Evaluating Stormwater Compliance Through Best Management Practices and Water Quality Trading in Virginia

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This

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Abstract

Stormwater has been recognized as a significant source of pollution and flooding which is aggravated by the increase in urbanization. During rainfall events, surface runoff washes nutrients and other pollutants into receiving waters. Impervious urban surfaces prevent infiltration and shorten the time required for runoff flows to peak, resulting in increased runoff volume and peak flows that lead to flooding. Best management practice facilities (BMPs) are commonly constructed to treat and control stormwater to meet regulatory requirements. Alternatively, water quality trading (WQT) may be allowed to achieve compliance. Under this option, regulated stormwater entities can purchase credits, representing reduced nutrient load resulting from mitigation achieved offsite by another party, to meet their stormwater regulatory requirements. However, our understanding of how compliance is achieved given the influence of Virginia's active WQT program is not well understood.

This dissertation advances our understanding of 1) how stormwater compliance is achieved in practice, 2) the associated challenges of achieving compliance, and 3) identifies opportunities for reducing compliance costs using the Virginia Department of Transportation (VDOT) and the City of Roanoke as case studies. The first study uses BMP inspection and condition rating data from the VDOT to describe quantitatively how basin-type BMP conditions change over time, the condition issues that influence condition changes, and compares those condition issues with issues identified for basins experiencing rapid decline in condition. The second study compares site characteristics and stormwater quality and quantity compliance choices for development projects in Roanoke. This was achieved using a novel dataset collated from data harvested from land development project documentation stored in Roanoke's permit tracking database. The third study develops GIS-based methods for calculating spatially explicit upper-bound estimates for WQT credits. The study applies the methodology on VDOT's 6-year improvement projects and compares VDOT's estimated credit needs with current credit supply levels in Virginia.

Key findings from this dissertation are (i) conditions of basin-type BMPs can fluctuate annually despite regular inspection and maintenance practices, as observed by nearly half of VDOT's basin-type BMPs that had three consecutive years of inspections (ii) the occurrence of rapidly declining basin-type BMPs is due to few, specific issues that may or may not differ from the most frequently noted issues corresponding with conditions of basins with the same declined state and irrespective of differences in individual VDOT district management practices (iii) nutrient credits, influenced by comparative lower costs, are the preferred method for achieving stormwater compliance by land developers in Roanoke, Virginia; however, water quality issues may be of concern due to the ubiquitous practice of downstream trading observed (iv) current credit supplies across much of the Commonwealth of Virginia are likely adequate to support upper-bound estimates of credit need for VDOT's 6-year improvement projects; however, the results of the applied methodology indicate the southwest region of Virginia does not currently have adequate credit supply to meet VDOT's estimated credit needs. The findings of this dissertation serve to inform practitioners, regulatory program managers, and researchers of current challenges of meeting stormwater regulations using BMPs and provides considerations and methods for supporting environmental integrity and participation in WQT.

To Charlotte and Abigail Nelson

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Contents

List of Tables

List of Figures

Chapter 1

1. Introduction

Increases in impervious surfaces associated with urban development result in higher peak flows and nutrient load concentrations in urban streams (Shuster et al., 2005; Vogel and Moore, 2016). Resulting peak flows and nutrient concentrations negatively impact the health of nearby receiving streams as well as more distant waterbodies (Walsh, 2000). Only recently in the United States has stormwater pollution management become a major focus, driven by Clean Water Act (CWA) amendments requiring the permitting of stormwater discharge for industrial and construction activities and municipal separate storm sewer systems (MS4s) in 1990 and 1999 (Delgrosso et al., 2019; EPA, 2022a; King et al., 2011). While regulations are established to protect water quality, the cost associated with regulatory compliance is high, with the stormwater sector noted for facing the highest costs (Jones et al., 2017).

Onsite stormwater best management practices (BMPs) are often used to achieve compliance with stormwater treatment regulations. This is due in part by the fact that stormwater treatment regulations often reflect a preference for onsite treatment practices (Stephenson and Shabman, 2017). BMPs are structural stormwater control devices that are designed to reduce runoff volume, lower peak discharge rates, and remove pollutants in stormwater runoff (Delgrosso et al., 2019; Yu et al., 2013). Traditionally, BMPs are implemented during construction for the purposes of managing construction-related and post-construction stormwater discharge as required. To facilitate compliance with construction and post-construction stormwater control, the United States Environmental Protection Agency (EPA) provides a national menu of BMPs that can be used (EPA, 2022b). States or local governments may also recommend certain BMPs in their respective guidance manuals for construction activities (MDEP, 2016; ODOT, 2023; VADEQ, 2013a).

Regular inspection and maintenance is necessary for ensuring desired stormwater BMP performance standards are met. Asset management systems are used to guide cost-effective practices, keep infrastructure in good condition, and meet infrastructure condition goals. These systems can be used to reduce the magnitude of condition decline by facilitating the evaluation of the asset's condition or performance (Konstantakos et al., 2019; Marlow and Burn, 2008; Peraka and Biligiri, 2020). Reducing the magnitude of condition decline is important as BMP maintenance has been frequently cited as expensive, with significant costs attributed to BMPs in poor or failed conditions (Dong et al., 2023; Kang et al., 2008; Weiss et al., 2007). The literature has described the growing adoption of inspection and maintenance management systems by state transportation departments (Taylor et al., 2014). However, despite the adoption of systems for BMP management, these systems have not been used to identify specific factors affecting BMP conditions, including conditions of BMPs that experience rapid decline in condition, or to characterize temporal changes in BMP conditions.

Water quality trading (WQT) is a market-based strategy designed to reduce the overall cost of water quality compliance in regulated watershed programs (Selman, et al., 2009; Shortle, 2013). In the United States, there have been 147 WQT programs or policies identified (BenDor et al., 2021) as of 2021. These programs operate by allowing buyers, such as regulated land developers or state transportation agencies, to offset their water quality treatment requirements through the purchasing of credits representing nutrient load reduction performed offsite. The buyers can apply the credits to meet their permit treatment obligations. Buyers are incentivized to purchase credits if the cost of the credit is less than the cost of implementing onsite treatment practices. The sellers, such as non-regulated agricultural landowners, are incentivized to reduce nonpoint source pollution from their sites if the credit price is higher than the cost to perform the mitigative work. While many WQT programs have historically seen low participation (Breetz et al., 2005; Shortle, 2013), high activity in water quality trading has been observed in programs that support stormwater compliance (Duke et al., 2020; Saby et al., 2021b; Stephenson and Shabman, 2011). Despite the higher participation, there are many important questions that need to be answered to understand the outcomes of the adoption and use of credits by regulated stormwater dischargers. Furthermore, research is needed to develop methods for coordinating future credit supply with estimated future credit need to support continuing participation.

1.1 Overview of Stormwater Compliance in Virginia

1.1.1 Virginia Stormwater Management Program

Virginia requires stormwater permits to be obtained in connection with land disturbance activities through the Virginia Stormwater Management Program (VSMP). A VSMP authority may be a regulated MS4, such as a municipality, or they may be a state entity, such as the VDOT (see Virginia Code 9VAC25-870-10). These VSMP authorities are responsible for regulating land disturbance associated with residential and commercial land disturbance activities (excluding agricultural and mining projects), and linear roadway projects. VSMP authorities review and approve development plans to ensure their compliance with Virginia's stormwater quality and quantity regulations, including authorizing the use of nutrient credits from the NPS WQT program. Generally, stormwater quality regulations require total phosphorus (TP) loads associated with land cover types (forest, turf, impervious) to be reduced to achieve a baseline load limit. VSMP quantity regulations include requirements to demonstrate that downstream channel erosion and flooding will not occur from discharging stormwater.

The Virginia Runoff Reduction Method (VRRM), based on the Runoff Reduction Method (RRM) is the approved method in Virginia for calculating required TP load reduction (Battiata et al., 2010; Davenport, 2016). Calculations for TP reduction vary based on the type of development (new or redevelopment) and disturbance area. New development refers to projects with no existing onsite impervious cover prior to land disturbance. Redevelopment projects refer to sites with pre-existing impervious cover. New development projects must reduce TP loads in excess of a standard baseline nutrient load limit based on calculated nutrient loads from post construction land cover. Redevelopment projects, however, must consider both the predevelopment land cover and post development land cover types when calculating required nutrient load reduction. For redevelopment sites, TP loads associated with any net increase in impervious cover must be treated to achieve the same baseline load as new development projects. However, nutrients generated from the non-impervious cover portion of the redevelopment site must be reduced 10% or 20% below the calculated predevelopment load, depending on the total area of land disturbance (Davenport, 2016). Redevelopment projects may be able to achieve nutrient load reduction by reducing post-construction impervious surface areas relative to pre-redevelopment impervious area. However, new development projects are not given this same option because their post development nutrient loads are only relative to a non-developed, baseline state. Furthermore, 75% of TP reduction requirements must be met onsite for both new and redevelopment projects that disturb five or more acres or whose total TP reduction requirement is 10 pounds or greater. Credits can be purchased through Virginia's NPS WQT program when either of these three treatment conditions have been met for a development site (see Virginia Code 9VAC25-870-69).

New and redevelopment projects must comply with the same stormwater quantity requirements to prevent downstream channel erosion and flooding. Compliance with channel protection requirements is achieved by releasing concentrated stormwater in a conveyance system that accommodates peak discharge for a standard storm event, accounting for specified contributing area beyond the project site (9VAC25-870-66.B). Flood protection is achieved by demonstrating either that stormwater discharge from the development site will not cause flooding in the receiving stormwater conveyance system or that existing localized flooding can be avoided through limited or reduced stormwater discharge into the conveyance system (9VAC25-870-66.C). Guidance in Virginia's stormwater regulations recommend detention be used to control stormwater discharge to achieve stormwater quantity compliance.

1.1.2 BMPs for Stormwater Quality and Quantity Compliance

There are several different types of BMPs approved by the Virginia Department of Environmental Quality (VADEQ) to meet stormwater quality, quantity or both sets of requirements (VADEQ, 2013a). BMPs used to treat stormwater typically do so either through providing time for nutrient settling, such as an extended detention basin or through filtering, such as bioretention or pervious pavement. These BMPs are included as compliance options that can be selected in the VRRM compliance spreadsheet tool to meet treatment requirements. Quantity control is achieved primarily by lowering peak flow rates by retaining and slowly discharging runoff over time (Sample et al., 2020).

1.1.3 Virginia's NPS WQT Program

Virginia's NPS WQT program has been recognized as the most active WQT program in the United States (Liu and Brouwer, 2023). Recent research supports this claim by documenting thousands of transactions between agricultural landowners and land development projects seeking compliance with stormwater permit requirements (Saby et al., 2021b). This activity may be explained by the fact that Virginia's program allows credits – each representing one pound of total phosphorus reduction – to be generated through the permanent conversion of agricultural land to land uses with lower nutrient pollution potential (e.g., forest). These generation sites, or mitigation sites, are referred to as credit banks. This policy simplifies credit generation to a one-time land conversion activity, and buyers can use the credits to achieve compliance in perpetuity as opposed to temporarily through term credits. Under this unique option, bankers are liable for the credit generation project after the credits have been sold as opposed to other one-time offset programs where liability remains with the buyer (Morgan and Wolverton, 2008). Forests planted to generate credits can also be timbered periodically, thereby adding additional incentive to the seller (see Virginia Code 9VAC25-900-120C). Additionally, Virginia's policies also allow responsibility for credit quality to be transferred to others after the sale of the credits. Furthermore, Virginia uses a one-to-one trading ratio, meaning that one pound of phosphorus treated offsite can be purchased for one pound of phosphorus generated onsite. While a one-to-one trading ratio is not explicitly unique to Virginia, other trading programs have been noted to use trading ratios requiring buyers to purchase nutrient reduction representing up to five times the onsite nutrient reduction requirement, potentially disincentivizing buyers from trading (Malik et al., 1993; Ribaudo and Gottlieb, 2011).

Virginia's program makes use of a hierarchy of watershed catchments developed by the United States Geological Survey (USGS), called hydrologic unit codes or HUCs (USGS, n.d.), to determine valid trades. HUCs are classified by size with fewer digits referring to larger catchment areas. The largest HUCs are called 2-digit HUCs (or HUC 2) and the smallest are called 12-digit HUCs (or HUC 12).

Under the previous regulations, prior to 2021, a buyer was allowed to seek credits first in the same HUC 8, and then in adjacent HUC 8 for banks with available credits. If no banks were available, the buyer could then look for banks within the corresponding HUC 6. However, if stormwater runoff from projects discharged into impaired waters, (i.e., dissolved oxygen, benthic community, chlorophyll-a, or nutrients), then the buyer would be limited to purchasing credits from available banks in the same HUC 12 as the development project (Saby et al. 2021a).

In the updated regulations, additional trading rules and restrictions were introduced. With the updated rules, buyers are allowed to purchase credits beginning within the same HUC 8, then the adjacent HUC 8 within the same HUC 6, and, if necessary, within the same HUC 6 basin. For projects that drain directly to water bodies with dissolved oxygen, benthic community, chlorophyll-a, or nutrients impairments, the interested buyer must first seek credits from banks immediately upstream from the project site (i.e., within the impaired catchment area) within the same HUC 12. If a bank does not exist upstream of the project site, or if credits are not available at an upstream bank, the buyer can then seek credits from banks in other areas within the same HUC 12 and, subsequently, in the same HUC 10, same HUC 8, adjacent HUC 8, and lastly, same HUC 6 if credits are not available at the smaller scales (see Virginia Code 9VAC25-900-91). This change encourages buyers to use banks nearer to projects in impaired watersheds (i.e., a watershed containing an impaired stream). If the impaired watershed has an active total maximum daily load (TMDL) for nutrients, meaning specific pollution load limits have been legally established for the impaired stream, then buyers are further restricted to purchasing credits only from banks located immediately upstream from the project site within the local TMDL area.

1.1.4 Available Stormwater Compliance Data

Evaluating stormwater compliance in Virginia is of particular interest due to its successful nonpoint source (NPS) WQT program and the availability of vast amounts of compliance data. Virginia's NPS WQT program has been acknowledged as the most active WQT program (Liu and Brouwer, 2023). Recent research has identified the occurrence of thousands of transactions between agricultural landowners and land development projects seeking compliance with stormwater permit requirements (Saby et al., 2021b). Trading data, including credit availability, credits purchased, and buyer and seller information is available for more than 90 mitigation sites (credit banks) in Virginia through the US Army Corps of Engineer's Regulatory In-lieu Fee Banking System (RIBIS) (Saby et al., 2021b; USACE, 2017). The Virginia Department of Transportation (VDOT), one of the largest state transportation agencies in the United States by roadway miles managed, uses a BMP inspection and condition rating system to facilitate generating maintenance work orders, report compliance to the Virginia Department of Environmental Quality (VADEQ), communicate with internal VDOT stakeholders, and justify requests for additional BMP maintenance funding. Their current system documents condition issues observed during inspection through a digital inspection survey comprising over 200 potential questions. Along with documenting general and specific issues, the system auto-assigns a condition rating for each BMP based on the responses provided. The City of Roanoke in southwest Virginia uses the eTRAKiT permitting software to approve and track the progress of land development projects within their jurisdiction, including those that are subject to stormwater regulations (Ahmadi et al., 2020). Within the eTRAKiT database are hundreds of project-related documents, including stormwater management reports and stormwater pollution prevention plans that describe stormwater treatment requirements and methods implemented to meet those requirements. Together, this vast amount of data supports the research to characterize and evaluate stormwater compliance methods to identify program outcomes, opportunities for cost-savings, and to inform future policy.

1.2 Knowledge Gaps and Objectives

There are three important knowledge gaps in our understanding of stormwater compliance in Virginia. These knowledge gaps are 1) we have limited understanding of how BMP conditions change over time and the factors responsible for those changes 2) the characterization of credit adoption by land developers and potential outcomes for such adoption is largely unknown 3) there are no current methods described for estimating future credit need for large credit buyers in Virginia. This dissertation addresses these knowledge gaps with three studies, as summarized in Figure 1.1.

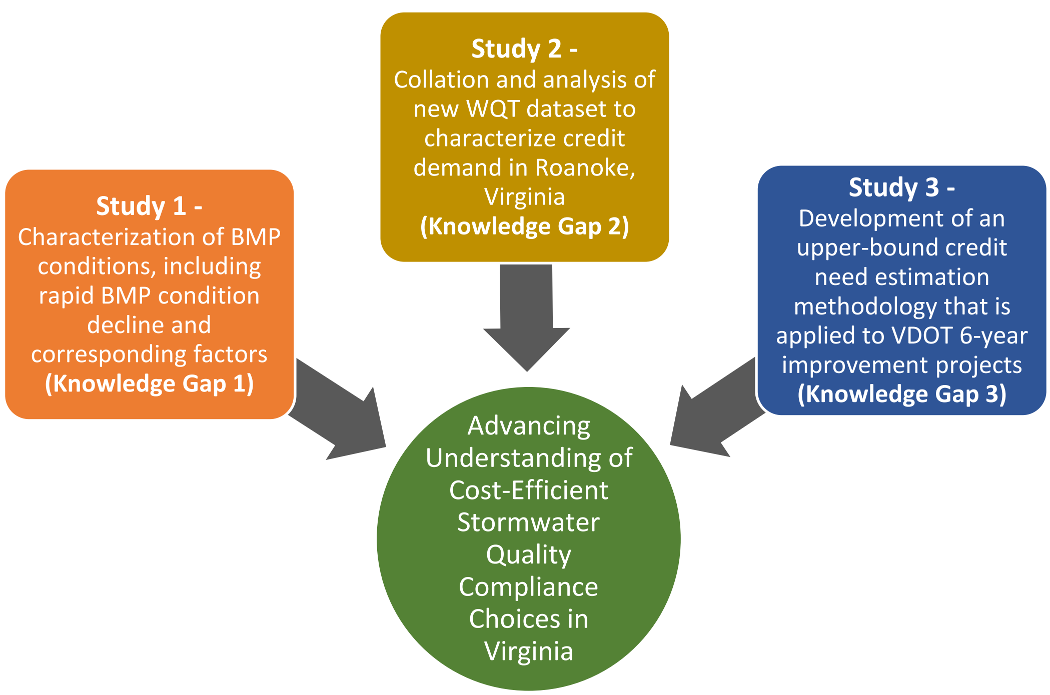

Figure 1.1: Summary of dissertation studies.

Study 1 (Chapter 2)

The primary objectives of Study 1 are to characterize the changes in condition ratings of basin-type BMPs over time and determine the specific condition issues that are associated with those changes. A secondary objective includes identifying basins that experience a rapid decline in condition and determining the specific condition issues that correspond with rapid decline. We achieve these objectives by analyzing inspection rating data provided by VDOT using Python. Basin condition level changes are characterized using graphical methods, including bar plots and heat maps. Using these techniques, several rapidly declining basins are identified, defined as basins whose condition level declines by at least two levels within a year's time. The specific factors and their frequency are quantified for general condition levels and compared with basins that experienced rapid decline in condition to determine probable cause for the rapid decline.

Study 2 (Chapter 3)

The objectives of Study 2 are to 1) characterize credit adoption of land developers, including site characteristics and corresponding treatment requirements, 2) compare projects that use credits for treatment compliance with projects that use BMPs, and 3) describe stormwater compliance outcomes observed. To achieve these objectives, a new stormwater compliance dataset was collated using Python and manual review of development project documentation contained in Roanoke's permit tracking system. The dataset, containing the attributes and stormwater compliance methods of 131 land development projects, is evaluated to determine trends of compliance for land developers.

Study 3 (Chapter 4)

The objectives of Study 3 are to 1) develop a methodology to estimate the upper-bound credit need of large credit buyers, and 2) compare quantities and locations of VDOT's estimated credit need with existing credit levels. These objectives are achieved through the development of a GIS-based methodology that implements the VRRM method for estimating nutrient reduction requirements. The methodology is applied to VDOT 6-year improvement projects and resulting estimated credit need is compared with current credit supply.

The following contents of this dissertation include the three studies as separate chapters. Each study contains a separate introduction section and additional, specific background information to support the study. Each study also contains a section for study-specific conclusions. The final chapter of the dissertation, Chapter 5, offers a summary across the three studies and the key conclusions resulting from the dissertation research.

Chapter 2

2. Characterizing Stormwater Basin Conditions Using Tracked BMP Inspection and Rating Reports from the Virginia Department of Transportation[1]

2.1 Introduction

Stormwater best management practices (BMPs) are structural devices used to treat and manage the release of stormwater into waterways (Delgrosso et al., 2019; Yu et al., 2013). Regular inspection and maintenance of BMPs is necessary to ensure intended control and treatment is achieved and to maximize the life of the asset (Taylor et al., 2014). Inspections may be scheduled at set frequencies (e.g., semi-annually, annually, etc.) to meet stormwater permit requirements or they may be triggered by an event such as construction or rainstorm events (Hirschman et al., 2009; Taylor and Barrett, 2013; Taylor et al., 2014; VADEQ, 2013b).

Asset management systems are used to inform practices that keep physical infrastructure in good condition and realize intended performance goals. These systems can reduce the magnitude of deterioration of infrastructure by informing proactive maintenance practices. This is accomplished, in part, by facilitating the evaluation of the condition or performance of the asset (Konstantakos et al., 2019; Marlow and Burn, 2008; Peraka and Biligiri, 2020).

Condition rating assessments and corresponding results are commonly described for many types of infrastructure, such as roads or bridges, but are less frequently described for stormwater BMPs. For example, Omar and Nehdi (2018) summarize several studies describing condition rating assessments for reinforced concrete bridges. Huntington and Ksaibati (2015) describe simplified procedures for determining condition ratings of unsealed roadways. Ruiz et al. (2019) describe several rating scales used for condition assessments of buildings. Some condition rating systems have been described for stormwater BMPs as well. Taylor et al. (2014) identified BMP condition assessment tracking systems being used by several state transportation agencies, including Maryland, Delaware, North Carolina, and Washington state transportation departments (DOTs). Virginia's DOT also uses an inspection and condition rating system (VDOT, 2021).

Few studies have leveraged the inspection data associated with the condition ratings of BMPs to characterize temporal changes in BMP conditions or conditions corresponding with BMPs that experience rapid decline in conditions. Using condition rating assessments, structurally deficient infrastructure can be identified and repaired and future maintenance be performed proactively to reduce costs (Kang et al., 2008; Kirk and Mallett, 2018; Ruiz et al., 2019). Such information could inform proactive BMP management practices that have historically been described as reactive (Venner et al., 2013).

This study serves to address two primary questions related to management issues associated with commonly used basin-type BMPs using annual inspection and condition rating data provided by the Virginia Department of Transportation (VDOT). VDOT defines basin-type BMPs to include multiple types of basins, with approximately 93% of their basins comprising

[1] This study is in preparation for submission to the American Society of Civil Engineers' Journal of Sustainable Water in the Built Environment.

dry detention, extended detention, enhanced extended detention, or retention ponds. These questions are 1) how do basin conditions change over time, and 2) what factors correspond with basins that experience rapid decline in condition and how do they compare with those of non-rapid declining basins in the same declined condition? We provide quantitative responses to these questions along with discussion about challenges and factors to consider for leveraging condition rating assessment data for informing maintenance decisions.

2.2 Materials and Methods

2.2.1 Study Area

The Virginia Department of Transportation (VDOT) serves as the case study to evaluate factors associated with BMP conditions due to the quantity and spatial spread of the BMPs managed by the agency. VDOT manages more than 2,600 BMPs under a municipal separate storm sewer permit, of which more than 1,600 BMPs are of basin-type (e.g., detention and retention basins). These BMPs are spread across the nearly 111,000 square kilometers that comprise the Commonwealth of Virginia (Norrell and Quittmeyer, 2023; Virginia Roads, 2023). VDOT delegates responsibility for BMP inspections and maintenance to nine independent management districts (Figure 2.1). Within each permit cycle, the Virginia Department of Environmental Quality (VADEQ) or the United States Environmental Protection Agency (USEPA) conducts a cursory audit comprised of randomly inspecting a subset of VDOT's BMPs to verify compliance with stormwater requirements. To facilitate compliance with permit requirements, VDOT has developed and implemented a BMP inspection and condition rating system, which is described in the following subsections.

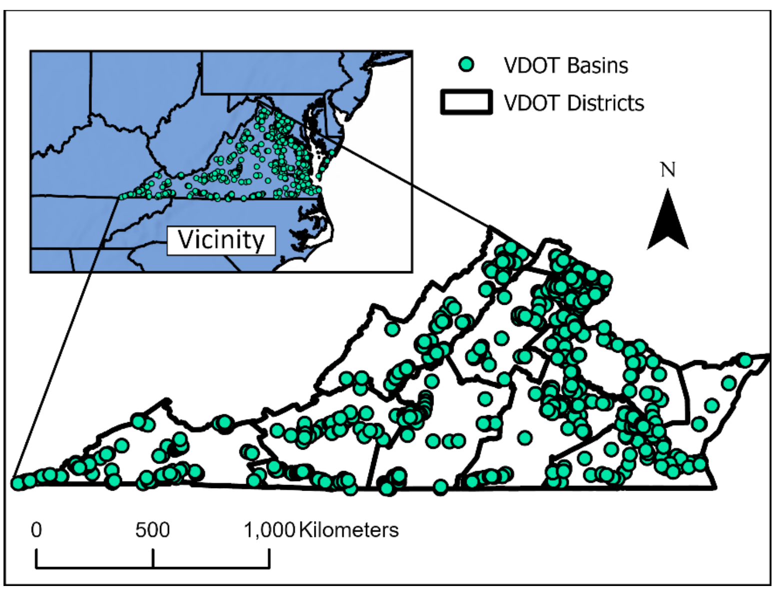

Figure 2.1: The BMP basins managed by VDOT along with the VDOT districts charged with the basin inspection and maintenance. Base layers made available through ESRI's ArcGIS Pro and the United States Geological Survey (USGS).

2.2.2 VDOT's Inspection and Condition Rating System

VDOT programmed a digital mapping and inspection system using Environmental Systems Research Institute (ESRI) software for managing BMP inspections. ESRI's ArcGIS Enterprise software is used for mapping the locations of the BMPs. The Survey 1-2-3 application is used to record inspections on portable electronic devices, including a smart phone. The Survey 1-2-3 application stores the inspections locally and then inspectors upload inspection reports to a central database when a Wi-Fi connection is available, though this is not recommended to be done while in the field to prevent data loss associated with unreliable Wi-Fi connections (VDOT, 2021). Each of the nine VDOT districts may choose to carry out inspections themselves, or they may choose to contract the work out to a private company. However, all inspections are to be performed using VDOT's standard inspection system.

BMP condition ratings are assigned using the Survey 1-2-3 application. The app includes a unique set of inspection questions that correspond with the type of BMP being inspected. For basin-type BMPs, inspectors may be prompted to review and respond to more than 200 questions that correspond with more than 60 basin site and component categories, depending on the conditions observed. Survey questions are presented in a hierarchal order according to the severity of the conditions observed for each specific component. The leading question for each component is a statement indicating there are no issues observed. Inspectors can select "Yes," affirming there are no problems, or they may choose "No" to indicate the contrary. By selecting "No," additional questions are presented, each describing incrementally more severe issues for that specific component being inspected. All subsequent questions may also receive either a "Yes" or a "No" response. There are several opportunities throughout the survey for inspectors to manually enter comments to add clarification to their answer.

The inspection system contains algorithms that assign a condition rating of "A," "B," "C," "D," or "E" for each question based on the response given, with ratings of "A" through "C" being assumed by VDOT to correspond with a fully functional BMP in terms of treatment and quantity control. "D" and "E" refer to non-fully functional condition, and "E" refers to a failed condition (VDOT, 2021). Upon completing the survey, the algorithm assigns an overall condition rating. Inspectors can see the final inspection rating but are prevented from observing the rating assigned to each individual question during the inspection or from changing the rating. VDOT may also periodically update inspection questions or the rating algorithm to meet the organization's needs.

VDOT's process for inspecting and assigning condition ratings for BMPs is described below in Figure 2.2. This process is initiated when an inspector conducts an annual inspection of a BMP. Upon filling out the inspection survey, a condition rating is assigned to that BMP. If the BMP receives an "A" rating, then no maintenance plans are required and regular, semi-annual preventative maintenance, such as grass trimming or trash pickup is considered sufficient. However, if the rating assigned is a "B" or lower, then a maintenance plan is developed, resulting in the generation of a maintenance request. Depending on the rating, maintenance plans may specify a timeline of a year or less to conduct the maintenance. For significant, corrective maintenance issues, inspections may be conducted during the maintenance activity to ensure maintenance is being carried out properly. Once the maintenance is complete, a reinspection occurs, triggering another condition rating issued. The best-case scenario is that the maintenance performed brings the condition of the BMP up to an "A" rating, resulting in only preventative future maintenance. However, the process may be repeated if the reinspection rating is not an

“A” rating. Additionally, the need for inspections may be triggered by severe storm events that exceed the capacity of the principal spillway (VDOT, 2021).

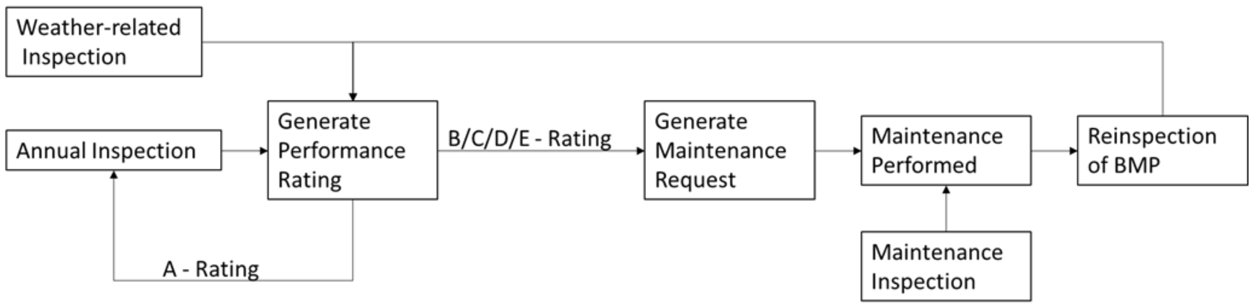

Figure 2.2: Inspection rating process for VDOT. Not shown in this flow diagram is the “Initial Inspection” category that is initiated when a basin is first constructed.

2.2.3 Composition of Basin Inspection Dataset

VDOT’s inspection dataset is comprised of 9,766 basin inspection records submitted between July 2, 2019 and March 27, 2023. These inspections correspond with condition ratings assigned to 1,677 basin BMPs, approximately 96% of VDOT’s existing basins, based on basin counts as of August 2023 (Virginia Roads, 2023). The inspections are comprised of six categories of inspections: annual, semi-annual, maintenance, reinspection, initial, and weather-related. There are 6,320 annual inspections (65%), 2,936 maintenance (30%), 386 semi-annual (4%), 115 reinspection (1%), three weather-related (less than 1%), and one initial inspection (less than 1%). Of the 9,766 inspections, 9,314 (95%) indicate a basin condition rating of “A” to “E”. Categories and percentages of inspections were obtained using the value_counts() and unique() functions in the Pandas python library.

Annual-type inspections captured the conditions associated with the highest percentage of VDOT’s basins. Table 2.1 shows there were 1,674 unique basins (96% of VDOT’s existing basins) that received at least one annual inspection within the duration of the dataset. Condition ratings provided by other types of inspections accounted for substantially fewer basins. For example, the second highest inspection-type category, “Maintenance Inspections,” only captures the conditions of 456 basins (26% of VDOT’s basins) (Table 2.1). Semi-annual inspections only included descriptions of actual maintenance performed. These reports did not contain any responses to the survey questions and subsequently no condition ratings were assigned based on these types of inspections. Weather-related inspections only accounted for three basins; each being inspected one time.

Table 2.1: Summary of Condition Ratings and Inspection Types

		Basin Condition Ratings						
Inspection Type	Number of Unique Basins	A	B	C	D	E	Blank	Total Inspections
Annual	1,674	2,377	2,191	1,411	270	14	57	6,320
Maintenance	456	2,928	4	2	1	1	-	2,936
Semi-annual	380	-	-	-	-	-	386	386
Reinspection	97	101	3	2	1	0	8	115
Weather-Related	3	3	-	-	-	-	-	3
Initial Inspection	1	-	-	-	-	-	1	1
Blank	5	4	1	-	-	-	-	5
	Total	5,413	2,199	1,415	272	15	452	9,766

Annual inspections captured the greatest variation in basin conditions, reflected in the condition ratings issued. There were 5,979 annual inspections (95% of annual inspections ratings) that corresponded with fully functional basins (basins rated A, B, or C). This is two times greater than the next highest category, being maintenance-type inspections. Annual inspections also captured 284 D and E rated basins, which comprises approximately 99% of all the D and E-rated basin in the dataset. We subsequently chose to use annual inspections for our analyses because of the quantity of inspections and variation in conditions captured relative to the other inspection types.

2.2.3 Preparation and Cleaning of Annual Inspections

Raw inspection records from VDOT's BMP Inventory database were labeled to indicate the component group and the type of question. This was done by adding a prefix to each of the column names corresponding with survey questions. The prefix included a numeric value representing a component group (e.g., 1, 2, 3, etc.) and either a "Positive" or "Negative" to categorize the questions. This was done to facilitate calculating the quantity and frequency of issues observed, which requires separating "Yes" responses to "Positive" questions or "No" responses to "Negative" questions from "No" responses to "Positive" questions and "Yes" responses to “Negative” questions. For example, a “Yes” response to a question labeled “Positive” would indicate that there are no issues observed for the BMP component being inspected. Likewise, a “No” response provided to a question labeled “Negative” would also suggest that the severity of the issue described in the question did not apply to the BMP. Without labels, it would be difficult to separate these responses from responses that indicate observed issues.

Inspection records were reviewed and removed from the dataset if they did not contain information or if they only contained manually entered comments. We established two criteria for determining the records to be removed. First, records that did not contain any responses or manually entered comments were removed. For example, there were six B-rated basins that did not have any issues reported and did not contain any comments. We assumed that a B-rating would indicate the presence of at least a minor issue, and therefore determined these to be erroneous. Second, records that were A-rated and only contained manually entered comments as opposed to filling out the “Yes”/”No” questions were also removed. This was done primarily because analyzing the comments to extract and categorize issues would not be feasible and the work required to do so is beyond the scope of the study. For example, there are nearly six thousand annual inspection records in the dataset, each containing 34 opportunities for different manual comments to be added. To extract and group issues described in the comments would require algorithms to be developed and applied, similarly as described by Dong et al. (2023). However, because the inspection reports include more than 200 detailed “Yes”/”No” questions, we were still able to gain meaningful insight into issues corresponding to basin condition ratings. Ultimately, there were 89 B-rated basins and 483 A-rated inspections that were excluded for the reasons described.

After performing the data preparation methods, the resulting annual inspection dataset was reduced to 5,666 inspections comprising 1,875 A, 2,096 B, 1,411 C, 270 D, and 14 E-rated inspections associated with 1,662 unique basins. This cleaned annual inspections dataset spans the time period of November 14, 2019 to March 27, 2023. Inspections capturing A-rated conditions were submitted at least one time for 1,054 different basins.

2.2.4 Assessment of Basin Condition Ratings

The proportions of each condition rating level (A-rating through E-rating) were compared for each complete year captured in the inspection dataset (2020-2022) to determine how the proportions of various condition ratings fluctuate over time. To do this, the Pandas python library was used to create a data frame containing the basin identification number (“SWMID”) and the corresponding ratings for 2020, 2021, and 2022. A comparative bar plot was created using the Matplotlib library in Python. The proportions of each condition rating for each year shown in the bar plot were then calculated. For an equivalent comparison from year to year, only basins that contained inspections for all three years were considered.

The magnitude of condition rating change, referring to the number of levels of improvement or decline in condition rating were calculated for the 2020 to 2021 period and the 2021 to 2022 period. We did this to describe the extent to which individual basin conditions, based on their respective ratings, changed from 2020 to 2022. This was done using the same data frame of basins and their corresponding inspection ratings from 2020 to 2022 as previously described. The difference in condition ratings was calculated for each basin, resulting in a difference in condition rating from 2020 to 2021 and from 2021 to 2022. The Matplotlib library was used to create a bar plot showing the frequencies of condition rating changes.

The change in individual basin ratings was evaluated for the 2020 to 2021 and 2021 to 2022 periods using heat map plotting techniques. To do this, the combination of the Pandas groupby(), value_counts(), and unstack() functions were used together to create a data frame containing the magnitude of change in condition rating per each inspection rating between 2020 and 2021, and subsequently between 2021 and 2022. The Matplotlib and Seaborn Python libraries were used to create heatmaps from the data frames.

2.2.5 Evaluation of Factors Corresponding with Ratings

Condition issues corresponding with condition ratings between 2020 and 2022 were evaluated to determine the quantity and frequency of issues observed during inspections. The quantity of issues accounts for two cases observed in the data. First, for general categories where only a “No” response is provided for a “Positive” question, a count is assigned, acknowledging that there is an issue related to the given general category. Second, if a general category was observed to have multiple subgroups of related questions, then the number of “Yes” responses to each of the corresponding “Negative” questions were added together. For example, the general group related to BMP surface inflow area contains specific “Negative” questions associated with sediment or trash build up in the inflow area as well as questions pertaining to erosion on the channel or check dams. The frequency of specific issues noted in the inspection reports do not account for issues that were only indicated by a “No” response to a “Positive” labeled question.

We used Chat-GPT V3.5 to develop syntax for quantifying the number of issues and frequency of issues associated with the basin conditions. This effort resulted in the development of a couple of python functions that, together, extract the group number information from the column headers and count the number of issues for each basin. For each group of questions (65 groups total), nine rules are considered before issuing a count per each category, as shown in Table 2.2. The counts are issued in the same row as the basin identification number and corresponding inspection rating, enabling us to identify the condition issues for each condition rating. Subsequently, the counts are summed in each row to determine the quantity of issues per inspection.

Table 2.2: Rules for Counting Number of Condition Issues

Rule Number	Rule Description
1	If all the group questions are blank, set the count to 0
2	If there is a yes response in the Positive column and all Negative columns are blank, set the count to 0
3	If there is a yes in the Positive column and not a yes in one or more Negative columns, set the count to 0
4	If there is a yes in the Positive column and a yes in one or more of the Negative columns, set the count equal to the number of yes responses in the Negative columns
5	If there is a no in the Positive column and blank responses in all of the Negative columns, set the count equal to 1
6	If there is a no in the Positive column and a yes in any of the Negative columns, set the count equal to the number of yes responses in the Negative columns
7	If there is a no in the Positive column and not a yes in any of the Negative columns, set the count equal to 1
8	If there is an empty Positive column and a yes in any of the Negative columns, set the count equal to the number of yes responses in the Negative columns
9	If there is a group that only contains Negative columns and there is at least one yes in a negative column, set the count equal to the number of yes responses in the Negative columns

2.2.6 Analysis of Rapidly Declining Basins

We compared specific factors corresponding with basins that experienced a rapid decline in condition. We use the term “rapid decline” to mean a decline in at least two condition rating levels in a year. To identify rapidly declining basins in the dataset, we first used the results of the heat maps to identify condition rating pairs that correspond with rapid decline. We then queried the Pandas data frame containing basin identification numbers and corresponding ratings for 2020, 2021, and 2022 based on the condition rating pairs identified. For example, if there were

A-rated basins identified that changed to a C-rating in the following year, we queried the data frame to only identify basins whose condition rating in the first year was "A" and "C" in the following year. We created a list of the rapidly declining basin identification numbers. Using these ID's, we joined spatial coordinates contained in VDOT's public-facing BMP dataset (Virginia Roads, 2023). We then plotted the rapidly declining basins in ESRI's ArcGIS Pro using the XY Table to Point tool to identify the corresponding VDOT districts.

2.3 Results

2.3.1 Temporal Patterns in Basin Conditions

The proportions of the different condition ratings assigned from the inspections are consistent over a three-year period, based on the three complete years of annual inspections from 2020 to 2022. In 2020, there were 1,413 condition ratings assigned. Of those, 480 (34%) were A-ratings, 504 (35%) were B-ratings, 347 (25%) were C-ratings, 76 (5%) were D-ratings, and less than one percent were E-ratings (Figure 2.3). In 2021, there were 1,248 ratings assigned. Of these, 408 (32%) were A-rated, 484 (39%) B-rated, 313 (25%) C-rated, 41 (3%) D-rated, and two E-rated basins (less than one percent). Similarly in 2022, there were 1,329 ratings issued, with 456 (34%) corresponding with A-ratings, 464 (35%) B-ratings, 345 (26%) C-ratings, 60 (5%) D-ratings, and four E-rated basins (less than one percent). The percentage of A-rated basins only fluctuated by a maximum of 3%. Similarly, the proportion of B, C, D, and E-rated basins only fluctuated by 4%, 1%, 2%, and less than 1%, respectively.

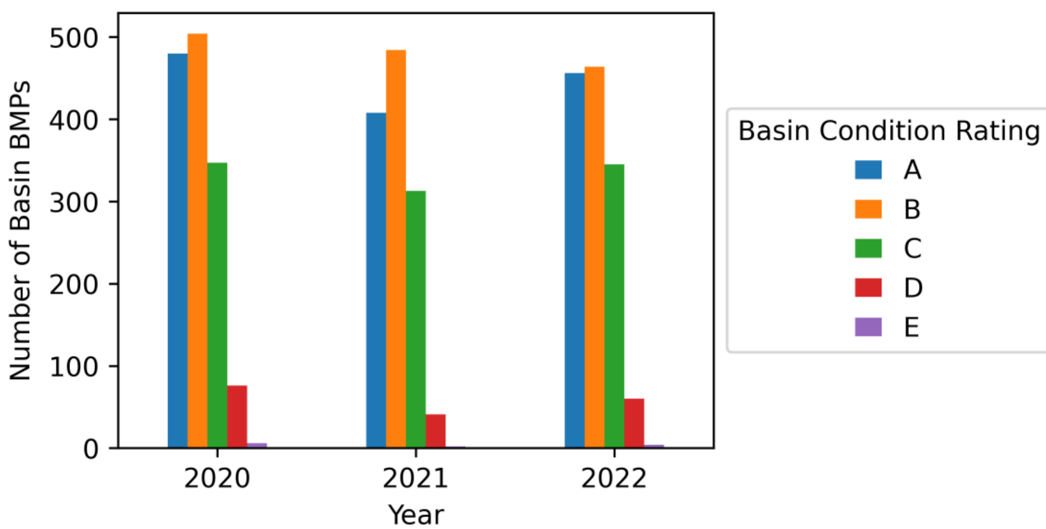

Figure 2.3: Basin condition ratings in 2020, 2021, and 2022. Condition ratings correspond to basins that received an annual inspection each year during the three-year period.

Despite the proportions of condition ratings being similar during the three-year study period, only a portion of the individual VDOT basins kept the same condition rating year after year. Figure 2.4 describes the magnitude and direction of condition rating changes observed for the 901 basins that each received an inspection and assigned condition rating in 2020, 2021, and 2022. The other basins did not have three consecutive years of inspection. Magnitude refers to the number of condition levels (e.g., a B-rating improving to an A-rating has a magnitude of "1"). Positive and negative values reflect conditions that improved and declined, respectively. "0" refers to basins whose conditions remained the same from 2020 to 2021 (Figure 2.4 A) and from 2021 to 2022 (Figure 2.4 B).

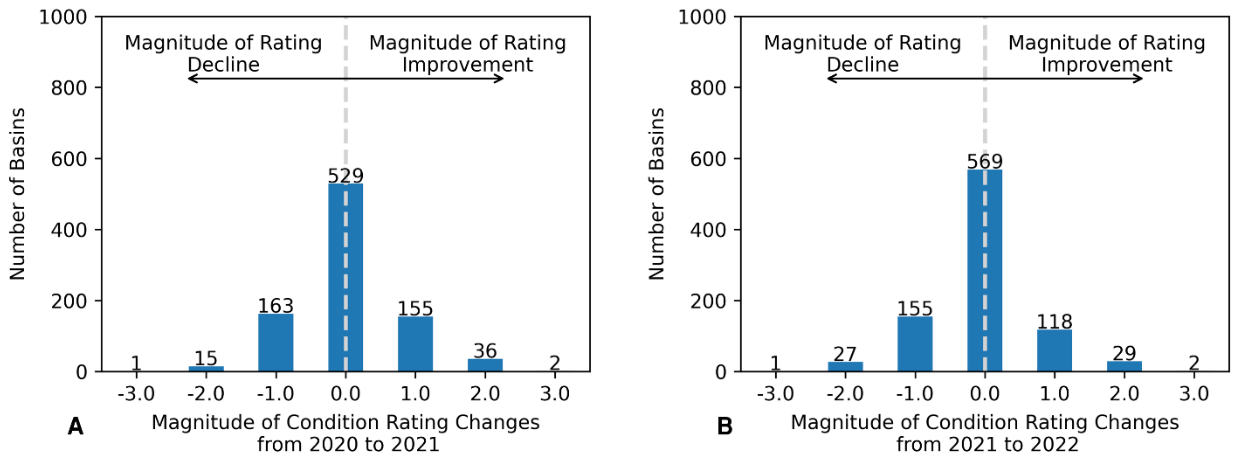

Figure 2.4: Magnitude and direction of condition rating changes from 2020 to 2021 (A) and from 2021 to 2022 (B).

There were 529 basins (59%) that kept the same condition rating in 2020 and in 2021. The remaining 372 basins (41%) experienced a change in conditions. A single condition rating improvement or decline was observed for 318 of the 901 basins (35%). Conditions for 51 basins (6%) changed by a magnitude of two. Two basins' conditions improved by three condition rating levels, with one declining by three levels.

A similar distribution of condition changes was observed for the same group of basins between 2021 and 2022. There were 569 basins (63%) that maintained the same condition rating from 2021 to 2022 (Figure 2.4 B). 273 basins (30%) experienced conditions that either improved or declined by a single condition rating level. 56 basins (6%) experienced a magnitude condition change of two between 2021 and 2022. Less than one percent changed by three condition rating levels. It should be noted that out of the 901 basins, there were only 384 basins (43%) that kept the same condition rating all three years from 2020 to 2022.

B-rated basins comprised the largest proportion of basins that held the same condition rating from 2020 to 2021 and 2021 to 2022 (Figure 2.5 A and B). There were 191 B-rated basins that did not experience a change in condition rating from 2020 to 2021, comprising 36% of the 529 basins with unchanging conditions in 2020 and 2021. From 2021 to 2022, there were 211 B-rated basins that kept the same condition for both years, comprising 37% of the 569 basins that kept their condition rating from 2021 to 2022.

Basin condition changes between A-ratings and B-ratings comprised a larger portion of the basins compared with condition changes that occurred between all other condition rating pairs (e.g., A/C-ratings, B/C ratings, etc.). From 2020 to 2021, there were 162 basins (18% of 901 basins) whose condition rating declined from an A-rating to a B-rating or improved to an A-rating from a B-rating. This is based on 74 A-rated basins that declined to a B-rating and 88 B-rated basins whose conditions improved to an A-rating in 2021 (Figure 2.5 A). The next highest condition rating pair was B and C-rated basins, where 132 basins (15% of 901 basins) changed either from a B to a C-rating or from a C-rating to a B-rating. These findings are consistent with the observed condition rating changes that occurred between 2021 and 2022 (Figure 2.5 B). From 2021 to 2022, there were 81 A-rated basins that declined to a B-rating, and 56 B-rated basins that improved to an A-rating, comprising 15% of the 901 basins. The B/C condition rating pair comprised the second largest number of basins per condition rating pair, with 60 B-rated basins declining to a C-rating, and 48 C-rated basins improving to a B-rating in 2022, comprising 12% of the basins.

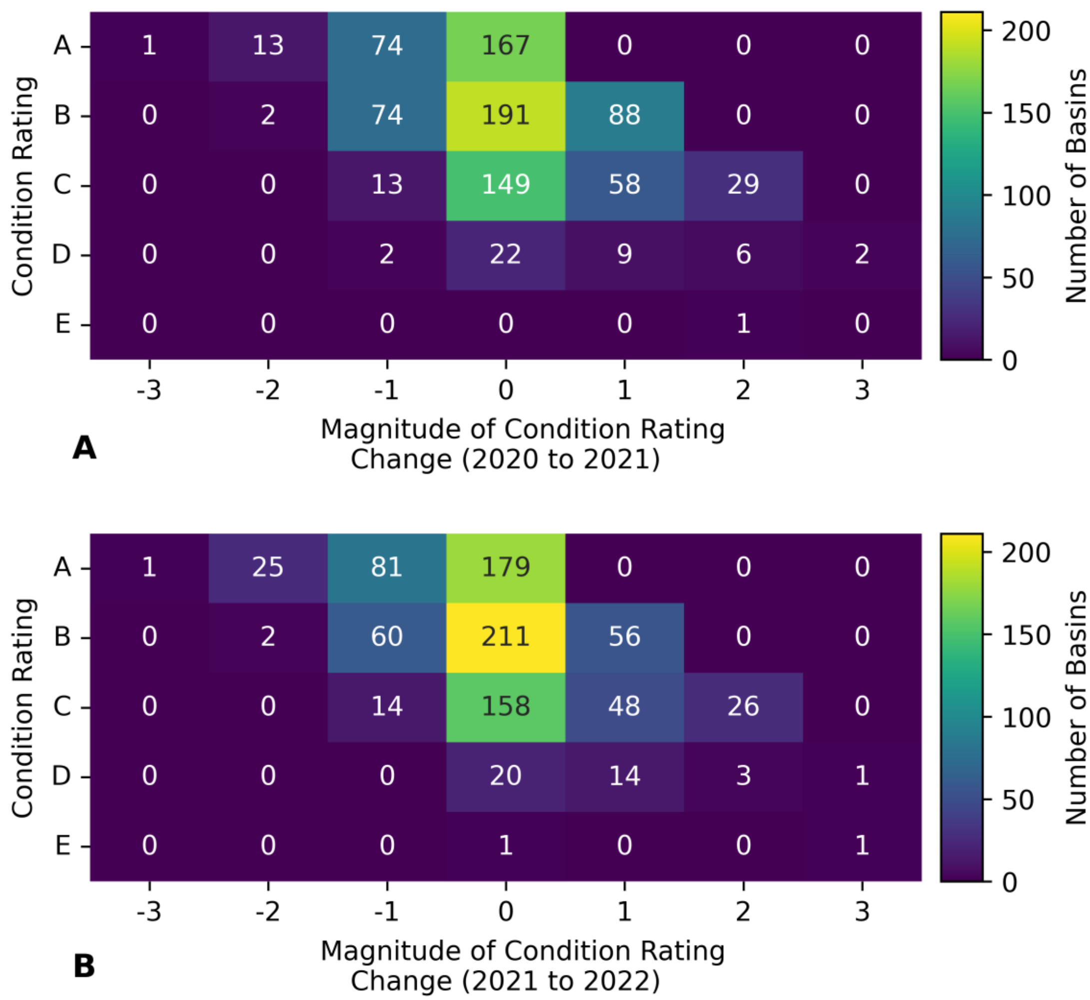

Figure 2.5: Heatmaps comparing the magnitude of condition rating change per each condition rating type for A) years 2020 to 2021 and B) 2021 to 2022.

2.3.2 Quantification of Issues per Rating Category

The number of condition-related issues was observed to increase as the condition rating of the basin declined (Table 2.3). For example, the median number of issues observed per each rating level increases from 0 for the A-rating level to 7.5 issues for the E-rating level. There were 3,789 total issues associated with 2,096 inspections that issued a B-rating, averaging 1.8 issues observed per inspection. The average number of issues for C-rated basins (3.7) was nearly twice as much as the average number of issues for B-rated basins. This trend of higher numbers of issues corresponding with lower rating levels is observed with lower inspection ratings as well, with an average of approximately 8 issues observed per E-rated inspection compared with approximately 6 issues observed on average per each D-rated inspection.

Table 2.3: Summary of Issues Observed Per Condition Rating Level (2020-2022)

Condition Rating	Number of Inspections	Min Number of Issues	Median Number of Issues	Max Number of Issues	Sum Total Number of Issues	Average Number of Issues per Inspection
A	1,875	0	0	4	231	0.12
B	2,096	1	2	13	6,428	3
C	1,411	1	5	20	7,814	5.5
D	270	1	7.5	22	2,127	7.9
E	14	1	12	21	165	11.8

2.3.3 Quantification of Issues for Rapid-Declining Basins

Between 2020 and 2022, there were 40 cases where an A-rated basin experienced a rapid decline in condition. We define rapid decline to mean a decrease in two or more condition ratings within a year. From 2020 to 2021, there was one A-rated basin that declined to a D-rating and 13 A-rated basins that declined to a C-rating. From 2022 to 2023, there was another A-rated basin that declined to a D-rating and 25 other A-rated basins that declined to C-rating conditions in 2022. Rapid decline was also observed for two B-rated basins that dropped to a D-rating from 2020 to 2021 and two additional B-rated basins that whose conditions fell to a D-rating from 2021 to 2022 (Figure 2.5 A and B).

The number of issues observed only slightly increased when rapid condition decline resulted in a D-rating. For example, A-rated basins whose conditions fell to a C-rating had a median of three issues observed at the C-rating level in both the 2020 to 2021 and 2021 to 2022 periods (Table 2.4). This was also the case for A-rated basins that rapidly declined to a D-rating in 2021 and in 2022. However, basins whose condition declined from a B to a D-rating had a median of 3.5 and 4.5 general issues. These results suggest fewer issues are associated with rapidly declined basins compared with basins in the same declined state (see Table 2.3).

Table 2.4: Number of Issues Associated with Basin Rapid Condition Decline

	Condition Ratings and Time Periods					
	A to C (2020-2021)	A to C (2021-2022)	A to D (2020-2021)	A to D (2021-2022)	B to D (2020-2021)	B to D (2021-2022)
Number of Basins	13	25	1	1	2	2
Min Number of Issues*	1	1	3	3	2	4
Median Number of Issues*	3	3	3	3	3.5	4.5
Max Number of Issues*	5	7	3	3	5	5
Sum Total Number of Issues*	33	76	3	3	7	9
Average Number of Issues Per Basin*	2.5	3.0	3	3	3.5	4.5

*Refers to the number of general issues observed in the latter condition rating of each period.

2.3.4 Spatial Evaluation of Rapidly Declined Basins

Basins that experienced rapid decline between 2020 and 2022 were found in six of VDOT's 9 district jurisdictions (Figure 2.6). 60 percent of the A-rated basins that declined to a C-rating were in the Lynchburg district and Northern Virginia (Northern VA) district. Of these basins, five were in the Lynchburg District (Figure 2.6, District #3) and four were in the Northern Virginia (District #9). 60 percent of the 25 A-rated basins that declined to C-rated condition from 2021 to 2022 occurred in the Salem district (Figure 2.6, District #2). Four separate districts (Salem, Lynchburg, Fredericksburg, and Culpeper) each had one B-rated basin that declined to a D-rating between 2020 and 2022. Lynchburg and Fredericksburg each had an A-rated basin that declined to a D-rating from between 2020 and 2022.

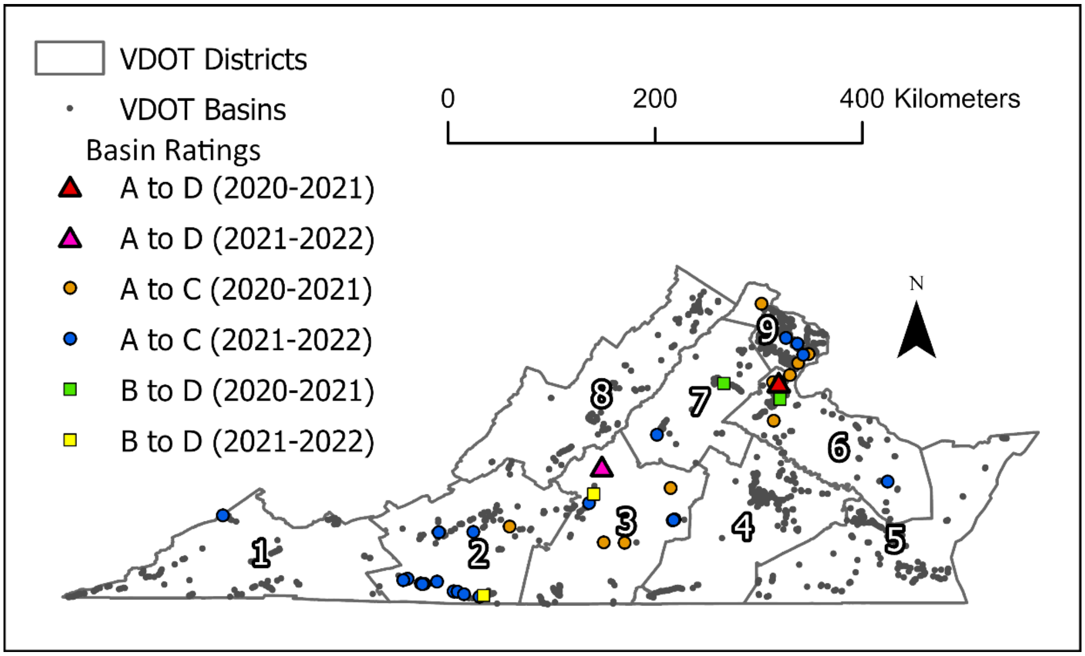

Figure 2.6: Locations of rapidly declined basins that occurred between 2020 and 2022. VDOT's districts include 1) Bristol, 2) Salem, 3) Lynchburg, 4) Richmond, 5) Hampton Roads, 6) Fredericksburg, 7) Culpeper, 8) Staunton, and 9) Northern Virginia. VDOT district base layer was made available through ESRI's ArcGIS Pro.

No trends were found to correspond with the districts and associated number of basins or number of inspections performed during the 2020 to 2022 period. For example, the Salem district had the highest number of basins that experienced rapid decline (17) (Table 2.5). This district also happened to have the highest percentage of their basins that experienced a rapid decline in condition (9.9%) while also having the lowest percentage of annual inspections submitted. However, Lynchburg had the second highest number of rapid declining basins (10) and the second highest percentage of basins that experienced a rapid decline in condition rating from 2020 to 2022. Lynchburg's inspections completion percentage was higher than the Fredericksburg, Culpeper, and Richmond districts, all which had fewer rapidly declining basins and lower percentages of declined basins.

Table 2.5: Rapid Declining Basins Per VDOT District

District	Number of Basins	Number of Rapid Declining Basins (2020-2022)	Percentage of Rapidly Declined Basins (%)[1]	Required Number of Annual Inspections (2020-2022)[2]	Actual Number of Annual Inspections (2020-2022)[3]	Percentage of Required Inspections Completed (%)[1]
Hampton Roads	230	0	0.0	690	634	92
Richmond	240	0	0.0	720	624	87
Staunton	149	0	0.0	447	428	96
Bristol	146	1	0.7	438	437	100
Culpeper	82	2	2.4	246	221	90
Fredericksburg	170	7	4.1	510	460	90
Northern VA	442	7	1.6	1,326	1,399	106
Lynchburg	120	10	8.3	360	331	92
Salem	171	17	9.9	513	404	79

[1] During the 2020 to 2022 period.

[2] Based on VDOT's requirement to inspect every basin once per year.

[3] Accounts for all annual inspections submitted from 2020 to 2022.

2.4 Discussion

2.4.1 Basin Condition Issues Reported per Rating Level

A-rated conditions of the basin BMPs corresponded with minimal issues. The most common group of issues observed was related to basin identification and signage (16 counts, 25% of A-level issues). The second most common group of issues observed was erosion, blockages, or signs of flooding associated with the outlet, receiving channel, or outlet pipe (7 counts, 11% of A-level issues). The third most common group of issues observed (7 counts, 11% of A-level issues) was problems associated with the low-flow orifice trash or debris rack. There were only 12 specific issues reported in the inspections. The most frequently reported issue was the presence of woody vegetation less than 5.08 centimeters (two inches) in diameter and/or other undesired vegetation observed in the outlet area within 7.62 meters (25 feet) of the structure (4 counts, 6% of A-level issues). Portions of fencing missing or in disrepair, missing signage were each reported one time. Other minor issues reported included sediment, trash, or debris-related issues. These materials were reported to be associated with minor basin inflow area blockages (blocking less than 25% of flows) (1 count, 2% of A-level issues), minor standing water in basin bottom (1 count, 2% of A-level issues), and low-flow orifice obstruction, with the low-flow orifice still accessible and in working condition (1 count, 2% of A-level issues).

The most common general issue types for B-rated basins corresponded with minor basin inflow area issues and identification/signage issues. There were 770 instances (20% of B-level issues) where the basin inflow area was observed to not be free of erosion, sediment, trash, or debris. The second most common general group of issues was related to identification and signage problems (317 counts, 8% of B-level issues). The specific issue most frequently reported was the presence of minor (less than 0.19 cubic meters or 0.25 cubic yards) sediment, trash, or debris accumulation in the surface inflow area blocking less than a quarter of the flow area (693 counts). The second most frequently identified issue that corresponded with basins with "B" ratings was BMP identification and/or signs missing, damaged, faded, or in unstable condition (248 counts).

The most frequently identified specific issues of C-rated basins also corresponded with the respective general issue categories. The general issue category most frequently noted pertained to the basin inflow area not being free of erosion, sediment, trash, or debris (489 counts, 9% of C-level issues). The second most frequent category of issues observed corresponded with the non-pool area of the basin bottom, pilot channel, excavated side slopes, or shoreline not being free of sediment accumulation (328 counts, 6% of C-level issues). The most frequently noted issue pertaining to a C-rated basin was excessive amounts (more than 0.19 cubic meters or 0.25 cubic yards) of erosion, sediment, trash, or debris in the basin inflow area that blocked or disrupted more than 25% of the flow area (230 counts, 4% of total C-level issues). The second most frequently identified issue (228 counts, 4% of total C-level issues) was more than 0.19 cubic meters or 0.25 cubic yards sediment observed in the non-pool area, bottom of the pilot channel, excavated side slopes, and shoreline that was blocking or disrupting flow. The third most common issue documented in the inspection reports (215 counts, 4% of total C-level issues) was missing, damaged, faded, or unstable BMP identification and/or instructional signs.

The most frequently identified issues corresponding with basins assigned a D-rating were related to issues related to animal burrows and excessive sediment observed in the non-pool area, pilot channel, excavated side slopes, and shoreline that was disrupting or blocking flow. The general issue category with highest frequency of issues observed was the non-pool area, pilot channel, excavated side slopes, and shoreline not being free of sediment accumulation (104 counts, 7% of total issues for D-level basins). The category with the second highest issue frequency was the category pertaining to the presence of animal burrows. The most frequently identified specific issue with D-rated basins was the presence of at least one animal burrow located on the dam embankment or emergency spillway (72 counts, 5% of total D-level issues). The inspection reports indicate that such burrows were observed to be "at a depth or alignment that could form a conduit through the embankment". The next most frequently observed condition issue (71 counts, 5% of total D-level issues) was the low-flow orifice being submerged or inaccessible due to accumulation of sediment, trash, or other debris. The third most observed issue was excessive sediment observed in the non-pool area, pilot channel, excavated side slopes, and shoreline that was disrupting or blocking flow (52 counts).

General observations noted for E-rated basins most frequently included oversight by a professional engineer and resulted in the recommendation for an emergency repair. This case was noted generally 14 times (12% of E-level issues). The second and third most frequently identified general issue categories included the presence of surface depressions or sinkholes on the embankment face and spillway (8 counts, 7% of E-level issues) and scour or erosion around the outlet area (8 counts, 7% of E-level issues). The most frequently cited specific issues were related to the most frequently identified general issue categories. For example, the need for oversight by a professional engineer and resulted in the recommendation for an emergency repair was noted 14 times (12% of E-level issues). The second most frequently identified specific issue was the presence of excessive sinking or sinkholes observed (8 counts, 7% of E-level issues). Excessive sinking refers to sinking that is deeper than 0.15 meters (0.5 feet) or larger than 0.84 square meters (1 square yard), or any sinking near a structure or conduit. Woody vegetation greater than 5.08 centimeters (2 inches) and/or other significant vegetation issues observed in the outlet area within 7.62 meters (25 feet) of the structure were both noted on six separate inspections was the third most frequently cited issue (6 counts, 5% of E-level issues).

2.4.2 Rapidly Declined Basin Condition Issues

Specific issues described in inspections for A-rated basins that declined to a D-rating in a single year corresponded primarily with corrosion. For the A-rated basin in 2020 that fell to a D-rating in 2021, major corrosion was one of the two specific issues identified. The other issue was illicit discharge observed either flowing into the basin or otherwise onto the VDOT property and into VDOT drainage. The Commonwealth of Virginia defines illicit discharge as “any discharge to a municipal separate storm sewer that is not composed entirely of stormwater,” acknowledging a few exceptions are recognized, including discharges from firefighting activities (9VAC25-870-10). Illicit discharges may include automotive fluids, cooking oils, paints or solvents, detergents, septic water, landscape waste such as grass clippings, or sediment, with additional examples provided in Table 2 of VDOT’s illicit discharge detection and elimination program manual (VDOT, 2020). The A-rated basin in 2021 that declined to a D-rating in 2022 had corrosion as the only specific issue observed. For this basin, corrosion was observed both on the metal of the control structure, imposing immediate risk of failure, as well as on the associated pipe.

B-rated basins that rapidly declined to a D-ratings were observed to have varying issues reported. The basins with B-ratings in 2020 that declined to D-ratings in 2021 had six specific issues identified between the two of them. The only common issue between the two basins was the presence of animal burrows on the respective emergency spillways. The burrows were noted to be potentially deep enough to form a conduit through the embankment of the basin. One basin was also observed to have excessive (more than 0.19 cubic meters or 0.25 cubic yards) sediment, trash, or debris accumulation observed in the inflow area, subsequently blocking flow. This basin also had excessive sediment that accumulated in the non-pool area of the basin, pilot channel, and shoreline that was blocking flow. Minor accumulations were observed in the basin bottom or shoreline that did not appear to be impacting flow. The other basin, apart from animal burrows, had minor vegetative issues observed in the outlet area.

There were no common specific issues common between the two B-rated basins in 2021 that declined to a D-rating in 2022. Specific issues reported for these basins included observed illicit discharge, excessive (more than 0.19 cubic meters or 0.25 cubic yards) sediment, trash, or debris in the inflow area of the basin, excessive sediment accumulation that is more than half the height of the check dam, excessive sediment in the non-pool area, pilot channel, excavated side slopes and shoreline that is blocking flow, and pipe joint issues including minor seepage or leaking observed and joint misalignment.

Several issues were associated with A-rated basins in 2020 that declined to a C-rating in 2021. In total, there were 27 specific issues noted with these basins. The most noted specific issue (4 counts, 15%) was sediment or other debris blocking the low-flow orifice, making it inaccessible. There were two cases (7%) where sediment or other debris accumulated at the low-flow orifice but was still in operable condition. Other issues included excessive sediment in the non-pool area, bottom of the basin, pilot channel, excavated side slopes and shoreline disrupting flow (2 counts, 7%), excessive flow obstruction, damage, or disrepair to channel or at the check dams (2 counts, 7%), minor sediment or other debris accumulation in the channel or check dams (2 counts, 7%), and standing water either not caused by flow blockages (2 counts, 7%) or not caused by clogged low-flow orifice (2 counts, 7%).

The A-rated basins in 2021 that declined to a C-rating in 2022 had more specific issues in common compared with the A-rated basins in 2020 that declined to C-rating in 2021. There were 69 specific issues observed for these basins. The most frequently noted specific issue was excessive sediment observed in the non-pool area of the basin, pilot channel, excavated side slopes, and shoreline disrupting flow (9 counts, 13%). Excessive sediment or other debris accumulation in the forebay (more than 0.19 cubic meters or 0.25 cubic yards) or other pre-treatment devices were observed for 7 basins (10%). The third most frequently noted issue (5 counts, 7%) was excessive (more than 0.19 cubic meters or 0.25 cubic yards) sediment or other debris accumulation observed in the inflow area of the basin blocking flow.

2.4.3 Comparison of Issues of Rapid and Non-Rapid Declining Basins

The specific factors corresponding with non-rapidly declined basin conditions may or may not be shared with basins that experienced a rapid decline in condition rating, depending on the condition rating level. The most common specific factors observed for basins that experienced rapid condition decline to a D-rating were corrosion, illicit discharges, and excessive sediment in the inflow area. Animal burrows were also noted as a factor observed. However, basins that did not rapidly decline to a D-rating had some specific issues that were different from rapidly declined basins of the same declined rating. These include animal burrows and excessive sediment in the inflow area, followed by submerged or inaccessible low flow orifices, and excessive sediment observed in the non-pool area, pilot channel, excavated side slopes, and shoreline that was disrupting or blocking flow. Sediment-related issues were common among basins that rapidly declined to a C-rating as well C-rated basins generally. Basins that rapidly declined to C-rating most frequently experienced excessive sediment observed in the non-pool area, pilot channel, excavated side slopes, and shoreline, forebay, inflow areas, and at the low-flow orifice area. Similarly, the most common specific issue for non-rapid declining C-rated basins was excessive sediment, erosion, trash, or other debris in the inflow area and excessive sediment in the non-pool area, pilot channel, excavated side slopes, and shoreline.

2.4.4 Improving Basin Condition Rating Data Quality

Insights into VDOT’s basin conditions are limited by incomplete inspection reports. This could be due to several possibilities, including inspectors filling out general category questions and only filling out the subsequent detailed questions as they feel is needed to convey what is observed. Incomplete surveys were observed with the B-rated inspections that were removed from analysis where detailed questions were not given responses and instead manual comments were added. Official training and certification for VDOT BMP inspectors is provided by VADEQ, so it is presumed that issues observed during inspections correspond with the training received rather than reflect the most easy-to-observe issues.

Verifying the quality of stormwater BMP compliance data is a challenge due to bias and non-uniformity in the data collection process. VDOT strives to collect accurate inspection rating data for their BMPs by ensuring the inspectors receive the inspection training required by VADEQ and by using a "blind" inspection process, meaning the inspectors do not see the individual rating assigned to each question. However, despite these efforts, it is possible that some bias or inaccuracies are introduced during the inspection process. For example, it is possible that inspectors may perform a less extensive inspection for BMPs that they are more familiar with, which could result in some issues being missed. It is also possible that some inspectors may be more or less stringent in their inspections compared with inspectors in other districts, despite the common training received. VDOT districts may or may not have a formal auditing process to verify the quality of their inspection data. Guidance issued by VDOT does ask that inspectors take and upload photos of all specific maintenance issues observed to the Survey 1-2-3 application used during the inspection. Ultimately, those images are captured in VDOT's BMP database and can be viewed by revisiting the specific inspection record. While these images could be reviewed to compare BMP conditions over time, this could be very time consuming depending on the thoroughness of the audit. Future research is needed to develop methods for verifying the quality of BMP inspection rating data. One way this might be accomplished is by leveraging artificial intelligence (AI) to classify images of BMPs by condition rating based on the issue or issues captured in the image. The rating determined by the AI model could then be compared with the rating assigned based on the responses of the inspection survey questions.

Manually entered comments in the inspection reports contain valuable information about BMP conditions that are not easily processible on a large scale. Dong et al. (2023) described a key word-search algorithm developed to categorize VDOT's maintenance work orders based on manually entered maintenance descriptions. However, similar methods require manual adjustment of the key words for every batch of reports processed. As such, the information contained in the manually entered comments of the inspection reports was not considered. However, there are other natural language processing (NLP) models that may be more robust and can better handle the uncontrolled vocabulary better than a manually adjusted key word search algorithm. The training and use of a robust NLP model could be useful in gleaning additional insights from the information contained in BMP inspection rating comments.

Condition rating questions and algorithms may require updates over time to better capture BMP conditions or support institutional goals. For example, VDOT updated their inspection and rating system in 2019 to include additional survey questions. Additionally, VDOT removed the rating algorithm from questions associated with illicit discharge in 2023. This was done because VDOT does not have statutory authority to locate or take action against responsible parties and because the discharges are temporary and believed to not indicate degradation of the BMP (VDOT MS4 Program Manager Scott Crafton personal correspondence, October 13, 2023). While these changes do not impact the findings of this study, awareness of inspection system updates is needed to accurately identify, assess, and compare BMP conditions over time.

2.4.5 Toward Proactive BMP Maintenance Planning

BMP condition ratings hold the potential for a more proactive approach to stormwater BMP maintenance and management, which is the goal of such condition rating systems. Using condition ratings, infrastructure managers can evaluate factors, including temporal trends corresponding with given BMP conditions. This information subsequently could be used to estimate future BMP maintenance needs ahead of time, thereby also providing time to account for such maintenance activities in maintenance budgets.

Budgeting for BMP maintenance is frequently cited as a challenge for stormwater infrastructure managers (Rieck et al., 2022; Taylor et al., 2014; Van Auken et al., 2016; Venner et al., 2013; Zhao et al., 2019). In addition to the challenge of acquiring adequate funding, there remains a knowledge gap between the specific factors that correspond with condition ratings and the specific costs required to address those specific factors, which can be used to justify additional funds. VDOT is working to close this gap through the integration of their BMP maintenance work order system with their BMP inspection system. Their maintenance work order system, described in detail by Dong et al. (2023) is currently set up to receive one description of work with quantity fields for inputting unit and total costs. Due to this structure, the work order form cannot receive itemized lists of specific maintenance tasks with their itemized costs. As a result, work orders may contain multiple maintenance activities with a lump sum cost. Dong also noted several work orders where several BMPs were lumped into a single work order with a lump sum maintenance cost, making it difficult to discern the cost of maintenance per individual BMP or BMP type. Connecting the maintenance work order to the specific inspection rating for the specific BMP along with including itemized costs would enable VDOT to have a much better idea of the cost required to improve a BMP from one specific rating level to the next. This information would also support budgeting practices that account for BMPs that experience rapid decline, which may be costly due to significant maintenance repairs needed. Predicting the occurrence of these BMPs may be difficult, as was observed with VDOT where rapidly declined basins were present in the majority of VDOT's districts under assumed regular annual maintenance. Tracking rapidly declining BMPs over time can be useful for estimating average costs for these BMPs which can then be factored into maintenance budgets.

2.5 Conclusions

Basin BMP conditions can change in a year's time despite annual inspection and maintenance practices. We found this to be the case with nearly half of the VDOT basins that had consistent inspections from year-to-year. Assuming regular inspection and maintenance, conditions most often change by a single condition rating level, with the most frequent changes occurring between the highest rated basins.

Rapid declining basins are often caused by few, specific issues that may or may not differ from the common issues observed in basins of the same declined state. The findings of this work highlight the potential for rapid decline of basin conditions to occur, despite regular inspection and maintenance practices. This is the case with VDOT where basins experiencing rapid decline were located in the majority of VDOT districts that each operate independently.

The methods described in this study are broadly applicable for evaluating BMP conditions from asset management systems, including BMPs that experience rapid decline in condition. These techniques will be beneficial as BMP condition tracking systems become more ubiquitous and evaluation techniques will be needed to realize the value of the data being collected.

Several future research opportunities are prompted as a result of this work. For example, we identified several data quality issues that should be considered when using BMP inspection rating data. Future work is needed to evaluate the use of generative artificial intelligence or robust natural language processing models for extracting valuable BMP condition details from manually entered comments in the inspection reports. Additionally, the findings of this research suggest basins experiencing rapid decline in condition may not be impacted by variations in BMP inspection and maintenance practices of VDOT’s independent districts. However, additional factors should be considered, including geophysical factors, to determine whether relationships exist among BMPs with similar condition ratings, including those that experience rapid decline.

Chapter 3

3. Exploring the Adoption of Water Quality Trading as an Alternative Stormwater Regulatory Compliance Strategy for Land Development Projects: Case Study for Roanoke, Virginia[2].

3.1 Introduction

3.1.1 Background

Urban stormwater runoff is a significant source of pollution to waterways (CBF, 2023; Müller et al., 2020; Yang and Lusk, 2018) as the increased magnitude and connectivity of impervious surfaces associated with urban development result in higher peak flows, larger runoff volumes and increased nutrient load concentrations in urban streams (Shuster et al., 2005; Vogel and Moore, 2016). The impacts to hydrology and water quality result in related impacts to ecological diversity of fish, benthic macroinvertebrates and other aquatic species (Walsh, 2000).

Stormwater "best management practices" (BMPs) have traditionally been used to achieve compliance with development-related stormwater discharge regulations (Hill and Horwitz, 2003). Stormwater BMPs are designed and built to reduce runoff volume, attenuate and/or lower peak discharge rates, and remove pollutants in stormwater runoff (Delgrosso et al., 2019; Yu et al., 2013). Traditionally, BMPs are implemented during the construction phase of land development projects for the purposes of managing construction-related and post-construction stormwater discharge as required by state and local stormwater and erosion/sediment control regulations. To facilitate compliance with construction and post-construction stormwater control, the United States Environmental Protection Agency (EPA) provides a national menu of BMPs that can be used (EPA, 2022b), though States and local governments may also recommend certain BMPs in their respective guidance manuals (MDEP, 2016; ODOT, 2023; VADEQ, 2013a). While post-construction BMPs are typically required by regulation, implementation of BMPs can introduce a significant marginal cost to a development project related to the land required to build the BMP, construction labor and material costs, and long term maintenance costs (Jones et al., 2017; Nobles et al., 2017; Rieck et al., 2022).

Water quality trading (WQT) is an alternative, market-based compliance strategy that may help to reduce the cost of stormwater compliance. In WQT, buyers, such as regulated land developers, may offset their stormwater treatment requirements by purchasing credits representing nutrient load reduction performed offsite. The buyers can then apply the credits to meet their permit treatment obligations. Buyers are incentivized to purchase credits if the cost of the credit is less than the cost of implementing and maintaining onsite treatment practices. The sellers are incentivized to convert land to a credit bank if the potential sale price of the credits generated is higher than the production value of the converted land plus the cost to create the bank. More than 100 WQT programs have been documented across the US, with the EPA reiterating their support for WQT in 2019 (BenDor et al., 2021; Ross, 2019). While WQT programs have historically seen low participation (Breetz et al., 2005; Shortle, 2013), high WQT

[2] This study has been submitted to the Journal of Environmental Management and is currently under review.

activity has been observed in programs that open their market to those engaged in post-construction stormwater compliance (Duke et al., 2020; Stephenson and Shabman, 2011).

One program that has experienced significant market activity related to post-construction BMPs is the Virginia WQT (Saby et al., 2021b) which is the focus of this paper. Given the high participation observed, this program may serve as a leading example of a functioning WQT program (Saby et al., 2023). However, our understanding of credit adoption in this program, including possible outcomes associated with traditional compliance methods and the local environment, is limited at the local level. This information is needed to understand how the program is working and to identify possible unforeseen program outcomes. The purpose of this paper is to characterize credit adoption by regulated land developers at the local level and describe observed outcomes of credit adoption on traditional stormwater treatment, control, and local water quality.

3.1.2 Study Objective

Although Virginia's WQT is known to have a large volume of transactions, neither the supply and demand market dynamics, nor the broader water quality and hydrology outcomes of the program are fully understood. While Saby et al. (2023) evaluated water quality and hydrology outcomes of the program, this study relied on a theoretical urban catchment model and did not use actual WQT transaction data. As demand-side (i.e. credit purchaser) data and the specifics of the development sites and projects for which WQT is used are not broadly available, this has limited the ability to study how Virginia's WQT program is being adopted for post-construction stormwater compliance and if the program is consistent with the intended outcomes of the VSMP and other related water quality programs.

Therefore, the objective of this research is to characterize the adoption of credits for water quality compliance from land developers with regulated stormwater discharge requirements for a case study locality in Virginia. Specifically, we 1) assess and compare the frequency of adoption of credits with other available compliance options (e.g., on-site BMPs), 2) compare the frequency of corresponding stormwater quantity compliance methods selected for projects using credits, and 3) map out both the credit generator and credit purchaser for each transaction and portray the transaction with respect to watershed boundaries. In general, this study is focused on further clarifying how WQT programs are being adopted by regulated stormwater entities is limited and informing new WQT policies that address how WQT is currently being adopted to support programs that are considering or currently support regulated stormwater dischargers.

3.2 Methods

3.2.1 Study Area

The City of Roanoke has a 43 mi^2 jurisdictional area located in southwest Virginia, United States (Figure 3.1) and has a population slightly above 100,000 (US Census Bureau, 2020). The City is positioned near the headwaters of the Roanoke River Basin and the entirety of the City's jurisdictional area drains to the Roanoke River. It is pertinent to note that the Virginia Department of Environmental Quality (VADEQ) has delegated authority to the City to administer the VSMP, meaning that the City is responsible for reviewing development plans for compliance with water quality and quantity criteria, and is able to authorize the use of WQT as a means of compliance.

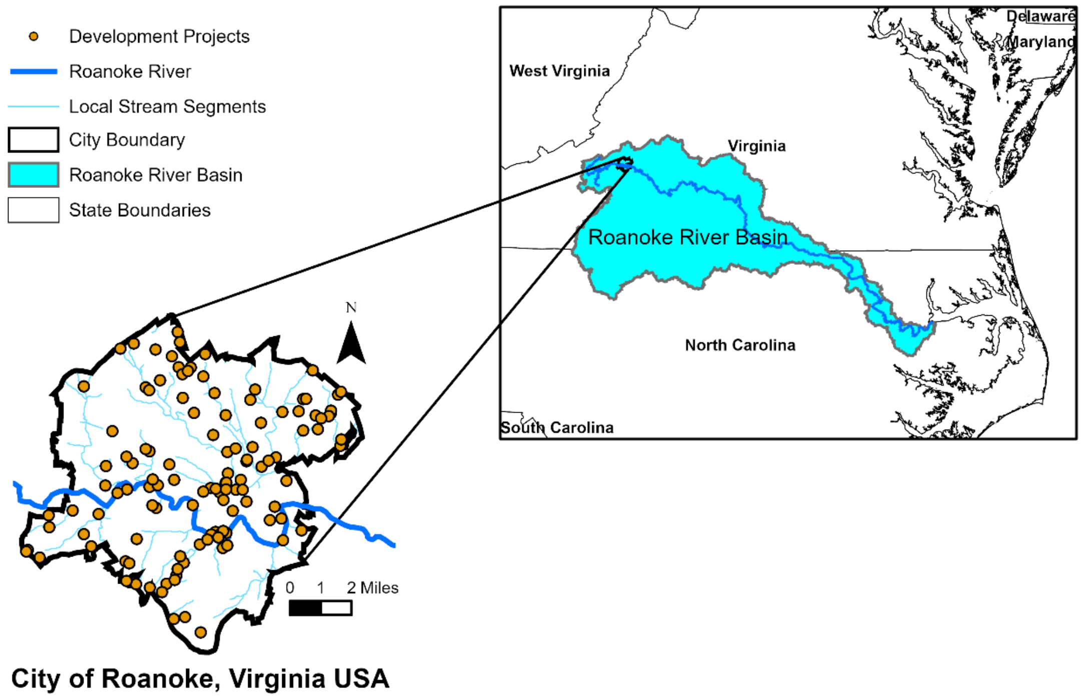

Figure 3.1: The City of Roanoke is located near the headwaters of the Roanoke River Basin in southwest Virginia. Locations of development projects occurring between December 2015 and March 2022 are shown as orange circles. Basemap layers provided by ESRI.

The City is a useful case study for WQT due to the observed volume of trading activity within the city limits and because the City's streams are subject to sediment and bacteria TMDLs, but not nutrient TMDLs which could limit the ability to use WQT based on the provisions of the program outlined in Section 1.1.3. This case allows us to compare development projects that are choosing on-site BMPs with projects that are choosing WQT for their stormwater compliance. Evaluating the adoption of compliance options is plausible due to the City's indication of an observed increase in land developers participating in WQT to achieve compliance with construction-related stormwater quality regulations and because development and corresponding WQT data can be publicly accessed through a web portal. This case also provides an opportunity to assess potential trading outcomes associated with development projects located near the headwaters of a watershed, as shown in Figure 3.1. Such locations are associated with limited upstream areas within the watershed for credit generation sites to support development projects, meaning that it is likely that most credit banks will be downstream of the City. Evaluating trade patterns for Roanoke's development projects can provide insight into regulatory challenges for such headwater edge-cases and inform future trading policy.

3.2.2 Data Aggregation

Roanoke uses a permitting software called eTRAKiT, that contains a database of development project documentation. Developers in Roanoke use this web-based software to apply for permits, submit construction-related documents for review, pay related fees, schedule inspections, and renew licenses (Ahmadi et al., 2020). In doing so, the developers upload required documentation for their projects to the eTRAKiT system, including stormwater management (SWM) reports, stormwater pollution prevention plan (SWPPP) reports, construction documents, and credit purchase affidavits as applicable. These reports are stored in their original format (e.g., PDF, XLSX, etc.), and links to the individual documents are provided in the database. Additionally, tabular project data is also contained in the system for each development project, including a description of the project, the name of the planner assigned to the project, the status of the project, and date information related to the application, review, or approval of the project. The software provides public access to the information stored in the system; however, the documents can only be obtained through the web interface by selecting a single project at a time and downloading a single document at a time - bulk information download is not possible. As such, a Python script was created to extract tabularized attributes and download documentation automatically.

Once the land development data had been retrieved from eTRAKiT, we added spatial attributes of the development projects and the corresponding nutrient credit banks to the dataset. Using Environmental Systems Research Institute's (ESRI) Polygon to Point tool in ArcGIS, Roanoke property parcels from the Roanoke GIS portal are converted into points representing the centroid of the parcel. The X and Y coordinates of the centroid points are then added to the dataset based on a common parcel Tax ID for each project. The coordinates of nutrient credit banks corresponding with credit trades in Roanoke were downloaded from the Regulatory In-lieu Fee and Bank Information Tracking System (RIBITS) in a Keyhole Markup Language (KML) format (USACE, 2017). Coordinate information was extracted by converting the KML file into a shapefile and then calculating the X and Y coordinate with Calculate Geometry tool in ArcGIS. The nutrient credit bank information was then joined to the dataset based on the name of the bank.

3.2.3 Data Analysis

We aggregated development projects together to compare the frequency of methods used by the Roanoke development projects to achieve stormwater quality compliance. To do this, we first assigned a compliance group attribute to each of the development projects based on their respective method used to achieve compliance (e.g., nutrient credits, BMPs, etc.). This allowed us to simplify the compliance methods into four groups: “Nutrient Credits”, “BMPs”, “Land Cover Change”, and “Combined”, where the “Nutrient Credits” group contains projects that used credits as well as projects that intend to use credits but may not have purchased them at the time of this study. We then used the “value_counts()” function in the Pandas package to generate a count of the frequency of the compliance methods used.

We developed queries to obtain and analyze different subsets of our dataset. Queries were developed using the “query” function in the Pandas Python package. For simple queries, only one condition was specified (e.g., creating a subset of development projects that all used the same compliance method). However, other subsets required multiple conditions to be incorporated into the queries (e.g., finding the total number of BMPs used for treatment or quantity control by projects that only used BMPs to achieve stormwater quality compliance). Once we obtained the desired subset, we then applied built-in functions in Python (e.g., sum(), len()) to calculate frequencies of compliance methods and quantify project characteristics such as disturbed area and total phosphorus (TP) load reduction required and number of BMPs used.

We plotted figures depicting the frequency of compliance options, disturbance area, TP load reduction requirements, cost of credits, and the locations of trades. Excluding the figure depicting location of trades, the bar plot and box plot figures were created using the Matplotlib and Seaborn packages in Python. Python syntax required to produce the figures was obtained using Chat-GPT. We used ArcGIS to map the locations of trades occurring between development projects in Roanoke and the corresponding credit generation sites. This was achieved using the ArcGIS XY to Line tool. This tool produces a line between two pairs of X and Y coordinates. The coordinate pairs represent the location of a development project and the location of the corresponding bank from which credits were purchased.

3.2.4 Dataset Description

The compiled dataset comprises 106 attribute fields associated with 131 projects in Roanoke, Virginia, spanning from December 31, 2015 to March 8, 2022. The dataset contains unique attributes that are not currently tracked in the WQT dataset managed by the Virginia Department of Environmental Quality (VADEQ). These attributes account for the method of treatment compliance and quantity control compliance pursued, the use of new or existing BMPs by BMP type, required TP load reduction, project classifications including type and whether the project is a new or redevelopment project, the engineering and architectural firm associated with the project, cost per credit, and project status, and corresponding dates and tax identification. Of the 131 projects, 111 (85% of total projects) required some form of stormwater quality compliance. The remaining 20 projects had a land disturbance area of less than 10,000 square feet, excluding them from being subject to stormwater treatment requirements. Stormwater quality compliance for the 111 projects was met using either a single compliance option (e.g., BMPs, nutrient credits, land cover conversion) or through a combination of compliance options.

3.3 Results

3.3.1 Stormwater Quality Compliance Preferences

Nutrient credits were the most frequently used option for achieving stormwater quality compliance, as shown in Figure 3.2. Of the 111 projects requiring stormwater quality compliance, 65 (59%) used nutrient credits as the only compliance method. Land cover conversion was the next most popular choice for meeting stormwater treatment requirements, used by 24 (22%) projects. Land cover conversion was achieved by replacing land cover types with higher nutrient loading per the VRRM (e.g., impervious cover) with types that disperse a lower nutrient load (e.g., turf or forest). For land cover conversion projects, nutrient loads were reduced below baseline treatment requirements. BMPs were the third most popular option, being used by 16 (14%) of the projects. Of these 16 projects, 6 projects (38%) did so by implementing at least two BMPs. This was typically done to account for multiple onsite drainage areas. In total, there were 32 unique BMPs used by the 16 projects. These BMP types include bioretention, manufactured filters, grass channels, dry swales, detention basins, permeable pavement, cisterns, and disconnecting rooftop drainage. Lastly, there were six projects that used a combination of BMPs and nutrient credits to meet compliance requirements.

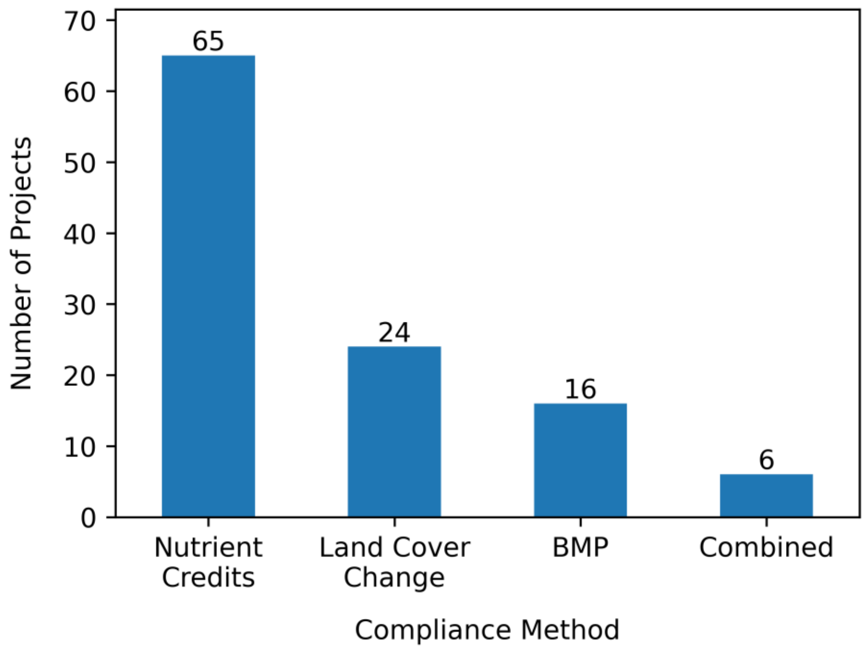

Figure 3.2: Stormwater quality compliance options selected for Roanoke development projects from December 2015 to March 2022.

3.3.2 Disturbance Area and Treatment Requirements

Projects using nutrient credits were found to have a lower corresponding median disturbed area compared with projects that used BMPs, as presented in Figure 3.3A. The median disturbance area for these projects was 1.36 acres (one of the 65 projects was excluded due to missing information). There were 16 projects that used BMPs exclusively to meet stormwater quality treatment requirements. For those projects, the median disturbance area was approximately 3 acres, more than double the median disturbance area of projects using credits. There were six other projects that used a combination of BMPs and credits for treatment compliance, and whose corresponding median disturbance area was 2.58 acres.

Projects using nutrient credits were also found to have lower corresponding median nutrient load reduction requirements compared with projects using BMPs (Figure 3.3B). The median TP load reduction requirement for projects exclusively using credits for quality compliance was 0.69 pounds per year. The median TP load reduction requirement for projects exclusively using BMPs for treatment was more than double that of projects using nutrient credits, at 1.68 pounds per year.

The combined TP load reduction required for projects exclusively using credits, meaning the sum of the TP load reduction, was twice as much as the combined (summed) TP load reduction required by projects using BMPs. The total nutrient load reduction required by projects using credits was 80.78 pounds of TP per year (Figure 3.3C). Projects using BMPs had a combined nutrient load reduction of 37.29 pounds of TP per year. The six other projects that used both credits and BMPs for treatment had a combined nutrient load reduction requirement of 32.44 pounds of TP per year.

The 24 projects meeting treatment requirements with land cover conversion practices had smaller disturbance areas and correspondingly lower treatment requirements compared with the other projects. The median disturbed area for projects implementing land cover conversion practices was 1.06 acres (Figure 3.3A), approximately 28% less than the median disturbed area for projects using credits. All the projects using land cover conversion exceeded the treatment requirements for their projects, with the median TP load reduction being 0.22 pounds of TP per year reduced below the baseline requirement (Figure 3.3B). Combined, the projects achieving treatment requirements using land cover conversion reduced TP loads 11.51 pounds per year below baseline treatment requirements (Figure 3.3C). This represents approximately 7% of the treatment requirements of projects using credits.

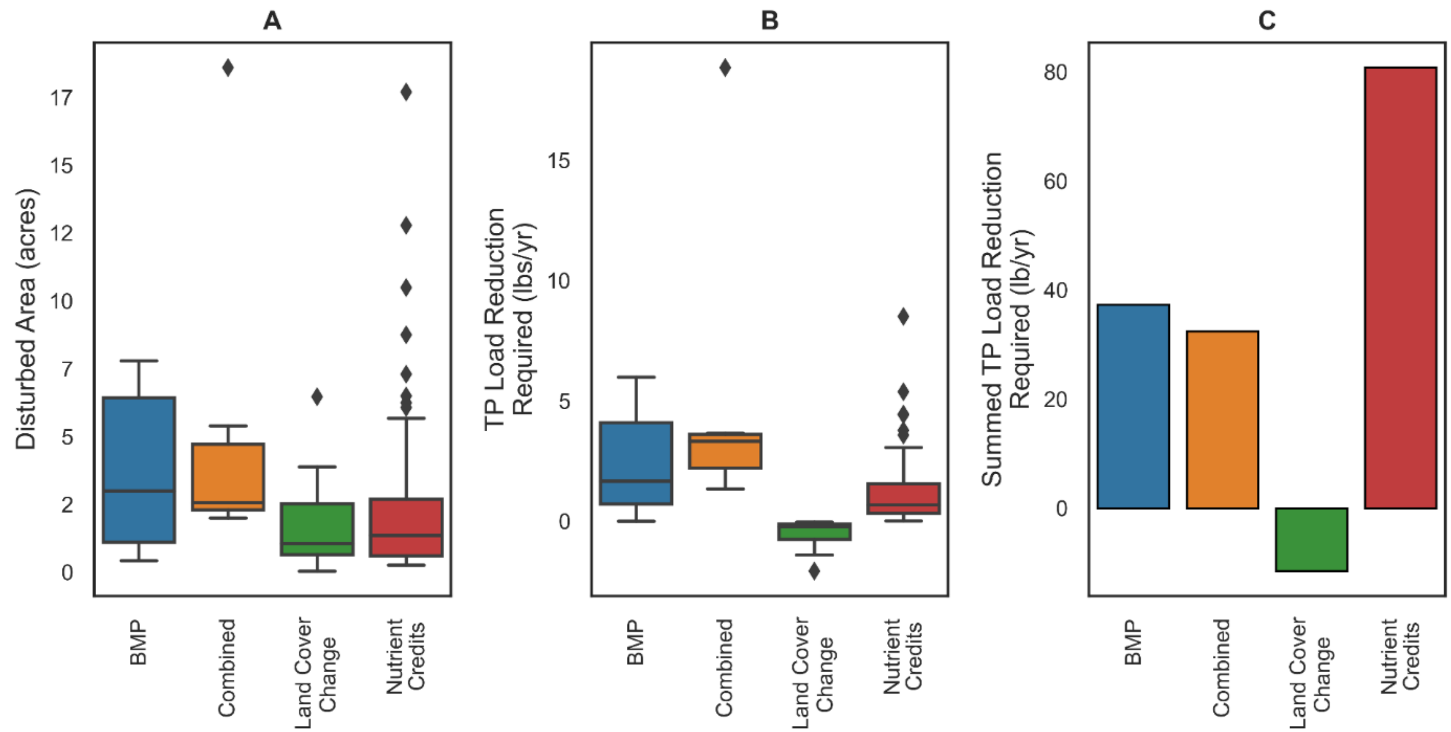

Figure 3.3: Comparative plots showing compliance choices for 131 land development sites using on-site stormwater best management practices ("BMP", n = 16), a combination of off-site water quality credits and on-site BMPs ("Combined", n = 6), land cover change (n = 24), or nutrient credits exclusively (n=64). (A) Box and whisker plot showing disturbed area in acres for all sites in each category; (B) TP load reduction required in lbs./yr. for all sites in each category; (C) sum of TP load reduction required in lbs./yr. in each category for all sites.

3.3.3 Compliance Choices for New and Redevelopment Projects

A greater proportion of new developments projects used credits for quality compliance compared with redevelopment projects. Of the 24 projects classified as new development, 20 projects (83%) used credits exclusively to achieve stormwater quality compliance. Of the 86 projects classified as redevelopment projects, only 45 projects (52%) used credits exclusively to meet treatment requirements. There were 24 (28%) of the redevelopment projects that were able to meet treatment requirements using land cover conversion practices. New development projects were not allowed to use land cover conversion for compliance. Virginia's regulations assume the predevelopment condition for new development projects is in a native state and therefore could not be improved when undergoing development.

3.3.4 Stormwater Quantity Compliance Corresponding with Credit Use

The majority of projects that used credits often achieved stormwater quantity compliance through means other than using onsite stormwater BMPs. Of the 65 projects that used credits exclusively for quality compliance, 38 projects (58%) did not use BMPs for stormwater quantity compliance and 27 projects did use BMPs. Of the 38 projects that did not use BMPs, 30 projects (79%) met the channel protection requirement for quantity compliance by discharging stormwater into an existing manmade conveyance system that would not experience erosion (9VAC25-870-66 Section B.1.a). Only one of these 38 projects discharged into a natural conveyance system triggering the need to reduce peak flow (9VAC25-870-66 Section B.3.a). By comparison, 13 of the 27 projects that used credits and quantity control BMPs (48%) discharged to manmade conveyance systems while 12 projects (44%) discharged to natural conveyance systems. Flood control for projects using credits and no quantity control BMPs was achieved primarily by demonstrating no localized flooding was occurring for 15 of 30 projects (50%), with 8 of 30 projects (27%) meeting requirements through a reduction in peak flow by reducing impervious area or grading the site to redirect or attenuate peak flows. On the other hand, 20 of the 27 projects using credits and quantity control BMPs (74%) experienced existing localized flooding, requiring peak flows to be reduced from these sites. The most common quantity control BMPs used were underground detention and detention basins, comprising 26 of 29 (90%) quantity control BMPs used by projects achieving quality compliance using credits.

3.3.5 Cost of Credits

Cost information associated with 12 transactions was identified in the dataset. The transactions corresponded to 12 unique projects (approximately 18% of the projects that purchased credits) and four unique banks (22% of the banks that traded credits with Roanoke land development projects). The unit credit prices offered by these four banks ranged from \$7,900 to \$16,000 per credit, with the median credit price being \$8,000 in US dollars (Figure 3.4A). The corresponding total cost of credits per development site ranged from \$960 to \$83,398 in US dollars (Figure 3.4B). The median total amount required for credits was \$12,402, with the sum of the total payment amounts for all 12 projects equaling \$296,356.

One unit credit price was significantly higher (see Figure 3.4A) compared with the other unit prices. This unit price (\$16,000) corresponded with a request for only 0.06 credits, with the total required payment amount equaling \$960. However, this is the only case observed in the data where a small number of credits was purchased at a high unit price. Excluding this transaction, the remaining 11 transactions included credit orders ranging from 0.42 credits to 8.51 credits, with corresponding unit credit prices ranging from $7,900 to $10,500. These findings suggest there is no economy of scale occurring for these 12 projects.

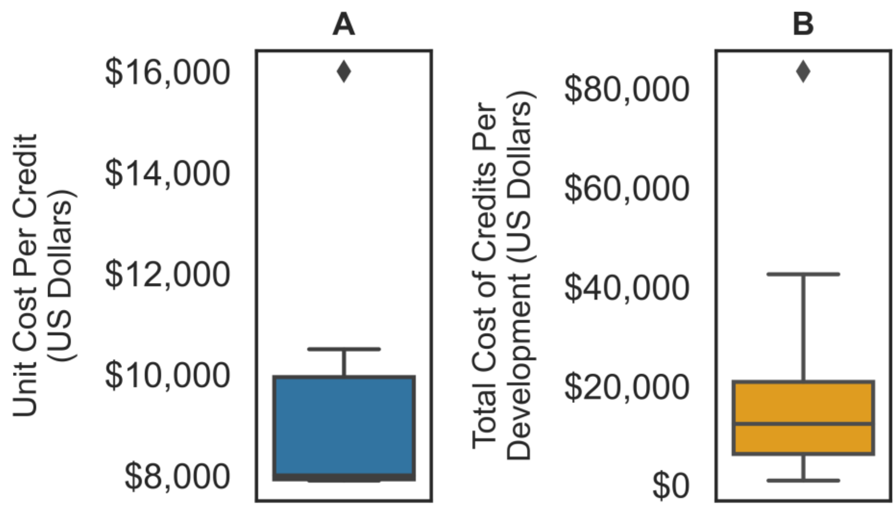

Figure 3.4: Available credit price information for 12 trades between 12 development projects and four banks. Boxplot A presents corresponding unit credit price information while Boxplot B describes the total cost of credits per development.

3.3.6 Local Industry Adoption of Credits

The majority of the engineering and architectural firms that supported projects in Roanoke used nutrient credits to achieve stormwater quality compliance. Of the 31 unique firms responsible for projects with stormwater quality requirements, including Roanoke's municipal engineering department, 19 (61%) used credits as the only compliance method for at least one of their projects over the period of analysis. The projects for which credits were used included residential, commercial, industrial, and public facilities type projects. 10 of the 31 companies (32%) used or proposed credits for multiple projects. There were two commercial firms that, together, designed 54 projects (49%) that had stormwater quality requirements. These two firms used credits 69% and 58% of the time, respectively, to meet the water quality requirements. The 12 firms that did not use credits each were responsible for only a single project during the period of analysis.

3.3.7 Spatial Analysis of Trades

All of the credits purchased by development projects in Roanoke were developed at sites located downstream from the projects and Roanoke City as a whole, as shown in Figure 3.5. In total, there were 56 trades mapped, based on available trading information, between the development projects and 18 different credit banks. Projects with mapped trades include 49 projects that purchased credits, five projects that used a combination of credits and BMPs, one project that proposed the use of credits as the only compliance method, and one project that used BMPs exclusively but purchased credits for later use. Their locations are represented by blue circles in the upper right corner of Figure 3.5. Credit banks are represented with a triangle symbol, with black triangles representing credit banks that supplied credits to Roanoke development projects. The thin grey lines represent the credit trade between the development project and the corresponding credit bank. These trades are allowed under Virginia's WQT regulations due to both projects and banks being located within the same river basin (9VAC25-900-91). Downstream trading ultimately is occurring due to there not being any credit banks located either in the City or upstream of the City.

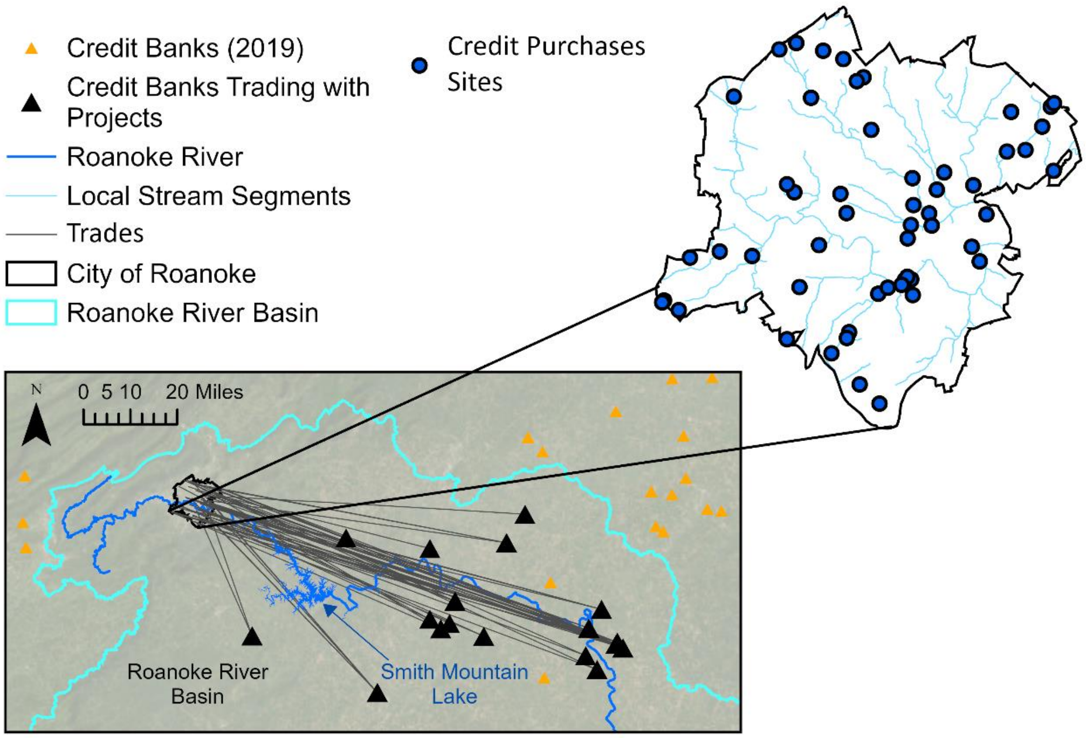

Figure 3.5: Downstream nutrient credit trading is observed for all participating development projects in Roanoke, Virginia. Service Layer Credits: Source: World Imagery (for Export): Esri, Maxar, Earthstar Geographics, and the GIS User Community.

3.4 Discussion

3.4.1 Consideration of Cost

The cost of credits relative to using BMPs is a contributing factor associated with the WQT participation observed in Roanoke. Research has acknowledged the significant cost associated with using BMPs to achieve stormwater treatment requirements (Jones et al., 2017). In addition to the high initial costs, BMPs require long-term operation and maintenance (O&M) support that accounts for a significant portion of the lifetime cost of the BMP (Kang et al., 2008; Urbonas and Olson, 2011; Weiss et al., 2007). However, research focusing on stormwater quality compliance costs for the Virginia Department of Transportation (VDOT) indicated that perpetual credits may serve as a less expensive compliance option compared with using BMPs (Nobles et al., 2017).

To demonstrate cost being a motivating factor for participation, we compared the median cost of a credit purchase order with the estimated cost range for bioretention BMPs (identified in our dataset as one of the most common BMPs used for treatment in Roanoke). Recall the available unit credit prices associated with the four credit banks in our dataset ranged from $7,900 to $16,000 per credit, with the median unit price being $8,000 and no economy of scale observed. Note these prices are also within range of credit prices reported previously for Virginia (Saby et al., 2021b). The median price paid for credits was calculated to be $5,520, based on applying the median unit price of the 12 transactions ($8,000) to the median nutrient load reduction required for the 65 development projects using credits (0.69 lbs TP/yr), acknowledging one credit is worth one pound of TP reduction per year. The Chesapeake Bay Program's estimated 2018 capital cost for bioretention with no underdrain on A or B soils in Virginia (a conservative BMP choice) ranged from $1,299 per acre treated (low-end estimate) to $59,092 per treated acre (high-end estimate) (CBP, 2023). Applying the median disturbance area for the 65 projects using credits (1.36 acres), this estimate roughly translates to a cost range of $1,767 to $80,365 for capital cost alone. O&M costs would add an additional $87 (low-end estimate) to $9,126 (high-end estimate) per year over a 20-year useful life (Price et al., 2021). Given this range of estimated capital and O&M costs, it is reasonable to suppose that at least in some cases, credits would be a cost-effective alternative to BMPs for land development projects, incentivizing developers' participation in WQT.

3.4.2 Consideration of Stricter Local Stormwater Regulations

Roanoke enforces stricter stormwater regulations that subject a greater portion of development projects to meet treatment requirements compared to state standards. Virginia has adopted the federal standard of requiring treatment for projects disturbing one or more acres of land but allows localities to enforce stricter requirements. Paralleling stormwater treatment requirements, Virginia also enforces sediment and erosion control regulations that trigger land stabilization requirements when more than 10,000 square feet are disturbed (9VAC25-840). Localities, such as Roanoke, can choose to simplify their regulations by adopting the same 10,000 square feet land disturbance limit to trigger requirements for stormwater treatment. Recalling that Virginia's trading regulations place limits on credit purchases only for larger developments (more than five acres of disturbance or more than 10 pounds of TP reduction required), tighter stormwater regulations could generate more trading than would otherwise be anticipated with the less-restrictive state-level regulations that require treatment for one or more acres of disturbance. This is beneficial for the WQT program as increased participation helps to thicken the market and stabilize credit prices (Banerjee et al., 2013). In Roanoke, 38% of the projects in our study that only used credits to achieve quality compliance disturbed less than the state's one-acre minimum requirement but more than Roanoke's 10,000 square feet minimum disturbance requirement. Without the stricter disturbance requirements, those projects would not have triggered treatment requirements and subsequently credits for those projects would not have been purchased.

3.4.3 Consideration of State-level WQT Regulations

Revisions to Virginia's stormwater regulations facilitated the WQT activity observed in Roanoke. Over a decade ago, Virginia adopted the VRRM with its sequential steps that gave preference for onsite treatment for achieving stormwater quality compliance. However, such sequences are designed to reduce demand for credits (Stephenson and Shabman, 2017). Virginia's 2011 regulations supported this sequence by requiring developers to demonstrate that compliance could not be achieved with BMPs before allowing them to purchase offset credits, making it difficult to participate in WQT (Virginia, 2011). However, the requirement to demonstrate the need for credits was subsequently removed from the regulations in 2012, thereby eliminating the need to iterate designs until treatment could be achieved using on-site BMPs (Virginia, 2012). This change made it easier to use credits to meet stormwater permit requirements in Virginia.

Virginia's WQT regulations support trading in Roanoke, even when credit banks are located downstream from the projects. As long as projects do not discharge stormwater directly to streams impaired for dissolved oxygen, benthic community, chlorophyll-a, or nutrients, credits can be purchased from anywhere within the HUC 8 or adjacent HUC 8 within the HUC 6 basin. The flexibility granted in these regulations eventually allows developers to purchase credits when banks are located downstream, regardless of if projects discharge to streams with relevant impairments (9VAC25-900-91). Such is the case with all of the development projects in Roanoke, due in part to Roanoke being located near the headwaters of the basin.

3.4.4 Consideration for Local Water Quality and Quantity

Local water quality outcomes associated with WQT need to be considered in addition to outcomes at the watershed-scale. In Virginia, the primary goal of WQT has been to support low-cost nutrient reduction to meet total maximum daily limit (TMDL) requirements for the Chesapeake Bay (Saby et al., 2021a). However, other goals exist to improve water quality at local scales, which may also support TMDL objectives. Roanoke, for example, is located within a localized high priority area for nonpoint source pollution potential related to urban phosphorus, designated by VADEQ and the Virginia Department of Conservation and Recreation (VADCR) (VADEQ and VADCR, 2022). This priority area refers to a location where support is most needed to reduce phosphorus loads. However, development projects in Roanoke that participated in WQT contribute an estimated 80.78 pounds of untreated TP per year to the local streams. Mitigation benefits associated with the corresponding credit banks will not be seen in Roanoke's urban streams due to the banks being located downstream.

Smith Mountain Lake, Virginia's second largest freshwater lake and popular recreation destination is located directly downstream from the development projects and likely receives untreated nutrients resulting from the trades (see Figure 3.5). Similar to the local streams in Roanoke, this lake also does not benefit from nutrient reduction from trading due to its location upstream of the mitigation sites. While algal blooms have been reported in this lake (VDH, 2023), it is not understood if those impacts are or could result from the untreated phosphorus from WQT. This is due to the difficulty in isolating nutrient loads from development projects with loads from other sources in the basin such as farms. Water quality monitoring could be used to quantify in-situ nutrient loads and possibly relate water quality issues back to specific sites.

It is challenging to predict water quality outcomes from future WQT participation. Our dataset only captures six years of trades. While the percentage of development projects using credits has generally increased over that period, the number of development projects occurring was seen to vary from year to year, which affects the total amount of phosphorus to be treated and subsequently the number of credits that may be purchased. Ultimately, the current WQT practices observed in Roanoke suggests current WQT practices are in some cases in conflict with local water quality goals of municipalities, VADEQ, and VADCR, and additional data would facilitate predicting future trading and subsequent foregone TP treatment.

The intent of the VRRM is to reduce nutrient loads by capturing and reducing runoff volume onsite. The use of credits results in foregone capture of runoff volume. In terms of TP load, Roanoke development projects are foregoing treatment for 80.78 pounds of TP per year. The foregone treatment volume reduction associated with this annual load is approximately three acre-feet per year, based on the relationship between TP load and treatment volume described in the VRRM and corresponding standard average annual rainfall of 43 inches and TP event mean concentration of 0.26 milligrams per liter. It is outside the scope of this study to evaluate whether these TP loads and corresponding treatment volume will have negative effects on local streams in Roanoke. However, there are several benefits of using BMPs for capturing treatment volume and treatment onsite that may be foregone when due to this trading. For example, onsite capture of treatment volume using BMPs facilitates groundwater recharge, helps protect downstream channels from erosion, and reduces nuisance flooding (Hirschman et al., 2008). Sediment and metals can also be captured along with the TP and other nutrients using BMPs (Fassman, 2012). Offsite mitigation practices would not be able to ameliorate these foregone benefits at the development site.

3.4.5 Broader Impact for WQT

The findings of this study highlight important considerations that inform water quality trading in other trading programs across the country, including programs that currently allow land developers to purchase credits to cover stormwater requirements as well as those that do not. For example, careful consideration for the strictness of local stormwater regulations is needed as strict requirements may influence higher participation in WQT, especially if credit prices are reasonable compared with implementing BMPs. Additionally, the spatial relationship between credit mitigation sites and credit purchase sites should be considered, including for edge cases. Roanoke was identified as an edge case in Virginia’s program due to its location near the headwaters of the river basin, which ultimately resulted in credit trading with credit banks downstream. Considering edge cases will inform trade rules that can better account for potential negative environmental outcomes across a wider spectrum of trading scenarios. Lastly, it is challenging to foresee all outcomes of a program prior to implementation. Tracking trading enables cities to identify and justify needed policy adjustments that account for unforeseen outcomes. Municipalities are likely already collecting trading information in the required documentation submitted by developers during the land development approval process. This was the case with Roanoke. Considerations for data collection and management practices will improve the useability of this information for making relevant policy decisions.

3.5 Conclusions

WQT is being used more often to achieve stormwater quality compliance in Virginia than previously understood. Through this study, we identified WQT credits as the most commonly used stormwater quality compliance option among land developers in Roanoke, Virginia. This study is the first known attempt to harvest land development and WQT demand-side data from a locality, and therefore presents the first quantitative evidence of WQT preference against other options. To understand conditions and factors surrounding this, we identified 111 of Roanoke’s

131 development projects that required stormwater treatment (December 2015 to March 2022). We analyzed the characteristics of those development projects with treatment requirements and compared the adoption of credits with stormwater BMPs.

Our work characterizes credit use in four ways. First, we characterized credit use based on required TP reduction requirements and land disturbance and compared these characteristics with projects that chose BMPs to achieve compliance. Second, we characterize credit use based on development classification (new development or redevelopment). Third, we described the adoption of credits by projects based on the projects' adoption of stormwater quantity control BMPs. Fourth, we characterize the local industry's adoption of credits.

Tracking the adoption of stormwater compliance methods, including WQT, is critical for evaluating policy outcomes and informing stormwater management decisions. This case study demonstrates some of the quantifiable insights that can be ascertained from tracking, including the locations and characteristics of projects treating or offsetting nutrient discharge and the relationships between selected quality and quantity compliance options. This information can be used to facilitate decision-making to evaluate the potential water quality consequences of forgoing upstream stormwater treatment for downstream credit trading. Additionally, this information enables modeling that more accurately reflects existing conditions and supports stormwater management and planning efforts.

Future research is needed to identify economic and environmental outcomes associated with ubiquitous adoption of credits for local land development projects. Land cover conversion, while not the most popular compliance option, was observed as a major compliance option that enabled developers to achieve stormwater quality and quantity compliance without BMPs or credits. Future research should also focus on methods to evaluate the efficacy of these practices in restoring hydrologic conditions of our urban watersheds.

3.6 Disclaimer

The contents of this article are the product of the authors and do not necessarily reflect the opinions of the City of Roanoke. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the authors or their respective organizations.

Chapter 4

4. A GIS Approach for Estimating State-Wide Water Quality Credit Need: Application for Planned Transportation Projects in Virginia[3]

4.1 Introduction

Water quality trading (WQT) programs have been established in countries around the world as a means of lowering the cost of meeting water quality standards (Corrales et al., 2013; Dennison et al., 2012). In the United States, as of 2021, there were 147 programs or policies describing permitted WQT within 355 distinct markets (BenDor et al., 2021). In such WQT programs, a seller may generate credits, representing a unit of nutrient load reduction per unit of time, by conducting nutrient reduction activities at a credit-generation site (e.g., a farmer practicing enhanced agricultural practices or conversion of farmland to forest). These credits can in turn be sold to buyers who can use the credits to offset their onsite nutrient load reduction requirements. The buyer is incentivized to purchase the credits if the cost of the credit is less than the cost to implement best management practices (BMPs) or other onsite technology (Hoag et al., 2017).

Despite the availability of WQT programs, minimal participation has historically been observed in the past (Breetz et al., 2005; Shortle, 2013). The U.S. Environmental Protection Agency (EPA) publicly reiterated its support for WQT and provided policy updates and clarification on its 2003 policy to encourage participation (Congressional Research Service, 2003; Ross, 2019). As with the EPA policies, over time, state and local program policies and mechanisms are reviewed and revised to improve support for program participants and environmental objectives (Industrial Economics Incorporated, 2008). Through these reviews, several challenges have been cited that contribute to lower participation. For example, high transaction costs and future credit supply and need uncertainty have been cited as deterrents for participating in WQT programs (Greenhalgh and Selman, 2012; Ribaudo and Gottlieb, 2011). Transaction costs are associated with several aspects of WQT, including credit creation, locating trade partners, market assessment (DeBoe and Stephenson, 2016; Rees and Stephenson, 2014), trading ratios (Su et al., 2021), and the implementation of complex trading rules or trading zones, which restrict trading to promote environmental integrity (Fisher-Vanden and Olmstead, 2013; Hahn and Hester, 1989; Horan and Shortle, 2011; Hosterman and Kramer, 2008). Strategies have been proposed to facilitate trades and lower transaction costs (Saby et al. 2021a), yet there remains a lack of approaches for facilitating the coordination of future credit trading in WQT programs (Motallebi et al., 2017; Walker and Selman, 2014).

State and county transportation departments, municipalities, federal agencies, or large private development companies may be responsible for the largest number of credit purchases in WQT programs (Saby et al. 2021b). These agencies typically have some knowledge of their planned projects in future years. This presents the opportunity to estimate their credit needs in coming years to reduce their own credit need uncertainty, defined as the buyer's inability to

[3] This chapter has been submitted to the Journal of American Water Resources Association and is currently under review.

know the number of credits that will be needed in the future to offset water quality impacts from planned development projects (e.g., a planned highway construction project).

In Virginia, the case study region for this paper, the nonpoint source (NPS) WQT program uses a version of the Runoff Reduction Method (RRM) to calculate required nutrient load reduction (Battiata et al., 2010). This required nutrient load reduction is then used to determine the number of credits the developer would need to purchase to offset impacts. This method, currently implemented through a standardized spreadsheet tool issued by the Virginia Department of Environmental Quality (VADEQ), requires soil and land cover characteristics for both existing and post construction conditions as inputs (Davenport, 2016). However, it is possible to implement the RRM in a geographic information system (GIS) to automate the estimation of water quality credit needs for a collection of state-wide planned projects. Doing so would provide buyers with ahead of time, spatially explicit information on their credit needs, thereby reducing the buyer's credit need uncertainty.

The use of ahead of time estimation has been shown to be helpful in managing uncertainty in future trading for other environmental resource markets. For example, Delorit and Block (2020) demonstrate the potential for long-term trade stability through the use of a season-ahead water quantity trading estimation. Raffensperger et al. (2017) highlighted the use of a smart market related to wetland restoration banking, which identifies strategic wetland construction locations that match credit need and supply. Mozelewski and Scheller (2021) showed how ahead of time estimation can be used to inform program managers when a program's status quo is insufficient, which can help guide needed policy changes to meet desired outcomes. However, despite its potential benefit in WQT markets, in the existing WQT decision support tools available from state and federal agencies (described further in the Virginia NPS WQT Program section), trading is not currently informed by a future statewide estimate of credit needs, thus preventing the matching of credit supply with credit need.

The purpose of this research is to create a methodology for estimating the future maximum potential credit need for large credit buyers while considering complex trading regulations. Specifically, we develop a GIS-based methodology for calculating an upper bound estimate of credit needs in Virginia's NPS WQT program, recognizing buyers may choose to purchase the maximum amount of credits possible for their development projects, given the historical lower cost of credits compared with BMPs (Nobles et al. 2017). We apply this methodology as a case study to calculate credit needs for Virginia Department of Transportation (VDOT) roadway and trail projects on a 6-year planning horizon while accounting for Virginia's NPS WQT program regulations. The methodology described could also serve as one part of a larger system to aid in managing not only credit need uncertainty, the topic of this paper, but also supply uncertainty by facilitating the coordination of supply with estimated credit need. Such a system could also provide other services (e.g., assisting in finding trading partners or guiding users through complex trading rules) that, ultimately, help to increase participation by lowering the transaction costs associated with WQT markets.

4.1.1 Available Water Quality Trading Tools

Virginia's NPS WQT program, like other WQT programs, has a limited set of tools to support participation. One tool, the Chesapeake Bay Nutrient Trading Tool (CBNTT) (WRI, 2020), makes use of the United States Department of Agriculture's Nutrient Tracking Tool (NTrT) (Saleh et al., 2011; USDA, n.d.) and the Chesapeake Bay Watershed Model (Chesapeake

Bay Program, 2020) to help sellers calculate the number of credits they can generate by estimating nutrient load reduction associated with credit generation projects (Duke et al., 2020). This tool also makes use of the marketplace features from NutrientNet (*Water and Agriculture*, 2006) to assist in connecting buyers with sellers (Walker, 2016). However, the CBNTT does not provide functionality for a buyer to input land cover changes associated with development projects and calculate the credits they could purchase to offset treatment requirements. Additionally, the tool has only been officially adopted for use in Maryland's WQT program ("World Resources Institute | NRCS," n.d.), and Virginia's new regulations have yet to be incorporated.

The Regulatory In-lieu fee and Banking Information Tracking System (RIBITS) a tool developed by the United States Army Corps of Engineers (USACE), benefits buyers by displaying nutrient credit banks' (a third-party seller in Virginia's WQT program) service areas along with the number of available credits at the banks (USACE, 2017). While this enables buyers to make general market assessments, pending transactions and potential credit reservations are not accounted for in the posted credit totals (USACE, n.d.). Additionally, the tool does not take into account the significant complexities recently added to the regulations associated with impaired waters or local TMDLs.

Recent research by Saby et al. (2021a) describes the development of a prototype decision support tool that leverages automation to reduce errors in credit transactions, in part, by identifying valid trade partners under Virginia's trading hierarchy prior to the 2021 regulation changes. While the tool is designed to be modified to account for changes in trading rules, it was not developed to reduce transaction costs associated with buyers estimating future credit needs for development projects on a statewide scale, the topic of this research.

4.1.2 Virginia Department of Transportation Example Purchaser

Saby et al. (2021b) found that VDOT is responsible for the largest number of transactions in Virginia's WQT program from 2012 to 2020, suggesting they are a significant player in Virginia's WQT program. VDOT manages transportation improvement projects which are planned six years in advance, providing them an opportunity to estimate their credit needs for these projects ahead of time. However, prior to this research, VDOT did not have a way to systematically estimate the water quality credit needs associated with their planned projects at the state scale due to changes made to the trading rules and the quantity and geographic spread of their projects across the state. Such factors make it difficult for VDOT to estimate and communicate their future credit needs with the credit bankers (VDOT regulatory manager John Olenik personal correspondence, August 4, 2022), which could leave VDOT to speculate whether credits will be available at the time of purchase and in accordance with the trading rules.

The purpose of the methodology developed in this study is to help VDOT estimate the location and maximum potential quantity of credits (referred to hereafter as "credit need" or "needed credits") associated with their planned projects within their 6-year improvement program. By sharing this information with the credit bankers, it is possible for VDOT to reduce the uncertainty associated with finding valid trading partners with available credits at their time of need to meet the nutrient load reduction requirements associated with their planned projects.

4.2 Methods

The proposed methodology is comprised of four general steps, as presented in Figure 4.1. In summary, the methodology (1) identifies the location of runoff discharge used to determine whether the simple or complex trading hierarchy should be used to find credits; (2) prepares data to be fed into the VRRM method; (3) executes an automated implementation of the VRRM and determines the maximum possible number of credits which could be purchased according to Virginia regulations; and (4) aggregates and maps credit needs. This process is repeated for each of the VDOT's planned projects (145 projects in total). These steps are described in detail in the following paragraphs.

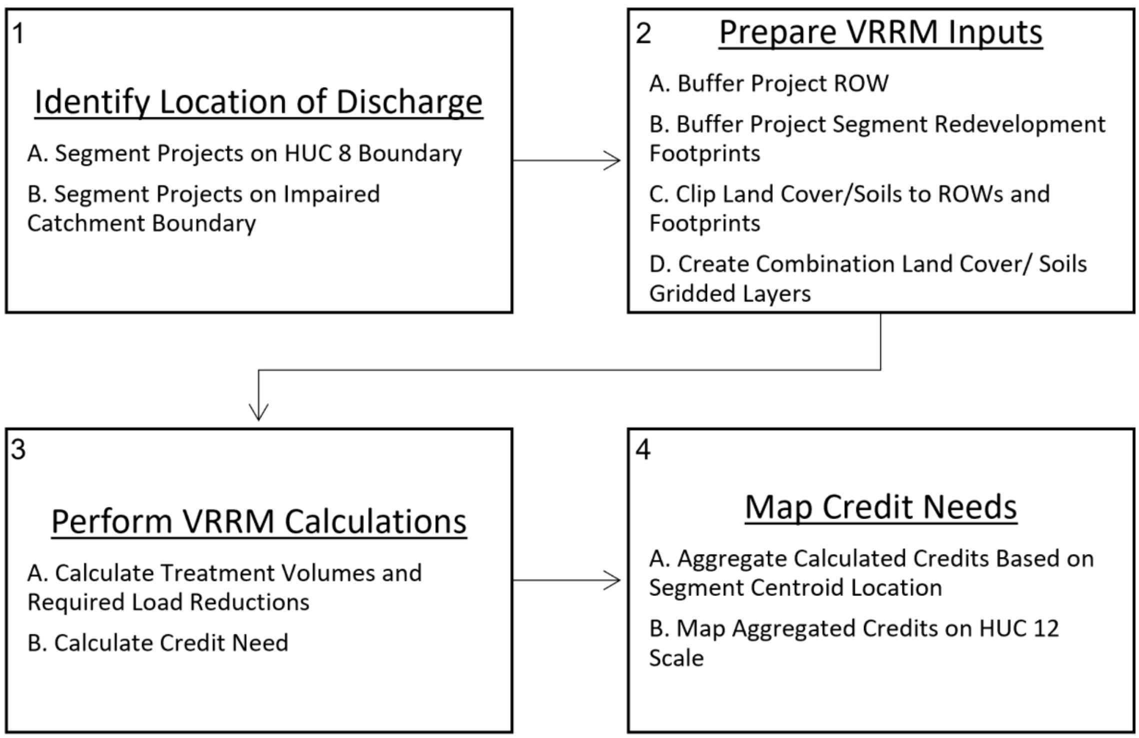

Figure 4.1: The proposed methodology to estimate the offset credit needs associated with VDOT's planned projects.

The methodology begins by determining the location of the runoff discharge from the project sites, which governs whether the simple or complex trading hierarchy must be used to find credits. We do this by splitting the projects along HUC 8 boundaries, assuming roads and trails generally follow the natural grade and runoff waters splits in either downslope direction at the natural crest located presumably at a HUC 8 boundary (see step 1A in Figure 4.1). The HUC 8 boundary also represents the HUC scale at which the simple trading hierarchy begins. Next, we segment the projects along impaired catchment boundaries to isolate sections of projects which would require the complex trading hierarchy to be used to find credits. The result of both segmentation processes is a new dataset comprised of 535 project segments, all of which contain the same tabulated attributes of their respective parent projects. We assume drainage discharge associated with each of these project segments is located at the centroid of the segments. The remainder of the methodology and the results described after are based on these 535 project segments and their respective centroid locations.

Land use and soil attributes corresponding with pre-redevelopment and post-redevelopment conditions are required as inputs for the VRRM method. To obtain these attributes for each of the project segments, a boundary (polygon layer) representing an estimated right-of-way (ROW) is created in ArcGIS to buffer the segment to a width based on the roadway classification included in the dataset and current VDOT practices (see step 2A in Figure 4.1). ROW widths range from 50 feet wide for urban roads to up to 200 feet wide for interstate roads.

The post redevelopment project segment footprint is estimated by buffering the segment polygon centerline to a width equivalent to the existing project segment width plus the additional width, as described in the project segment description attribute in the dataset (see step 2B in Figure 4.1). The project descriptions in the original dataset were not standardized and required a manual review to determine the additional width to be added to the project segment. Furthermore, the existing project widths, based on the number of roadway lanes, were also not provided in the original dataset. We subsequently assumed the number of existing lanes for each project segment, based on the roadway classification attribute provided in the original dataset. These assumptions include six lanes for interstate roads, four lanes for primary roads, three lanes for secondary roads, and two lanes for urban roads, which are within the current range of lanes corresponding to existing VDOT roadway classifications (VDOT, 2019). Additional assumptions include 12-foot wide lanes and shoulders; trail widening projects include an additional four feet of width; and pedestrian improvements equate to 10-feet wide impervious surfaces. The assumptions made regarding lane, shoulder, and trail widths can be adjusted if more detailed information is available. The ROW boundary is then used in ArcGIS to clip corresponding land cover and soils data, thereby capturing the existing project footprint (see step 2C in Figure 4.1). A gridded (or raster) dataset containing values representing both land cover type and soils type is created by multiplying the individual gridded values representing land cover and soils together using raster algebra in ArcGIS and is subsequently converted to a polygon layer containing individual polygons representing each corresponding combination of land cover and soil type within the ROW (see step 2D in Figure 4.1). The ROW land cover and soils combination layer contains the existing project footprint, representing pre-redevelopment conditions. For post-redevelopment conditions, the buffered post development project footprint polygon, with impervious land cover attributes assigned, is converted to a gridded layer and incorporated with the ROW's land cover and soils combination layer using the Mosaic to New Raster tool in ArcGIS.

The VRRM method for linear, redevelopment projects, selected based on a manual review of project descriptions, was automated in ArcGIS to calculate the required TP load reductions for each of the project segments (see step 3A-B in Figure 4.1). The automation included the calculation of pre-redevelopment and post-redevelopment treatment volumes and TP loads (*9VAC25-870-63. Water quality design criteria requirements.*, n.d.). Equations for the VRRM are based on the Virginia Runoff Reduction Method User's Guide (Davenport, 2016).

Next, the disturbed area and required TP load reduction were compared for each project segment to determine the maximum number of credits VDOT could purchase to offset stormwater quality treatment requirements in accordance with § 62.1-44.15:35 (*Va. Code Ann.*, 2015) and as described in the Buyer's Determination of Needed Credits subsection. If a project had less than five acres of total disturbed area, or if the project had less than 10 pounds of TP reduction required, then the offset credits for that project were made equal to the calculated treatment reduction, given one credit is equal to one pound of TP reduction per year. If the project had more than five acres of disturbed area or more than 10 pounds of TP reduction required, then the corresponding offset credits needed were calculated as 25 percent of the required TP load reduction, recognizing that 75% of the treatment for those projects would be required on site.

Credit needs were then aggregated and mapped at the HUC 12 scale, which is the smallest HUC scale available and more accurately identifies the watershed areas corresponding with the location of the projects' centroids compared with other HUC scales. Mapping credit need was achieved by generating a point layer representing the centroid locations for each project segment, with each point containing the estimated needed credits attribute for its corresponding segment (see step 4A in Figure 4.1). These centroid points and their corresponding estimated credits were then aggregated and joined to each corresponding HUC 12 polygon. The joined credit need includes segments both in and outside of impaired catchment areas. However, we provide a description of credit needs specifically for projects within impaired catchments.

Once VDOT's estimated credit need has been calculated for all HUC 12s using the described methodology, we next compare the estimated credit need with the total available credits in Virginia's NPS WQT program as of May 2021, including pending credits in the process of being approved, to identify locations where credit supply will or will not be adequate to support VDOT's credit needs. This was done by spatially joining the nutrient credit banks and corresponding available credits to the HUC polygons to add up the total available credits for each HUC. The project segments, with their respective credit needs contained in the project segment attributes, are matched to the different HUC layers, as was done with the nutrient credit bank credits, to sum the possible credit need at each HUC. The aggregated credit need is subtracted from the aggregated number of available credits resulting in either a positive total, meaning a surplus of credits exists, or a negative total, meaning there is not enough credits currently available to meet the future credit needs at that HUC level (assuming trades across HUC boundaries is not possible). This process is repeated for HUC 12, HUC 10, HUC 8, and HUC 6 polygon layers as the regulations encourage purchases from the closest applicable bank or an upstream bank when runoff from the project discharges into impaired streams.

4.2.1 Statewide Impaired Catchment Layer

In order to identify VDOT projects located within areas directly draining to impaired waters for dissolved oxygen, benthic community, chlorophyll-a, or nutrients, semi-automated workflows were developed using ESRI's ArcGIS ModelBuilder. The data used in this process is detailed in Table 4.1.

Table 4.1: Spatial Data Used in Delineation of Areas Draining to Impaired Waters

Name	Type	Resolution/ Scale	Source
Digital Elevation Model	Raster	10m	USGS National Elevation Dataset (NED)
Streamflow Lines	Vector (line)	1:24,000	USGS National Hydrography Dataset (NHD) Plus High Resolution
Impaired Streams	Vector (line)	1:24,000	Virginia Dept. of Environmental Quality (DEQ)
8-digit Hydrologic Unit Code Watershed Boundaries	Vector (polygon)	1:24,000	USGS National Hydrography Dataset (NHD) Plus High Resolution

The workflow for developing the impaired catchment areas is comprised of four steps. First, the digital elevation model (DEM) is hydrologically conditioned so that flow across the landscape is enforced and corresponds with the NHD streamflow lines. This layer is known as a hydroDEM. Second, flow direction rasters (grids), are generated that specify the direction of water flow in each cell of the hydroDEM. Third, the ArcGIS Basin tool is used to delineate all of the areas draining to NHD streamflow lines. And fourth, impaired catchments are identified by intersecting the impaired streamflow lines with the catchment layer. Because this workflow is computationally intensive, these steps were performed on the NHD streamflow lines within a single HUC 8 polygon at a time. Once processing is complete for all of the impaired catchment areas in Virginia, the impaired catchments are merged into a single layer. An example of the workflow is presented in Figure 4.2.

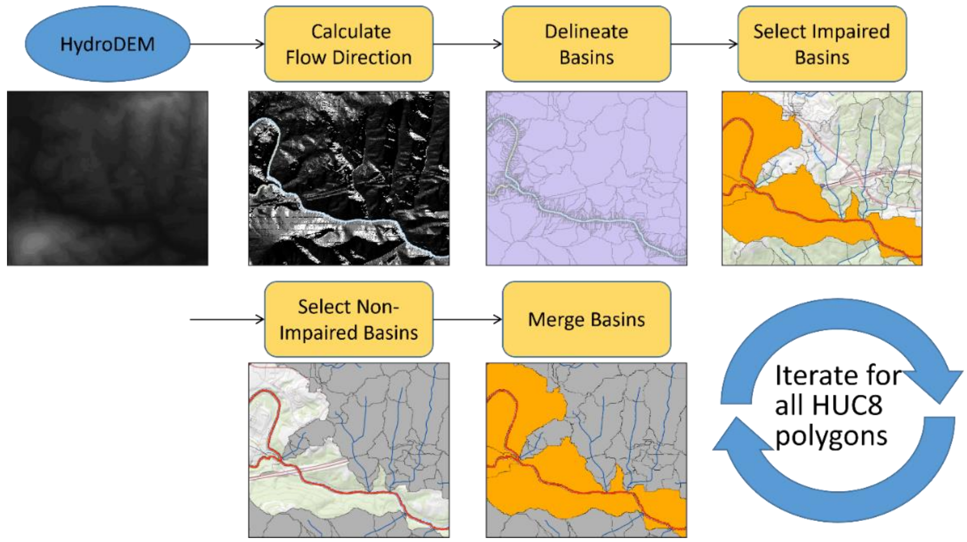

Figure 4.2: Geospatial workflow for development of impaired catchments.

4.2.2 Datasets

The datasets used in the development of the methodology are described in Table 4.2, with additional description provided thereafter.

Table 4.2: Datasets Used in Credit Need Estimation Methodology

Name	Type	Resolution/ Scale	Source
Virginia Department of Transportation Planned Project Dataset	Vector (line)	NA	Virginia Department of Transportation (VDOT)
Nutrient Credit Bank	Vector (point)	NA	RIBITS
12, 10, 8, and 6-digit Hydrologic Unit Code Watershed Boundaries	Vector (polygon)	1:24,000	USGS National Hydrography Dataset (NHD) Plus High Resolution
SSURGO Soils Dataset	Vector (polygon)	1:12,000 - 1:63,360	NRCS/SSURGO Downloader
Streamflow Lines	Vector (line)	1:24,000	USGS National Hydrography Dataset (NHD) Plus High Resolution

Impaired Streams	Vector (line)	1:24,000	Virginia Dept. of Environmental Quality (DEQ)
Digital Elevation Model	Raster	10m	USGS National Elevation Dataset (NED)
Land Cover Dataset	Raster	1m	Virginia Geographic Information Network (VGIN)

The VDOT roadway dataset contains centerline vector features and associated attributes for 1,878 planned projects located across Virginia. The projects vary in length, footprint, and type (e.g., roadway widening, shoulder widening, adding rumble strips, pedestrian trails, etc.) and are not confined by HUC boundaries. A review of the project descriptions suggested that the projects in the dataset are redevelopment-type projects in nature, involving the improvement of existing infrastructure on land that has previously been developed. Projects in the dataset that were deemed to most likely not qualify for credits, such as street lighting, roadway resurfacing, and sidewalk installations, were filtered out from dataset. Projects were also filtered out if corresponding attributes indicated the given projects were already completed. The remaining 145 projects, comprised of 535 project segments (see step 1 in Figure 4.1), were used for the credit need estimation.

A nutrient credit bank point shapefile containing available nutrient credit banks was obtained from VADEQ in May 2021. Figure 4.3 illustrates the locations of project segments and nutrient credit banks across Virginia. Pending banks may have some approved credits for sale. Nutrient credit banks are categorized as either approved for selling credits or are pending approval as of May 2021.

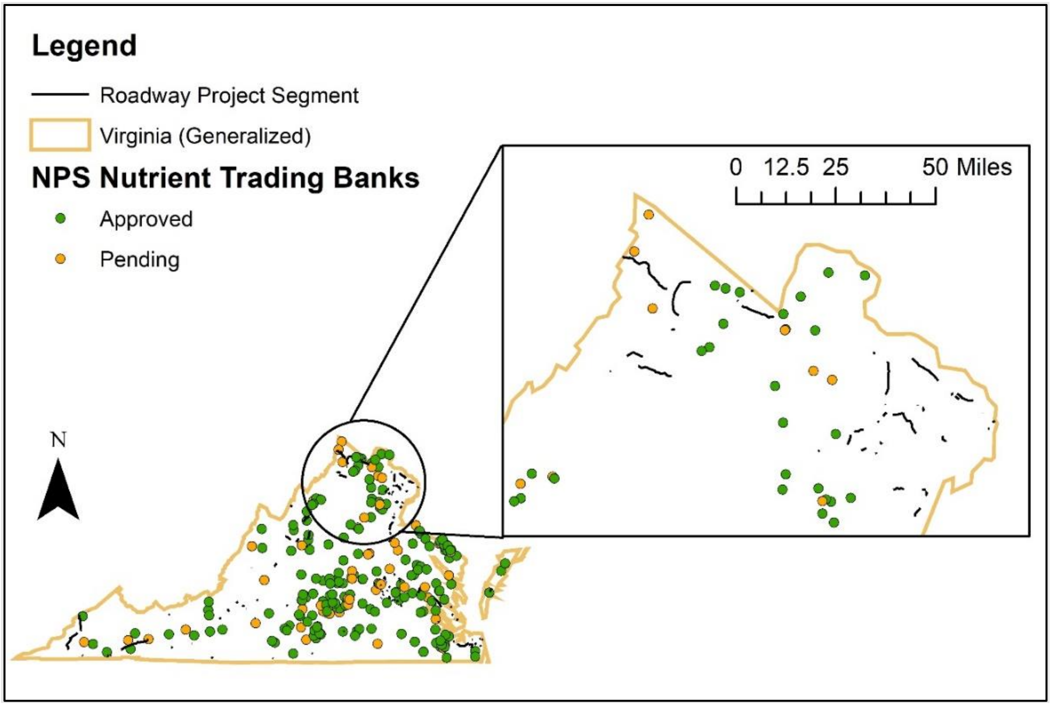

Figure 4.3: Project vector line segment data from the Virginia Department of Transportation.

The streamflow lines and impaired streams datasets (impaired for dissolved oxygen, benthic community, chlorophyll-a, or nutrients) were used along with a 10-meter DEM in the development of "impaired catchment" polygons, which were requisite for including project segments that discharge directly to impaired streams in the methodology. Local nutrient TMDLs were excluded from this methodology because they cover a small area, with the median TMDL area being only 14 square miles and the total combined TMDL areas only cover approximately 6% of the state land area. TMDL areas are available through VADEQ's NPS Nutrient Trading data viewer tool ("NPS Nutrient Trading Data Viewer," n.d.), and projects located in these TMDL areas can still participate in trading, provided that a bank is collocated upstream of the project in the corresponding TMDL area.

4.3 Results

4.3.1 Credit Need Estimation

The results of the credit estimate identify locations and upper bound quantities of credits VDOT will likely need for its planned projects within the next six years. Figure 4.4 shows the location of the estimated credit need for planned VDOT project segments. Credit need quantities are mapped on a HUC 12 scale and differentiated by color shades, with higher quantities of credits needed corresponding with darker shades of red.

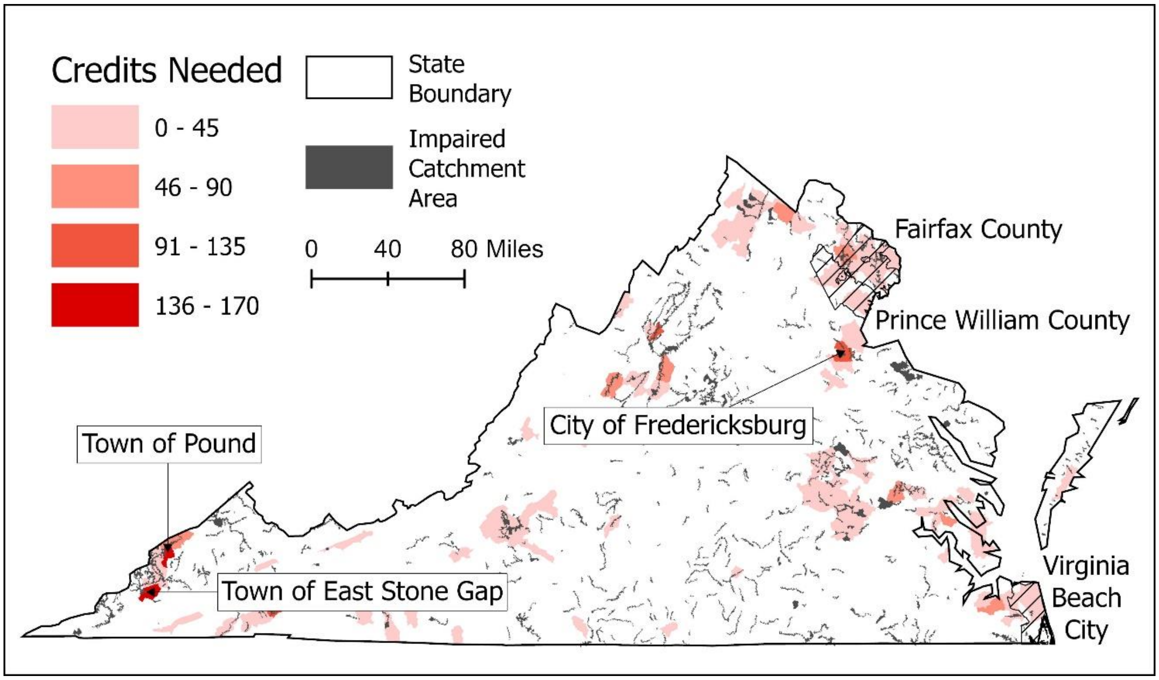

Figure 4.4: Estimated credit need for VDOT 6-year improvement project segments.

The results indicate that VDOT's water quality credit need is spread throughout the Commonwealth, with isolated areas of high credit need (more than 100 credits). These isolated areas of highest credit needs do not correspond with TMDL areas and include locations near the Town of East Stone Gap (162 credits), the Town of Pound (138 credits), and the City of Fredericksburg (120 credits) (see Figure 4.4). Approximately 66% of the HUC 12 polygons with estimated credit need correspond with urbanizing areas with a population ranging from approximately 6,470 to 282,250 people, based on ESRI 2020 population estimations based on ESRI's 2021 vintage time series population estimate (ESRI 2021). VDOT project segments corresponding with the highest population centers (Fairfax County, Prince William County, and Virginia Beach City) have an estimated 266 needed water quality credits compared with the total Commonwealth-wide estimated need of 2,664 credits to meet water quality regulations. The observed clustering of these projects in urbanizing areas is consistent with the findings of Saby et al. (2021b). The results are also appropriate given that the projects included in the estimate are roadway projects which may run through rural areas to connect population centers together, but are also concentrated in urban areas. We might expect greater clustering of projects if other types of development projects, such as commercial developments, were included in the estimate.

The impaired catchment areas are of particular interest due to the stricter trading restrictions that are applied to them. We summarize the distribution of planned project segments used in the estimate across HUC 12 watersheds and impaired catchments is summarized in Table 4.3.

Table 4.3: Distribution of Planned Project Segments Across Impaired Catchments and HUC 12 Watersheds in Virginia

Number of Project Segments	Number of HUC 12 Watersheds in Virginia	Number of HUC 12 Watersheds Containing Impaired Catchments	Number of Planned Project Segments in Impaired Catchments	Number of HUC 12 Watersheds Containing Planned Project Segments	Number of HUC 12 Watersheds Containing Project Segments in Impaired Catchments
535	1,285	753 (59%)	129 (24%)	111 (9%)	35 (3%)

We observe that 59% of Virginia's HUC 12 watersheds contain impaired catchment areas. The results indicate that 24% of VDOT's planned project segments used in the estimate are located within these impaired catchment areas, but these project segments fall in only 3% of the total HUC 12 watersheds. The total credit needs associated with project segments in impaired catchment areas is 463 credits, approximately 20% of VDOT's overall estimated credit need. Virginia regulations require the buyer (VDOT in this case) to purchase credits upstream of the project, if possible, or within the same HUC 12 before being able to purchase credits from more distant banks. Thus, a banker that develops a new nutrient credit bank within these impaired HUC 12 polygons may be the sole supplier of credits to VDOT for those projects.

4.3.2 Comparison of Estimated Credit Need with Current Credit Supply

To assess VDOT's impact on the current supply of credits, the estimated VDOT credit need was aggregated with the current (May 2021) credit supply and mapped at HUC scales ranging from HUC 12 to HUC 6, which coincide with Virginia's trading hierarchy. The results show the locations of HUCs containing VDOT's unmet credit need (shaded in red) and HUCs with remaining credit supply (shaded in blue) after accounting for VDOT's credit needs, as illustrated in Figure 4.5.

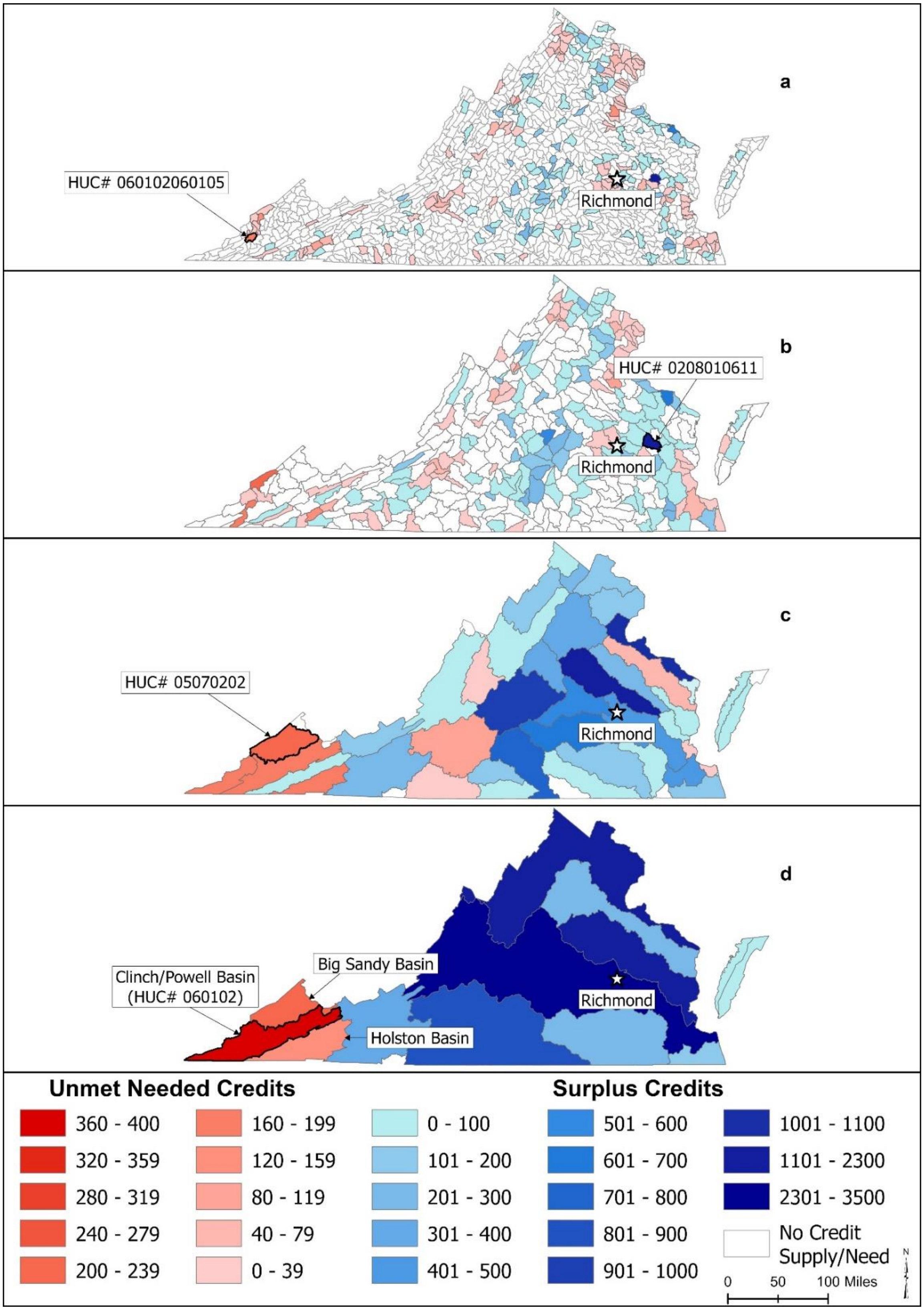

Figure 4.5: Aggregation of estimated credit needs and credit supply at a) HUC 12 scale, b) HUC 10 scale, c) HUC 8 scale, and d) HUC 6 scale.

Figure 4.5 shows the number of surplus credits increases as the scale increases from the HUC 12 scale to the HUC 6 scale, as expected. At the HUC 12 scale, there are multiple HUC 12 watersheds estimated to have unmet credit needs, based on VDOT project segments, summing to a total of 2,338 credits. However, there are other HUC 12 watersheds estimated to have a remaining supply of credits, with the combined surplus totaling 10,866 credits. This suggests that credits are likely to be available at larger HUC scales. The results also reveal that collocation of both project segments and banks predominantly occurs at the HUC 8 level where the majority of HUC 8 watersheds are projected to have enough credits to meet VDOT's credit needs. At the HUC 8 level, there is roughly a 50% reduction in unmet credit need across Virginia compared with unmet credit need at the HUC 10 level.

Looking more closely at Figure 4.5a, the planned project segments reside within 252 of the HUC 12 polygons, or 19.6% of the total number of HUC 12 polygons within Virginia. Out of those polygons, 41.3% are projected to have unmet credit needs, with the greatest number of unmet credits observed (162 credits) being associated with HUC# 060102060105, located in southwest Virginia, resulting from approximately 26 miles of roadway shoulder installation and no currently existing collocated banks from which to purchase credits.

Figure 4.5b-d presents similar information at other HUC scales. In Figure 4.5b, the maximum credit surplus observed at an individual HUC 10 polygon is 1,628 credits, located approximately 25 miles east of the City of Richmond at HUC# 0208010611. However, despite being only 25 miles away from the City of Richmond, Richmond is in another HUC 6, meaning that projects in city limits would not be able to purchase credits in this HUC 10. Figure 4.5c identifies approximately 24 percent of the HUC 8 polygons as having unmet credit needs. The maximum number of unmet credits is 211, located in HUC# 05070202 along Virginia's southwestern border. Figure 4.5d indicates a total of 9,250 remaining credits (excluding the southwest region) estimated at the HUC 6 scale. However, 724 needed credits were found to not be met with the current credit supply in the southwest region of Virginia. The maximum unmet need in a HUC 6 polygon in this region is 372 credits (HUC# 060102). There are currently no TMDL areas restricting trading in the southwest region. While we observe a total of 8,526 remaining credits across the state, trades are not permitted across HUC 6 boundaries. The results of this analysis suggest that additional credits will need to be generated in HUC 6 areas with indicated unmet credit needs to support planned VDOT projects.

We also estimated unmet credit need associated with VDOT's planned project segments located in impaired catchment areas (Table 4.4) and the potential value of credit sales associated with these potential trades. According to the trading hierarchy established for such cases, VDOT would need to purchase credits from banks nearest to these project segments.

Table 4.4: Credits Needed for Planned VDOT Project Segments in Impaired Catchments and HUC 12 Polygons

Location of Project Segments	Number of Needed Credits	Unmet Needed Credits[4]
Impaired catchments[1]	463	392
Impaired HUC 12 Watersheds[2]	2,263	1,955
All HUC 12 Watersheds[3]	2,664	2,338

[1] Impaired catchment areas reside within HUC 12 watersheds.
[2] HUC 12 watersheds that contain impaired catchment areas; project segments reside within the HUC 12 watershed and either within or outside of impaired catchment areas.
[3] Includes all HUC 12 watersheds containing project segments.
[4] Unmet credit need is associated with project segments. Unmet credits are determined by subtracting the number of needed credits from the available credit supply in HUC 12 watersheds that correspond with the project segments.

Approximately 25% of VDOT's planned project segments (129 project segments) were identified as being located within impaired catchment areas and comprise 16.8% of the unmet credit need (392 credits) estimated in HUC 12 watersheds (Table 4.4). Approximately 22% of these needed credits correspond with project segments located in the southwest region of Virginia (refer to Figure 4.5d). According to the Maryland-DC-Virginia Solar Energy Industries Association (MDV-SEIA), recent (2020) prices for a credits representing one pound of TP in Virginia ranged between $10,800 and $24,000 in US dollars (MDV-SEIA, 2020), which are similar to the 2014 price ranges reported by Nobles et al. (2017) and seek to account for the perpetual nature of the credits (Saby et al. 2021a). However, VDOT indicated that their current contracts range between $7,747 and $46,000 in US dollars (VDOT regulatory manager John Olenik personal correspondence, July 21, 2021). Applying the 2020 range of credit prices to the calculated unmet credit need for project segments in impaired catchments, and assuming that 1) resources for generating credits are available in the HUC 12 polygons, and 2) purchasing credits is more economical than meeting all the treatment requirements on site (Nobles et al. 2017), the range of potential credit sales is between $4.2 million and $9.4 million dollars for the 392 needed credits (Table 4.4).

4.4 Discussion

4.4.1 Benefit for Buyers, Sellers, and Regulators

An ahead of time estimate of water quality credit need can help large credit buyers understand their own credit needs, helping them to make more informed and strategic decisions. In the case with VDOT, the estimation informs the location and quantity of credit needs. The buyers (e.g., VDOT) in turn can use the estimate to help reduce the supply uncertainty they may experience by communicating their credit needs to bankers to help bankers position future banks in locations that satisfy the need. In Virginia, an ahead of time estimation may be beneficial for buyers with projects located in the southwest Virginia where a total credit need from VDOT alone is estimated to exceed current supply by 724 credits and where buyers are permitted to look for additional credits beyond their respective HUC 6 basins. Credits are likely in limited supply in the southwest region of Virginia because much of the region is already forested and there are fewer opportunities for credit banks to be created through agricultural conversion practices.

While the credit estimation, based on planned projects, would primarily benefit large credit buyers, it could also benefit small credit buyers. For example, many of VDOT's future projects will require a large number of credits in comparison with the credit needs of a small developer. A banker would probably be more motivated to try to site a new credit generation project nearer a larger VDOT project compared with a small development project, acknowledging there are many factors involved with siting banks, including the price and availability of land. Yet the smaller developer would likely benefit as more credits are generated. At least in Virginia, the trading rules are flexible enough that even if the future bank was not adjacent to the small development project, the developer would most likely still be able to purchase credits from the nearest bank or another nearby bank. Furthermore, the addition of credit need information from large credit buyers may help to encourage competition and a credit cost reduction, which is also of benefit to the large and small buyer. However, it must be noted that reduction in credit price could make credit generation less desirable for some potential bankers, which could in turn lead to shortages in credit supply.

The seller can leverage the information provided by the credit need estimation to maximize credit sales and credit generation, thereby reducing their own uncertainty about future need for credits. The credit estimation supports the effort to maximize credit sales by identifying the location and quantity of future credit needs, allowing for new banks to be developed nearer the planned projects. Furthermore, the estimation can also be used in connection with other geospatial datasets, including land cover, water quality, or state conservation datasets, to help sellers identify areas where credit production can be maximized and most environmentally beneficial, while coinciding with the locations of the planned projects.

The results communicate the locations and quantity of probable credit need and help provide regulators with insight as to where development is likely to occur. While the projects used in this methodology did not have specific estimated completion dates, data with more specified dates could be used in the estimation allowing credit need to be tracked over time. In addition, comparing historical and current purchase records to the estimation results can help regulators identify the actual rate at which participants end up buying credits, which can be helpful in identifying areas of program transaction processes or policy improvements.

4.4.2 Impact on the Environment

The results of the credit estimation can also be used to identify possible environmentally at-risk locations resulting in high concentrations of credit purchases. For example, the estimation results are based on calculated nutrient loads for each of the project segments included in the estimate. Regulators could use these loads from the estimation as an input in environmental models, from which the potential environmental impacts could be estimated as well as the prioritization of water quality monitoring locations. Program policies could then be reevaluated from an environmental perspective.

4.4.3 Opportunity for Implementation into Existing WQT Decision Support Systems

There are limited tools and resources currently available to assist buyers and sellers with participation in WQT programs, and none of the current tools have the ability to estimate future need. The two most prevalent tools available in Virginia's WQT program are RIBITS and CBNTT as described previously. Both of these existing tools are potential candidates for implementing an ahead of time credit estimation methodology. The RIBITS tool already tracks the number of available credits at each of the existing banks. The CBNTT already has the functionality required to estimate nutrient loads and credits. With a modification to the CBNTT's marketplace platform, buyers could upload planned projects, estimate the credits required, and connect with sellers. Information on available credits at existing banks could be pulled into the CBNTT from RIBITS via an application programming interface (API). The estimate would then allow the sellers to move into preferred locations and estimate the possible number of credits that could be generated at the new banking locations. Developing these tools could also potentially allow for new sellers other than traditional bankers to participate, including stream restoration projects and enhanced agriculture, who may not have the resources to participate otherwise. Adding ahead of time credit need estimation capabilities to the existing tools would theoretically increase the usage of the tools, providing an increased return on investment from the perspective of the agency responsible for the tool's development.

VADEQ has developed and manages a web map tool called the "NPS Nutrient Trading Data Viewer" ("NPS Nutrient Trading Data Viewer," n.d.). This web map contains static layers depicting HUC levels, impaired stream segments, Virginia counties and localities, major TMDL areas, and NPS banks which are updated weekly by VADEQ. This web map tool would make a suitable interim solution in that it can host and display the individual needed credit estimation layers along with the other data layers in a single, central location. This would allow users to view the estimated results with the other important datasets together, allowing for more informed decision-making. However, it would need to be noted that the estimation results may not update at the same rate as the NPS bank information, which could cause confusion and would subsequently need to be addressed.

4.4.4 Opportunity for Future Research

VDOT, of course, is not the only credit purchaser in Virginia's WQT program. While data is not currently available to estimate VDOT's market share, we expect that additional unmet credit needs might be seen, especially in existing urban areas, with the inclusion of other buyers. Additional research exploring methods for identifying development projects for other public or private agencies could help to complete the picture on nutrient credit needs in coming years.

Additional research is needed to create methods for estimating needed credits for projects in local TMDL areas. In this study, we assumed that the relatively small spatial extent of TMDL areas (6% of Virginia's land area) would not limit the buyers' ability to purchase credits for projects located in those areas. Including local TMDLs in the estimate would not change the resulting unmet credit need, but it may provide a more accurate comparison of credit surpluses or potential unmet credit need if credit supply is not collocated with a given project in a local TMDL.

The processes in the methodology are semi-automated and still require some manual steps. Through future work, they could be fully automated. If fully automated, they could be easily rerun when new project data or credit supply data becomes available to update the ahead of time needed credit estimate. That said, the processing steps as currently implemented are computationally intensive requiring several days of processing on a typical desktop computer. Opportunities to optimize the processing for computational efficiency may be possible and should be explored if the methodology is used for regular and frequent estimation.

Finally, there were some assumptions made in how to represent the VDOT planning level data in the GIS analysis. For example, it is possible that an existing three-lane road could be estimated as a two-lane road. More work to specify project details from available information in other data resources could result in further improvements to improve the accuracy of the estimation results.

4.5 Conclusions

This research presents a GIS-based methodology for estimating credit needs for large agencies, like Departments of Transportation, based on their projects planned in coming years. Quantifying future credit needs can help reduce the uncertainty associated with matching future water quality credit need in WQT programs, potentially helping to further establish these markets. The methodology was demonstrated using planned project data from the Virginia Department of Transportation, using the Virginia Runoff Reduction Method to estimate required post redevelopment nutrient load reductions for each of the planned projects in the agency's 6-year planning horizon. Water quality credits were calculated for each of the georeferenced project segments. Then these credits were aggregated at the HUC 12, HUC 10, HUC 8, and HUC 6 scales. This credit need was subsequently subtracted from credits available at the time of this analysis, giving a measure of watersheds remaining credit supply or unmet credit need.

Based on the results of the credit estimate, a quarter of the Commonwealth's HUC 6 basins lack available credit supply (724 credits) to meet VDOT's projected credit need. This may impact the planned projects because, under current regulations in Virginia, VDOT would not be permitted to purchase credits from an adjacent HUC 6 if the HUC 6 where the project is located does not have available credits. Our results show that, across the Commonwealth, Virginia's WQT program has a surplus of credits (8,526 credits) after accounting for the possible credit needs from VDOT over the next six years. It is unknown what fraction VDOT represents in the overall WQT market, but we believe it is safe to assume sufficient credits exist at the state-level to support buyer's needs. However, the potential unmet credit need at the HUC 6 level from VDOT's planned projects suggests the need to develop additional credits in the southwest region of the state. The current trading rules, while striving to encourage both participation and environmental integrity, should continue to monitor for adverse effects for credit purchases.

Currently available WQT tools do not provide ahead of time estimation of needed credits. This research can be used to include needed credit estimation as part of these existing tools. Doing so would provide a more streamlined approach to data collection, estimation, evaluation, and regulation, with the potential to increase the existing tool's use. Further research is required to quantify credit needs from buyers beyond VDOT, which would provide a clearer understanding of the total credit need across Virginia. Future research is also needed to determine if and how the ability to estimate future credit need might impact credit supply. It is anticipated that credit bankers may be able to respond to estimated credit need through the construction of new credit banks, which would also help regulators evaluate the effectiveness of their trading policies. Finally, additional research is needed to identify ways to understand the impact of estimating credit need on credit supply, which could further motivate creating accurate, spatially explicit credit need estimates like the one described in this paper.

Chapter 5

5. Conclusion

5.1 Research Contributions

This dissertation advances our current understanding of stormwater compliance practices, challenges, and opportunities for cost savings. Novel datasets were used to characterize stormwater compliance challenges and opportunities, including inspection and condition rating data from VDOT's BMP inspection and condition rating system, land development project and compliance data from the City of Roanoke in Virginia, and VDOT's 6-year improvement roadway project dataset. There are several contributions from this research, including 1) a detailed characterization of temporal stormwater basin condition patterns and specific condition issues identified to correspond with those changes, including basins that experience a rapid decline in condition, 2) a thorough characterization of nutrient credit usage by land developers in the City of Roanoke, 3) a novel land development water quality trading dataset, and 4) a GIS-based methodology for a statewide upper-bound estimation of future credit need. This dissertation highlights the need for tracking stormwater compliance practices, including water quality and quantity methods. Doing so makes it possible to evaluate outcomes of current practices and inform policy adjustments when undesired outcomes are observed.

Chapter 2 of this dissertation improved our understanding of how BMP conditions change over time and the specific condition issues associated with condition change. This work contributed a methodology that was used to identify frequent, specific issues that influence BMP condition. The methodology was further used to identify BMPs that experienced a rapid decline in condition. This work identified specific differences in the issues associated with basins that experienced a rapid decline in condition rating compared with the issues of basins in the same declined state, which has previously not been studied using data-driven approaches. This chapter also contributed several important considerations for managing BMP inspection and condition rating data quality. Ultimately, the challenges associated with managing BMPs, as described in this chapter, help to motivate the adoption of maintenance-free stormwater quality compliance options, such as WQT.

Chapter 3 of this dissertation deepened our understanding of how nutrient credits are being used by land development projects to meet stormwater treatment requirements. This chapter describes the methods used to harvest, collate, and evaluate land development project data from the City of Roanoke's land development project permit tracking system. This work identifies the use of nutrient credits as the primary method used by land developers to achieve compliance with stormwater requirements. This finding informs the current understanding of participation in water quality trading and highlights the beneficial use of these programs as a cost-effective alternative to traditional BMPs. Through the comparison of compliance preferences, this work identifies factors that prompted the participation of Virginia's water quality trading program to achieve stormwater compliance. The work also highlighted spatial trading patterns that may have negative impacts to the quality of local urban streams.

Chapter 4 of this dissertation advanced our understanding of potential future market conditions in Virginia's WQT program. This study contributed a novel GIS-based methodology for estimating statewide upper-bound future credit need. This methodology leveraged automation techniques to systematically apply the Virginia Runoff Reduction Method to estimate credit need for VDOT's 6-year improvement projects. By mapping the results of the methodology, regions within Virginia were identified where the amount of currently available credits would not be adequate to meet VDOT's future credit needs. This work facilitates the coordination of credit generation projects with projects in need of credits, accounting for regulations that encourage the collocation of projects with credit generation sites where runoff from projects would discharge to impaired streams.

Together, the findings from this dissertation add new, detailed characterizations of stormwater compliance practices to the literature. This dissertation advances proactive BMP maintenance practices that can reduce the number of costly BMPs due to missed or foregone maintenance, highlights favorable circumstances associated with cost-effective participation in water quality trading, and improves understanding of how to balance credit supply levels with estimated future credit need at a state-wide scale. The dissertation describes useful sources of data for evaluating stormwater compliance and contributes new datasets that may be useful for future study. Due to the nature of the datasets, all datasets generated from this research are available upon request.

5.2 Opportunities for Future Research

This dissertation identifies several opportunities for future research. These opportunities are organized by the corresponding dissertation chapter that supports the research needs.

Chapter 2 identifies the need for large language models to be used to extract additional information contained in the free response comments of VDOT's BMP inspection dataset. This would add additional clarification to the BMP issues commonly observed during inspection. Additionally, image evaluation methods could be developed to assist with inspection data quality verification. BMP inspection data is currently difficult to verify, and limited methods are available to achieve that objective.

Chapter 3 highlights the need to account for water quality trading participation in stormwater models. In Roanoke, it was observed that many development projects that used credits for water quality compliance ultimately achieved stormwater quantity compliance through means other than structural BMPs. It is likely that municipalities' stormwater models do not account for such impacts in their stormwater models. Additional research is needed to evaluate the impact that concentrated participation in water quality trading is having or could have on existing stormwater collection systems and infrastructure. Additionally, future research is needed to evaluate possible water quality impacts resulting from trades. The dataset collated as part of Chapter 3 can be useful for that work as it identifies the specific locations of projects that used credits and the number of credits purchased at each site.

Chapter 4 emphasizes the need for tools to be developed to facilitate the coordination participants in water quality trading programs, including both credit buyers and credit sellers. The methods in Chapter 4 were semi-automated. This was in part due to the challenge of working with very large, high-resolution datasets. There is a need to improve computational efficiency to be able to generate accurate results on a large scale. Chapter 4 described several limitations associated with the associated methods. Future research could investigate the use of other data sources, including remotely sensed data to improve the accuracy of estimating statewide credit need. Such data may prove to capture the change in roadway footprints better than using manually drawn GIS data. Furthermore, the addition of methods to estimate credit need for non-linear roadway projects, such as development projects would enhance the methods and enable more projects and participants to be captured in the credit need estimate.

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