Assessing Nutrient Credit Trading and Local Water Quality in the Rivanna Watershed

by

Kettie Holland Rupnik

Dr. Kateri Salk, Adviser

April 24, 2020

Masters project proposal submitted in partial fulfillment of the

requirements for the Master of Environmental Management degree in

the Nicholas School of the Environment of

Duke University

Executive Summary

The purpose of this report is to evaluate nutrient credit trading within the Rivanna watershed and to evaluate potential impacts to local water quality. Currently, regulations in Virginia allow for developers in urbanized areas to purchase nutrient credits in lieu of installing post-construction best management practices (post-construction BMPs). Post-construction BMPs include green infrastructure, which help to reduce pollutants in urbanized stormwater runoff that would otherwise be discharged to receiving waters. This is of particular concern, as approximately 44 % of stream miles in the United States do not meet water quality standards, and a significant source of this pollution is from urbanization and land use changes associated with development (USEPA 2010).

To evaluate the impact of nutrient credit trading on local water quality, it is necessary to understand trends of nutrient credit trading, where the credits are being generated, and benefits that may not be recognized when purchasing nutrient credits instead of installing post-construction BMPs, particularly green infrastructure. This report presents a high-level overview of nutrient credit trading occurring within the larger James River watershed, and the local Rivanna watershed.

The first part of the report provides necessary background information, including the impact of development, land use changes, and urbanization on water quality. This section of the report also provides an overview of the municipal separate storm sewer system program under the Clean Water Act and the role that green infrastructure plays in treating urban stormwater and providing co-benefits to the community. A brief introduction to water quality impairments is also provided, and creates a lens for viewing the connection of impairments between the Chesapeake Bay, smaller watersheds, and the role of nutrient credit trading across watershed boundaries.

This is followed by a presentation of the pros and cons of nutrient credit trading programs for water quality. Specifically, those in favor of nutrient credit programs see them as a more cost-effective alternative method to conventional command-and control methods of pollution reduction. Those opposed to nutrient credits find that credit trading creates the opportunity for misplaced and misrepresented water quality benefits between local watershed and the larger watershed. While nutrient credit trading may help to reduce the overall pollutant load of nutrients to the Chesapeake Bay, trading may not provide local water quality benefits to the Rivanna watershed; particularly if credits generated in one watershed can be purchased by a project occurring in an adjacent watershed.

The third and fourth sections of the report define the objectives of the study, the materials, and methods used for data analysis. This includes the data gaps and limitations with the available data and overall trends in nutrient credit trading. The methods section of the reports highlights the approaches for compiling summary statistics of the data, conducting a time series and spatial analysis, and comparing costs of green infrastructure implementation compared to purchasing nutrient credits.

Lastly the report presents the results and conclusions from the research. The summary statistics show that higher loading (per pound) is being purchased for nitrogen credits than phosphorous credits, and that most projects are purchasing small volumes of nutrient credits (as compared to single large purchases). Results also show that nutrient credit purchases within the James River watershed are increasing over time. While most nutrient credits were purchased within the

watershed where they were generated, 32 % of the nutrient credits within the James River Watershed were generated outside of the watershed where the projects occurred, with over 90 % of the projects within the Rivanna watershed purchasing credits generated from outside of the watershed. This creates a discrepancy in which Rivanna watershed does not benefit from credits generated from outside of the watershed. Increases in nutrient credit purchases and nutrient credits across watershed boundaries may be the result of several factors. First, conservative estimates showed that the cost of purchasing nutrient credits was 30% cheaper than installing green infrastructure. Additionally, as available land availability decreases as a result of urbanization, projects may not have the space available to install green infrastructure. Lastly, several sub watersheds within the James River watershed do not have nutrient credit banks, meaning that they must purchase credits from outside of their watershed.

Based on the conclusion, the report informs several recommendations:

- Reporting of information in the nutrient credit ledgers should be improved. Specifically, nutrient credit banks should report on standard, editable forms, that are easy for data analysis. This information should also be made readily available to the public.
- The inequivalent pricing of nutrient credits in comparison to installing green infrastructure should be further evaluated. The pricing discrepancy may provide cost signals to developer, encouraging them to pursue the cheaper option, resulting in negative impacts to local water quality and co-benefits to communities.
- An in-depth policy analysis should be conducted to evaluate the impact of allowing nutrient credit trading across watershed boundaries impacts local water quality, and how this policy could be improved to benefit local and regional watersheds.

Contents

1. Introduction and Background

According to the United States Environmental Protection Agency (EPA), urban stormwater pollution is the primary cause of impairment of 13 % of rivers, 18 % of lakes, and 32 % of estuaries (USEPA 2010). Sources of stormwater pollution are largely separated into two main categories: point and non-point source discharges. Point sources are defined as pollutant sources where a single identifiable source of pollution from which pollutants are discharged can be identified. This encompasses discharges from municipal wastewater treatment facilities and manufacturing plants. Non-point sources are generated from an area where a single point of pollutant discharge cannot be identified. This may include land runoff, such as stormwater from urbanized areas, and agricultural runoff. A significant source of non-point source stormwater pollution results from urbanization, development, and overall land use changes (USEPA 2010).

Urbanization alters the hydrology of ecosystems in many ways. One of the most impactful ecosystem disruptors of urbanized systems is the transformation of pervious surfaces into impervious surfaces (Moyers 2001). Impervious surfaces reduce habitat for wildlife, alter soil composition, reduce ecological function, change geomorphic structures, degrade water quality and alter the hydrology of natural ecosystems (Figure 1; Walsh et al. 2005). With regard to stormwater management, impervious surfaces also increase the quantity and peak flows of runoff, which cause hydrologic impacts such as scoured stream channels to localized receiving waters. Additionally, a study by Barbec et al (2002) presents a positive correlation between the severity of stream degradation and the amount of impervious cover within the urban landscape. The negative impacts to water quality from increases in impervious surfaces is known as the "urban stream syndrome" (Meyer et al., 2005).

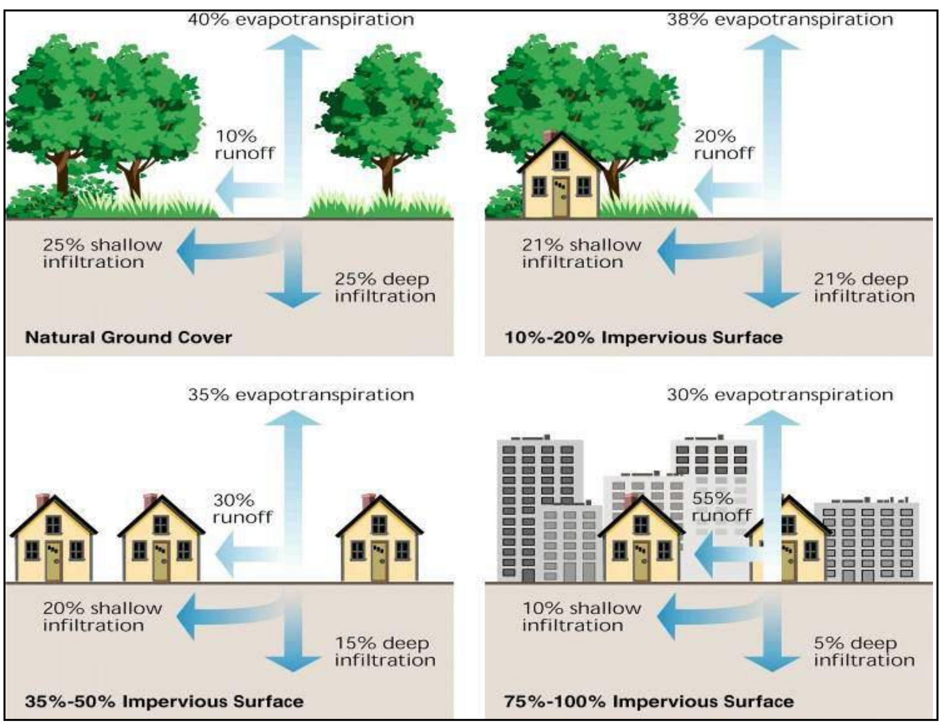

Figure 1. Stormwater in Natural, Suburban, and Urban Settings (EPA, 2010).

Another significant impact from urbanization includes localized and regional flooding. Specifically, development and land use changes increase flooding hazards, presenting ecological and public safety risks. Stormwater flow rates may double when the imperviousness of a space is increased by 10 % (Odefey et al., 2012). Over a ten-year span (1995 to 2015), flooding accounted for nearly half of all-natural hazard costs, worldwide (Colgan, 2017). Floods and storms were reported to have affected 3 billion people and damaged over 87 million homes (Colgan, 2017). In the United States alone, approximately 10,000 deaths have been attributed to flooding since 1990 and economic damages estimated at $7.1 billion nationally in 2001 (Odefey et al., 2012).

In consideration of the impact urbanization has on natural hydrology and public health, effective stormwater management is essential to communities. Over the past twenty years, the focus of urban stormwater management has shifted from grey to green infrastructure (Copeland, 2014). For example, communities first focused on ways to collected and convey stormwater quickly from urbanized areas to receiving waters to reduce flooding in communities and protect public safety (Copeland 2014). Although an important priority, there was little consideration of ecological impacts of this practice. Further research identified that through conventional grey methods, higher concentrations of pollutants were washed into receiving waters and less water was available for groundwater recharge (Walsh et al 2005). Current stormwater management methods focus on restoring the natural hydrology of the area and increasing rates of stormwater infiltration utilizing nature-based solutions, such as green infrastructure and low impact design (LID). Not only does green infrastructure increase groundwater recharge, it provides solutions to reduce localized flooding, among other benefits.

The Municipal Separate Storm Sewer (MS4) Program and Green Infrastructure

To control discharges of pollutants to receiving waters, EPA developed the National Pollutant Elimination System (NPDES) Program, under the Clean Water Act. The NPDES Program identifies point and non-point sources of pollutants and regulates these discharges through various programs. Many of the NPDES programs involve obtaining permit coverage and implementing procedures to control pollutant discharges. In 1990, EPA adopted regulations requiring urbanized areas with populations of 100,000 or more to obtain NPDES permit coverage under the Municipal Separate Storm Sewer (MS4) program. The MS4 program aims to prevent pollutants from being washed or dumped into the conveyance systems that lead to receiving waters. In 1999, under Phase II of the MS4 program, EPA required other entities and urbanized areas to obtain coverage under the MS4 permit, including smaller cities, universities, departments of transportation, prisons, and hospitals (USEPA 2010).

The Virginia Department of Environmental Quality (VDEQ) has been delegated authority from the EPA to implement and enforce the MS4 program within the State of Virginia. Among other entities, the City of Charlottesville and Albemarle County are covered under the Phase II General MS4 Permit (hereafter Permit) from VDEQ to control discharges from their respective MS4s. Under their MS4 permits, Albemarle County, and the City of Charlottesville are required to implement several programs, including the six minimum control measures, through the use of various best management practices (BMPs). BMPs are defined as schedules of activities, prohibitions of practices, maintenance procedures, and structural and/or managerial practices, that when used singly or in combination, prevent or reduce the release of pollutants and other impacts to receiving waters (USEPA 2010).

Structural stormwater BMPs are items that are engineered, designed, and built to collect and treat stormwater runoff. This can be achieved either by reducing flow rates, removing pollutants, or both (USEPA 2010). Structural BMPs include extension and detention basins, silt fences, gravity separators, rocky swales, vegetated buffers, and others. Green infrastructure is another category of structural BMPs, focusing on restoring the natural hydrology of an area by reducing the velocity of stormwater flow and encouraging filtration and infiltration into the ground. Examples of green infrastructure include rain gardens, tree boxes, pervious pavement, constructed wetlands, bio-swales, infiltration basins, and other manufactured devices (e.g., stormceptors) (USEPA 2010).

Total Maximum Daily Loads (TMDLs)

The Clean Water Act grants the authority for delegated states to develop water quality standards, which are the benchmark against which monitoring data are compared to assess the health of waters. When a water body is in alignment with the WQS, it is deemed fit to support the protection of wildlife and recreation in and on the water (USEPA, 2000). On the other hand, when water bodies do not water quality standards, the CWA requires that these water bodies be assessed for impairment. EPA then works with the states to identify the water bodies that are in need of a Total Maximum Daily Load (TMDL), which EPA defines as, "the maximum amount of a pollutant that a water body can receive and still meet the water quality standard, with an allocation to all pollutant sources" (2001).

Chesapeake Bay and James River Watersheds and TMDLs

Virginia's streams and rivers include approximately 100,923 miles and are divided into nine river basins (VDEQ, 2018). Of these nine river basins, four of them ultimately discharge to the Chesapeake Bay. The Chesapeake Bay is one of the largest estuaries in the United States and is a significant source of ecological and economic resource for the east coast. In December 2010, EPA approved a TMDL for the Chesapeake Bay, for nutrients (phosphorus and nitrogen) and sediment. The current TMDL requires load reductions for nitrogen, phosphorus, and sediment by 25 %, 24 %, and 20 %, respectively by 2025 (EPA, 2011).

The James River Basin is the largest of Virginia's Chesapeake Bay watersheds, encompassing urbanized and rural areas in addition to protected areas, like national forests (Commonwealth, 2005). The James River covers approximately 24 % of the state and is divided into three sub-watersheds (Upper James, Middle James, and Lower James River sub-basins) (VDEQ, 2018). The Rivanna River and its watershed are located within the Middle James River basin.

The Rivanna River and watershed are located within central Virginia and encompass approximately 760 square miles (TNC, 2002) (Figure 2). VDEQ has identified several segments of the Rivanna River that are impaired, resulting in the development of bacteria and benthic TMDLs. Although the Rivanna River is impaired, it is not impaired for phosphorus or nitrogen (hereinafter referred to as N and P, respectively), which are the constituents of impairment for the Chesapeake Bay. Therefore, nutrient credits can be traded within the Rivanna watershed,as part of the nutrient reductions to the Chesapeake Bay, regardless of impairments of other parameters.

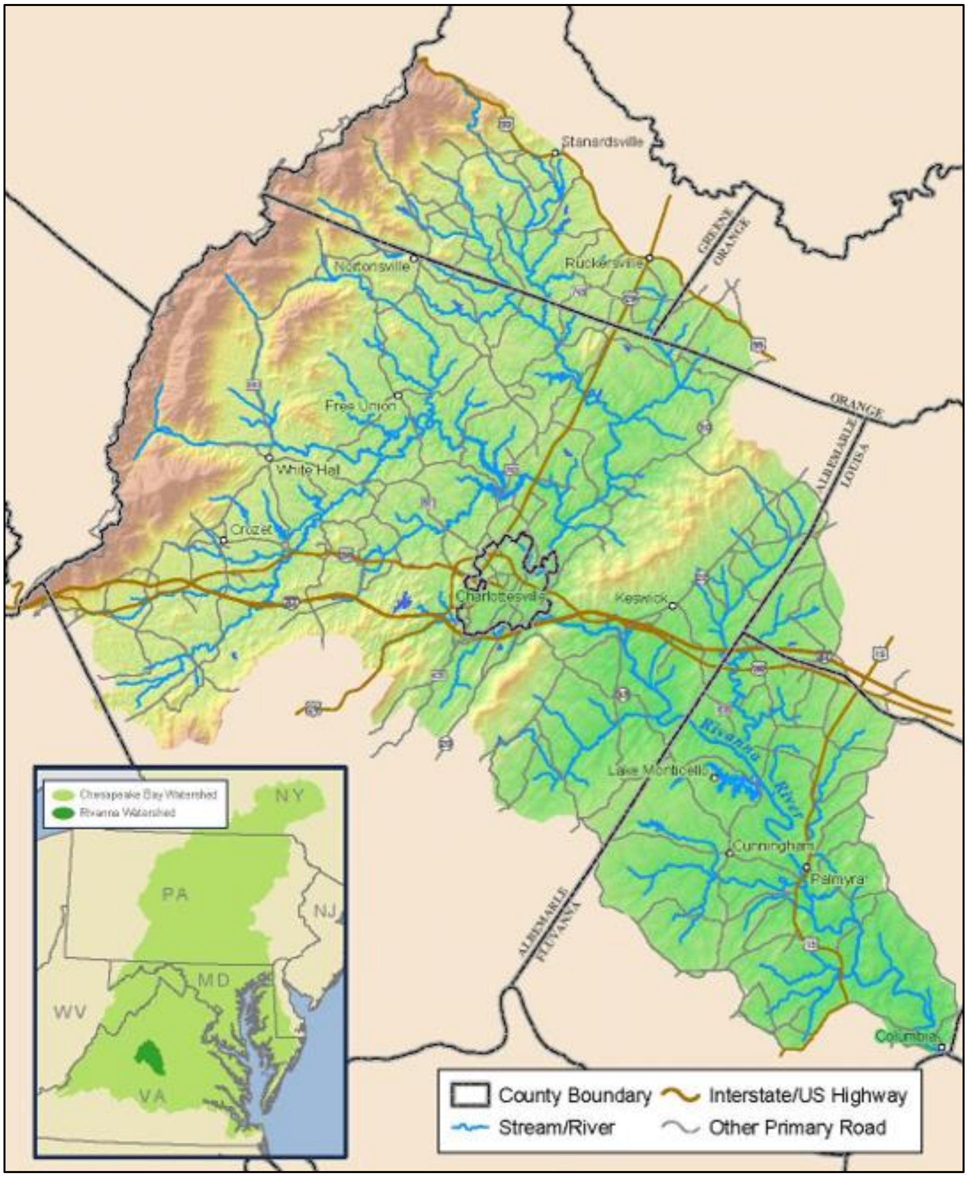

Figure 2. Map of the Rivanna River Watershed (Rivanna River Basin Commission ND).

Land Use within the Rivanna Watershed

Development and urbanization activities within the localities and other non-point sources of pollution (i.e., agriculture) have contributed to water quality impairments within the Rivanna River. Of the Rivanna River watershed, approximately 72 % is forested, 22 % is open land, and 3.2 % is impervious (RRBC, 2009). During a rainfall event (assuming 1 inch of precipitation), one acre of forest will release 750 gallons of runoff in comparison to an acre of impervious surface, which will release 27,000 gallons of runoff under similar conditions (Penn State Extension). Therefore, it is estimated that 61,371,000 gallons of runoff would result from one-inch of precipitation in the City of Charlottesville (City, 2017). Given the volume of stormwater discharged from the City of Charlottesville (City), and the negative impacts associated with increased impervious surfaces, the City has adopted codes through the MS4 regulations to reduce impacts from development.

Section10-22(a)(1) of the City code requires that when development or redevelopment projects disturb 6,000 square feet of land or more, post-construction BMPs must be implemented. The federal regulations require that the threshold of disturbance be 1 acre, thus, the City code is more stringent than federal requirements. However, developers have found it to be increasingly difficult to implement post-construction BMPs, given the lack of available space for installing larger on-site post-construction BMPs, such as retention ponds. To provide a cost-effective option and reduce nutrient loadings to the Chesapeake Bay, VDEQ has developed and implement a nutrient credit trading program.

Nutrient Banks

Nutrient banks and the practice of nutrient trading have recently gained significant attention as an alternative method to conventional command and control pollutant-reduction methods. Nutrient trading is described as a tool for controlling pollutant discharges to receiving water utilizing a market-based approach (Penn State 2006). The most notable successes of credit trading are exemplified through EPA's utilization of the Clean Air Act to reduce sulfur dioxide emissions from manufacturing facilities.

VDEQ is the regulatory authority that oversees the issuance of nutrient credits and has established procedures on how credits can be generated, issued, utilized, and traded. During 2005, legislation (Title 62.1, Chapter 3.1, Article 4.02 of the Code of Virginia) passed to create the Chesapeake Bay Watershed Nutrient Credit Exchange Program. The regulations allow point and non-point sources in Virginia to meet required pollutant reductions through nutrient trading. This study focuses on the non-point source trading program, and does not address point-source credit trading.

Nutrient credits are primarily generated from the conversion of agricultural land (through restoration and conservation). This includes the conversion of agricultural land to an undeveloped site or conducting stream restoration projects. The conversion of agricultural land requires that the land no longer be used for crop production or cattle crazing. This includes prohibiting the use of fertilizer or other chemicals, and may also include enhanced restoration methods for degraded streams. The goal is for the area to be "pristine" in nature and replicate an undeveloped area of land (Virginia Nutrient Bank, ND). Currently, 77 of the 79 nutrient banks listed on the VDEQ's registry rely on conversion of agricultural lands. Credits may also be generated through stream restoration projects and urban BMPs (Figure 3).

In 2014, VDEQ adopted VAC25-870-69, allowing stormwater nutrient credits to be purchased by developers in lieu of installing onsite post-construction BMPs. For example, instead of installing a rain garden, a developer could purchase credits generated from stream restoration at an offsite location. Section 62.1-44.15:35 of the Virginia Code states that nutrient credits must be generated within the same or adjacent eight-digit Hydrologic Unit Code (HUC, i.e. watershed) for which land disturbing activities occur. According to the Code of Virginia, Section 62.1-44.15:35 nutrient credits may be purchased and applied for construction projects that meet the following criteria:

> *1) less than five acres of land will be disturbed; 2) post-construction P control requirement is less than 10 pounds (lbs.) annually; or 3) the state permit applicant*

> *demonstrates to the satisfaction of the Virginia Stormwater Management Program authority that (i) alternative site designs have been considered that may accommodate onsite BMPs, (ii) onsite BMPs have been considered in alternative site designs to the maximum extent practicable, (iii) appropriate onsite BMPs will be implemented, and (iv) full compliance with post-development nonpoint nutrient runoff compliance requirements cannot practicably be met onsite. For purposes of this subdivision, if an applicant demonstrates onsite control of at least 75 % of the required phosphorous nutrient reductions, the applicant shall be deemed to have met the requirements of clauses (i) through (iv).*

Brokers are hired to act on behalf of the nutrient bank landowners where credits are generated. The amount of credits is calculated utilizing the efficiency and attenuation rates of the nutrient banks (e.g., stream restoration or agricultural land conversion). The brokers calculate the number of credits available through the site and track credit sales through nutrient credit ledgers, which are also maintained through VDEQ and local stormwater control authorities (e.g., utilities and municipalities).

The effectiveness of nutrient credit trading to reduce pollutant loading to rivers and streams has been a long-time topic of discussion and debate. Those in favor of nutrient credit trading find that purchasing pollutant credits is an attractive alternative to installing and maintaining post-construction BMPs and that nutrient credit trading provides an economically feasible approach to achieving pollutant reductions. Those opposed to nutrient credit find that it negatively impacts local water quality and presents a missed opportunity to implement post construction BMPs, particularly since re-development projects may happen once every 30-50 years. Thus, development projects may not have the opportunity to implement post-construction BMPs during that timeframe, resulting in untreated pollutants discharging to local streams. Additionally, the cost reflected in these credits does not account for the loss of ecosystem services associated with foregone green infrastructure. When pollutant credits are purchased, co-benefits from green infrastructure may not be realized in local communities.

Although credit trading may be a method for achieving pollutant reductions for the larger Chesapeake Bay watershed, the impact to local water quality from trading across watershed boundaries must be considered. For example, a local nutrient bank wasn't available for the Rivanna watershed until 2019, so all nutrient credits purchased before that time were generated outside of the watershed. Therefore, the water quality benefits were likely recognized in watersheds where the credits were generated, but these benefits were not realized in the watersheds where the project (and urbanized stormwater pollution) originated. According to the World Resources Institute (2017), "Stormwater planning, including engaging in nutrient trading, must include consideration of local TMDLs and local water-quality impairments. Trading across watershed boundaries to reduce nutrient loads to the Chesapeake Bay could potentially harm local water quality by shifting pollution reduction efforts away from locally impaired systems."

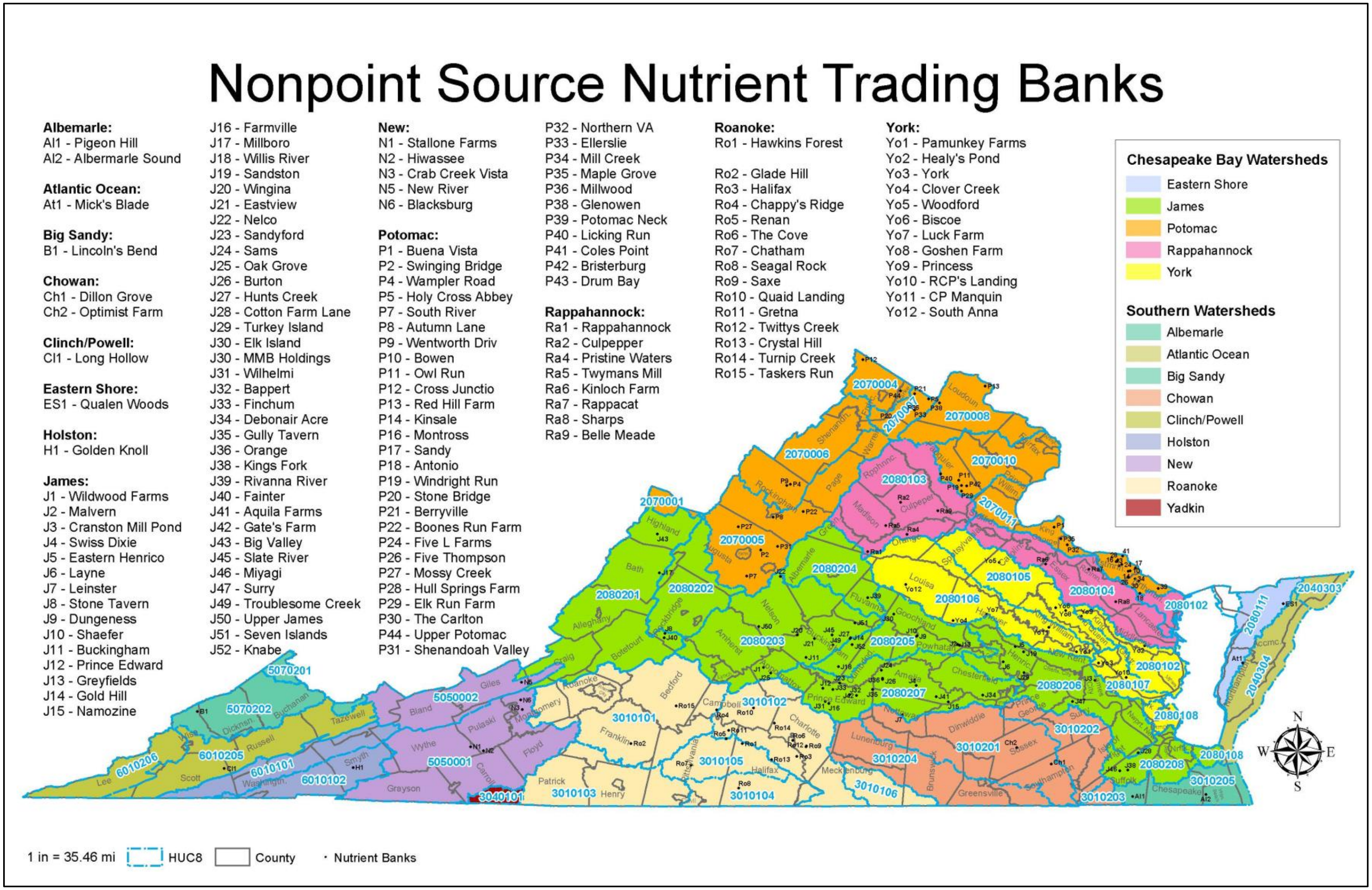

Figure 3. Map of Nonpoint Source Nutrient Trading Banks in Virginia, arranged by Watershed. (VDEQ, 2019b).The different colored areas represent various watersheds. The grey borders on the map delineate counties, while the blue lines represent watershed boundaries and associated HUCs. The black dots represent the location of nutrient credit banks.

2. Objectives

To further understand the universe of nutrient credit trading, I evaluated the extent to which nutrient credits were being purchased, the opportunity for water quality impacts on a local and watershed-level, and reasons why nutrient credit trading may be an attractive alternative to post-construction BMPs. Overall, the objectives of the study include the following:

1. Quantify the extent to which nutrient credits are used in re-development projects in lieu of implementation of post-construction BMPs.
2. Evaluate the potential impacts and lost opportunities of nutrient credit trading to water quality within the Rivanna Watershed.
3. Compare costs of issuing nutrient credits versus installing post-construction BMPs (or green infrastructure).
4. Assess how the issuance of credits in lieu of post-construction BMPs may impact the realization of co-benefits by the community.

3. Materials and Methods

Data Collection

I requested the nutrient credit agreements from Albemarle County officials, which were provided during June 2019. I also requested Nutrient Credit Ledgers (hereinafter, Ledgers) from VDEQ, which were provided on August 28, 2019. The data analysis of this document is based on the information provided in the Ledgers and is supplemented by other information, including Albemarle County nutrient credit ledgers and other sources of public information regarding nutrient credit banks in the James River Watershed.

Data Analysis

After receiving the PDF versions of the Ledgers, I entered the data into an editable spreadsheet, which included a total of 975 entries. Of the 975 entries, 15 were excluded because critical information was missing, including nutrient bank name and HUC or project name and HUC. Entries were also excluded if more than one project location HUC was reported.

Although some entries were incomplete (apart from the 15 excluded entries), I supplemented the entries with publicly available information. Specifically, I referenced existing VDEQ materials to identify the nutrient bank HUC when it was not reported on the Ledger.

Summary Statistics

After refining the dataset, I compiled summary statistics for each of the nutrient credit banks. The summary statistics included the following:

- Number of credit transactions
- Maximum loading purchased for N and P (lbs.)
- Minimum loading purchased for N and P (lbs.)
- Mean loading purchased for N and P (lbs.)
- Number of transactions occurring outside of the HUC where the project occurred

I compiled the summary statistics for the overall dataset in addition to summary statistics for each of the nutrient banks to identify which banks had the highest number of transactions, loading trading, and projects that purchased credits which were generated outside of the HUC of the project.

Time Series Analysis

To understand how nutrient credit trading has changed over time, I grouped and analyzed the data based on year. I reviewed the number of transactions that occurred annually from 2011 through 2018. Since 2019 data was incomplete (January 1 to August 1, 2019), these entries were not included as a component of the time series analysis. In addition to reviewing the number of transactions occurring per year, I also analyzed the loading purchased for N and P by year.

Spatial Analysis

To evaluate the number of projects occurring outside of the nutrient bank HUC where credits were generated, I conducted a spatial analysis using Excel and R software. I began by reviewing data from the statistical summary to understand the number of projects that purchased nutrient credits from outside of their HUC. I then sorted the useable dataset for projects based on HUC codes, and compared the project HUCs to the nutrient bank HUCs. I compiled a table with counts of the number of instances when a project HUC matched or did not match a nutrient bank HUC. For example, if we are focusing on projects that occurred within the 2080203 HUC, I would review the number of transactions that occurred when nutrient credits were purchased within the same HUC (nutrient bank has 2080203 HUC) or from a nutrient bank outside of the HUC (e.g., 2080201, 2080205, as shown in Table 1). I would then count the number of instances when these transactions occurred.

Table 1. Example of relationships between HUCs during Spatial Analysis.

Project HUC	Nutrient Bank HUC	Counts
2080203	2080203	9
2080203	2080201	1
2080203	2080205	3

After compiling the project HUC and Nutrient Bank HUC spreadsheet with counts, I used R software (version 3.6.2) to produce a Sankey diagram that depicted the spatial relationship between project HUCs and nutrient banks. To analyze the spatial relationship on a smaller scale, I focused on the transactions occurring within the 02080204 HUC, representing the Rivanna watershed. I conducted the same spatial analysis as mentioned above, but focused only on the projects located within the 02080204 HUC. I created another Sankey diagram to depict the relationship between the projects occurring within the Rivanna watershed and the nutrient banks outside the watershed where credits were generated.

Cost Comparison Analysis

To evaluate the cost differences between purchasing nutrient credits and installing BMPs, I reviewed costing data provided in the nutrient credit ledgers. Of those reviewed during the project, only the Gold Hill Nutrient Credit Bank and MMB Holdings provided cost information in their Ledgers. Additional costing information was supplemented by the nutrient credit agreements (including the bill of sale) and other documents provided by Albemarle County (Ivy Creek Nutrient Bank, Chesapeake Bay Nutrient Land Trust, LLC (Cranston's), Greyfields, and Oak Grave Nutrient banks).

After compiling costing information, I ran a summary statistics analysis with Excel to identify the number of transactions, minimum and maximum nutrient credit costs, unit costs, and average costs. I then compared this costing information to data compiled during literature reviews in addition to select green infrastructure technologies: rain gardens and bioswales.

I used the National Green Values™ Calculator to generate the costs of installation and maintenance of green infrastructure. The National Green Values™ Calculator takes several factors into account, including geographical and climate information regarding annual rainfall, size of property, soil types, existing land cover, and types of green infrastructure that may be used. The calculator provides a costing sheet presenting the initial cost of GI installation and annual maintenance, in comparison to conventional stormwater BMPs. After listing costing assumptions (such as the size of the land development area and other site-specific elements), I presented the cost of purchasing nutrient credits to the cost of installing and maintaining green infrastructure BMPs.

4. Results and Observations

Assumptions and Limitations

VDEQ utilizes Ledgers to track the sale and purchase of credits, and locations of nutrient credit banks. I received the Ledgers for the James River Watershed in a PDF format. Many of the Ledgers differed in format and the information reported. As a component of the data analysis, I hand-entered the information from the PDFs into a workable and editable Excel Document. As of August 2019, there were a total of 52 nutrient credit banks within the James River watershed (see Table 2).

Table 2. Summary of Nutrient Credit Banks in the James River Watershed (VDEQ, 2019a).

Nutrient Bank	Type of Bank	Bank Sponsor	Broker	HUC Code	County	Credits Released	
						P	N
Aquila Farms	Ag land Conversion	ME Nutrient Holdings, LLC	ME Nutrient Holdings, LLC	2080207	Amelia	79.51	275.5
Bappert	Ag land Conversion	R&J Investments, LC	R&J Investments, LC	2080207	Prince Edward	58.61	196.18
Big Valley	Ag land Conversion	Big Valley Nutrient Farm, LLC	Big Valley Nutrient Farm, LLC	2080201	Highland	5.05	6.76
Buckingham Nutrient Bank	Ag land conversion	Overland VA, LLC	Overland VA, LLC	2080203	Buckingham	36.29	121.46
Burton	Ag land Conversion	R&J Investments, LC	R&J Investments, LC	2080207	Amelia	17.95	60.07
Cotton Farm Lane	Ag land conversion	SNC, LLC	Eco-Cap, LLC	2080206	Suffolk	25.65	217.6
Cranston Millpond	Urban BMP	Cranston Mill Pond, LLC	Chesapeake Bay Nutrient Land Trust, LLC	2080206	James City	752	1655
Dungeness Nutrient Bank	Ag land conversion	Sara M. Grattan	Sara M. Grattan	2080205	Goochland	22.81	102.48
Eastern Henrico Nutrient Bank	Golf Course Conversion	Dominion Golf, LLC	Midview Management Corp.	2080206	Henrico	127.73	475.95
Eastview Farm	Ag land Conversion	CBAY-VA LLC	Resource Environmental Solutions, LLC	2080203	Buckingham	45.12	60.45
Elk Island	Ag land Conversion	Andrew Pryor	Hills Dale Farm, LLC	2080205	Goochland	97.11	436.21
Farmville	Ag land conversion	Sterling Investments, LLC	VCCE, LLC	2080207	Prince Edward	44.02	187.13
Finchum	Ag land Conversion	R&J Investments, LC	R&J Investments, LC	2080207	Prince Edward	49.74	166.46
Gates Farm	Ag land Conversion	Sterling Investments, LLC	VCCE, LLC	2080207	Prince Edward	14.21	58.6

Gold Hill	Ag land conversion	Hotel Street Capital, LLC	HSC-NOTB, LLC	2080203	Buckingham	27.3	92.04
Greyfields	Ag land conversion	James K. Timmons Jr., Trustee and Marian Free Timmons	James K. Timmons Jr., Trustee and Marian Free Timmons	2080205	Powhatan	22.58	101.43
Gully Tavern	Ag land Conversion	R&J Investments, LC	R&J Investments, LC	2080207	Prince Edward	54.96	246.87
Hunts Creek	Ag land Conversion	R&J Investments, LC	R&J Investments, LC	02080203 02080205	Buckingham	37	123.82
Kings Fork Farm	Ag land Conversion	Eco-Cap, LLC	Eco-Cap, LLC	2080208	Suffolk	70.46	606.6
Layne	Ag land conversion	Osborne Glenn, LLC	Wilton Family Investment Trust	2080206	Henrico	78.39	646.24
Leinster	Ag land conversion	Leinster Nutrient Exchange, LLC	Leinster Nutrient Exchange, LLC	2080207	Nottoway	23.06	103.57
Malvern Landbank	Ag land conversion	Le Moulin, LLC	Stadia Development	2080205	Powhatan	62.04	278.66
Millboro	Ag land conversion	Claude W. Burns	Claude W. Burns	2080201	Bath	27.71	124.45
Namozine	Ag land conversion	R&J Investments, LC	R&J Investments, LC	2080207	Amelia	23.96	80.2
Nelco	Ag land Conversion	Nelco Holdings, LLC	Chandler Van Voorhis	2080203	Nelson	20.8	65.61
Oak Grove	Ag land Conversion	Chesapeake Bay Nutrient Land Trust LLC	Chesapeake Bay Nutrient Land Trust, LLC	2080203	Appomattox	63.78	141.96
Orange	Ag land Conversion	RLP Investments, LC	R&J Investments, LC	2080207	Amelia	12.75	42.67
Prince Edward	Ag land conversion	Leinster Nutrient Exchange, LLC	Leinster Nutrient Exchange, LLC	2080207	Prince Edward	50.17	143.48
Rivanna River	Golf Course Conversion	Hotel Street Capital, LLC	Hotel Street Capital, LLC	2080204	Fluvanna	178.52	817.1
Sams	Ag land Conversion	R&J Investments, LC	R&J Investments, LC	2080207	Amelia	12.32	55.35

Sandston	Ag land conversion	Wilton Acquisitions, LLC	Wilton Family Investment Trust	2080206	Henrico	30.12	274.82
Sandyford	Ag land Conversion	Sandyford, LLC	Ecosystem Services, LLC	2080207	Prince Edward	18.38	82.56
Shaefer Nutrient Bank	Ag land conversion	Joy P. Massie and James P. Massie, Jr. Irrevocable Trust u/a December 21, 2012	RRG, LC	2080205	Goochland	131.56	590.97
Slate River	Ag land Conversion	Ostrya Conservation Inc.	Ostrya Conservation Inc.	2080203	Buckingham	25.34	84.82
Stone Tavern Nutrient Bank	Ag land conversion	Stone Tavern, LLC	Stone Tavern, LLC	2080201	Rockbridge	20.11	26.94
Swiss Dixie	Ag land conversion	R&J Investments, LC	RRG, LC	2080207	Amelia	328.78	1100.41
Turkey Island	Ag land Conversion	CBAY-VA LLC	Resource Environmental Solutions, LLC	2080206	Henrico	60.57	389.96
Wildwood Farm	Ag land conversion	Chesapeake Bay Nutrient Land Trust LLC	Chesapeake Bay Nutrient Land Trust, LLC	2080203	Appomattox	111.95	412.64
Willis River	Ag land conversion	Wetland Resource Management, LLC	Wetland Resource Management, LLC	2080205	Buckingham	21.85	78.88
Wingina	Ag land Conversion	Overland VA II, LLC	Ovarland VA II, LLC	2080203	Nelson	47.73	214.38

However, several pieces of information from the Ledgers were inconsistently reported. Specifically, the following information was not reported for the following banks within the James River Watershed (

Table ***3***). The checks in the table represent the information that was reported on the Ledgers. The blue shaded spaces represent information that was not reported on the Ledgers.

Table 3. Information reported in Ledgers.

Nutrient Bank	Date	Project Name	Nutrient Bank Name	Nutrient Bank HUC	Purchaser	Project HUC	Loadings purchased (lbs.)
(No Name bank)	✓	✓			✓		✓
(No Name bank)	✓				✓		✓
Buckingham Nutrient Bank	✓	✓	✓	✓ [1]	✓	✓ [2]	✓
Burton Nutrient Bank	✓	✓	✓	✓	✓	✓	✓
CBAY-VA LLC - Eastview	✓	✓	✓	✓	✓	✓	✓
Chesapeake Bay Nutrient Land Trust, LLC - Cranston's Mill pond	✓	✓	✓	✓ [1]	✓	✓	✓
Dungeness Nutrient Bank	✓	✓	✓	✓ [1]			✓
Eastern Henrico Nutrient Bank	✓	✓	✓	✓ [1]	✓		✓
Elk Island Nutrient Offset Trading Bank	✓	✓	✓	✓ [1]	✓	✓	✓
Fainter Nutrient Bank (Stone Tavern)	✓		✓	✓ [1]			✓
Farmville Nutrient Banks - James 16	✓	✓	✓	✓ [1]	✓	✓	✓
Finchurn Nutrient Bank	✓	✓	✓	✓	✓	✓	✓
Gold Hill Nutrient Credit Bank	✓	✓	✓	✓ [1]	✓		✓
Greyfields Nutrient Bank	✓	✓	✓	✓ [1]	✓	✓	✓
Gully Tavern Nutrient Bank	✓	✓	✓	✓	✓	✓	✓
Ivy Creek Nutrient Bank	✓	✓	✓		✓	✓	✓
Kings Fork Farm Nutrient Bank	✓	✓	✓	✓ [1]	✓	✓	✓
Knabe Nutrient Bank	✓	✓	✓	✓ [1]	✓	✓	✓
Layne Nutrient Bank	✓	✓	✓	✓	✓		✓
Malvern Exchange	✓	✓	✓	✓	✓	✓	✓
Millboro Bank	✓	✓	✓	✓	✓	✓	✓
Miyagi Creek	✓	✓	✓	✓ [1]	✓	✓	✓
MMB Holdings	✓	✓	✓	✓	✓	✓ [2]	✓
Namozine Nutrient Bank	✓	✓	✓	✓	✓	✓	✓
Oak Grove	✓	✓	✓	✓ [1]	✓	✓	✓
Orange Nutrient Bank	✓	✓	✓	✓	✓	✓	✓
Prince Edward Nutrient Bank	✓	✓	✓	✓ [1]	✓	✓	✓

Prince Edward Phase II	✓	✓	✓		✓		✓
Rivanna River Nutrient Offset	✓	✓	✓	✓ [1]	✓		✓
Sams Nutrient Bank	✓	✓	✓	✓	✓	✓	✓
Sandston	✓	✓	✓	✓	✓		✓
Sandyford Nutrient Bank	✓	✓	✓	✓ [1]	✓	✓ [2]	✓
Seven Islands	✓	✓	✓	✓ [1]	✓	✓	✓
Shaefer Nutrient Bank	✓	✓	✓	✓	✓	✓	✓
Slate River Nutrient Bank	✓	✓	✓	✓ [1]	✓	✓	✓
Surry Nutrient Bank	✓	✓	✓	✓ [1]	✓		✓
Swiss Dixie Nutrient Bank	✓	✓	✓	✓ [1]	✓	✓	✓
Turkey Island Nutrient Bank	✓	✓	✓	✓ [1]	✓	✓	✓
Upper James Nutrient Bank	✓	✓	✓	✓ [1]	✓	✓	✓
Wilhelmi Nutrient Bank	✓	✓	✓	✓ [1]	✓	✓	✓
Willis River Nutrient Bank	✓	✓	✓ [2]	✓ [1]	✓	✓ [2]	✓
Wingina Nutrient Bank	✓	✓	✓	✓ [1]	✓	✓	✓

[1] Nutrient Bank HUC identified through supplemental documents.
[2] Partial information reported in Ledger

Summary Statistics

The summary statistics of the overall dataset varied, as both large and small projects purchased nutrient credits from nutrient banks in varying locations. The data included a total of 956 nutrient credit transactions within the James River Watershed. There was a range in P loading purchase from 0.01- 40 lbs., with a mean of 1.70 lbs. (Figure 4). There was a range in N loading purchase from 0.02 - 234 lbs., with a mean of 5.64 lbs. (Figure 5). The nutrient bank with the highest number of transactions was Chesapeake Bay Nutrient Land Trust, LLC - Cranston's Mill pond (2080206 HUC) with a total of 408 transactions, 89 of which included projects that occurred outside of the 2080206 HUC. The nutrient bank with the least number of transactions was the Ivy Creek Nutrient Bank (HUC 02080204), with one transaction, occurring within the same HUC. Most nutrient banks experienced a greater number of smaller nutrient credit purchases, particularly in the 2082008 HUC (Figure 4).

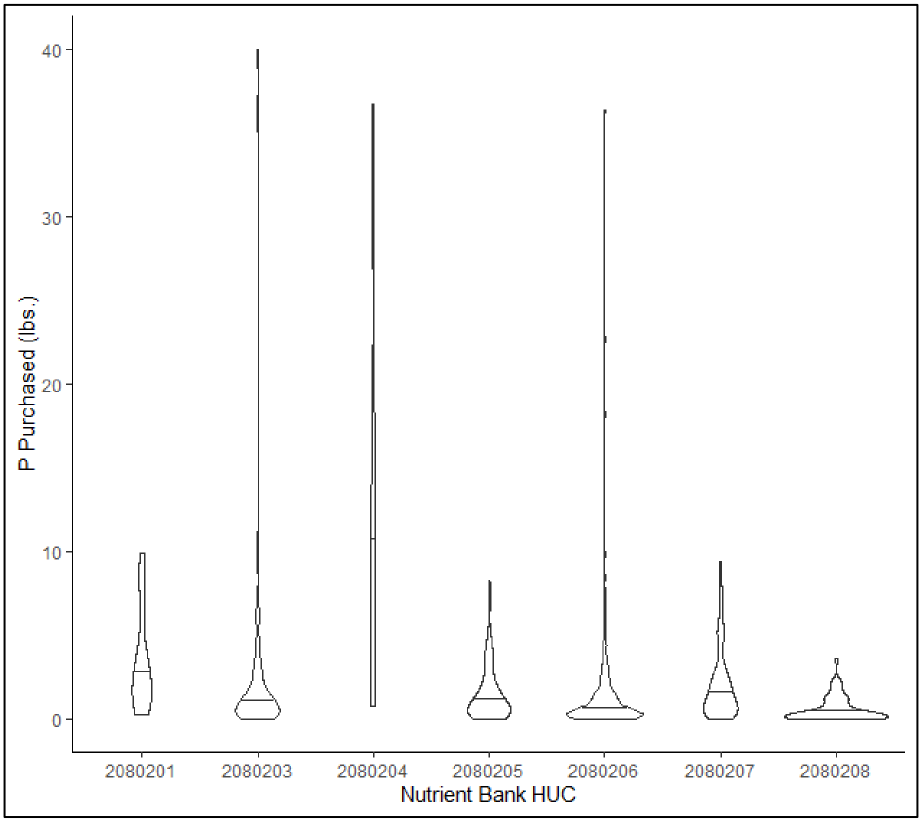

Figure 4. Distribution of P credit loading purchased, based on Nutrient Bank HUC. Violin plots depict the density of P loading credits, with wider portions of each violin representing a larger proportion of values. Note the line though the middle of each violin represents the median lbs. of P purchased.

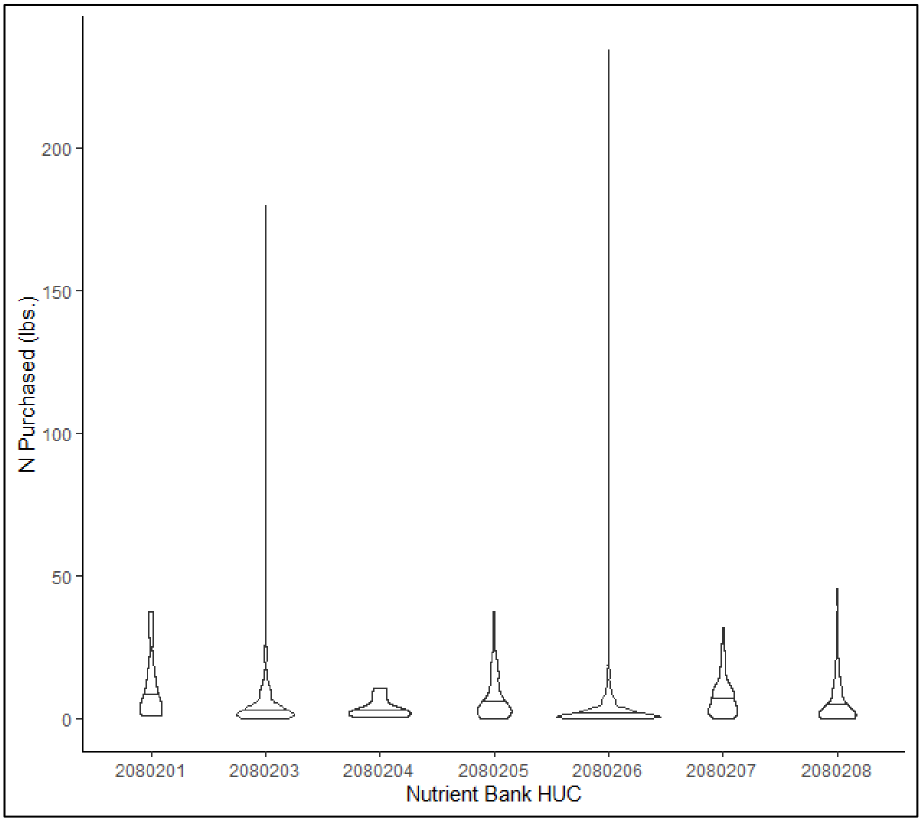

Figure 5. Distribution of N credit loading purchased, based on Nutrient Bank HUC. Violin plots depict the density of N loading credits, with wider portions of each violin representing a larger proportion of values. Note the line though the middle of each violin represents the median lbs. of N purchased.

Time-Series Analysis

The number of nutrient credit purchases in the James River Watershed have increased since 2001, with the smallest number of transactions in 2011 (10), and the largest in 2018 (280).The number of transactions steadily increased for the first four years, with more substantial increases occurring after 2016. The largest increase in purchases occurred during 2016 - 2017 and 2017 - 2018, with 88 additional credit transactions (Figure 6).

The amount of P and N loading purchased increased annually, apart from 2012, when the amount of N purchased was less than 2011. The least amount was purchased in 2011 (12.07 lbs. of P and 54.2 lbs. of N), and the most was purchased in 2018 (460.08 lbs. of P and 1,784.44 lbs. of N).

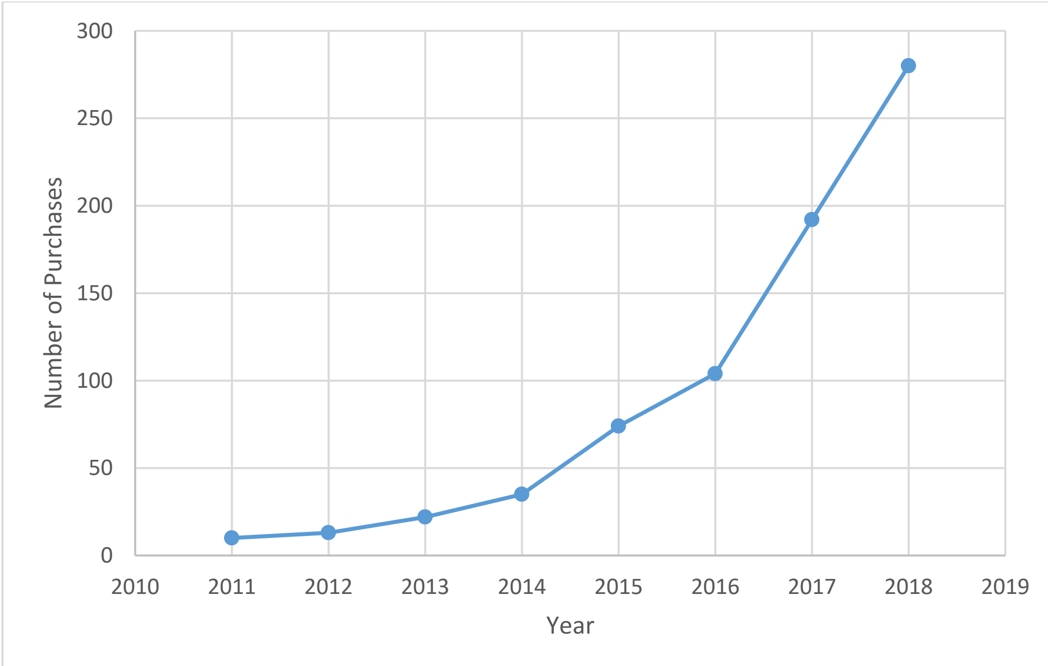

Figure 6. Number of Credits Purchased in the James River Watershed over time.

The largest increase in the amount of P loading purchased was between 2017-2018, when an increase of 181.05 lbs. of P were purchased. The smallest increase in the amount of P loading purchased was between 2011 and 2012, when an increase of 2.99 lbs. purchased (Figure 7).

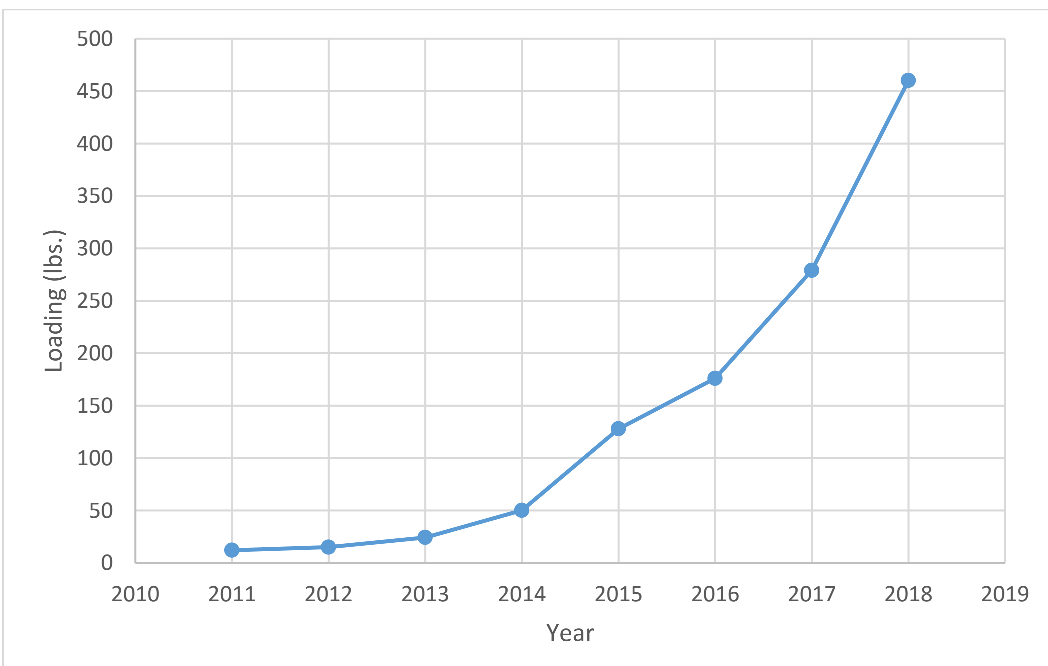

Figure 7. Amount of Phosphorous (lbs.) Purchased in the James River Watershed over time.

The largest increase in the amount of N loading purchased was between 2017-2018, when an increase of 827.36 lbs. of N were purchased. A decrease in the amount of N loading purchased initially decreased between 2011-2012, when the amount of N loading purchased decreased by 10.89 lbs. (Figure 8).

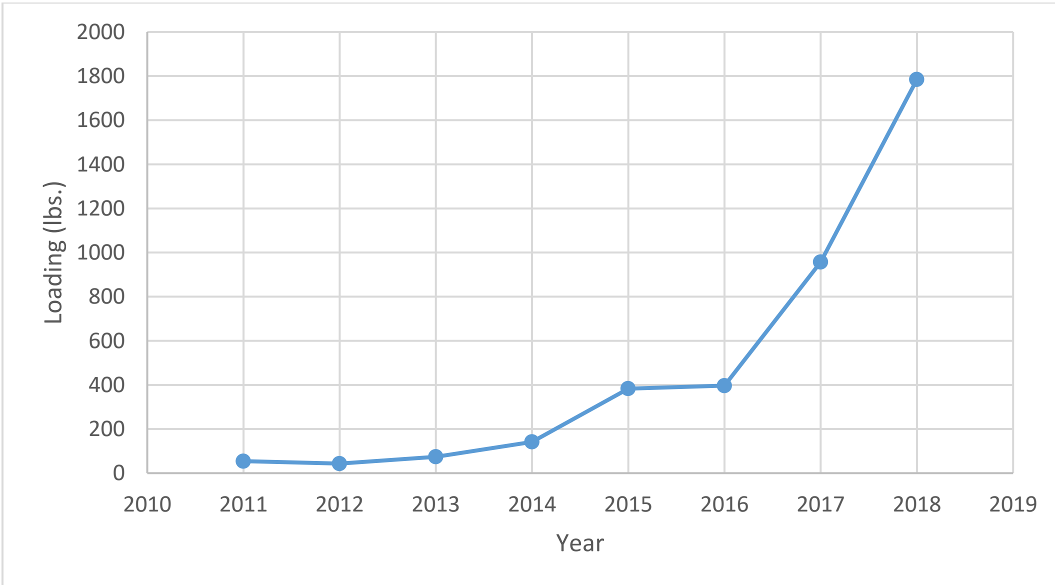

Figure 8. Amount of N (lbs.) Purchased in the James River Watershed over time.

Spatial Analysis

Since the focus of the project is analyzing local water quality benefits, it is necessary to review the data from a watershed location, regarding the eight-digit HUCs where projects occur and the eight-digit HUCs where nutrient credits are generated (Figure 9). The HUCs on the left-hand column represent the different HUCs where projects were located and the HUCs on the right represent those HUCs where nutrient credits are generated (i.e., where nutrient banks are located). For example, for projects occurring with HUC 2080205 (represented by the yellow boxes), nutrient credits for these projects were purchased from nutrient banks within the same HUC (HUC 2080205, also represented by a yellow box) in addition to HUC2080206 (represented by a light yellow box), and HUC 2080203 (represented by a green box). This analysis showed that there were many instances in which projects purchased nutrient credits from within and outside of the HUC where the nutrient credits were generated.

The thickness of the grey lines is proportional to the amount of credits purchased. For example, for projects that occurred within HUC 2080207 (shown as light blue in Figure 9) show connections to the following nutrient banks: HUC 2080207, HUC 2080203, HUC 2080206, and HUC 2080205. The grey line connecting the projects occurring within HUC 2080207 are thickest when leading to HUC 2080207, indicating that the majority of the projects purchased credits generated within the HUC 2080207, with supplementary credits purchased for the nutrient banks located in HUC 2080203, HUC 2080205, and HUC 2080206. Of the 781 projects occurring in the James River watershed that purchased nutrient credits, 252 of the projects purchased credits that were generated outside of the watershed where the project occurred. Note that the black boxes in the left column represent watersheds without nutrient banks, forcing credits to be purchased outside of the HUC where those projects occur.

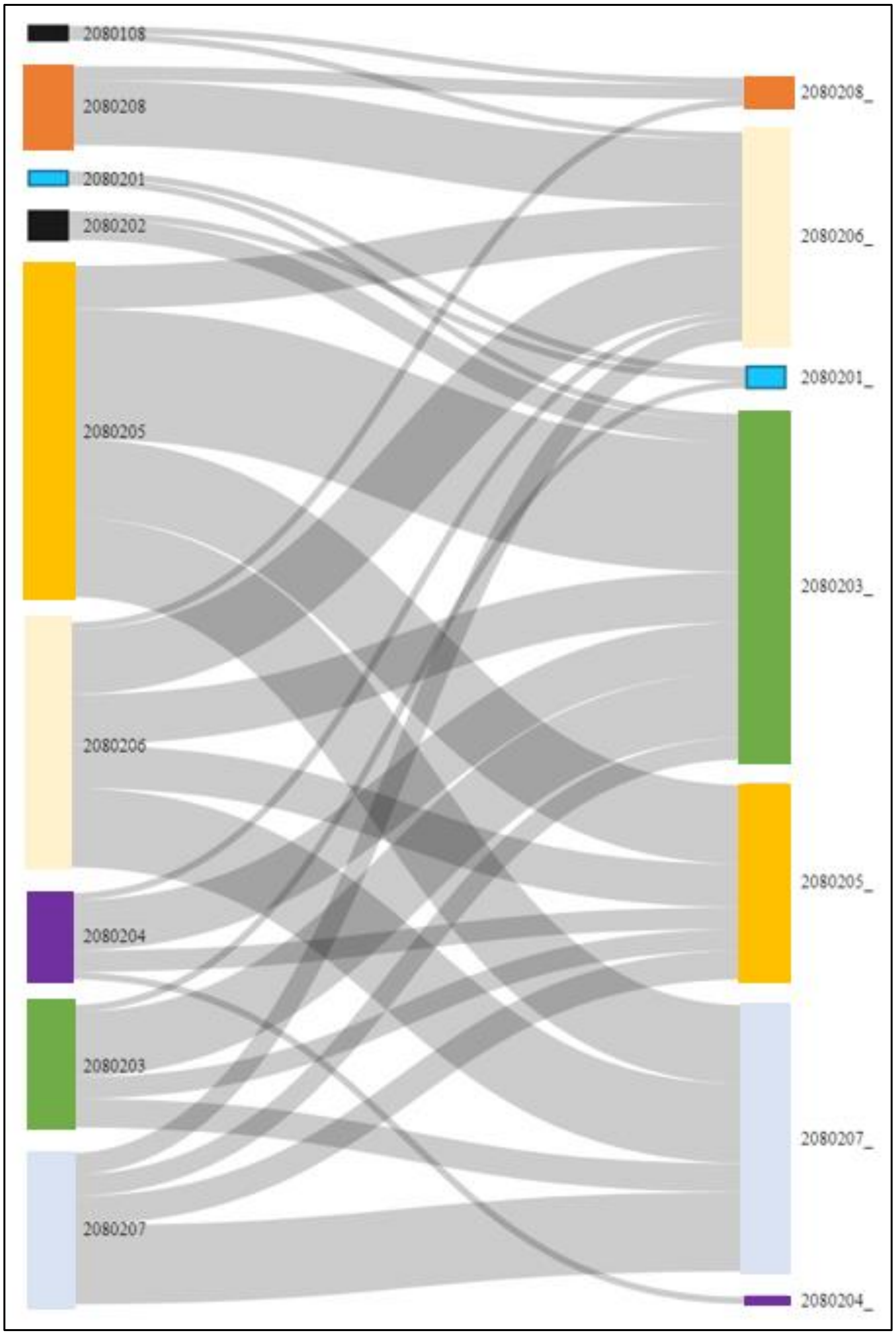

Figure 9. Sankey Diagram showing spatial relationship between project location HUCs and Nutrient bank HUCs. Each of the different HUC codes is represented a different color to aid in depicting the connection between project HUC location and nutrient bank location. Note that the black boxes depict project locations in HUCs where credits were no credits were purchased within the same HUC.

A Closer Look: Focusing on HUC 2080204

The data shows that 49 purchases were made within the HUC 2080204. At the time of this report, the Ivy Creek Nutrient Bank was the only nutrient bank within HUC 2080204, with one purchase recorded during 2019. The remaining 48 transactions involved projects located within the HUC 2080204 purchasing credits from adjacent HUCs, including the following:

- Buckingham Nutrient Bank (HUC 2080203)
- CBay-VA LLC- Eastview (HUC 2080203)
- Elk Island Nutrient Offset Trading Bank (HUC 2080205)
- Greyfields Nutrient Bank (HUC 2080205)
- Malvern Exchange (HUC 2080205)
- Oak Grove (HUC 2080203)
- Seven Islands (HUC 2080203)
- Slate River Nutrient Bank (HUC 2080203)
- Turkey Island Nutrient Bank (HUC 2080206)

Table 4 and The one transaction for the Ivy Creek Nutrient Bank included selling 6.97 lbs. of P and 10.75 lbs. of N. Therefore, the total amount of loading that was purchased outside of the 2080204 HUC (not including those generated from the Ivy Creek Nutrient Bank) was 80.24 lbs. of P and 262.77 lbs. of N.

Table 5. Summary of Loading Purchased for Nutrient Credit Banks Outside of the 02080204 HUC for projects within the Rivanna Watershed.

	P (lbs.)	N (lbs.)
total	80.24	262.88
minimum	0.01	0.02
maximum	9.95	37.31
mean	1.67	5.47

Table 6 present the summary statistics of nutrient credit purchases for projects within 02080204 HUC. Note that more pounds of loading were purchased for N than P, resulting in N having higher maximum and mean values.

Table 4. Summary of Loading Purchased for projects occurring within the 02080204 HUC.

	P (lbs.)	N (lbs.)
total	87.21	273.51
minimum	0.01	0.02
maximum	9.95	37.31
mean	1.78	5.58

The one transaction for the Ivy Creek Nutrient Bank included selling 6.97 lbs. of P and 10.75 lbs. of N. Therefore, the total amount of loading that was purchased outside of the 2080204

HUC (not including those generated from the Ivy Creek Nutrient Bank) was 80.24 lbs. of P and 262.77 lbs. of N.

Table 5. Summary of Loading Purchased for Nutrient Credit Banks Outside of the 02080204 HUC for projects within the Rivanna Watershed.

	P (lbs.)	N (lbs.)
total	80.24	262.88
minimum	0.01	0.02
maximum	9.95	37.31
mean	1.67	5.47

Table 6. Number of purchases by year from projects within the 02080204 HUC.

Year	Number of Transactions
2015	10
2016	4
2017	3
2018	21
2019	11

Many of the projects occurring within the Rivanna watershed (2080204 HUC) purchased credits located outside of the watershed (Figure 10). The largest number of transactions occurred during 2018, with 21 transactions (Table 6). The smallest number of nutrient transactions occurred during 2017, with three. The nutrient banks that had the most transactions from projects within the Rivanna included Oak Grove and Malvern Exchange with 18 and 11 transactions, respectively.

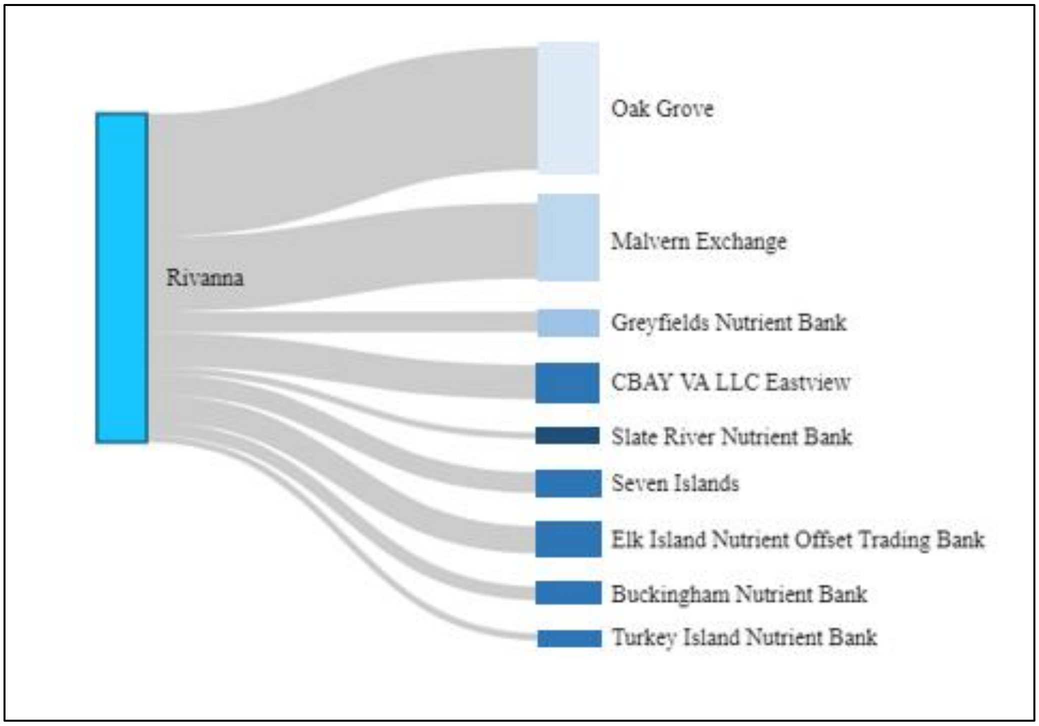

Figure 10. Sankey Diagram showing spatial relationship between project location HUCs and Nutrient bank HUCs within the Rivanna Watershed.

Cost Comparison Analysis

This cost comparison simply functions as a method to compare the general cost difference between installing post-construction BMPs and purchasing nutrient credits. Not all of the nutrient credit ledgers contained costing information, but results from complete data entries showed that the price per nutrient pound (unit cost) varied considerably (Table 7). Price variability is to be expected with nutrient credit trading, as this is a market-based approach, where cost is determined as a function of supply and demand. The costs of the credits are established through VDEQ, nutrient credit brokers, and are managed through a clearinghouse.

Table 7. Summary of Pricing Information Per Nutrient Credits, as Reported by Select Nutrient Banks in the Ledgers from 2016 to June 2019.

Number of Transactions	32
Minimum total cost	$1,045.00
Maximum total cost	$104,550.00
Minimum unit cost	$1,818.18
Maximum unit cost	$5,903.44
Average total cost	$20,765.53
Average unit cost	$2,731.79

A 2014 study conducted by the Virginia Department of Transportation (VDOT) compared the cost of post-construction BMPs of varying sizes with nutrient credit purchases (Nobles et al., 2014). The study found that the cost savings of purchasing nutrient credits in lieu of installing post-construction BMPs varies greatly, between 5 % and 75 % of total costs (Nobles et al., 2014). Extended detention basins were the primary type of post-construction BMP utilized, with additional information provided for a sand filter. The total cost of the post-construction BMP includes pre-construction costs (designing, permitting, and contingency cost), construction, and operation and maintenance over the lifetime of the BMP. The study did not evaluate the cost of green infrastructure as a post-construction BMP (Nobles et al., 2014).

Table 8. Summary and Comparison of Costs for Installing Post-Construction BMPs versus Purchasing Nutrient Credits (Nobles et al., 2014).

BMP Type	Impervious Area Treated (Acres)	Total BMP Cost[1]	Credit Cost	Difference
Extended Detention Basin[1]	2.44	$34,368	$20,000	$14,368
Extended Detention Basin[1]	8.01	$92,181	$19,000	$73,181
Extended Detention Basin[1]	15.15	$362,710	$18,700	$344,010
Sand filter[1]	4.40	$339,850	$18,700	$321,150
Extended detention enhanced basin	9.20	$547,538	$18,700	$528,838

1. Excludes right-of-way

In an effort to evaluate the cost of green infrastructure in comparison to nutrient credits, I compiled information from the Green Values website. The typical size of a rain garden ranges between 100 and 300 square feet, and is typically designed to infiltrate 20 % of the area that is being drained (Groundwater Foundation, nd). For this example, if we assume that a rain garden will be built to drain an impervious area of 2,000 ft^2 (0.05 acres), the rain garden would need to be sized at 400 ft^2.

Table 9. Summary of Costs for Constructing and Maintaining Rain Garden and Bioswale BMPs (Green Values, 2019).

Rain Garden			
Costing Range	Construction Cost (per ft^2)	Maintenance Cost (per ft^2)	Component Lifespan (years)
Low	$5.15	$0.31	25
Medium	$7.00	$0.34	30
High	$16.05	$0.61	50
Bioretention Swale[1]			
Costing Range	Construction Cost (per ft^2)	Maintenance Cost (per ft^2)	Component Lifespan (years)
Low	$5.50	$0.06	20
Medium	$15.00	$0.12	30
High	$24.00	$0.21	50

1. Data presented for the bioretention swale assumes bioretention swales utilized in parking lots.

Table 10. Summary of Total costs associated with Rain Garden and Bioswale BMPs (assuming size of 400 ft^2).

GI BMP	Construction Cost[1]	Maintenance Cost[1,2]	Total Cost
Rain Garden	$2,800.00	$4,080.00	$6,880.00
Bioretention Swale	$6,000.00	$1,440.00	$7,440.00

1. Construction and maintenance costs assume medium cost.
2. Assuming a life-span of 30 years.

Table 11. Comparison of Costs between Purchasing Nutrient Credits and Installing Rain Garden and Bioswale BMPs (assuming size of 400 ft^2).

BMP Type	Total Cost[1,2]
Rain Garden	$6,880.00
Bioretention Swale	$7,440.00
Purchasing Nutrient Credits	$2,731.79

1. Construction and maintenance costs assume medium cost.
2. Assuming a life-span of 30 years.

Given these assumptions, the cost of purchasing nutrient credits is not equivalent to the cost of installing green infrastructure, and provides a general savings of approximately 30 % when purchasing nutrient credits in lieu of installing green infrastructure (Tables 9 through 11). This is generally consistent with the findings from Nobles et al. (2014) study, although the green infrastructure assessment is on a much smaller geographical scale in comparison to the large detention ponds. Note that the cost of installing green infrastructure may vary greatly depending on the selected BMP, size of impervious area that is being drained, and overall removal efficiency of the BMP.

Cost Limitations

The largest possible limitation to the costing information regarding green infrastructure BMPs is that these values do not include the monetary value associated with ecosystem benefits, such as improved air quality and reduced heat island effect that are associated with green infrastructure. Additionally, these cost estimates do not include an assessment of the cost of avoided damages from flooding and other hazards in addition to the reduced cost of constructing conventional stormwater assets. Lastly, the cost comparison does not account for the cost of land, and the potential profits that may be recognized when selling the land for development versus the installation of green infrastructure.

The valuation of ecosystem services of are often difficult to quantify because the inherent value of ecosystem services themselves are difficult to quantify. The benefits of GI are more significant than just stormwater management, as green infrastructure provides co-benefits to the public and also to ecological systems (Table 12).

Table 12. Summary of co-benefits associated with Green Infrastructure.

Increase vegetation	Improve air quality
	Reduce heat island effect
	Provide food for pollinators
	Provides terrestrial habitat
	Carbon capture

	Soil protection
	Reduced erosion
Stormwater infiltration	Groundwater recharge
	Filtering and removing stormwater pollutants
Ecosystem	Creates habitat
	Provides pollen and food sources
Public Health	Increases resilience to natural disasters
	Improves human connection to nature (associated with improved mental health)
	Reduces localized flooding
	Provides green space
	Noise reduction
Others	Aesthetics
	Energy conservation/improvements to energy efficiency

6. Conclusions & Recommendations

While most credits were purchased within the watershed where they were generated, 32 % of projects purchased credits from outside of the watershed. Comparatively, 98 % of the projects purchasing nutrient credits within the Rivanna watershed were generated from outside of the watershed. This may be attributed to the lack of watershed-specific nutrient bank available prior to 2019. For the Rivanna watershed, 80 lbs. of P and 262 lbs. of N were purchased over the course of five years, and were generated from nutrient banks outside of the watershed. Therefore, the reduction of 80 lbs. of phosphorous and 262 lbs. of N were not realized by the local watershed. Although the Rivanna is not impaired for nutrient discharges, the additional contribution of these pollutants may have tangential impacts to the river's impairments (bacteria and benthic).

The analysis also shows that the number of nutrient credit purchases within the James River watershed are increasing over time, which is consistent with the increasing trend of credit purchases within the Rivanna watershed. The increase in purchases is likely associated with the lower price of purchasing credits instead of installing post-construction BMPs, as nutrient credit purchases are estimated at 30 % cheaper than installing post-construction BMPs. The increase in credits is also likely attributed to the lack of available space to install post-construction BMPs, and overall land availability, and may be the result of the profitability of land used for development instead of post-construction BMPs.

Based on the inconsistency of information submitted in the nutrient credit ledgers, this study recommends that a consistent form be utilized by each nutrient bank to ensure that consistent and standardized data is reported. This data can be utilized to evaluate the program and inform future decisions, including policy decisions. This study also recommends that a policy analysis be conducted to evaluate the potential for a shift in policy to improve local water quality. The current regulations of allowing trading across watersheds should be evaluated and modified, as needed, to ensure that the benefits from nutrient credit trading are recognized by the locality.

Lastly, the cost of nutrient credit purchases is not equivalent to the cost of installing green infrastructure or post-construction BMPs. This cost estimate does not include the foregone co-benefits to the community related and ecosystem services related to green infrastructure. The inequivalent pricing of nutrient credits in comparison to post-construction BMPs may provide a cost signal to developers in favor of nutrient credit purchases, reducing the water quality benefits realized when installing post-construction BMPs. The cost of the nutrient credits also does not consider the negative externality that exists when nutrient credits are purchased outside of a local watershed. This study recommends that an in-depth cost analysis be conducted to evaluate and revise the base price of nutrient credits to be at least consistent with the cost of implementing post-construction BMPs to account for potentially displaced water pollution and clear price signals.

Literature Citations

Bay Journal, 2018. *Chesapeake Bay Watershed Nutrient Trends and Goals.* https://www.bayjournal.com/documents/ChesBayNutrientTrendsGoals.pdf

Brabec, E. 2002. *Impervious Surfaces and Water Quality: A Review of Current Literature and Its Implications for Watershed Planning.* Journal of Planning Literature 16(4):499—514

City of Charlottesville, 2012. *Phase II Watershed Implementation Plan*. http://rivannariverbasin.org/wp-content/uploads/Charlottesville_WIPIISubmittal_12Feb01.pdf

City, 2014. *Complete Map Series: General Land Use Plan.* https://www.charlottesville.org/home/showdocument?id=31845

City, 2018. *City GreenPrint 1.0 Charlottesville's Green Infrastructure Guide*. http://www.gicinc.org/PDFs/GIC%20PG/Charlottesville%20GI%20GreenPrint%201.0%20-%20July%202018%20Final.pdf

Colgan, C., Beck M, Narayan S. 2017. Financing Natural Infrastructure for Coastal Flood Damage Reduction. Lloyd's Tercentenary Research Foundation, London.

Copeland, C. 2014. *Green Infrastructure and Issues in Managing Urban Stormwater*. Congressional Research Service. 7-5700. Available from: http://nationalaglawcenter.org/wp-content/uploads/assets/crs/R43131.pdf

Commonwealth of Virginia. 2005. *Chesapeake Bay Nutrient and Sediment Reduction Tributary Strategy for the James River, Lynnhaven and Poquoson Coastal Basins*. https://www.deq.virginia.gov/Portals/0/DEQ/Water/ChesapeakeBay/Trib%20Strat/tsjamesall032805.pdf

Fazio, J., 2010. *How trees can retain stormwater runoff.* Tree City USA Bulletin 55: 1-8.

Flynn, C. and Davidson, C 2016. *Adapting the Social-ecological System Framework for Urban Stormwater Management: The Case of Green Infrastructure Adoption.* Ecology and Society 21, no. 4 (2016). http://www.jstor.org/stable/26270003.

Groundwater Foundation, nd. *More about raingardens.* https://www.groundwater.org/action/home/raingardens-more.html

Herrera Environmental Consultants, Inc., 2016. *Pacific Northwest Bioretention Performance Study Synthesis Report.* Prepared for City of Redmond Department of Public Works by Herrera Environmental Consultants, Inc., Seattle, Washington.

Jones, C. et al, 2017. *Working Paper: Nutrient Trading by Municipal Stormwater Programs in Maryland and Virginia: Three Case Studies.* World Resources Institute.

Moshiri, G.A. (ed.) 1993. *Constructed Wetlands for Water Quality Improvement.* CRC Press, Boca Raton, FL. 632 pp.

Moyers, B. 2001. PBS - Bill Moyers Reports: Earth on Edge - Urban Ecosystems, accessed September 10, 2018, https://www.pbs.org/earthonedge/ecosystems/urban1.html.

Meyer, J.L, et al. 2005. *Stream Ecosystem Function in Urbanizing Landscapes*. Journal of North American Benthological Society. 26:602-612.

Murphy, J. 2011. *Land Use and Stream Health in the Rivanna River Basin, 2007-2009.* https://www.rivannariver.org/wp-content/uploads/2016/11/Land-Use-and-Stream-Health-in-the-Rivanna-Basin-2007-2009.pdf

Nobles, A. et al., 2014. *Investigating the Cost-Effectiveness of Nutrient Credit Use As an Option for VDOT Stormwater Permitting Requirements.* http://www.virginiadot.org/vtrc/main/online_reports/pdf/15-r9.pdf

Odefey, J. et al. 2012. *Banking on Green: A Look at How Green Infrastructure Can Save Municipalities Money and Provide Economic Benefits Community-Wide.*

Penn State Extension. 2006. *A Primer in Water Quality Credit Trading in the Mid-Atlantic Region.* https://extension.psu.edu/a-primer-on-water-quality-credit-trading-in-the-mid-atlantic-region

Prudencio, L and Null, S. 2018. *Stormwater Management and Ecosystem Services:* A Review. Environ. Res. Lett. 13 033002. Available from: http://iopscience.iop.org/article/10.1088/1748-9326/aaa81a/pdf.

Rivanna River Basin Commission. 2009. *Rivanna Watershed and Vicinity Land Use/Land Cover Map.* http://rivannariverbasin.org/about-the-rivanna-river/

Rivanna River Watershed Commission. (RVWC). ND. http://rivannariverbasin.org/watershed-info.php

The Nature Conservancy 2002. *TNC Rivanna Watershed Conservation Area*.

U.S. Environmental Protection Agency (EPA), 1999. Constructed Wetland Fact Sheet.
U.S. EPA, Office of Water. 2000. National Water Quality Inventory – 1998 Report to Congress. EPA-841-R-00-001. Washington DC.

U.S. EPA, 2001. Protocol for Developing Pathogen TMDLs. Office of Water, EPA-841-R-002, Washington DC.

U.S. EPA, Office of Water. 2005. Stormwater Phase II Final Rule, Post-Construction Runoff Minimum Control Measure Fact Sheet. EPA 833-F-00-009.

U.S. EPA., 2010. *Green Infrastructure Case Studies: Municipal Policies for Managing Stormwater with Green Infrastructure*. Pp. 61-63. Available from: http://www2.ku.edu/~kutc/pdffiles/Green%20Infrastructure%20Case%20Studies.pdf

U.S. EPA, 2011. *Chesapeake Bay TMDL Fact Sheet.* https://www.epa.gov/chesapeake-bay-tmdl/chesapeake-bay-tmdl-fact-sheet

Virginia Department of Environmental Quality (VDEQ). 2008a. *Benthic TMDL Development for Rivanna River Watershed.* March 2008. Accessed from http://www.rivannariverbasin.org/docs/Rivanna-Clearinghouse/Sediment_TMDL_Rivanna_Mar08.pdf

VDEQ. 2008b. *Trading Nutrient Reduction from Nonpoint Source Best Management Practices in Chesapeake Bay Watershed: Guidance for Agricultural Landowners and Your Potential Trading Partners.* Accessed from https://www.deq.virginia.gov/Portals/0/DEQ/Water/PollutionDischargeElimination/VANPSTradingManual_2-5-08.pdf

VDEQ. 2012. *Moores Creek, Lodge Creek, Meadow Creek, and Schenks Branch Watersheds TDML Implementation Plan, Albemarle County and City of Charlottesville, Virginia.* http://www.rivannariverbasin.org/docs/Rivanna-Clearinghouse/Draft_Cville_Streams_IP_12Sept06.pdf

VDEQ. 2018*. Final 2016 305(b)/303(d) Water Quality Assessment Integrated Report*.https://www.deq.virginia.gov/Programs/Water/WaterQualityInformationTMDLs/WaterQualityAssessments/2016305b303dIntegratedReport.aspx

VDEQ. 2019a. *NonpointCreditRegistry_1_14_2019_website.xl* https://www.deq.virginia.gov/Portals/0/DEQ/Water/PollutionDischargeElimination/NPS%20Trading/NonpointCreditRegistry_11_16_2018.xlsx?ver=2018-12-07-075025-300

VDEQ. 2019b. *Nonpoint Source Nutrient Trading Banks Statewide Map*.

Virginia Nutrient Bank ND. *What are Credits?* https://www.virginianutrientbank.com/about-2/what-are-credits

Walsh, C. et al. 2005. *The Urban Stream Syndrome: Current Knowledge and the Search for a Cure*. Journal of North American Benthological Society. 24(3):706-723.