overall costs, as well as the role of specific compliance practices in MS4s' overall behavior are not impacted by fungibility concerns.

Table B.14: Costs and Strategies Used to Achieve Chesapeake Bay TMDL, Full and Limited Trade

Water Quality Objective(s):	Chesapeake Bay TMDL	
Trade:	Full Trade & Limited Trade	
Total Annualized Cost:	$4,186,398	
Compliance Strategy:		**Quantity**
Rest of MS4:		
	Stream Restoration; Public-Adj.	1,136.3 feet
	Stream Restoration; Private-Adj.	18,738.7 feet
Nutrient Credit Purchases		
	NPS Perpetual Credits	2,811.3

Note: The fungible nature of reductions toward the Bay TMDL from any watershed make watershed-specific placement of activity incurred in response to Bay TMDL obligations potentially arbitrary. Findings related to overall costs, as well as the role of specific compliance practices in MS4s' overall behavior are not impacted by fungibility concerns.

Table B.15: Costs and Strategies Used to Achieve Chesapeake Bay TMDL, No Trade

Water Quality Objective(s):	Chesapeake Bay TMDL	
Trade:	No Trade	
Total Annualized Cost:	$11,990,373	
Compliance Strategy:		**Quantity**
Rest of MS4:		
	Wet Pond Wetland; Imp. Public	288.7 acres
	Wet Pond Wetland; Imp. Private	976.404 acres
	Wet Pond Wetland; Perv. Public	539.5 acres
	Wet Pond Wetland; Perv. Private	4883.9 acres
Goose Creek Portion of MS4:		
	Wet Pond Wetland; Imp. Public	16.7 acres
	Wet Pond Wetland; Perv. Public	40.7 acres
Bull Run Portion of MS4:		
	Wet Pond Wetland; Imp. Public	23.5 acres
	Wet Pond Wetland; Perv. Public	76.9 acres

Note: The fungible nature of reductions toward the Bay TMDL from any watershed make watershed-specific placement of activity incurred in response to Bay TMDL obligations potentially arbitrary. Findings related to overall costs, as well as the role of specific compliance practices in MS4s' overall behavior are not impacted by fungibility concerns.

Table B.16: Incremental Annualized Compliance Costs Calculated in Sensitivity Analyses

		Incremental Cost of Bay TMDL ($/yr)		
Analysis Scenario	*Description*	*Full Trade*	*Limited Trade*	*No Trade*
Baseline	-	$23,706	$330,813	$3,660,005
Sens. 1	New facilities on imp. land.	$21,982	$318,577	$2,184,016
Sens. 2	Retrofits costlier than anticipated.	$23,706	$330,813	$3,655,401
Sens. 3	Public land has value.	$23,706	$330,813	$3,823,719
Sens. 4	Private land easements costlier than expected.	$23,706	$330,813	$3,704,066
Sens. 5	Public land has value; no easements for private land.	$23,706	$330,813	$3,767,540
Sens. 6	O&M on private land is same as on public land.	$23,706	$330,813	$3,423,482
Sens. 7	Costlier O&M on private land than anticipated.	$23,706	$330,813	$3,745,040
Sens. 8	½ initial land & stream constraints.	N/A	N/A	N/A
Sens. 9	Stream constraints expanded.	$52,867	$826,591	$9,015,422

Table B.17: Incremental Annualized Compliance Costs Calculated in Sensitivity Analyses

		Inc. Cost of Bay TMDL, Relative to Bay and Local TMDls		
Analysis Scenario	*Description*	*Full Trade*	*Limited Trade*	*No Trade*
Baseline	-	0.21%	2.88%	24.73%
Sens. 1	New facilities on imp. land.	0.28%	3.91%	21.82%
Sens. 2	Retrofits costlier than anticipated.	0.20%	2.71%	23.57%
Sens. 3	Public land has value.	0.21%	2.88%	25.52%
Sens. 4	Private land easements costlier than expected.	0.21%	2.86%	24.78%
Sens. 5	Public land has value; no easements for private land.	0.21%	2.91%	25.43%
Sens. 6	O&M on private land is same as on public land.	0.23%	3.07%	24.69%
Sens. 7	Costlier O&M on private land than anticipated.	0.20%	2.72%	24.04%
Sens. 8	½ initial land & stream constraints.	N/A	N/A	N/A
Sens. 9	Stream constraints expanded.	1.30%	17.04%	69.14%

Table B.18: Total Annualized Compliance Costs Calculated in Sensitivity Analyses

		Total Annualized Cost of Bay & Local TMDLs ($/yr)		
Analysis Scenario	*Description*	*Full Trade*	*Limited Trade*	*No Trade*
Baseline	-	$11,160,954	$11,468,061	$14,797,252
Sens. 1	New facilities on imp. land.	$7,846,432	$8,143,026	$10,008,465
Sens. 2	Retrofits costlier than anticipated.	$11,878,216	$12,185,322	$15,509,910
Sens. 3	Public land has value.	$11,180,749	$11,487,856	$14,980,762
Sens. 4	Private land easements costlier than expected.	$11,269,737	$11,576,844	$14,950,097
Sens. 5	Public land has value; no easements for private land.	$11,071,983	$11,379,090	$14,815,818
Sens. 6	O&M on private land is same as on public land.	$10,467,077	$10,774,183	$13,866,852
Sens. 7	Costlier O&M on private land than anticipated.	$11,854,851	$12,161,958	$15,576,185
Sens. 8	½ initial land & stream constraints.	Infeasible	Infeasible	Infeasible
Sens. 9	Stream constraints expanded.	$4,077,402	$4,851,125	$13,039,956

Table B.19: Total Annualized Compliance Costs Calculated in Sensitivity Analyses

		Total Annualized Cost of Local TMDLs ($/yr)		
Analysis Scenario	*Description*	*Full Trade*	*Limited Trade*	*No Trade*
Baseline	-	$11,137,248	$11,137,248	$11,137,248
Sens. 1	New facilities on imp. land.	$7,824,449	$7,824,449	$7,824,449
Sens. 2	Retrofits costlier than anticipated.	$11,854,510	$11,854,510	$11,854,510
Sens. 3	Public land has value.	$11,157,043	$11,157,043	$11,157,043
Sens. 4	Private land easements costlier than expected.	$11,246,031	$11,246,031	$11,246,031
Sens. 5	Public land has value; no easements for private land.	$11,048,277	$11,048,277	$11,048,277
Sens. 6	O&M on private land is same as on public land.	$10,443,371	$10,443,371	$10,443,371
Sens. 7	Costlier O&M on private land than anticipated.	$11,831,145	$11,831,145	$11,831,145
Sens. 8	½ initial land & stream constraints.	Infeasible	Infeasible	Infeasible
Sens. 9	Stream constraints expanded.	$4,024,534	$4,024,534	$4,024,534

Table B.20: Total Annualized Compliance Costs Calculated in Sensitivity Analyses

		Total Annualized Cost of Bay TMDL ($/yr)		
Analysis Scenario	*Description*	*Full Trade*	*Limited Trade*	*No Trade*
Baseline	-	$4,186,398	$4,186,398	$11,990,373
Sens. 1	New facilities on imp. land.	$3,396,786	$3,490,093	$7,394,492
Sens. 2	Retrofits costlier than anticipated.	$4,186,398	$4,186,398	$12,753,656
Sens. 3	Public land has value.	$4,186,398	$4,186,398	$12,165,187
Sens. 4	Private land easements costlier than expected.	$4,186,398	$4,186,398	$12,240,153
Sens. 5	Public land has value; no easements for private land.	$4,186,398	$4,186,398	$11,915,455
Sens. 6	O&M on private land is same as on public land.	$3,885,830	$3,885,830	$11,373,629
Sens. 7	Costlier O&M on private land than anticipated.	$4,383,465	$4,383,465	$12,561,984
Sens. 8	½ initial land & stream constraints.	$4,300,021	$4,300,021	$12,151,513
Sens. 9	Stream constraints expanded.	$4,073,882	$4,093,837	$11,990,373

Table B.21: Strategies Used to Achieve Compliance in Sensitivity Analysis 9, i.e. Compliance Under Expanded Stream Restoration Constraints

Practice Used	**Units of Activity**
Bay and Local TMDLs, Full Trade	
Stream Restoration, Public-Adj., Rest of MS4	40.4 ft
Stream Restoration, Public-Adj., Goose Creek	594.6 ft
Stream Restoration, Private-Adj., Goose Creek	813.6 ft
Stream Restoration, Public-Adj., Bull Run	1,418.1 ft
Stream Restoration, Private-Adj., Bull Run	30,596.2 ft
PS Term N Credits	12,859.2 credits
Bay and Local TMDLs, Limited Trade	
Stream Restoration, Public-Adj., Goose Creek	594.6 ft
Stream Restoration, Private-Adj., Goose Creek	813.6 ft
Stream Restoration, Public-Adj., Bull Run	1,418.1 ft
Stream Restoration, Private-Adj., Bull Run	30,596.2 ft
NPS Perpetual Credits	1,296.6 credits
Bay and Local TMDLs, No Trade	
Wet Pond Wetland; Imp. Pub. land; Rest of MS4	288.7 acres
Wet Pond Wetland; Perv. Pub. land; Rest of MS4	539.5 acres
Wet Pond Wetland; Perv. Priv. land; Rest of MS4	2,465.5 acres
Wet Pond Wetland; Imp. Pub. land; Goose Creek	16.7 acres
Wet Pond Wetland; Perv. Pub. land; Goose Creek	40.7 acres
Wet Pond Wetland; Perv. Priv. land; Goose Creek	648.3 acres
Wet Pond Wetland; Imp. Pub. land Bull Run	23.5 acres
Wet Pond Wetland; Imp. Priv. land; Bull Run	535.5 acres
Wet Pond Wetland; Perv. Pub. land; Bull Run	76.9 acres
Wet Pond Wetland; Perv. Priv. land; Bull Run	1,754.8 acres
Stream Restoration; Public-Adj.; Bull Run	1,418.1 ft
Stream Restoration; Priv.-Adj.; Bull Run	17,537.6 ft

Note: Full Trade: NPS perpetual and PS term credits eligible for purchase. Limited trade: NPS perpetual credits eligible for purchase.

Table B.22: Strategies Used to Achieve Compliance in Sensitivity Analysis 9, i.e. Compliance Under Expanded Stream Restoration

Practice Used	**Units of Activity**
Local TMDLs, Full, Limited, & No Trade	
Stream Restoration, Public-Adj., Goose Creek	594.6 ft
Stream Restoration, Private-Adj., Goose Creek	813.6 ft
Stream Restoration, Public-Adj., Bull Run	1,418.1 ft
Stream Restoration, Private-Adj., Bull Run	30,596.2 ft
Bay TMDL, Full Trade	
Stream Restoration, Public-Adj., Rest of MS4	2,272.6 ft
Stream Restoration, Private-Adj., Rest of MS4	31,190.3 ft
PS Term N Credits	12,859.2 credits
Bay TMDL, Limited Trade	
Stream Restoration, Public-Adj., Rest of MS4	2,272.6 ft
Stream Restoration, Private-Adj., Rest of MS4	24,670.8 ft
NPS Perpetual Credits	1,348.9 credits
Bay TMDL, No Trade	
Wet Pond Wetland; Imp. Public land; Rest of MS4	288.7 acres
Wet Pond Wetland; Imp. Private land; Rest of MS4	976.4 acres
Wet Pond Wetland; Perv. Public land; Rest of MS4	539.5 acres
Wet Pond Wetland; Perv. Private land; Rest of MS4	4,883.9 acres
Wet Pond Wetland; Imp. Public land; Goose Creek	16.7 acres
Wet Pond Wetland; Perv. Public land; Goose Creek	40.7 acres
Wet Pond Wetland; Imp. Public land; Bull Run	23.5 acres
Wet Pond Wetland; Perv. Public land; Bull Run	76.9 acres

Note: Full Trade: NPS perpetual and PS term credits eligible for purchase. Limited trade: NPS perpetual credits eligible for purchase.

Appendix C

Third Appendix: Overdose Outcomes and Syringe Exchanges: Empirical Evidence from North Carolina

Table C.1: SEP Coverage, by County Urban/Rural Status

Year	**Counties**	**Counties Served**		
		Primary SEP	**Secondary SEP**	**Any SEP**
2017	All	28	24	52
	Rural	7	16	23
	Urban	21	8	29
2018	All	34	35	69
	Rural	11	24	35
	Urban	23	11	34
2019	All	42	39	81
	Rural	11	27	38
	Urban	31	12	43

Sources: NCDHHS, n.d.c, d, 2019, 2020a.

Table C.2: Summary Statistics of Overdose Deaths, Per Million (2017)

Substance	**Fatal Overdoses, Per Million**				
	Min.	**Max.**	**Median**	**Mean**	**Std. Dev.**
Any Opioids	0	475	161	186	103
Heroin	0	226	45	52	46
Prescription	0	273	66	69	53
Synthetic	0	475	103	120	92

Note: Based on observations from all 100 NC counties. Source: NCDHHS, n.d.f.

Table C.3: Summary Statistics of Overdose Deaths, Per Million (2018)

Substance	**Fatal Overdoses, Per Million**				
	Min.	**Max.**	**Median**	**Mean**	**Std. Dev.**
Any Opioids	0	382	160	163	82
Heroin	0	175	48	56	46
Prescription	0	243	43	51	45
Synthetic	0	317	108	114	71

Note: Based on observations from all 100 NC counties. Source: NCDHHS, n.d.f.

Table C.4: Summary Statistics of Overdose Deaths, Per Million (2019)

Substance	**Fatal Overdoses, Per Million**				
	Min.	**Max.**	**Median**	**Mean**	**Std. Dev.**
Any Opioids	0	550	154	184	104
Heroin	0	319	50	62	59
Prescription	0	249	38	45	41
Synthetic	0	498	121	140	95

Note: Based on observations from all 100 NC counties. Source: NCDHHS, n.d.f.

Table C.5: Median Annual Fatal Overdose, by County Subset

Counties	**Substance**	**Median County Fatal Overdose**		
		2017	**2018**	**2019**
Any	Any Opioids	161	160	154
	Heroin	45	48	50
	Prescription	66	43	38
	Synthetic	103	108	121
Rural	Any Opioids	133	151	158
	Heroin	31	41	44
	Prescription	66	36	42
	Synthetic	93	83	123
Urban	Any Opioids	189	174	150
	Heroin	54	59	59
	Prescription	63	49	35
	Synthetic	121	124	117

Sources: NCDHHS n.d.c; f.

Table C.6: Summary Statistics of Control Variables, 2017-2019

Control Variables	**Summary Statistics**				
	Min.	**Max.**	**Median**	**Mean**	**Std. Dev.**
Unemployment Rate	0.03	0.09	0.04	0.05	0.01
Felony Rate	0.01	0.07	0.03	0.03	0.01
SNAP Per Person	0.04	0.31	0.14	0.15	0.06
Lack of Health Insurance	0.09	0.22	0.14	0.14	0.02
Opioid Prescriptions Per 100	0.00	166.40	65.25	64.60	32.55

Note: Observations are based on 300 total county-year observations, except for Opioid Prescriptions Per 100, for which censoring precluded two county-years. Sources: U.S. Census Bureau, n.d., 2020; NC Department of Commerce, n.d.a, n.d.b, n.d.c; CDC, n.d.b, n.d.c, n.d.d, 2021b; North Carolina Judicial Branch, n.d.; Cromartie, 2020.

Table C.7: Results of SEP Service on Natural Logarithm of Fatal Overdose

Specification Class	**(1)**	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**
SEP Coverage	Primary	Any	Primary	Any	Primary	Any
County Sample	All	All	Rural	Rural	Urban	Urban
Impact on Dependent Variables						
Fatal Unintentional Any Opioid Overdoses, Per Million						
SEP Coefficient	0.040	-0.040	-0.061	-0.005	0.240	-0.068
Std. Error	0.100	0.084	0.146	0.124	0.137	0.119
P value - Coefficient	0.685	0.637	0.677	0.969	0.082	0.569
P value - Model	0.228	0.224	0.352	0.370	0.320	0.647
# observations	287	287	151	151	136	136
Fatal Unintentional Heroin Overdose, Per Million						
SEP Coefficient	-0.115	-0.089	-0.124	0.116	-0.096	-0.184
Std. Error	0.127	0.108	0.177	0.161	0.193	0.153
P value - Coefficient	0.367	0.413	0.486	0.475	0.619	0.233
P value - Model	0.000***	0.000***	0.001***	0.001***	0.337	0.235
# observations	239	239	107	107	132	132
Fatal Unintentional Prescription Overdose, Per Million						
SEP Coefficient	0.033	-0.068	0.067	0.183	0.080	-0.261
Std. Error	0.132	0.119	0.188	0.172	0.196	0.174
P value - Coefficient	0.804	0.57	0.723	0.289	0.682	0.137
P value - Model	0.000***	0.000***	0.015**	0.010**	0.001***	0.001***
# observations	256	256	126	126	130	130
Fatal Unintentional Synthetic Overdose, Per Million						
SEP Coefficient	0.079	-0.014	-0.042	-0.003	0.277	-0.021
Std. Error	0.120	0.103	0.184	0.160	0.161	0.140
P value - Coefficient	0.513	0.889	0.821	0.983	0.089	0.883
P value - Model	0.299	0.337	0.643	0.650	0.228	0.520
# observations	274	274	138	138	136	136

Note: Significance is conveyed via the following: *: P<0.1; **: P<0.05; ***:P<0.01. Variability of observations is due to omission of certain county-year observations in response to data shortages and/or censoring.

Table C.8: Results of Sticky SEP Service on Fatal Overdose

Specification Class	**(1)**	**(2)**	**(3)**
SEP Coverage	Sticky	Sticky	Sticky
County Sample	All	Rural	Urban
Impact on Dependent Variables			
Fatal Unintentional Any Opioid Overdose, Per Million			
SEP Coefficient	-6.513	3.314	-15.745
Std. Error	17.737	25.369	24.773
P value - Coefficient	0.714	0.896	0.527
P value - Model	0.050**	0.0914*	0.207
# observations	298	161	137
Fatal Unintentional Heroin Overdose, Per Million			
SEP Coefficient	-3.556	-8.616	6.793
Std. Error	9.660	15.057	11.464
P value - Coefficient	0.713	0.568	0.555
P value - Model	0.001***	0.032**	0.067*
# observations	298	161	137
Fatal Unintentional Prescription Overdose, Per Million			
SEP Coefficient	-10.362	0.469	-20.155
Std. Error	10.768	15.862	14.088
P value - Coefficient	0.337	0.976	0.156
P value - Model	0.065*	0.579	0.004***
# observations	298	161	137
Fatal Unintentional Synthetic Overdose, Per Million			
SEP Coefficient	-0.949	7.514	-8.302
Std. Error	16.641	25.651	19.505
P value - Coefficient	0.955	0.77	0.671
P value - Model	0.115	0.105	0.800
# observations	298	161	137

Note: Significance is conveyed via the following: *: P<0.1; **: P<0.05; ***:P<0.01. Variability of observations is due to omission of certain county-year observations in response to data shortages and/or censoring.

Figures

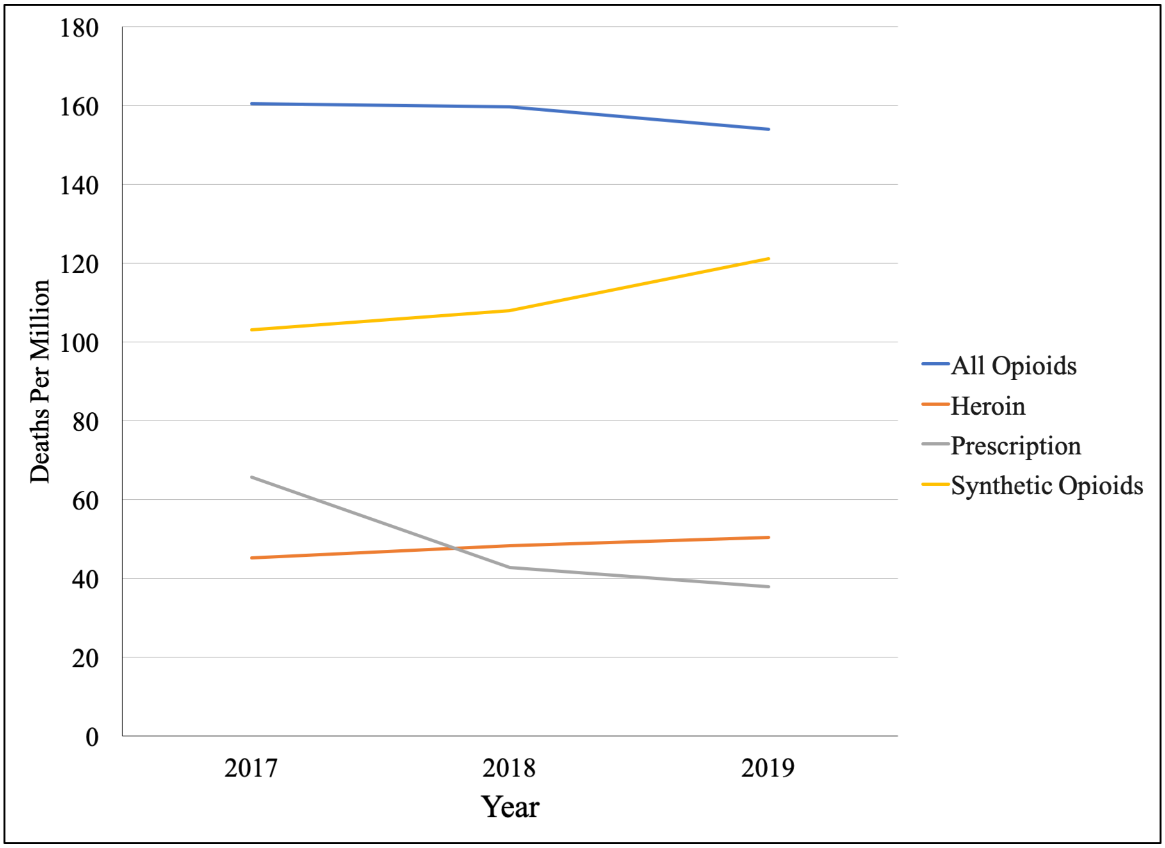

Figure C.1: Median Fatal Overdose, Per Million, vs. Year

Sources: NCDHHS, n.d.f; Cromartie, 2020.

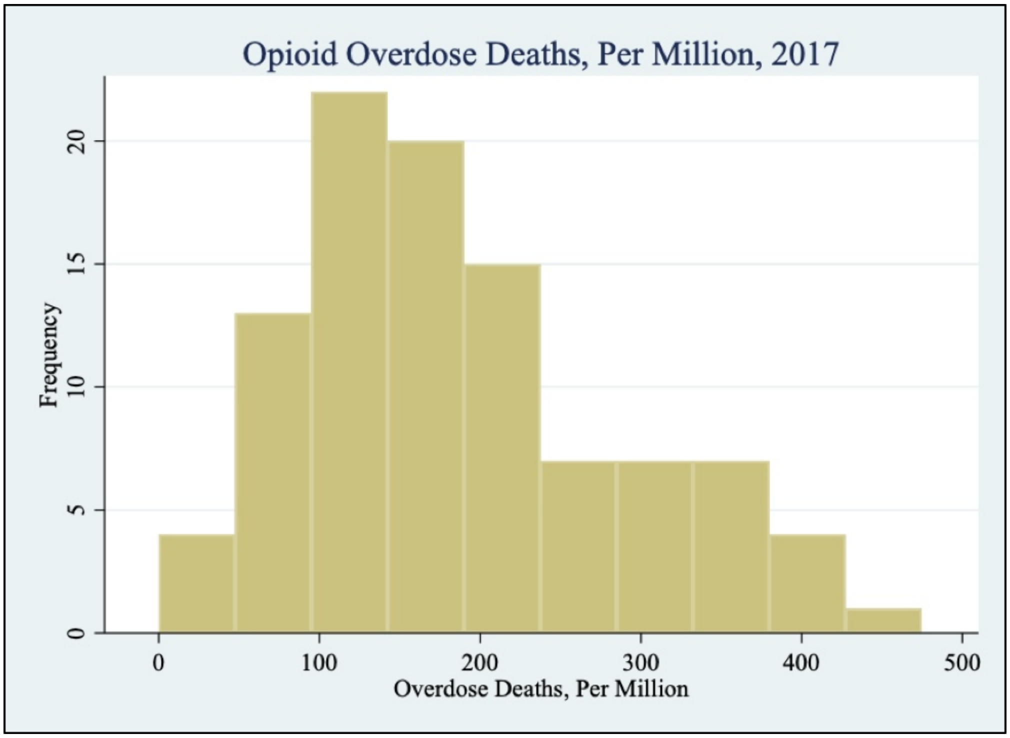

Figure C.2: Histogram of Fatal Opioid (All) Overdose, Per Million (2017)

Sources: NCDHHS, n.d.f; Cromartie, 2020.

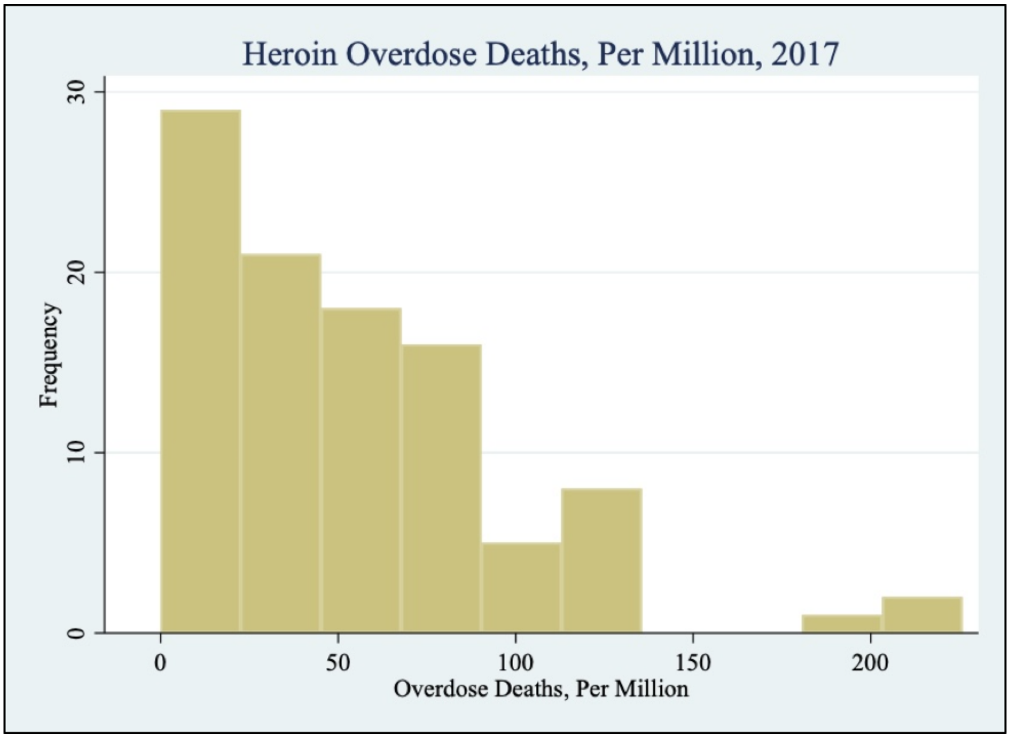

Figure C.3: Histogram of Fatal Heroin Overdose, Per Million (2017)

Sources: NCDHHS, n.d.f; Cromartie, 2020.

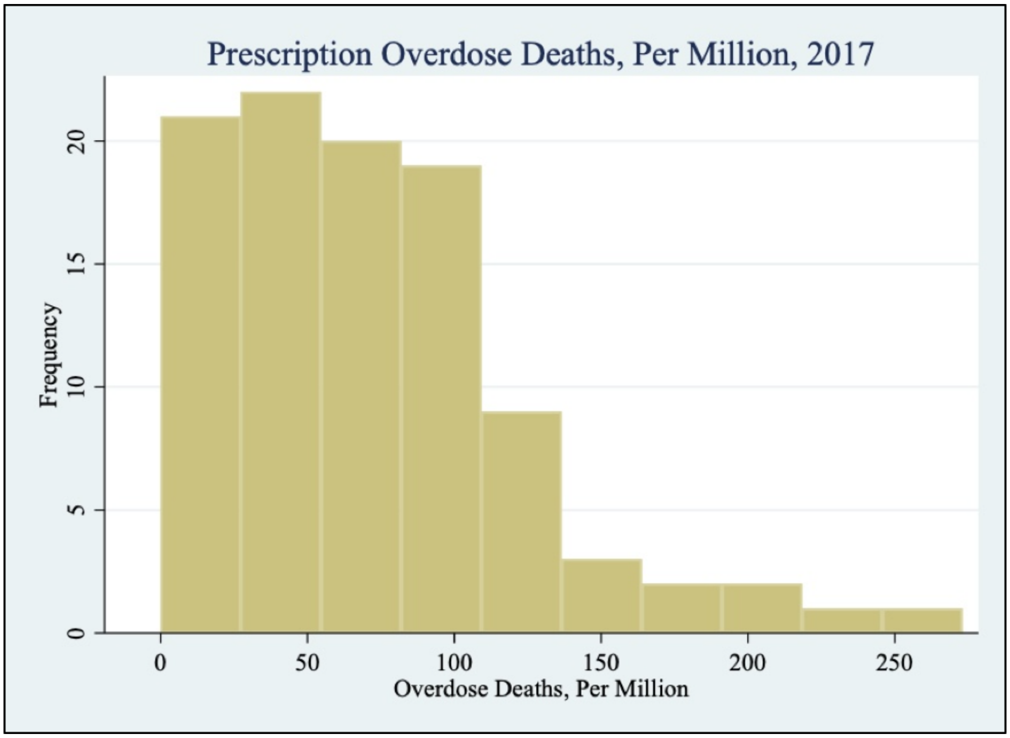

Figure C.4: Histogram of Fatal Prescription Overdose, Per Million (2017)

Sources: NCDHHS, n.d.f; Cromartie, 2020.

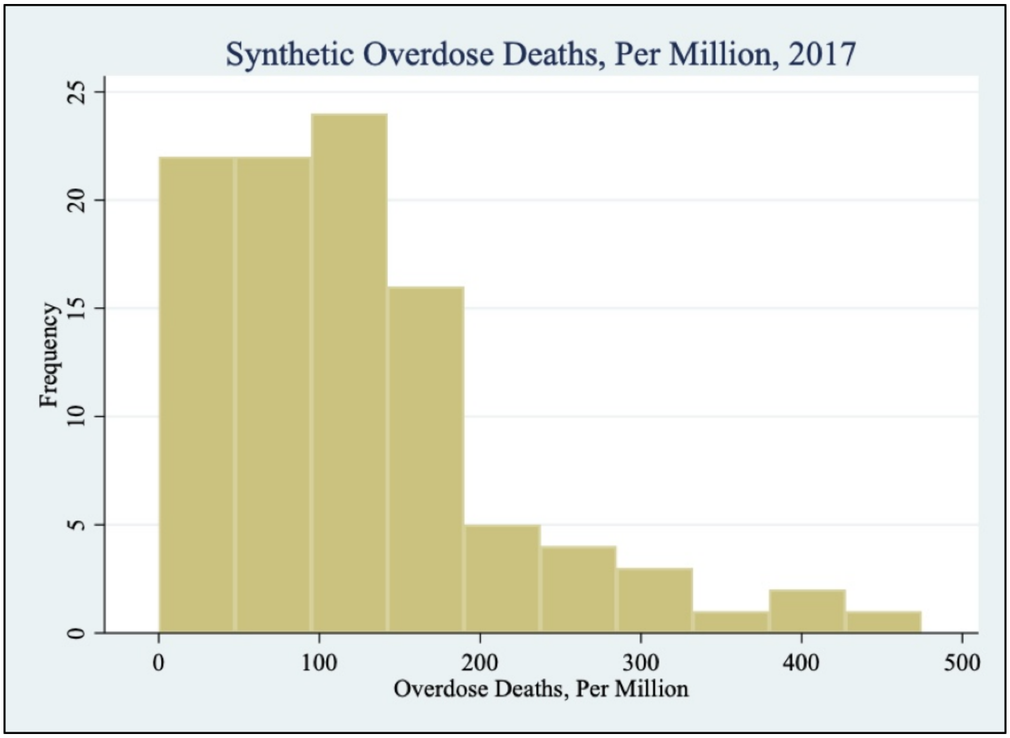

Figure C.5: Histogram of Fatal Synthetic Overdose, Per Million (2017)

Sources: NCDHHS, n.d.f; Cromartie, 2020.