ANALYSIS OF THE WATERSHED RESOURCES REGISTRY USING GIS TO EVALUATE STORMWATER RESTORATION PRACTICES IN THE CHRISTINA RIVER WATERSHED

by

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ABSTRACT

The Watershed Resources Registry is a new interactive online mapping tool, created by federal, state, and local partners. The tool prioritizes areas for preservation and restoration practices in different landscapes across an entire state by using a variety of absolute and relative criteria to rank areas from 1- (least) to 5-stars (most suitable). The State of Delaware launched its Watershed Resources Registry in 2016. Potential applications of the Watershed Resources Registry are promising; however, few studies have been completed to assess the validity of the Watershed Resources Registry in Delaware.

The Municipal Separate Storm Sewer System Permit Program, under the United States Environmental Protection Agency's Clean Water Act, requires New Castle County, Delaware Department of Transportation, and other permittees to develop Water Quality Improvement Plans for two watersheds over the next year. The purpose of this research is to determine if the Watershed Resources Registry is suitable to predict sites for water quality improvement projects. If the Watershed Resources Registry is a suitable predictive tool it can be used to develop Water Quality Improvement Plans for New Castle County and Delaware Department of Transportation. To determine suitability: a relationship was examined between Watershed Resources Registry ranks and pre-treated pollutant loads and then a spatial resolution threshold was defined for the Watershed Resources Registry's site selection. This study used a completed Water Quality Improvement Plan for the Christina River Watershed that provided 26 proposed best management practice sites. The Watershed Resources Registry ranks were obtained from the stormwater compromised infrastructure restoration layer and pre-treated pollutant loads of total nitrogen, total phosphorus, and total suspended solids in pounds per acre per year were calculated by the Delaware Urban Runoff Management Model. Geographic information systems were used to map and interpret data.

This study concluded three key results. One, the Delaware Urban Runoff Management Model is a model that can be used in tandem with the Watershed Resources Registry. The Watershed Resources Registry now offers a new perspective when using the Delaware Urban Runoff Management Model because loads can be associated with Watershed Resources Registry ranks in different watersheds. Two, the higher Watershed Resources Registry ranks associated with higher pollutant loads on a larger scale. Three, the Watershed Resources Registry is best suited for at least a 4-acre resolution. This resolution provides “hot spot” areas to focus on, rather than specific site locations, therefore it should only be used for a screening tool. The Watershed Resources Registry has potential to be widely used as a screening tool to locate stormwater restoration practices throughout the Mid-Atlantic states.

Chapter 1

INTRODUCTION

For decades, poor water quality has plagued our nation’s waterways and specifically Delaware’s waterways (Ackerman et al. 1973 and Kauffman and Collier 2018). The Delaware River watershed is 13,539 square miles, fed by 216 tributaries from Pennsylvania, New Jersey, New York, and Delaware, flowing through the greater Philadelphia metropolitan area and beyond (Figure 1.1). Five percent of the nation’s population, or 16 million people, rely on the river for drinking water (Kauffman and Collier 2018). Prior to the American Revolution, Philadelphia became one of the largest growing cities and had many issues with domestic and industrial pollution, specifically in and around Dock Creek, which fed into the Delaware River, when over 500 people were diagnosed with yellow fever due to polluted water becoming breeding grounds for mosquitos (Westcott n.d.). Benjamin Franklin helped establish a comprehensive act which prioritized a seven-year cleanup of Philadelphia’s urban environment, including expansion of the stormwater drainage system and creation of specific requirements for disposal of sweepings, ash, shavings, or manure (Pennsylvania 1810 and McMahon 1992). Despite these initial measures, health of the river continued to decline and the Interstate Commission on the Delaware River Basin (1940) proclaimed that the Delaware River at Philadelphia was “one of the most grossly polluted areas in the United States.”

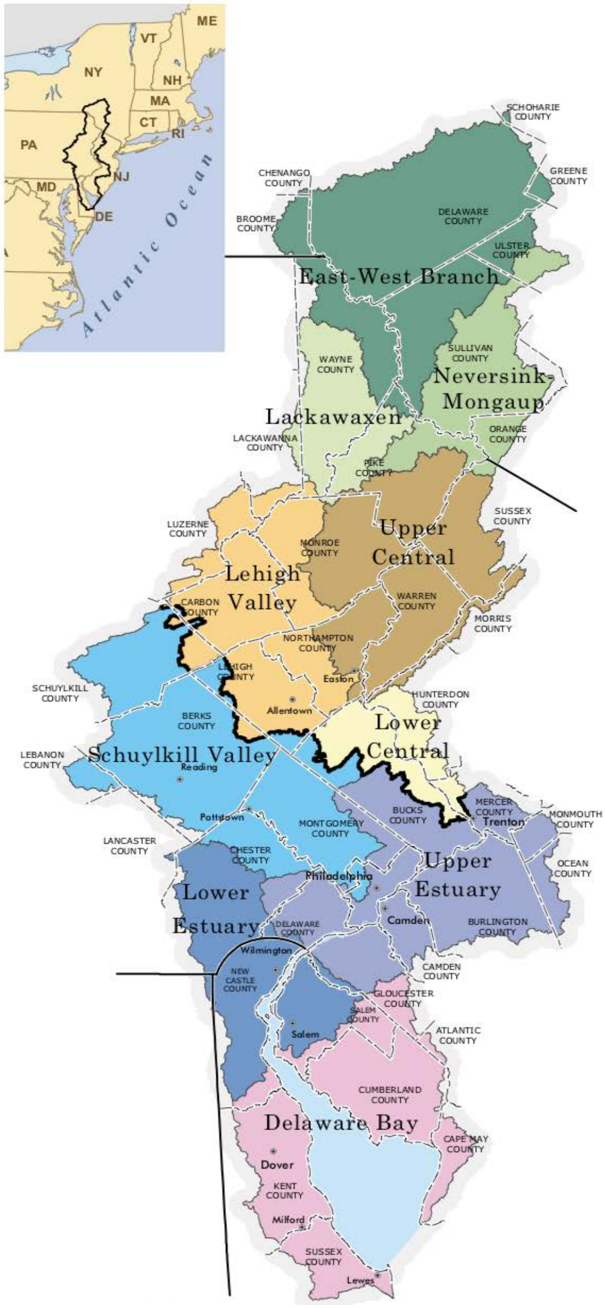


Figure 1.1: Delaware River watershed (DRBC 2008)

Delaware contains about eight percent of the entire Delaware River watershed, as the Delaware River mouth is the Delaware Bay (Kauffman and Collier 2018). Within this eight percent is the Christina Basin, which consists of four watersheds: Brandywine Creek, Christina River, Red Clay Creek, and White Clay Creek (DNREC et al. 2011). Previously, the Christina River has been on the United States Environmental Protection Agency's (EPA) 303(d) listing based on fish consumption advisories for polychlorinated biphenyls, dieldrin, dioxin and furan toxic equivalency factor, dichlorodiphenyltrichloroethane and metabolites, and chlordane. Updated in 2016, the Christina River is still listed by DNREC (2018) for dieldrin, while chlordane and polychlorinated biphenyls were removed from the list because they "are no longer a contaminant for concern in fish consumption advisories for these waters."

As the human footprint has grown across the nation, forests have been removed (Greeley 1925 and Foreman and Wolke 1992) and have been replaced by developed or impervious surfaces, which cause a cascade of environmental impacts. The Delaware River Basin Commission (DRBC) mapped the Delaware River watershed showing developed areas versus forests and waterways (Figure 1.2). Impervious surfaces shorten the lag time between rain events and peak runoff discharges, which result in degraded water quality (Arnold and Gibbons 1996). Water quality can be degraded by floods, soil erosion, and sedimentation (Anderson 1970 and McMahon and Cuffney 2000). Water quality also begins to degrade when watersheds become seven to ten percent impervious (Figure 1.3) as determined by Booth and Jackson (1997) and Schueler (1992).

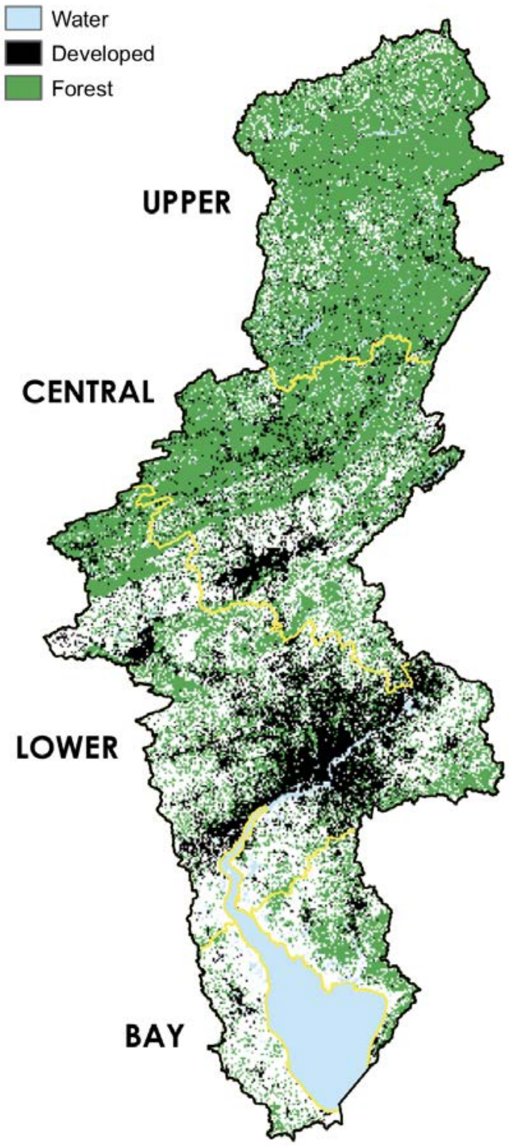


Figure 1.2: Land use in the Delaware River watershed (DRBC 2008)

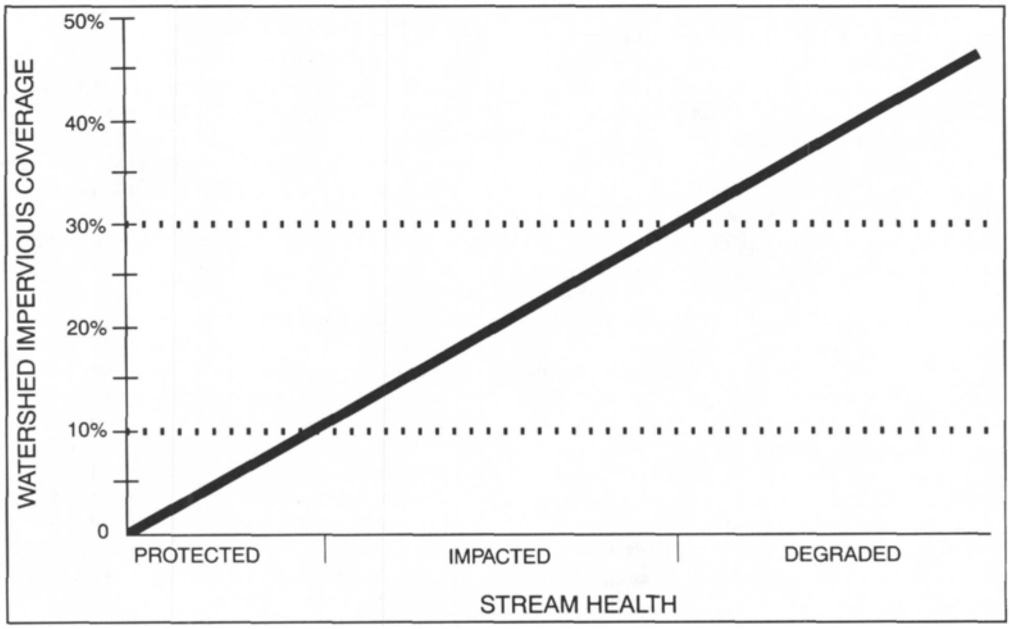


Figure 1.3: Relationship between watershed impervious cover and stream health (Arnold and Gibbons 1996 and Schueler 1992)

The Christina River is used for both drinking water and recreational purposes and supports hundreds of acres of freshwater and tidal wetlands (Jeannette et al. 2014). The Christina River watershed's development is growing vastly with at least 59 percent of land use classified as urban or suburban while about 81 acres of wetlands have been converted between 1992 and 2007 alone (Brandywine Conservancy et al. 2018 and Jeanette et al. 2014). Because population trends in Delaware follow concentric outward growth, this has impacted nearly every stream in Delaware with increased impervious cover. In total, 94 percent of Delaware's rivers and streams do not support fish and wildlife, while 84 percent do not support recreational swimming (DNREC 2015).

With the surge in growth comes an increase in nonpoint source pollution of sediment, nitrogen, and phosphorus. One of the leading causes of deteriorating water quality health in the United States is nonpoint nitrogen pollution sources, such as fertilizers from lawns, grass, and pet waste (Carpenter et al. 1998). A study was completed by Jones et al. (2001) that showed suspended sediment loads are positively correlated with an increase of urban cover in a watershed, while wetland and riparian forest covers are negatively correlated. Waschbusch et al. (1999) completed a study in Wisconsin during 1991 that determined streets contributed to 80 percent of the total watershed suspended sediment loads, 58 percent of total phosphorus, and 46 percent of dissolved phosphorus. Lawns also contributed with seven percent of suspended sediment loads, 14 percent for total phosphorus, and 22 percent for dissolved phosphorus. Another study was completed in 1994 that showed similar results, except both types of phosphorus had more contributions from lawns than streets (Waschbusch et al. 1999).

It is important to understand the environmental impacts of urbanization and increasing imperviousness, especially to water quality and aquatic life. It is likewise paramount to be proactive instead of reactive when dealing with water quality issues. Although some measures have been implemented, there is always room for improvement, specifically when planning and expanding urbanized areas. Best management practices (BMPs) are implemented as a pollution control measure in structural or vegetative forms to prevent, reduce, and treat water pollution (EPA 2007 and West et al. 2015). Along with improving water quality, BMPs can also be used for flood control because they slow down runoff rates and volumes from entering the storm drains and streams (EPA 2007).

A variety of BMPs can be employed to guide treatment and solutions for water quality. For example, detention ponds are recommended for nitrate or nitrogen treatment, while vegetation, or filter strips, are one of the recommendations for phosphorus reduction (West et al. 2015). One example of a success story from BMP implementation is along Arcadia Creek in Kalamazoo, Michigan. Total phosphorus (TP) and total suspended solids (TSS) reductions were met when two watershed management plans were developed, incorporating eight different BMPs (EPA 2015a).

Strategic location of BMP implementation is critical for improving water quality. Installing a BMP in a less critical area can result in significantly less water quality improvement. An interactive online mapping tool called the Watershed Resources Registry was designed to aid in the BMP site selection process. The Watershed Resources Registry prioritizes areas based on absolute and relative criteria, meaning criteria that has to be met (absolute) and criteria that can be met (relative). The Watershed Resources Registry assigns a 1- to 5-star ranking, as 1 being the least suitable and 5 being the most suitable area (EPA 2017a). This tool has great potential to be very powerful because it was built through consensus of statewide partners. It can be used in the first phase of Water Quality Improvement Plans (WQIPs), which are created under the National Pollutant Discharge Elimination System (NPDES) permit program (New Castle County and DelDOT 2016). The purpose of this research is to examine if the Watershed Resources Registry can be a useful tool to increase efficiency in the WQIP planning process, so more BMPs can be designed and water quality can improve over time.

Based on a review of current literature, there has been no published research assessing the validity of mining information in the Watershed Resources Registry for integration into implementation planning for WQIPs. There are four categories within the Watershed Resources Registry, each having a preservation and restoration sub-category: upland, wetland, riparian, and stormwater. This research applies the stormwater compromised infrastructure restoration Watershed Resources Registry layer in the Christina River WQIP. Site selection has already been completed for the WQIP using alternative methods later described. These sites were used as the samples to compare to the Watershed Resources Registry rank output. The Delaware Urban Runoff Management Model (DURMM) was used to provide pre-treated nutrient and sediment loads for each site. To determine if any relationship was present the Watershed Resources Registry ranks were compared to the selected sites, along with identifying a spatial scale that the Watershed Resources Registry is best suited for. If a correlation was present between Watershed Resources Registry rankings and pollutant loads, meaning higher ranks associated with higher pollutant loads, then a relationship was confirmed so the Watershed Resources Registry could be used as a beneficial tool to aid New Castle County and Delaware Department of Transportation (DelDOT) in their WQIPs, or other entities identifying stormwater BMP locations.

Specific questions addressed in this research include:

(1) Is the Watershed Resources Registry a viable tool to predict suitable sites for water quality improvement plans?

(2) Does the Watershed Resources Registry have a resolution threshold when selecting a viable stormwater restoration project location?

(3) How can the Watershed Resources Registry 1- to 5-star rank be translated into quantitative water quality improvements in terms of total nitrogen, total phosphorus, and total suspended solids?

(4) If the Watershed Resources Registry is a viable tool, how can it be applied to other watersheds within Delaware, Maryland, Pennsylvania, Virginia, and West Virginia?

Key hypotheses related to the questions above are:

(1) The Watershed Resources Registry will be able to detect best management practice sites that correlate to higher pre-treated nutrient loads.

(2) The Watershed Resources Registry can identify sites on a broad scale versus a small scale.

(3) Higher Watershed Resources Registry ranks will be associated with higher pollutant loads.

This research was one of the first studies to engage the Watershed Resources Registry data for the purpose of water quality planning. The goal was to prove if the Watershed Resources Registry could be a viable tool to effect positive change in the design and implementation of WQIPs. Similarities between the BMP site selections of the Watershed Resources Registry and the Christina River WQIP were hypothesized. The degree of spatial resolution was estimated to be a large area, instead of a specific BMP site location. The higher Watershed Resources Registry rankings were theorized to be associated with higher pre-treated pollutant loads, but the extent was unknown prospectively. Novel aspects to this study included delineating BMP catchment areas using a new approach in a geographic information system (GIS) and overlaying the DURMM with the Watershed Resources Registry rankings to determine the validity of the Watershed Resources Registry.

Chapter 2

LITERATURE REVIEW

This review provides an overview of several key statues and regulations that drive clean water including the Clean Water Act, National Pollutant Discharge Elimination System, and the Municipal Separate Storm Sewer System (MS4) Permit Program. Following, this chapter examines Delaware's Water Quality Improvement Plans, specifically the Christina River Water Quality Improvement Plan and its site selection processes. The Watershed Resources Registry is also surveyed, starting from its creation and purpose, to its modeling inputs and application. Lastly, three different load reduction models are reviewed.

2.1 The Clean Water Act

Historically as a developing nation, legislative efforts to address water safety and cleanliness existed piecemeal only at the state level, and there was widespread inconsistency among states' ability and willingness to administer water pollution control laws. Such discrepancies resulted in continued water pollution to varying degrees. As a result, the first nationwide water quality legislation, the Federal Water Pollution Control Act, was enacted to unify water quality standards and enforcement across the nation (The Democratic Staff of the Committee on Transportation and Infrastructure 2002). The Act was revised in 1972, 1977, while being renamed the

Clean Water Act, and 1987 (Table 2.1) as chronicled by Hines (2012) and Copeland (2016). The Clean Water Act is the seminal water quality legislation driving water quality improvements by limiting surface waters from discharged pollutants, otherwise known as point source pollution (EPA 2002). However, the Clean Water Act would not be as robust as it is today without the EPA.

Table 2.1: A list of the Clean Water Act and its major amendments (Copeland 2016)

Year	**Act**	**Public Law Number**
1948	Federal Water Pollution Control Act	P.L. 80-845 (Act of June 30, 1948)
1956	Water Pollution Control Act of 1956	P.L. 84-660 (Act of July 9, 1956)
1961	Federal Water Pollution Control Act Amendments	P.L. 87-88
1965	Water Quality Act of 1965	P.L. 89-234
1966	Clean Water Restoration Act	P.L. 89-753
1970	Water Quality Improvement Act of 1970	P.L. 91-224, Part 1
1972	Federal Water Pollution Control Act Amendments	P.L. 92-500
1977	Clean Water Act of 1977	P.L. 95-217
1981	Municipal Wastewater Treatment Construction Grants Amendments	P.L. 97-117
1987	Water Quality Act of 1987	P.L. 100-4

The 1972 amendments to the Clean Water Act were critical for establishing the intricate network of the NPDES program, which still exists today. Prior to the 1972 Clean Water Act, poor water quality posed dangerous health issues to humans and animals leading to disease and death (Hines 2012). While there were numerous examples of water pollution (Adler et al. 1993), the most iconic is the Cuyahoga River in Ohio. Beginning in 1968, the Cuyahoga River caught fire 13 times as a result of intense pollution. The most notorious fire in 1969 was not the most damaging but received national attention as a result of emerging technology to broadcast the news (Stradling and Stradling 2008). Following this fire, Congress passed the National Environment Policy Act on January 1, 1970, which eventually led to the establishment of the EPA on December 2, 1970 (Lewis 1985). One of the EPA's initial groundbreaking successes was the promulgation of the Clean Water Act regulations in 1972. By this time, only one-third of the nation's water quality goals were met (The Democratic Staff of the Committee on Transportation and Infrastructure 2002).

The Clean Water Amendments of 1977 intensified the focus on the wastewater industry by codifying stronger controls on toxic pollutants and delegating control of maintaining federal programs to the states (Cech 2009). The updated Clean Water Act had six primary principles that focused on improving water quality regarding discharged toxic pollutants and advancing better treatment processes for wastewater (Copeland 2016). This helped rectify more point source pollution problems because individual pipes and discharges were regulated. Nonpoint source pollution remained a problem because of the diffuse nature of the source.

In 1987, Congress passed the Water Quality Act to increase assessment and monitoring of water bodies to ensure water quality standards (Water Quality Control Act of 1987). Water quality standards have been and are still established by each state for all water bodies. The EPA created the Total Maximum Daily Load (TMDL)

Program to control point and nonpoint source pollution and therefore meet specific water quality standards (National Research Council 2001). Total maximum daily loads indicate the total amount of pollutants that a waterbody can receive and still maintain water quality standards (Copeland 2016). States are required to specify how much pollution needs to be reduced in order to meet TMDLs (National Research Council 2001).

2.2 National Pollutant Discharge Elimination System

The NPDES is a national program designed to completely control the issuing, modifying, terminating, and enforcing of permits under sections 307, 402, 318, and 405 of Clean Water Act (EPA 2017b). The NPDES permit program addresses water pollution by controlling point sources and require permits to discharge pollutants into nation's navigable waters (Cech 2009). The NPDES permit program is delegated to state, tribal, and territorial governments. Authority is given to execute aspects of the program, such as permitting, administrative, and enforcement. There are currently 46 states and one territory delegated under the NPDES program (EPA 2017b). The NPDES program covers a variety of areas such as: animal feeding operations, municipal wastewater, pesticide permitting, and stormwater (EPA 2016).

An NPDES permit specifies two types of control. The first includes technology-based limitations. These are based on the discharger's ability to control discharge of pollutants in wastewater, for example. The second includes water quality-based limitations to protect the body of water receiving the discharge. In order to further eliminate discharged pollutants, industrial facilities are mandated to meet two levels of technology criteria: Best Practicable Control Technology Currently Available and Best Available Technology Economically Achievable (EPA 2010).

The 1977 Clean Water Act identified technology-based limitations that fell short of preventing water pollution caused by discharged toxic pollutants. Congress amended the Clean Water Act with the 1987 Water Quality Act to address this issue. The amended Act required industrial stormwater discharges and water quality standards to meet the equivalent of Best Available Technology Economically Achievable and Best Conventional Technology effluent quality standards. Now, MS4s must develop controls that reduce pollutant discharges (EPA 2010). MS4s are further discussed in Section 2.3.

2.3 Municipal Separate Storm Sewer System

An MS4 is a system of conveyances, owned by either a state, city, town, village, or other public entity, that primarily conveys stormwater. An MS4 is not a combined sewer and is not part of a sewage treatment plant; however older cities often have a combination of the two (EPA 2015b). As precipitation falls over impervious surfaces, polluted runoff is generated, transported through MS4s, and discharged into nearby rivers and streams untreated. This can have major implications on water quality as common pollutants in the stormwater runoff include: oil, grease, pesticides, salt, trash, and more. The purpose of having an MS4 stormwater management program is to mitigate pollutant entry into waterways (EPA 2005). Figure 2.1 shows locations of

Phase I and Phase II MS4s in the United States. Phase I includes municipalities greater than or equal to a population of 100,000 and Phase II consists of populations less than 100,000 (Corrozi Narvaez et al. 2012). There are about 855 Phase I MS4s and 6,695 Phase II MS4s (EPA 2015b). There are six minimum control measures for the MS4 program as well. Those are: (1) public education and outreach, (2) public participation and involvement, (3) illicit discharge detection and elimination, (4) construction site runoff control, (5) post-construction runoff control, and (6) pollution prevention/good housekeeping (EPA 2016).

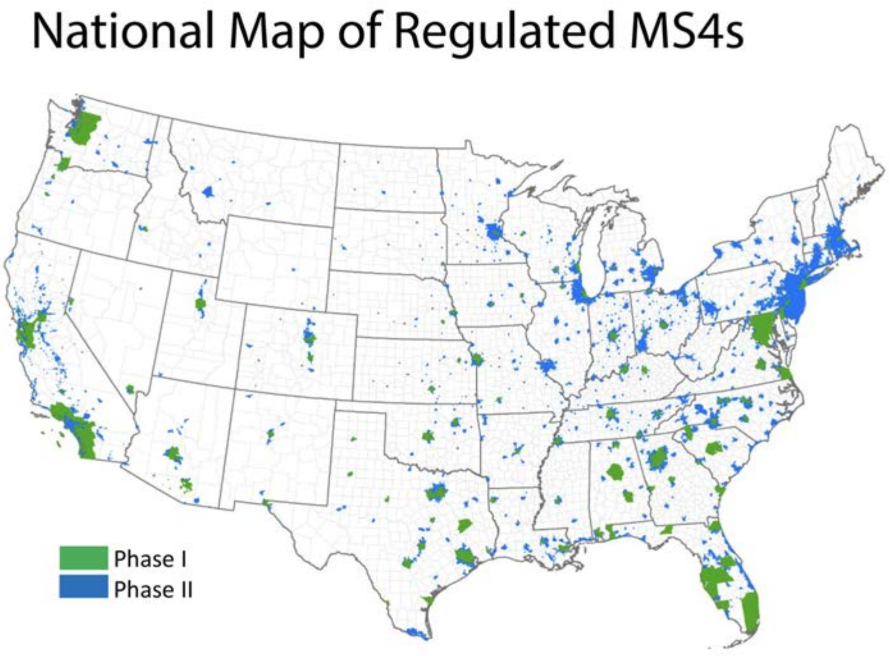


Figure 2.1: Municipal Separate Storm Sewer Systems in the United States (EPA 2015b)

The Department of Natural Resources and Environmental Control's (DNREC) NPDES program is managed by DNREC's Surface Water Discharges Section. In 1974, Delaware's MS4 program was established as part of a consent decree from the EPA (EPA 2004). On April 5, 1993 part one of the first permit application for Phase I MS4 coverage was submitted and on September 27, 1996 a part two draft application was submitted on to DNREC (DNREC 2013c). After revisions, DNREC issued a Phase I NPDES permit on May 1, 2001 to the principal permittees of New Castle County and DelDOT. Currently in Delaware there are the following permits: Phase I-New Castle County and DelDOT (principal permittee) with Bellefonte, Newport, Elsmere, Delaware City, New Castle, and Wilmington; Phase II DelDOT; Phase II Newark/University of Delaware; Phase II Middletown; Phase II Dover (DNREC 2013c). Phase I permits cover a larger population and typically have more requirements than phase II. In particular, the 2013 Phase I permit in Delaware requires the development of two WQIPs (DNREC 2013c).

2.4 Water Quality Improvement Plans

In Delaware, WQIPs are implemented through the MS4 program, under the current Phase I NPDES permit, which requires permittees to develop two WQIPs. DNREC (2013a) states the permit requires permittees to develop a plan to implement projects that treat 3 percent of the effective impervious area (EIA). Sutherland (2000) describes EIA as the portion of total impervious area (TIA) within a watershed that directly connects to the drainage collecting system. Based on population, in Delaware, the following are required to develop two WQIPs: New Castle County, DelDOT, and six municipalities: Bellefonte, Delaware City, the Town of Elsmere, the City of Middletown, the City of New Castle, and City of Wilmington (DelDOT 2014).

This review discusses only Delaware's WQIPs; however, other states do implement these plans, such as California, Maryland, Pennsylvania, and New York. For example, one of California's WQIPs was proposed by seven cities and the county of San Diego for the Carlsbad watershed. Their permit focuses on adaptive management by having a five-year cycle of planning, implementation, and assessment phases that all interconnect to have a stronger outcome and make water quality improvements (Mikhail Ogawa Engineering 2016).

Effective Impervious Area

As stated, Delaware's WQIPs are required to treat 3 percent EIA in a given watershed. Examples of EIA are parking lots, street surfaces, roofs, and sidewalks contiguous with curbed streets. In most watersheds, the EIA is less than the TIA, but in highly urbanized watersheds, the EIA can almost equal the TIA (Sutherland 2000). The amount of EIA in a watershed can greatly impact runoff volume. Impervious areas not contributing to direct runoff should be subtracted from the TIA to calculate the EIA. This helps obtain better accuracy when estimating runoff volumes (Sutherland 2000).

There are several ways to calculate EIA in a watershed. Direct measurement in the watershed is most accurate, but is a timely and expensive. It requires documentation and evaluation of the effective hydraulic connectivity between each of the major collector systems and impervious areas. Alternatively, calculations can be done through various models, such as the Stormwater Management Model, which calibrates the EIA (Sutherland 2000). A United States Geological Survey (USGS) empirical equation shown below (Equation 2.1) can also be used (Laenen 1983):

$$\mathrm{EIA} = 3.60 + 0.43\,(\mathrm{TIA}) \tag{2.1}$$

It works accurately for providing EIA values given TIA values between 10 percent and 50 percent, but values outside of this range produce inaccurate EIA. In more urbanized areas, the Sutherland equations are used. The most general form is below in Equation 2.2.

$$\mathrm{EIA} = A(\mathrm{TIA})^{B} \tag{2.2}$$

Where:

A and B = combination of numbers based on watershed type to meet these criteria:

1. If TIA = 1 then EIA = 0%
2. If TIA = 100 then EIA = 100%

Delaware's Water Quality Improvement Plans

New Castle County and DelDOT (2016) describe the focus of WQIPs are streams, in specific watersheds, that have "achieved or are near achieving total maximum daily loads and water quality standards." The WQIP identifies potential projects, estimates BMP costs, and provides potential sources of funding for projects directed at meeting total maximum daily load requirements (DNREC 2013a). A watershed priority list was created to aid in selecting the watersheds to develop WQIPs (Table 2.2). The specific process for Delaware is detailed in Section 2.5. Table 2.3 provides an example of Delaware's criteria to consider when selecting watersheds.

Table 2.2: List of available watersheds in New Castle County with permittees (DNREC 2013a)

Watershed	Responsible Permittee(s)
Appoquinimink River	New Castle County, DelDOT
Army Creek	New Castle County, DelDOT, City of New Castle
Blackbird Creek	New Castle County, DelDOT
Bohemia Creek	New Castle County, DelDOT
Brandywine Creek	New Castle County, DelDOT, Wilmington
C&D Canal East	New Castle County, DelDOT, Delaware City
C&D Canal West	New Castle County, DelDOT
Chester River	New Castle County, DelDOT
Christina River	New Castle County, DelDOT, Elsmere, Newport, Wilmington
Delaware Bay	New Castle County, DelDOT
Delaware River	New Castle County, DelDOT, City of New Castle, Wilmington, Delaware City
Dragon Run	New Castle County, DelDOT, Delaware City
Elk Creek	New Castle County, DelDOT
Naamans Creek	New Castle County, DelDOT
Perch Creek	New Castle County, DelDOT
Red Clay Creek	New Castle County, DelDOT
Red Lion Creek	New Castle County, DelDOT
Sassafras River	New Castle County, DelDOT
Shellpot Creek	New Castle County, DelDOT, Bellefonte, Wilmington
Smyrna River	New Castle County, DelDOT
White Clay Creek	New Castle County, DelDOT

Table 2.3: Criteria to consider when establishing the watershed priority list (DNREC 2013a)

Criteria for the Watershed Priority List
State of Delaware 2010 Combined 305(b) Report and 303(d) List
Wild and Scenic River
Relevant Total Maximum Daily Loads
Waters of Exceptional Recreational or Ecological Significance (ERES)
Drinking water sources
Flood prone areas
Areas with combined sewer overflow/sanitary sewer overflow impacts
Existing population and impervious cover
Projected growth, development and impervious cover
Other stream assessments (e.g., Revised Stream Assessment Technique, Unified Stream Assessment, Rapid Bio Assessment)

There are two phases for the development of WQIPS. Phase I is the initial BMP selection, typically using a desktop analysis, and Phase II is the field verification. There are 21 watersheds within New Castle County, and each are categorized as “Restoration” and “Preservation” based on their ratio of EIA to the total drainage area. Restoration watershed tags were given if the ratio was greater than or equal to 0.30 percent and preservation watersheds’ ratio was less than or equal to 0.19 percent. Table 2.4 lists a series of criteria used to rank watersheds within each category (New Castle County and DelDOT 2016). Low scores equal 1 to 2 points while high scores are 3 to 4 points.

Table 2.4: Ranking of the 21 watersheds in New Castle County (New Castle County and DelDOT 2016)

Criteria for Weighted Score in Each Watershed	**Ranking Calculation**	**Score (High/Low)**
1. 303(d) list delisting of streams for nutrients	Total removed streams / # square miles in watershed	High: greater ratios Low: lesser ratios
2. 303(d) list delisting of streams for bacteria	Total removed streams / # square miles in watershed	High: greater ratios Low: lesser ratios
3. Reductions required to meet the total maximum daily load for nutrients and bacteria	Reductions based on Table A.1. in the National Pollutant Discharge Elimination System Permit, expressed as a percent	High: lesser reductions Low: greater reductions
4. 3 percent of effective impervious area	Effective impervious area / total watershed area	High: greater ratios Low: lesser ratios
5. Planned State of Delaware Department of Transportation projects	Linear miles of proposed projects	High: greater miles Low: lesser miles
6. New Castle County future growth areas (high and low intensity)	Percentage area of high-intensity growth + 1⁄4 of the percentage area of low-intensity growth	High: Greater growth Low: Lesser growth
7. Public and private open space	Area of land cover type / total area of watershed	High: Greater open space Low: Lesser open space
8. Exceptional Ecological or Recreational Value Stream	Watersheds with any Exceptional Ecological or Recreational Value Stream	Score of 4: Watersheds with any Exceptional Ecological or Recreational Value Stream Score of 1: Watersheds without any Exceptional Ecological or Recreational Value Stream
9. Drinking water sources (surface)	Amount of area upstream of surface drinking water / total watershed area	Value used as score basis No intakes = score of 0
10. Flood-prone areas	100-year Federal Management Emergency Agency floodplain / total watershed area	High: high percentages Low: low percentages
11. Areas affected by combined sewer overflows	Number of combined sewer overflows in a watershed	High: At least 1 combined sewer overflow present Score of 0 if no combined sewer overflows present

The two watersheds selected must be located within the most recent US Census data's urbanized area boundary. In this case, all of New Castle County was considered and New Castle County and DelDOT selected the Christina River watershed and Dragon Run watershed. The final watershed selection was submitted to DNREC for review and approval was needed by the fourth year of the permit (DNREC 2013a). The focus of this study is the Christina River because WQIP development is substantially complete, whereas Dragon Run is in draft form. The site and BMP selection processes are discussed in Section 2.5.

Phase 1 of the process determines how to treat EIA. Each WQIP is required to define a long-term schedule delineating the processes for achieving the 3 percent effective impervious area treatment goal. This should be done through the development of new or retrofitting old BMPs (DNREC 2013a). There are specific references to use when designing, selecting, and locating BMPs, such as the EPA's stormwater practice design guide, Center for Watershed Protection's manual for urban stormwater retrofit practices, DNREC's Green Technologies Standards and Specifications document, the Delaware Urban Runoff Management Model, and DNREC's Delaware Erosion and Sediment Control Handbook (DNREC 2013a).

2.5 Christina River Water Quality Improvement Plan

The Christina River watershed covers Delaware, Maryland, and Pennsylvania; however, the watershed boundary was modified for WQIP development. Areas outside the state of Delaware are not incorporated and three major tributaries of the Christina River: The City of Newark was removed because they have Phase II MS4 coverage.

Combined sewer overflows are not being considered because they have individual NPDES permits and are not included in New Castle County and DelDOT's NPDES permit. The watershed area for the Christina River WQIP was extrapolated to/calculated as 57.9 square miles (DelDOT and New Castle County 2019). Figure 2.2 illustrates the newly revised area versus the entire watershed. The Red Clay Creek, White Clay Creek, and Brandywine Creek are also not included as they are separate watersheds.

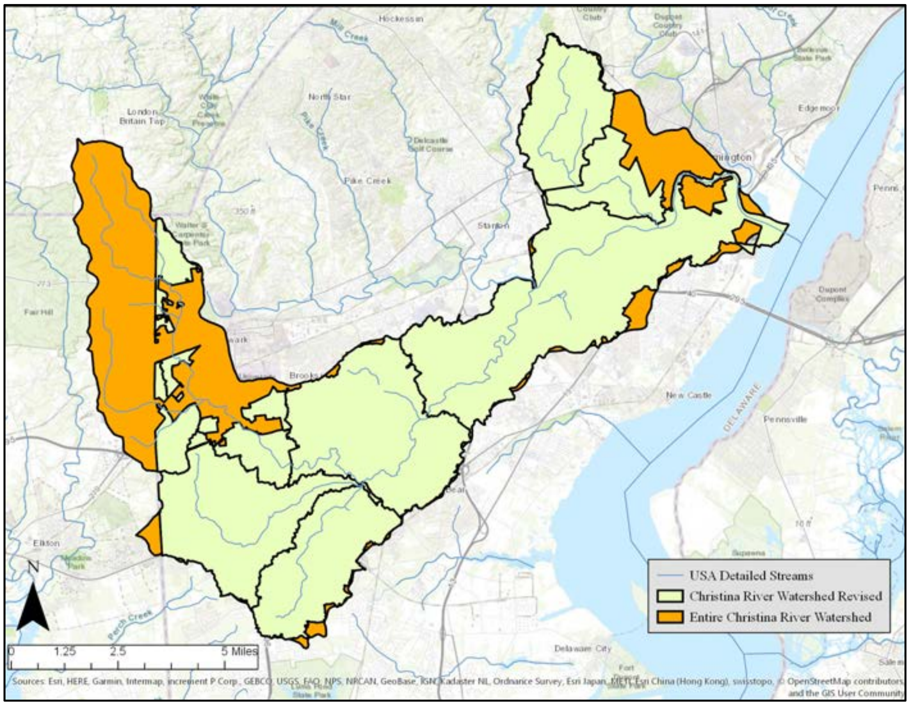


Figure 2.2: Christina River watershed

The EIA was calculated following the Sutherland equation. There are 10,601 acres of total impervious cover and 7,481 acres of EIA, so 3 percent of the EIA treatment equals out to be 224 acres (Century Engineering, Inc. 2016).

Century Engineering used a two-pronged approach for BMP site selection in the WQIP. First, Century Engineering deployed a two-step desktop screening. The first step included an automated screening using the criteria in Table 2.5. The second step incorporated an engineering review of the results in step one, which included datasets from sources such as the Delaware Geological Survey and the United States Department of Agriculture (DelDOT and New Castle County 2019).

Table 2.5: Criteria required to complete automated screening for a site selection (DelDOT and New Castle County 2019)

Sites Must Have:	**Must Not Have:**
An effective impervious area ratio ≥ 10%	Location on or within close proximity to environmentally hazardous site
Location on public agency owned or managed property	Location on or within close proximity to archaeologically sensitive or historic sites
Area available for BMP implementation	Location on or within environmental resources
Access to site	Location in 100-year floodplain
Ability to tie into drainage network	

The engineering review consists of a point ranking system using GIS. The ranking criteria are listed in Table 2.6, which provides the ranking category, type of each ranking, and the score. A final desktop review is required to sum together the initial score field with more detailed ranking criteria. Some of these criteria included issues such as determining if is space available for BMP construction or expansion and potential for infiltration (DelDOT and New Castle County 2019).

Table 2.6: A list of the ranking criteria used for the engineering review (DelDOT and New Castle County 2019)

Ranking Category	Ranking Type	Score
SWM BMP/Outfall Points		
	ROW Type (Public/Private)	6: County, state, transportation, or if owner is State of Delaware Department of Transportation 0: Other
	Wetland	6: Not present 0: Present
	Floodplain	6: Not present 0: Present
	Soil Hydrologic Group	6: A 4: B 2: C 0: D / U
SWM BMP Footprints (polygons)		
	ROW Type (Public/Private)	6: County, state, transportation, or if owner is State of Delaware Department of Transportation 0: Other
	Wetland	6: Footprint contains <= 50% 0: Footprint contains > 50%
	Floodplain	6: Footprint contains <= 50% 0: Footprint contains > 50%
	Soil Hydrologic Group	6: A, 4: B, 2: C, 0: D / U
	Depth to Water Category	6: A, 4: B, 2: C, 0: D

Field inspections were conducted to confirm what was found in GIS. Site selection is determined for both new and existing BMPs. New BMPs need potential for infiltration or filtration. An existing BMP is eligible for retrofit selection if it does not have filtration or infiltration. The main types of locations analyzed were (1) an outfall, (2) existing BMP, or (3) a location for a new BMP that had no outfall. Existing outfalls were documented with impervious cover and drainage area confirmed from the desktop analysis. Due to the high cost to retrofit existing BMPs, not too many existing BMPs were included. If they were, a dry pond or grassed roadside swale was recommended. New BMP types at the end of the inspection were restricted to infiltration, filtration, or both in order to gain the most water quality improvements. A filtration BMP is primarily dependent on the amount of land available. An infiltration BMP has specific limiting factors including: soil type, depth to groundwater, and land available (DelDOT and New Castle County 2019). From this process, a list of the top 35 BMP sites was selected. For this research, only 26 sites were used with explanation in Chapter 2. Table 2.7 lists the 26 sites with its name, BMP identification (ID) numbers, and type of proposed BMP.

Table 2.7: Best management practice sites in the Christina River watershed

Location Name	**Best Management Practice Identification Numbers**	**Type of Best Management Practice**
Robscott Manor Park	306 307	Bioswale
Gauger Cobb/Breezewood	701 702	Traditional bioretention with underdrain
Raven Glenn	901	Traditional bioretention with underdrain
Taylor Towne Park	1001	Traditional bioretention with underdrain
Glendale Park	1101	Infiltration basin
Coventry	1301 1302 1303	Traditional bioretention with underdrain
Chelsea Manor	1401 1402 1403 1404	Traditional bioretention with underdrain
Banning Park	1501 1502	Infiltration basin
Becks Pond	1601 1602 1603	Traditional bioretention with underdrain Infiltration trench
Brack Ex	2201	Bioswale
Fairhorne / Al High School	2601 2602 2603 2604	Traditional bioretention with underdrain Porous asphalt
Breezewood	3001	Traditional bioretention with underdrain
Old DMV	3101	Surface sand filter

2.6 The Watershed Resources Registry

The Watershed Resources Registry is an interactive online mapping tool, created through consensus of federal, state, and local partners. The State of Delaware launched its Watershed Resources Registry in March 2016. Major partners involved with creating Delaware's Watershed Resources Registry are DNREC, DelDOT, US Fish and Wildlife Service, EPA Region 3, US Army Corps of Engineers, Philadelphia District, US Federal Highway Administration, and Delaware Center for Inland Bays (EPA 2017a).

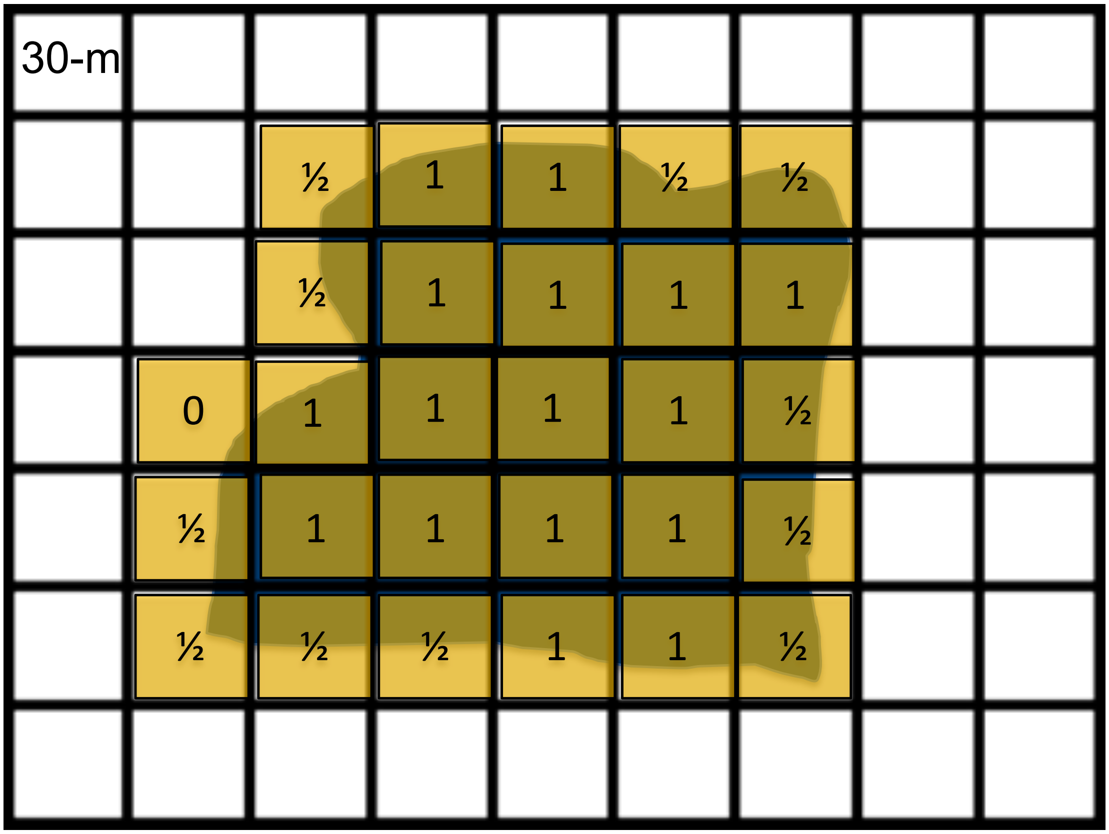
The Watershed Resources Registry prioritizes BMP implementation areas for preservation and restoration in landscapes across an entire state. There are four sets of restoration and preservation categories that provide a suitability analysis: upland preservation and restoration, wetland preservation and restoration, riparian preservation and restoration, and stormwater natural infrastructure preservations and stormwater compromised infrastructure restoration. The Watershed Resources Registry is available for five states: Delaware, Maryland, Pennsylvania, Virginia, and West Virginia (EPA 2017a).

The Watershed Resources Registry uses a 30-meter resolution to identify criteria which can then be given a rank. There are a variety of absolute and relative criteria for each of the four sets of restoration and preservation categories. For example, in Delaware, the stormwater compromised infrastructure restoration layer has seven absolute criteria and five relative criteria listed and shown in Table 2.8 (EPA 2017a).

Table 2.8: Criteria for stormwater restoration Watershed Resources Registry layer (EPA 2017a)

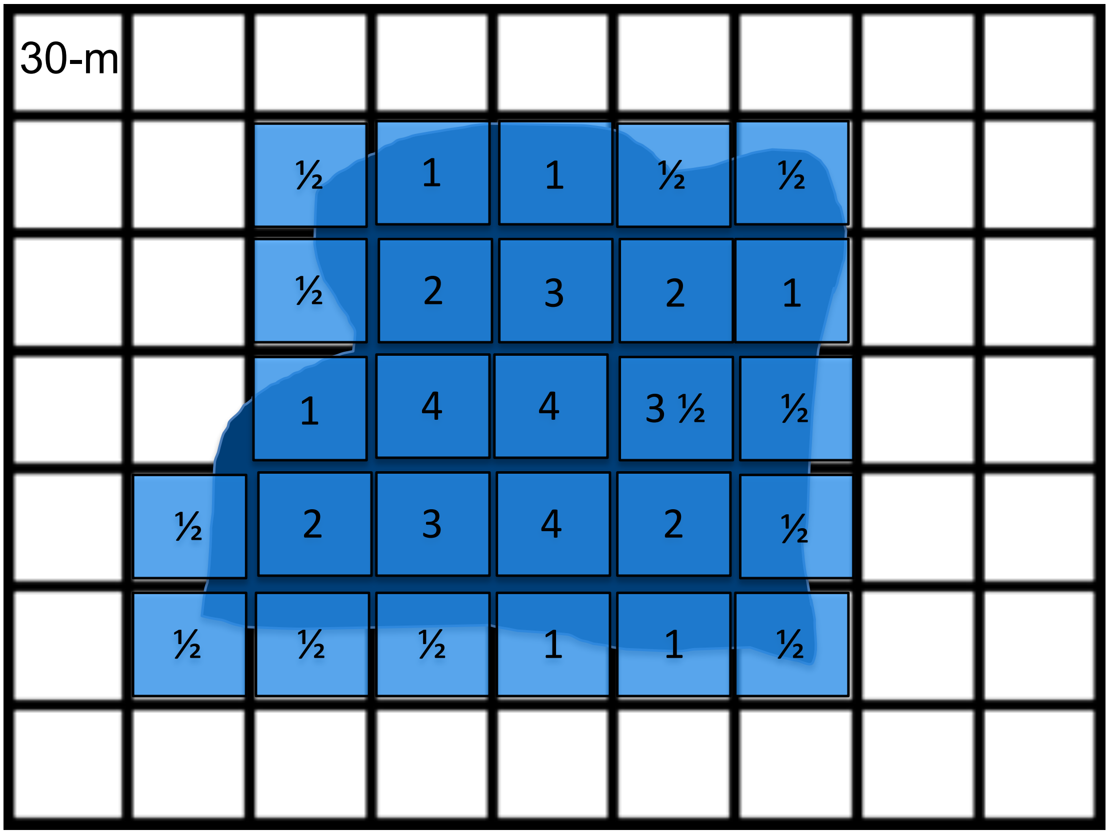
Absolute Criteria	Relative Criteria
Cannot be a wetland	Is an area of relatively higher impervious surfaces, 10 percent to 20 percent, as indicated by United States Geological Survey impervious layer
Cannot be cropland	Is in a community built prior to 1991
Cannot be forested, as indicated by United States Geological Survey 30-meter land cover	Is in a tax ditch system
Cannot be in a spray irrigation zone	Is in an impaired watershed as indicated by §303(d)
Cannot be in karst geology	Is in an urban area
Cannot be in open water	
Cannot be poorly or very poorly drained	

Determination of rank is completed by mapping the available GIS data, such as land use and land cover, wetlands, and floodplains. Next, each of the criteria are assessed and given a point if met within the gridlines. If an absolute criterion is met, it receives a point. If a relative criterion is met, it also receives a point. If points are given for relative criteria, but any of the absolute criteria are not met, no points are given. Figure 2.3 represents a theoretical example of the gridlines and criteria, where criteria is represented by the shape within the gridlines. The numbers represent the points received for having one of the criteria met within a square. Once all criteria are assessed, the points are totaled for each of the squares in the grid (Figure 2.4). The areas that did not meet one or more of the absolute requirements are removed. The total amount of points is divided by 5 to represent the 1- through 5-star rankings. The new totals, from the summed and removed data, are graphed with point values on the x-axis and number of squares to receive the point value on the y-axis (Figure 2.5). The point values are then assigned a score between 1- and 5-stars (Conn et al. 2014).



30-m								
		½	1	1	½	½		
		½	1	1	1	1		
	0	1	1	1	1	½		
	½	1	1	1	1	½		
	½	½	½	1	1	½		

Figure 2.3: Points received within the gridlines for a single criterion



30-m								
		½	1	1	½	½		
		½	2	3	2	1		
		1	4	4	3 ½	½		
	½	2	3	4	2	½		
	½	½	½	1	1	½		

Figure 2.4: Total points for all criteria analyzed

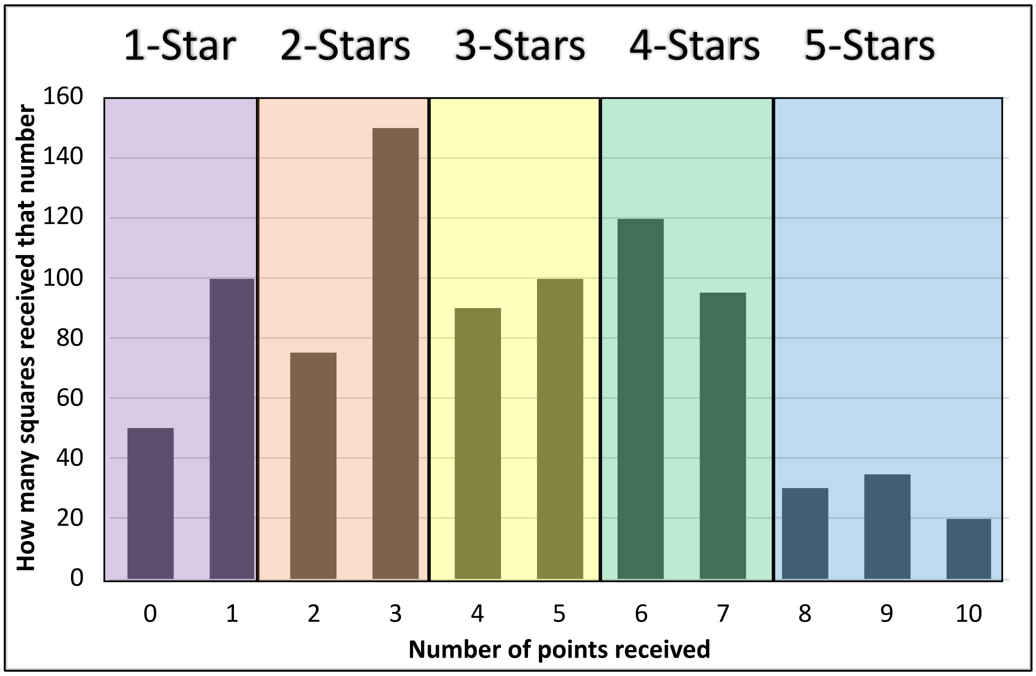
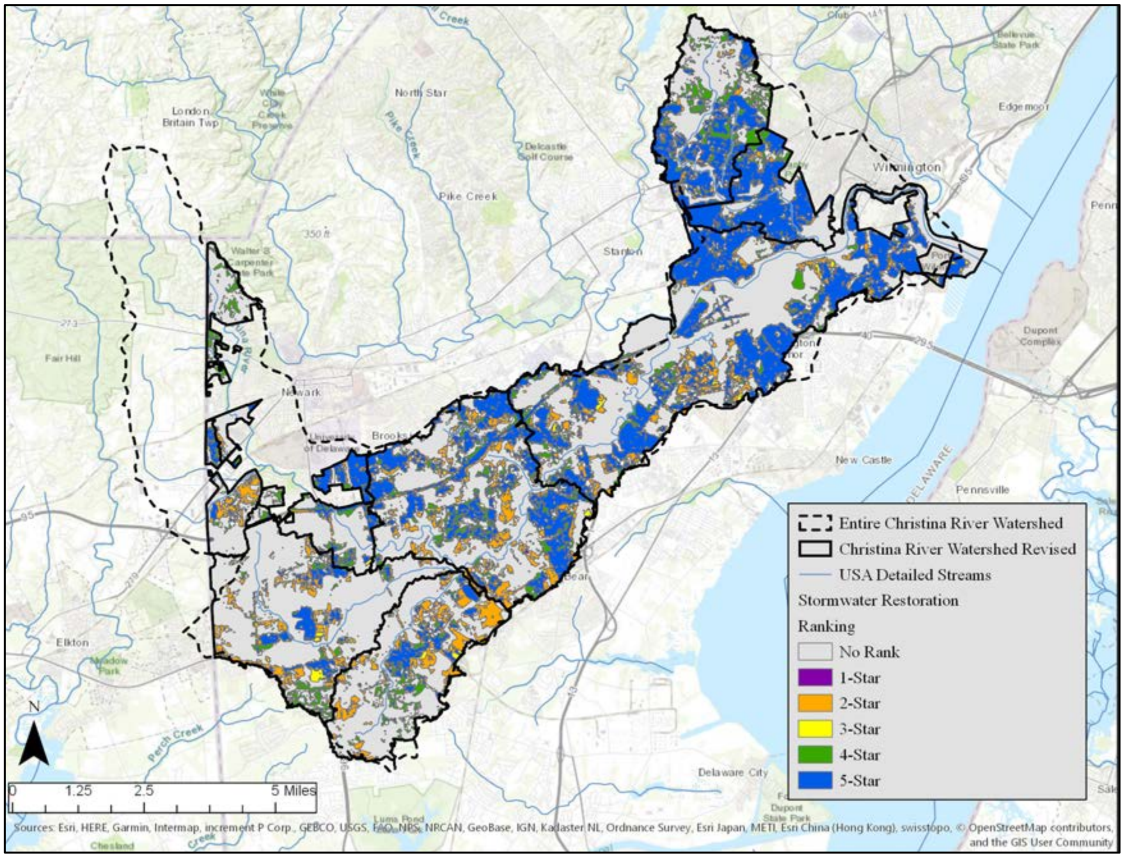


Figure 2.5: Points received in relation to their ranking

A 1-star ranking represents the least suitable area, while 5-stars represents the most suitable area. Depending on each state, the spatial analyses criteria changes based on the partners input. The 1- to 5-star rankings are mapped throughout the revised Christina River watershed in Figure 2.6.



Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), swisstopo, © OpenStreetMap contributors, and the GIS User Community

Figure 2.6: Watershed Resources Registry rankings in the Christina River watershed

The Watershed Resources Registry has potential for utility in a wide array of work, including development of WQIPs. The Watershed Resources Registry would also be quite useful for land-use planning, potential monitoring projects, and a regulatory and non-regulatory decision-making tool. There have been no published research papers assessing the validity of the Watershed Resources Registry and its applicability use to a WQIP. One documented case study occurred in the Willis Run-

Codorus Creek watershed in York County, Pennsylvania, which borders Maryland. The Maryland Environmental Service used the Watershed Resources Registry for a desktop analysis to find potential stormwater restoration projects. The suitability of a site was compared using the Watershed Resources Registry, Esri GIS products including ArcGIS Desktop, and professional judgement. Twenty sites were selected by the collaborators based on drainage area, estimated ease of development, and reduction amounts. It was concluded the proposed BMP site selections, overlaid with the calculated load reductions, could remove approximately 4,500 pounds of nitrogen, 160 pounds of phosphorus, and 200,000 pounds of sediment (Maryland Environmental Service n.d.).

2.7 Load Reduction Models

Watershed models are developed to quantify and examine flow and pollutant transport processes. They can simulate runoff, erosion, sedimentation, and can evaluate BMPs and land use changes. Watershed-scale and water quality models were combined together, noticeably after the Clean Water Act amendments in 1987, to focus on water quality and quantity, along with TMDL requirements (Borah et al. 2019). Crawford and Linsley (1966) developed the first computer-based, watershed-scale hydrologic model, called the Stanford Watershed Model. Watershed models are created for both small- and large-scale watersheds (Singh and Frevert 2002a and Singh and Frevert 2002b). Three load reduction models are reviewed: the DURMM, the

Long-Term Hydrologic Impact Analysis (L-THIA) model, and the Spreadsheet Tool for Estimating Pollutant Load (STEPL) model.

The Delaware Urban Runoff Management Model

The DURMM was designed for the State of Delaware to integrate hydrologic processes that identify the infiltration and interception contributions of soils impacted by land cover characteristics, soil type, and runoff volumes corresponding to rainfall amounts (Lucas 2003). It addresses urban runoff by designing water to flow through swales, separating discharge from infiltration elements, and separating combinations of land cover and soil type based on the curve number method designed by Technical Release-20 (Lucas 2004). The first version of DURMM was created for Green Technology best management practice development in Delaware, such as bioretention facilities, buffers, and rain gardens (DNREC 2000). DURMM has two versions, DURMM REL 1.1 and DURMM Version 2, with Version 2 being the model focused here. It was created using Microsoft's Excel 2010 spreadsheet program. The DURMM can be used for a concept level analysis or a design level analysis at a site (DNREC 2013b). New Castle County and DelDOT are required to use the DURMM model based on DNREC's guidelines (DNREC 2013a).

The DURMM is unlike others because it calculates separate pervious and impervious runoff volumes. This allows the model to predict impervious area disconnection impacts, meaning water that flows over roads, parking lots, roofs, and sidewalks that are transferred over lawns or through bioswales to treatment BMPs. Connected impervious areas include when water flows from roads, parking lots, roofs, and sidewalks along curbs or through pipes to treatment BMPs. This helps calculate a better suited runoff curve number (RCN) for the area being analyzed.

The DURMM calculates pollutant loads by using event mean concentrations. Impervious and pervious land covers have varying event mean concentrations for pollutant mass loads (Baldys et al. 1998). The DURMM calculates pollutant loads by calculating an area-weighted average event mean concentrations for both impervious and pervious surfaces (Lucas 2004).

The DURMM consists of eight worksheets in Microsoft Excel, each having cells for user input, pre-set values or additional output, and calculated results. The first worksheet is called C.A. RCN because it determines the weighted runoff curve number for the analyzed area. This worksheet requires the project name, subarea ID, county location, and unit hydrograph. The user then needs to enter land cover data in acres by hydrologic soil group (HSG) and hydrologic condition. The total acreage and weighted RCN of the analyzed area are calculated to give the total contributing area with upstream areas in acres. The upstream contributing areas are then divided by the total contributing area to calculate the RCN (DNREC 2013b).

The second worksheet is called LOD, or limit of disturbance, and calculates the runoff reduction for the given LOD of the subarea's drainage in cubic feet per second per acre. This may align with the total contributing area for the BMP. The hydrologic soul group is required for the LOD acreage, along with any pre-developed woods or meadow and post-developed imperviousness, all in acres. The third worksheet is entitled OLOD, or outside limit of disturbance, and is only for runoff that is outside the LOD. If the LOD and the total contributing area are the same, the OLOD worksheet can be skipped (DNREC 2013b). For this research, all contributing areas were within the LOD.

The fourth worksheet is called RPv and is used to calculate the runoff reduction for the selected BMP for the area and also checks the resource protection event for compliance to see if the required reduction has been met. The user selects the type of BMP, inputs the storage volume if the BMP has a retention storage component, such as a wet pond, and the proportion of A/B soils is entered if the BMP has a runoff reduction component. If the required runoff reduction has not been met, the model will give the offset shortfall value (DNREC 2013b).

The fifth worksheet is called TMDL and is used to check for compliance with TMDL requirements. The user selects the land use category and TMDL watershed from a list. The model then calculates total nitrogen (TN), TP, and TSS in milligrams and pounds. The load reduction is calculated using the runoff reduction from the RPv worksheet and the model verifies if the required pollutant load reduction is met (DNREC 2013b).

The sixth through eighth worksheets do not require data input. The sixth worksheet is called Cv and calculates the impacts of practices focused on runoff reduction for non-flooding situations, also called conveyance events. The selected BMPs from the Rv worksheet are used and data from previous worksheets are inserted automatically. The seventh worksheet is called Fv and calculates the effect of runoff reduction practices for a flooding event. This research does not look at flooding event scenarios, so it is omitted (DNREC 2013b).

The eighth worksheet is called DURMM Report and summarizes the results from the previous seven worksheets. The biggest takeaway is it tells the user whether or not runoff and pollutant reduction requirements were met, and if not, it provides offset requirements (DNREC 2013b).

The Long-Term Hydrologic Impact Analysis

The Long-Term Hydrologic Impact Analysis model was created by the College of Engineering at Purdue University with the primary purpose of determining the relationship between water quality and quantity and land use (Nejadhashemi et al. 2011). It can estimate long-term impacts of both direct runoff and non-point source pollution. The model calculates runoff using the Soil Conservation Service Curve Number method and pollutant loads using a pollutant coefficient, or event mean concentrations (Park et al. 2013).

There have been several studies using the L-THIA model. Changes in land use and increased runoff in the Wildcat Creek watershed in north central Indiana were modeled using L-THIA (Pandey et al. 2000). Tang et al. (2005) analyzed two watersheds, the Little Eagle Creek in Indiana and Little Muskegon River in Michigan, using L-THIA to evaluate the changes in runoff due to increased urbanization. Researchers also used L-THIA for the Little Elk Creek in Indiana where the model showed a 60 percent increase in nitrogen and phosphorus loads due to a 19 percent increase in urbanization (Bhaduri et al. 1997). Bhaduri et al. (2000) concluded the L-THIA model creates suitable results for initial assessments of land use impacts on hydrology. In the Pomona Lake watershed in Topeka, Kansas a study was commissioned with the purpose of comparing and assessing four watershed models, one being L-THIA, evaluating L-THIA's abilities to estimate long-term average pollution loads, and its ability to prioritize critical pollution source areas (Nejadhashemi et al. 2011). L-THIA underpredicted the long-term average sediment, nitrogen, and phosphorus loads, as the model only accepted eight land use classes. L-THIA was similarly unreliable in identifying high-priority locations because of the insensitivity to varying types of pollutants (Nejadhashemi et al. 2011).

Spreadsheet Tool for Estimating Pollutant Load

Tetra Tech, Inc. developed the Spreadsheet Tool for Estimating Pollutant Load model for the EPA to be used in a Microsoft Excel template as a screening tool for quick assessments of water quality health and management practices for watersheds and sub watersheds. The model calculates nonpoint source pollution for annual pollutant loads from different types of land use (Borah et al. 2019). STEPL can calculate surface runoff, sediment delivery, five-day biological oxygen demand and nutrients of nitrogen and phosphorus on an annual scale based on land use and watershed type. Parameters needed for this model include: BMP practice, land use type, number of animals in study area, illegal discharges, runoff volume, and number of failed septic systems (Nejadhashemi et al. 2011). STEPL's pollutant sources are from six land use types, septic systems, and animal agriculture, such as horses, dairy cattle, and chickens (Borah et al. 2019). The nutrient loads are calculated for a watershed by multiplying the runoff volume and pollutant concentration. Urbanized locations are circumscribed from estimates of runoff by the National Resources

Conservation Service (NRCS) method. Soil and land cover data are used to determine the drainage area and pollutant concentrations are taken from wet weather sampling data (Borah et al. 2019). BMPs are shown using user-defined efficiencies in pollutant and sediment load declines. STEPL yields results for a BMP's pollutant load reduction, treated and untreated loads, and percent reduction for each pollutant analyzed. STEPL does have its detractors: Park et al. (2013) argued the STEPL uses an incorrect method to calculate average annual direct runoff, as it uses curve numbers, which typically calculate daily- or event-based direct runoff, not annual. Borah et al. (2019) researched 14 different watershed models and determined STEPL's strength is the generation of annual nutrient loads and sediment yields from different land use types but is limited by its empirical basis and cannot generate loads for a daily or seasonal timeframe.

Chapter 3

METHODS

3.1 Site Description

The focus area of the study is the Christina River watershed, primarily located in Delaware with smaller areas in Maryland and Pennsylvania. The watershed is 59 percent urbanized, 25 percent forested and wetland, 15 percent agriculture, and 1 percent water (NOAA Coastal Services Center 2016). This study only considered the Delaware portion of the watershed, while excluding the City of Newark and City of Wilmington, as stated in Section 2.5, which is 57.9 square miles (DelDOT and New Castle County 2019). The Christina River watershed is one of four watersheds that make up the Brandywine-Christina Basin. The others include: Brandywine Creek, Red Clay Creek, and White Clay Creek (Figure 3.1). Figure 3.2 displays how the Christina River watershed is the most highly urbanized of the four sub-watersheds, characterized by dense residential, commercial, and industrial uses (Brandywine Conservancy et al. 2018). The Christina River watershed is part of the Delaware River watershed, which spans 13,539 square miles (34,660 km^2) and is the source of drinking water for nearly 15 million people (Kauffman et al. 2011).

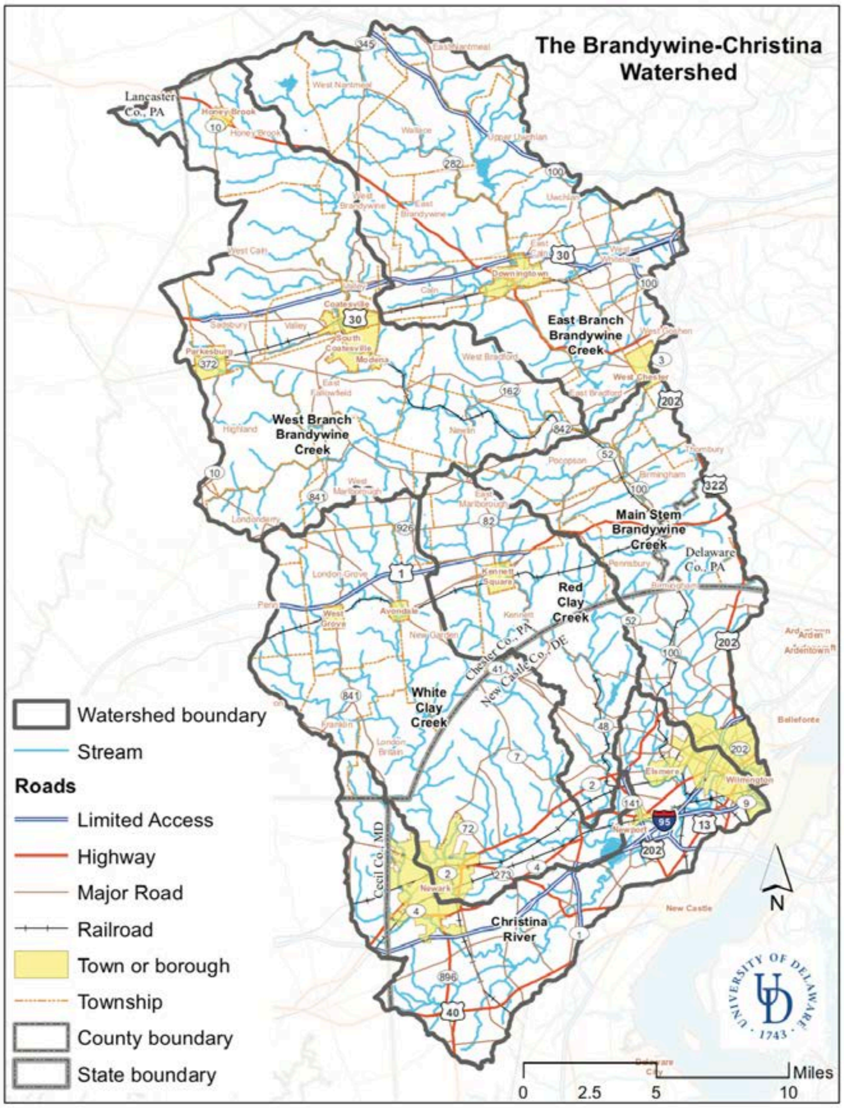


Figure 3.1: The Brandywine-Christina watershed divided by watershed (Brandywine Conservancy et al. 2018)

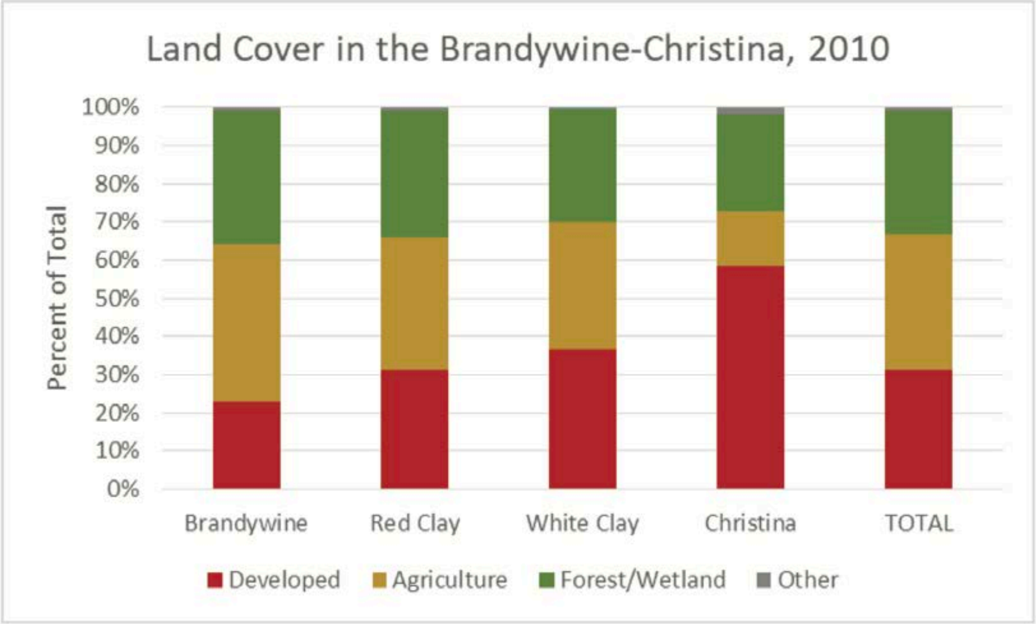


Figure 3.2: Land cover in the Brandywine-Christina watershed (Brandywine Conservancy et al. 2018)

3.2 Analyses

Best Management Practice Sites in the Christina River Water Quality Improvement Plan

The Christina River WQIP originally identified 110 potential sites for installation or retrofit of stormwater BMPs. After careful evaluation, as described in Chapter 2, 35 best management sites were selected by Century Engineering, New Castle County, and DelDOT for the Christina River WQIP. Each BMP site was associated with a parcel and a particular parcel may have had more than one BMP site.

Figure 3.3 displays the difference between a typical parcel (blue fill) and associated BMP sites (red circles). Since the selected model, DURMM, did not enable analysis of regenerative stormwater conveyances (RSCs), those BMP types were excluded from the analysis, resulting in a total of 26 BMP sites (Figure 3.4).

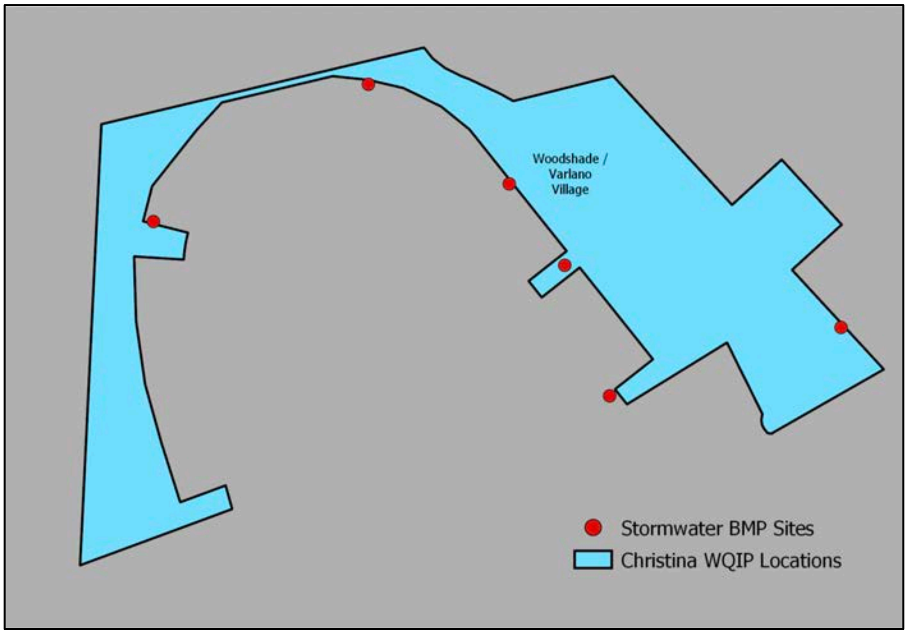
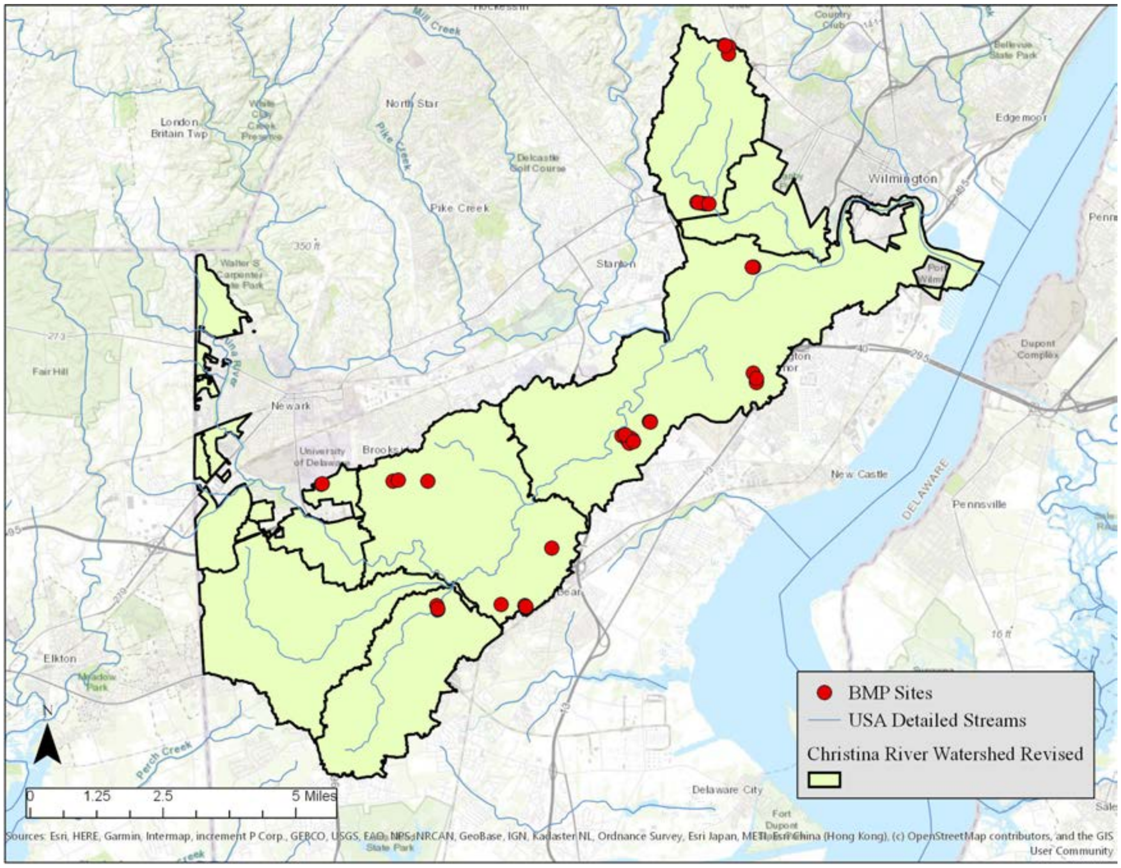


Figure 3.3: Parcel location and stormwater best management practice sites



Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), (c) OpenStreetMap contributors, and the GIS User Community

Figure 3.4: Christina River watershed with best management practice sites

Data Acquisition

In order to complete this study, multiple data sets were required to calculate inputs needed for the DURMM. All data were processed in ArcGIS Pro. Delaware's Watershed Resources Registry provided the stormwater compromised infrastructure restoration layer. The Christina River flow direction data was created using LiDAR data in 2014. The LULC datasets included the Delaware 2012 LULC (FirstMap Delaware) and High-Resolution Land Cover Delaware River Basin (University of

Vermont Spatial Analysis Lab). The residential land use type was provided by New Castle County. Soils data were sourced from the USDA Soil Survey Geographic (SSURGO) data.

The model selected for this study, the DURMM, calculates pre-treatment pollutant loads for TN, TP, and TSS. The amount of pollutant load entering the BMP could not be calculated without delineating a catchment area for each BMP. A novel approach used to delineate the catchments was developed at the University of Delaware Water Resources Center. In order to delineate a catchment area, several layers were needed in GIS: BMP site points, stormwater conveyances, and the Christina River flow direction data. The location of stormwater conveyances, such as inlets and outfalls, were needed to understand where stormwater runoff would travel (Figure 3.5). The flow accumulation layer was imperative in creating the catchment area because it indicated the direction water would flow if present (Figure 3.6). Once the data were layered in GIS, each BMP site was individually analyzed to make sure all conveyances and potential flow paths were encompassed. Following this procedure, the watershed delineation tool in GIS was used to create the catchment shapes. The output map provided catchment areas for the 26 BMP sites (Figure 3.7). Each delineation was then checked individually, and adjustments were made if the catchment area did not encompass a feature such as a stormwater conveyance inlet or outfall.

Figure 3.5: Stormwater conveyances with the best management practice sites

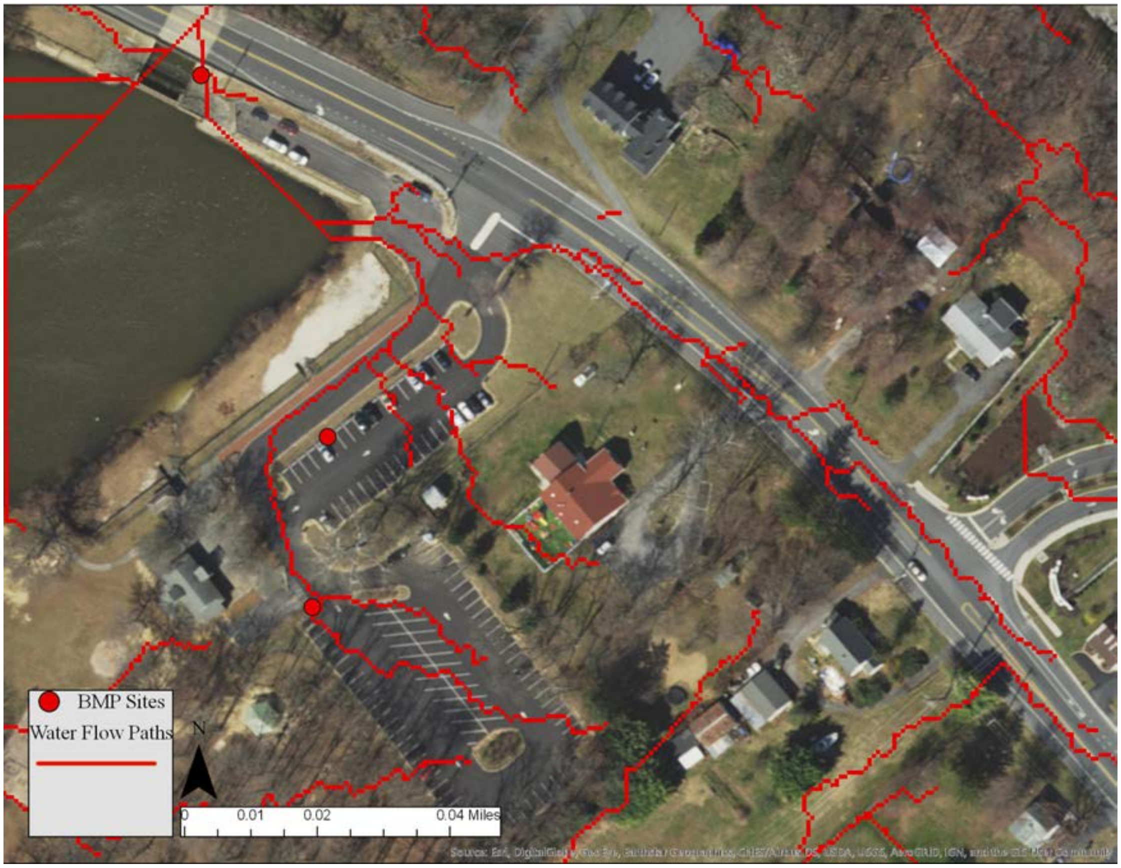


Figure 3.6: Water flow paths defined by LiDAR

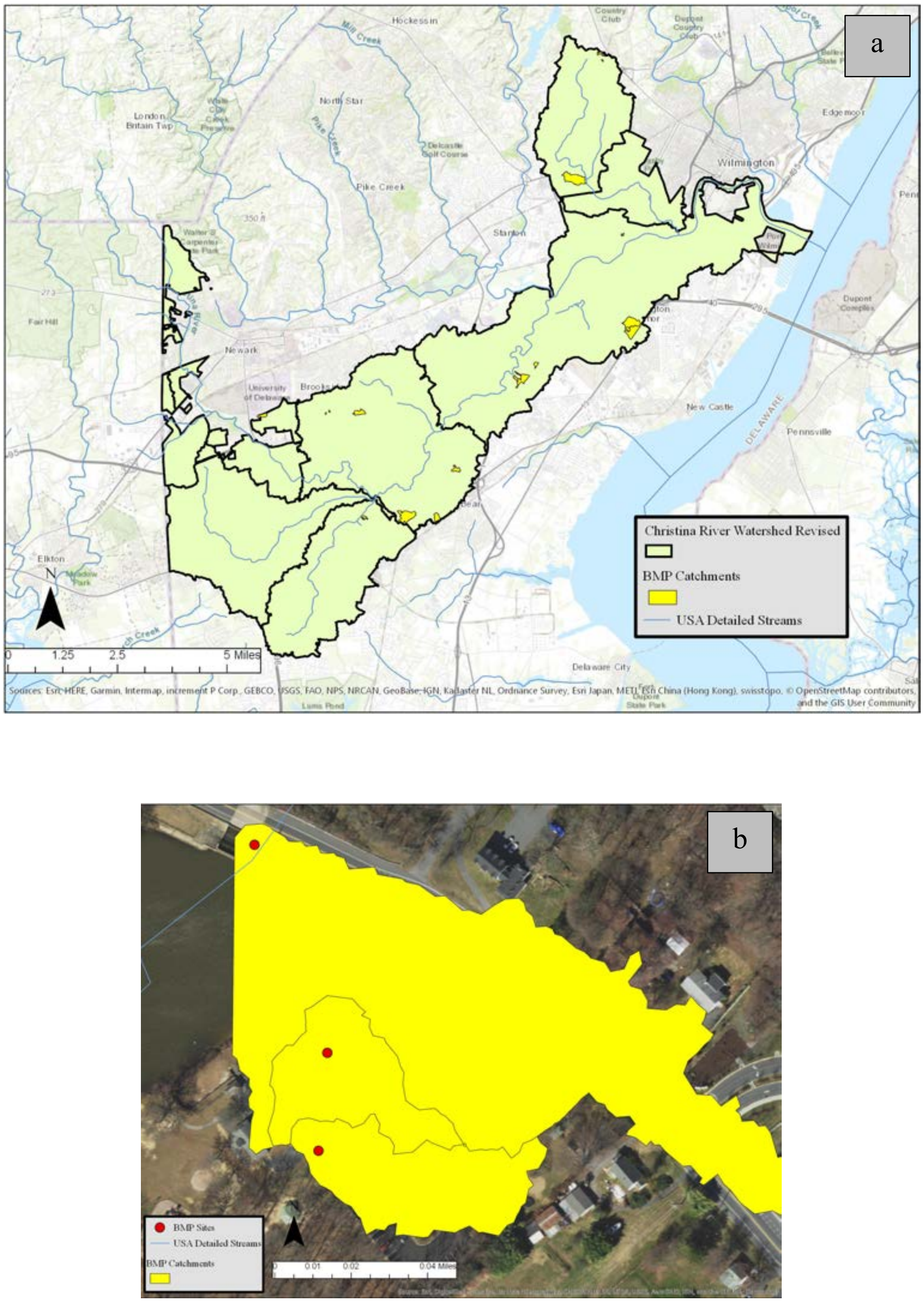


Figure 3.7: Christina River watershed with all best management practice catchments (top) and three delineated catchments (bottom)

The Delaware Urban Runoff Management Model

The DURMM is used by the State of Delaware to calculate stormwater pollutant loads and load reductions based on specific types of proposed BMPs. This research only used the annual stormwater pre-treated load given in pounds per acre per year (lb/ac/yr). The final adjusted load (lb/ac/yr), or treated load, was not used because the Watershed Resources Registry is a screening tool used for BMP site selections and does not predict the type of BMP to implement.

Model Requirements

The DURMM model requires multiple parameter inputs within four of the worksheets as stated in Chapter 2. The first set of inputs required the county location, unit hydrograph, and LULC acreage with associated hydrologic soil group. The unit hydrograph gave two selections: Delmarva Unit Hydrograph or standard dimensionless unit hydrograph. The standard dimensionless unit hydrograph was selected for all 26 BMP sites because the Delmarva Unit Hydrograph was only used for projects south of the Chesapeake Bay and Delaware Canal. The LULC calculation method is described in the next section. The LULC cover types include: cultivated agricultural lands, other agricultural lands, fully developed urban areas, and developing urban area. Within each cover type are specific treatments (Table 3.1). For example, within the cover type, fully developed areas are "residential districts by average lot size" and the categories are 1/8-acre (town houses), 1/4-, 1/3-, 1/2-, 1-, and 2-acres. The remaining inputs included the limit of disturbance, proposed BMP, either storage volume or proportion of A/B soils in BMP footprint, depending on the type of

BMP selected, and overall land use type. The limit of disturbance equaled the specific catchment area for each BMP. The proposed BMP type was based on Century Engineering, New Castle County, and DelDOT’s analysis. There were seven BMP types proposed: traditional bioretention with underdrain, infiltration basin, infiltration trench, bioswale, surface sand filter, porous asphalt, and regenerative stormwater conveyance. The only BMP type not included in the DURMM was the RSC because the model did not enable analysis for an RSC. The calculations for storage volume, proportion of A/B soils in BMP footprint, and overall land use type are given in the next section.

Table 3.1: Delaware Urban Runoff Management Model cover types and treatments (DNREC 2013b)

Cover Type	**Treatment**
FULLY DEVELOPED URBAN AREAS (Veg Established)	
Open Space (lawns, parks, etc.)	
	Poor condition; grass cover < 50%
	Fair condition; grass cover 50% to 75%
	Good condition; grass cover > 75%
Impervious Areas	
	Paved parking lots, roofs, driveways
	Streets and roads
	Paved; curbs and storm sewers
	Paved; open ditches (w/ right-of-way)
	Gravel (w/ right-of-way)
	Dirt (w/ right-of-way)
Urban Districts	
	Commercial and business
	Industrial
Residential districts by average lot size	
	1/8-acre (town houses)
	1/4-acre
	1/3-acre
	1-acre
	2-acre

Calculating and Selecting Model Inputs

In order to input the parameters into the DURMM, several data layers and pre-processing steps were required. GIS was used to create a new layer that encompassed the various land uses for each catchment: LULC, residential district size, and impervious cover with their associated HSGs. The three land use layers were merged together, which allowed the impervious area data to supersede from land use parcels in the layer (Figure 3.8). The residential district size was calculated using the midpoint between each of the acreage categories: 1/8-acre (town houses), 1/4-, 1/3-, 1/2-, 1-, and 2-acres (Table 3.2). A "DURMM code" was created to number each land use type in the DURMM which was then matched in GIS if present. Once the land use types were defined, the soils data were combined to create a composite map of all LULC types with their associated HSGs in each catchment.

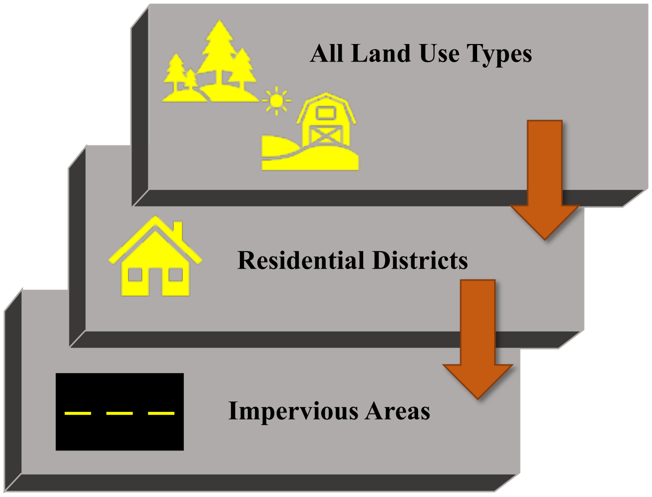


Figure 3.8: Geographic information system layers used to identify impervious areas

Table 3.2: The midpoints between each acre with the associated midpoint

Area (ac)		Midpoint (ac)
1/8	0.125	
		0.1875
1/4	0.25	
		0.2915
1/3	0.333	
		0.4165
1/2	0.50	
		0.75
1	1.00	
		1.50

The DURMM requires storage volume, in cubic feet, for certain BMPs in this research: traditional bioretention with underdrain, infiltration basin, infiltration trench, or porous asphalt. The proportion of A/B soils in BMP footprint, as a percent, was required if either bioswale or surface sand filter was selected. The storage volume was determined by multiplying the length, width, and depth of the BMP. The length and width of each BMP site were determined using GIS. The specific details about the size of the BMP were not given, but pictures detailing the proposed BMP placement were used to help decide the length and width of the BMP. Specific depths are given for the four BMP types requiring storage volume based on DNREC regulations (Table 3.3). Figures 3.9 provides an example of a cross section of a bioretention with underdrain.

Table 3.3: Total depth parameters for specific stormwater best management practice type (DNREC 2019)

Best Management Practice Type	**Parameters**	**Total Depth (ft)**
Bioretention with underdrain	1 foot of stone sump at 40 percent voids 2 feet of biosoil media at 40 percent voids 1 foot of storage above	5.6
Infiltration trench Porous asphalt	3 feet of stone at 40 percent voids	1.2
Infiltration basin	2.5 feet of storage depth	2.5

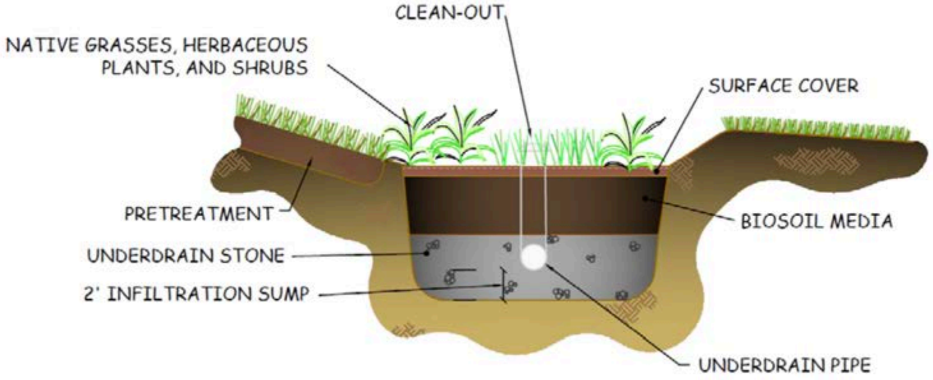


Figure 3.9: Bioretention area with underdrain best management practice (DNREC 2019)

The proportion of A/B soils in BMP footprint was calculated by determining if any soils were in HSG A or B. If so, they were divided by the total amount of acres of all HSG groups and a percentage was found.

Lastly, the overall land use type was required for the BMP catchment. The LULC category with the highest acreage was selected because there could only be one selection based from: urban open space, residential, commercial, industrial, rural road, or urban road/highway. Impervious cover did not have its own category, so if it had the highest LULC type, it was paired with the next highest associated cover type that could be selected, such as commercial and business, industrial, or residential.

Model Assumptions

Several assumptions were made because data were not available without specific site evaluation. If a cover type category had the option of poor, fair, or good condition, fair condition was chosen because it was the least skewed, or middle ground option. HSG D was used if an HSG type was determined B/D or C/D, as well as if there was impervious surface present because it was better to be more conservative until specific site evaluation could be performed, and urban soils are compacted and manipulated so they have decreased infiltration. These 26 BMP sites were all within urbanized areas.

Another assumption was all impervious areas were paved parking lots, roofs, driveways, and streets. The specifics for the impervious area could not be delineated using GIS and because this watershed is highly urbanized, the impervious surfaces tend to be paved parking lots, roofs, and driveways.

Specific site details were not provided, so the length and area used to determine storage volume created another assumption. As stated previously, pictures of each site were used to estimate the length and width. There was only one selection allowed for the overall land use category, so the DURMM assumes which ever land use had the greatest acreage.

Using an Area-Weighted Average to Rank the Best Management Practice Sites

In order to examine a correlation between loads and the Watershed Resources Registry ranks, each BMP catchment needed its own rank. Each BMP catchment could have more than one rank in its location, such as 2- and 4-stars (Figure 3.10). For reference, 1-star indicates least suitable and 5-stars represents most suitable area. The Watershed Resources Registry stormwater layer and BMP catchments were overlaid together in GIS to tabulate the amount of area of each rank by each site. The percentage of each rank in the catchment was multiplied by the corresponding rank and then summed together to calculate the new rank (Table 3.4). Each of the 26 catchments were given a new area-weighted averaged rank, consisting of only one number, ranging from 1- to 5-stars.

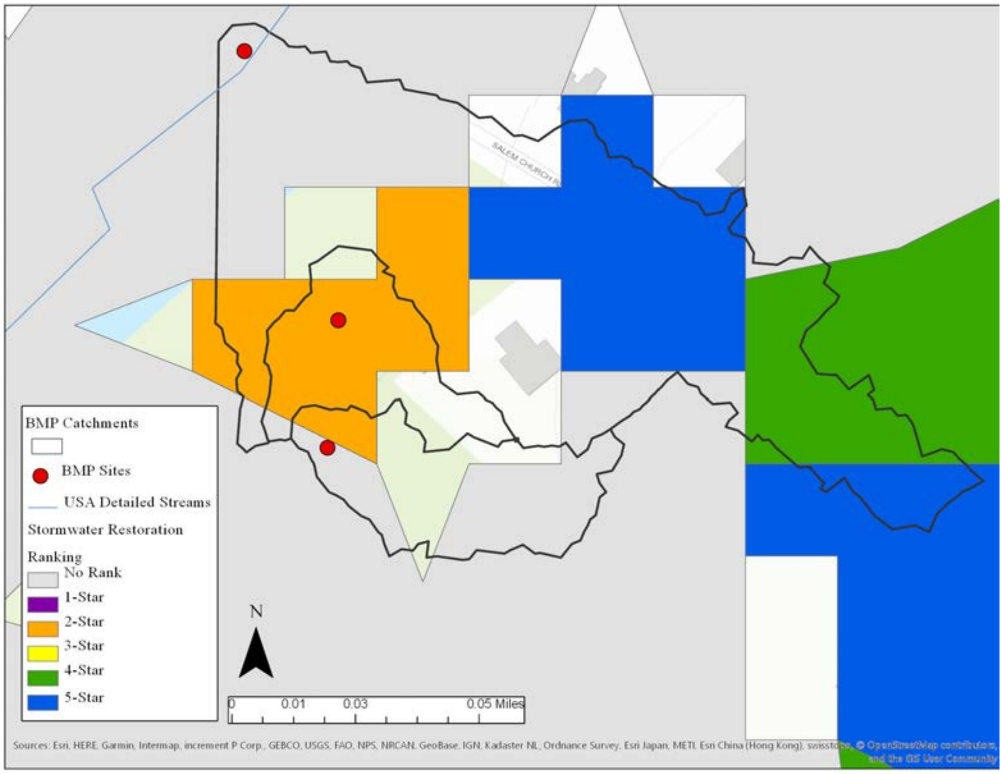


Figure 3.10: Catchment areas with variations of Watershed Resources Registry ranks

Table 3.4: Rank within 26 best management practice catchments

BMP ID	No Rank (%)	2-Star (%)	4-Star (%)	5-Star (%)
306	9.59	0.00	0.00	90.41
307	100.00	0.00	0.00	0.00
701	0.00	0.00	0.00	100.00
702	0.00	100.00	0.00	0.00
901	16.99	56.97	2.37	23.67
1001	12.95	0.00	18.04	69.02
1101	8.25	0.00	47.56	44.18
1301	1.36	0.00	6.80	91.84
1302	4.37	0.00	0.00	95.63
1303	0.00	0.00	9.27	90.73
1401	0.00	0.00	3.19	96.81
1402	0.00	0.00	29.87	70.13
1403	0.00	0.00	7.33	92.67
1404	1.79	0.00	0.72	97.49
1501	20.23	0.00	79.77	0.00
1502	94.54	0.00	5.46	0.00
1601	87.99	12.01	0.00	0.00
1602	4.14	95.86	0.00	0.00
1603	33.93	13.79	14.75	37.53
2201	1.25	13.41	6.27	79.07
2601	0.00	0.00	3.30	96.70
2602	5.60	0.00	0.00	94.40
2603	0.00	0.00	0.00	100.00
2604	100.00	0.00	0.00	0.00
3001	61.59	9.54	9.27	19.60
3101	0.00	7.17	0.00	92.83

Correlating Ranks with Loads

The goal of this research is to determine if the Watershed Resources Registry is a suitable tool to use for WQIPs. There were two ways to approach this. The first was to determine if higher pollutant loads correlated with higher Watershed Resources Registry ranks. The second was to establish a spatial resolution range the Watershed Resources Registry was best suited for.

Each of the 26 BMP sites had its own weighted average Watershed Resources Registry rank, catchment area (acres), and pre-treated pollutant loads for TN, TP, and TSS (lb/ac/yr). The Watershed Resources Registry rank, BMP catchment area, and TN, TP, and TSS loads were graphed in a statistical software program called JMP. The data were first plotted all together and then separated into quartiles, by sorting the acreage from lowest to highest, to view if any relationship was present. The r-squared values from the quartiles were then graphed in Excel.

To determine if a spatial resolution range was present, the r-squared values of the first, second, and third quartiles of data were graphed for TN, TP, and TSS loads. The purpose was to determine the best suited resolution for the Watershed Resources Registry. The r-squared values were graphed, with one data point subtracted from the overall sample size for each point in the graph. The first square on the left size represented all 26 BMP sites, followed by the next square which signified 25 BMP sites, with the lowest BMP catchment removed. Continuing to remove the lowest catchment area's size determined the number of acres the Watershed Resources Registry is best suited for when selecting BMP locations because an increase in the r-squared values was present.

The graph was designed to show if an r-squared value increased, or jumped, at a certain acreage, so the first data point on the left side represents the r-squared value for all of the data. The next point on the graph represents all but the lowest BMP catchment. The third data point does not include the lowest two BMP catchments. This pattern continues until 75 percent of the data have been graphed, or essentially stops at the upper 25 percent of BMP catchments. If an r-squared value increased, the spatial resolution range could be determined for which the Watershed Resources Registry is best suited for. The results of the methodology above are described in Chapter 4.

Chapter 4

RESULTS

4.1 Composition of Best Management Practice Catchment Areas

The total amount of area within the BMP catchments ranged from 0.16 to 59.95 acres with their associated weighted average Watershed Resources Registry ranks ranging from 0- to 5-stars (Table 4.1). The average Watershed Resources Registry rank was 3.46-stars. The 26 catchment area's distribution data was skewed towards smaller acreage (Figure 4.1). The data within the left-skewed portion under 10 acres was graphed in Figure 4.2.

Table 4.1: Weighted average Watershed Resources Registry ranks

BMP ID	Total Acres	Area-Weighted Average Rank
307	0.16	0.00
2603	0.32	5.00
701	0.54	5.00
702	0.65	2.00
1602	0.69	1.92
1501	0.70	3.19
2604	0.76	0.00
1601	0.84	0.24
1502	1.03	0.22
2602	1.42	4.72
1402	1.58	4.70
1302	2.28	4.78
2601	3.35	4.97
1403	3.82	4.93
1603	3.87	2.74
3101	4.34	4.78
1303	4.55	4.91
306	7.81	4.52
1001	9.88	4.17
1101	12.35	4.11
3001	14.71	1.54
1301	23.27	4.86
1401	33.53	4.97
1404	40.89	4.90
901	46.55	2.42
2201	59.95	4.47

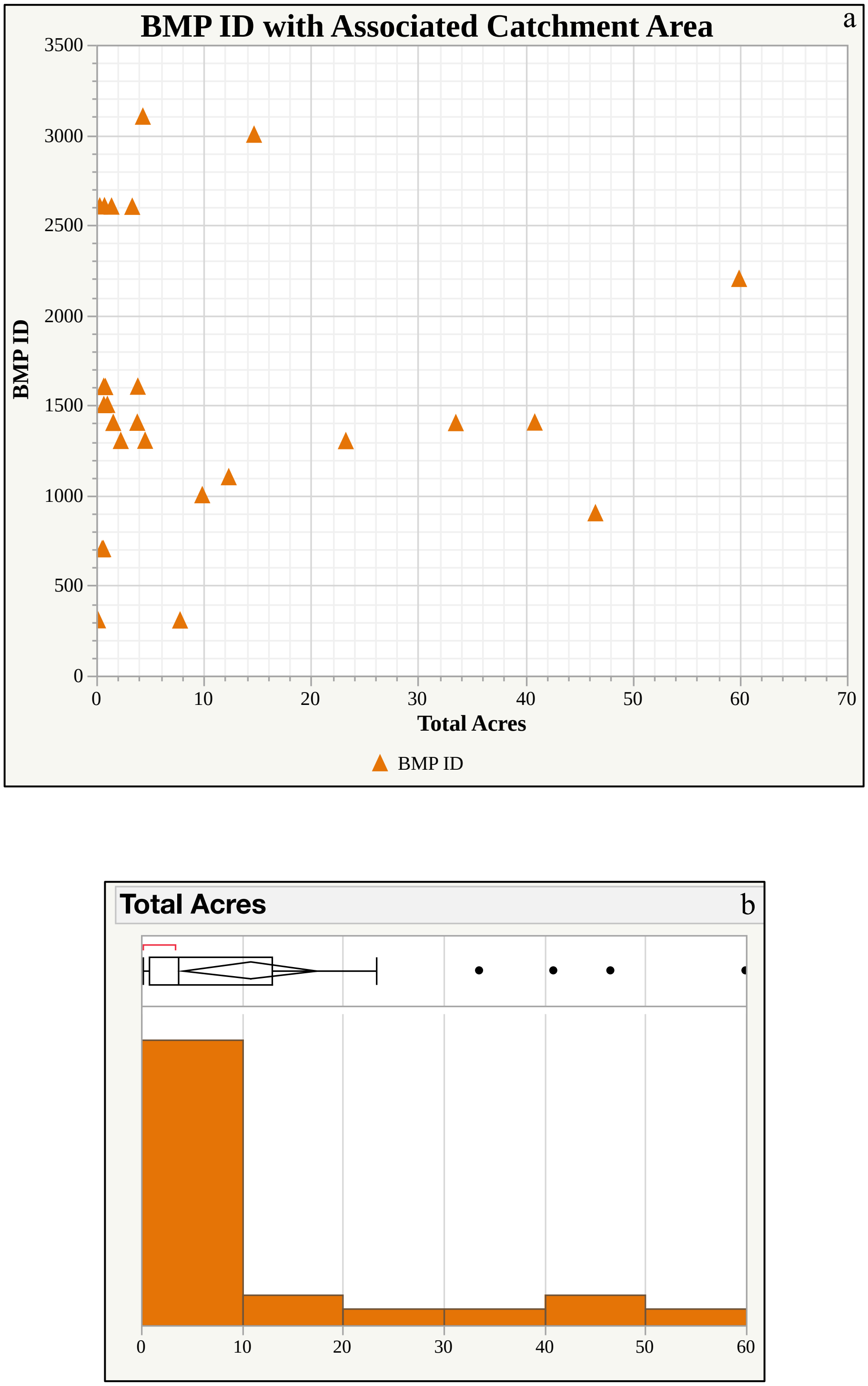


Figure 4.1: Best management practice catchment areas

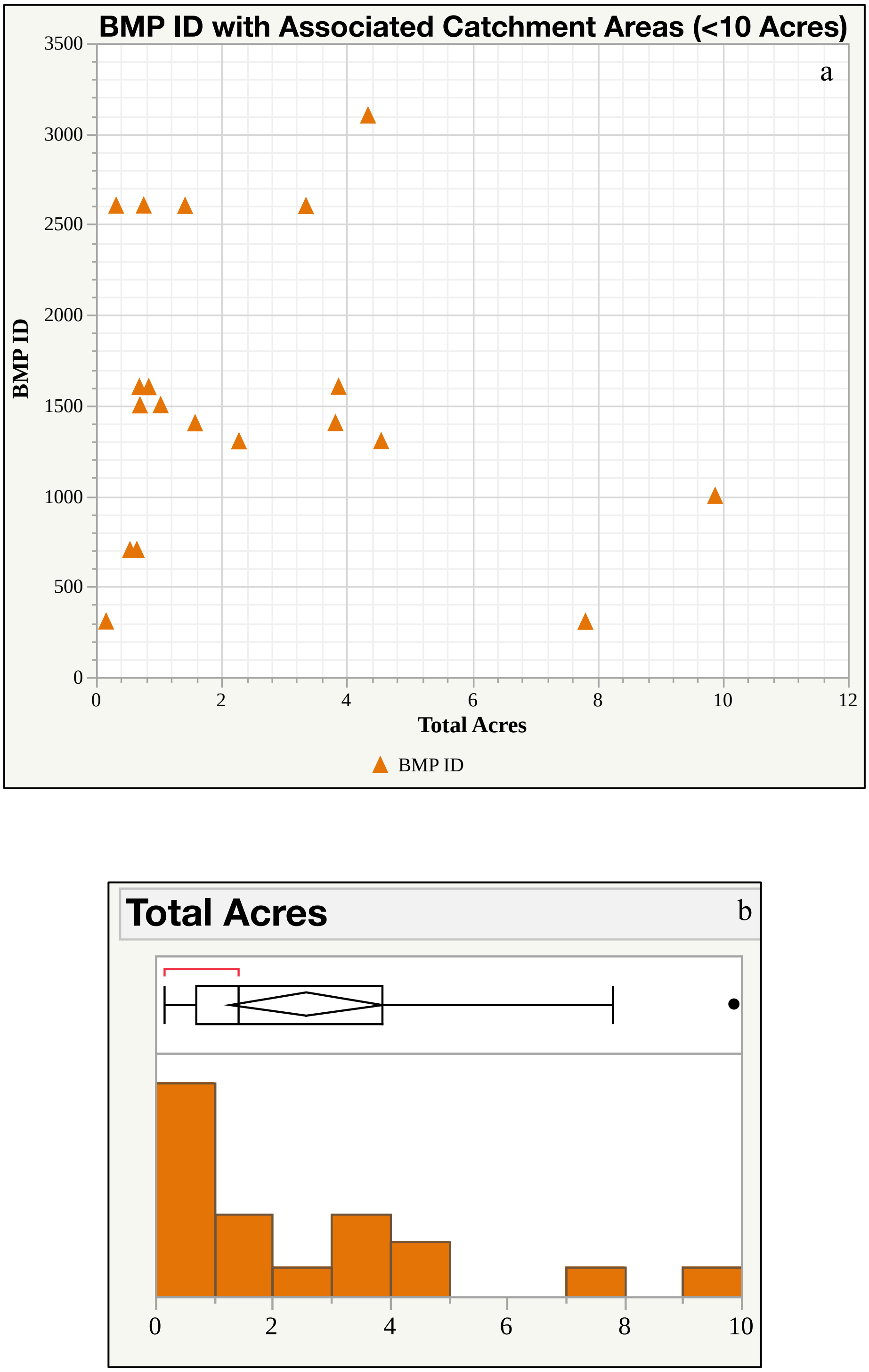


Figure 4.2: Best management practice catchment areas under 10 acres

The DURMM's cover type's treatments are sub-categories of the overall cover type. Each treatment varied within catchments from woods (fair), open space, impervious areas, commercial and business, industrial, residential, and newly graded area. Table 4.2 lists the treatment types with the areal coverage within the 26 BMP catchments. The treatment type with the largest acreage was impervious cover (128.57 acres), second was residential (109.43), followed by commercial and business (23.27), open space (10.10), industrial (4.53), woods (3.92), and newly graded area (0.01). The residential coverage included all possible sizes of 1/8-acre, 1/4-, 1/3-, 1/2-, 1-, and 2-acres.

Table 4.2: Delaware Urban Runoff Management Model treatment

Type of Treatment	**Total Area (Acres)**
Impervious Areas	128.57
Residential	109.43
Commercial and Business	23.27
Open Space (fair)	10.10
Industrial	4.53
Woods (fair)	3.92
Newly Graded Area	0.01

Each individual BMP catchment had varying sizes of treatments. Table 4.3 lists the BMP IDs within the treatment groups: woods (fair), open space (fair), commercial and business, industrial, and newly graded area. Impervious area represents paved parking lots, roofs, driveways, streets, and roads and Table 4.4 lists the BMP IDs and their associated acreage with their corresponding hydrologic soil groups. Residential districts are listed in Table 4.5.

Table 4.3: Best management practice identification number treatment groups

Woods, fair				
BMP ID	**HSG A (ac)**	**HSG B (ac)**	**HSG C (ac)**	**HSG D (ac)**
901	0.019	0.007	-	-
1001	-	-	0.16	-
1401	0.006	-	-	-
2604	-	0.006	-	0.18
3001	3.54	-	-	-
Open Space, fair				
BMP ID	**HSG A (ac)**	**HSG B (ac)**	**HSG C (ac)**	**HSG D (ac)**
306	-	-	-	0.01
307	-	-	-	0.03
1101	-	3.27	-	-
1301	-	-	-	3.08
1302	-	-	-	0.01
1401	0.14	-	0.11	-
1402	0.03	-	0.36	-
1403	0.09	-	0.013	-
1404	0.66	-	-	-
1501	-	0.10	-	-
1502	-	0.68	-	-
1601	-	-	0.04	-
1602	-	-	0.15	-
1603	-	-	0.40	0.36
2201	-	-	-	0.10
3001	0.47	-	-	-

Table 4.3: Continued

<table>
<tr><th colspan="5">Commercial and Business</th></tr>
<tr><th>BMP ID</th><th>HSG A (ac)</th><th>HSG B (ac)</th><th>HSG C (ac)</th><th>HSG D (ac)</th></tr>
<tr><td>306</td><td>-</td><td>-</td><td>-</td><td>1.20</td></tr>
<tr><td>701</td><td>-</td><td>-</td><td>-</td><td>0.25</td></tr>
<tr><td>702</td><td>-</td><td>-</td><td>-</td><td>0.16</td></tr>
<tr><td>901</td><td>3.91</td><td>3.17</td><td>0.31</td><td>0.82</td></tr>
<tr><td>1001</td><td>-</td><td>-</td><td>3.95</td><td>-</td></tr>
<tr><td>1401</td><td>-</td><td>-</td><td>2.95</td><td>-</td></tr>
<tr><td>1404</td><td>-</td><td>-</td><td>0.03</td><td>-</td></tr>
<tr><td>1603</td><td>-</td><td>-</td><td>0.015</td><td>0.0005</td></tr>
<tr><td>2201</td><td>-</td><td>0.83</td><td>-</td><td>-</td></tr>
<tr><td>2601</td><td>-</td><td>-</td><td>-</td><td>1.48</td></tr>
<tr><td>2602</td><td>-</td><td>-</td><td>0.11</td><td>0.50</td></tr>
<tr><td>2603</td><td>-</td><td>-</td><td>-</td><td>0.15</td></tr>
<tr><td>2604</td><td>-</td><td>0.031</td><td>0.32</td><td>0.23</td></tr>
<tr><td>3001</td><td>1.66</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>3101</td><td>-</td><td>-</td><td>-</td><td>1.18</td></tr>
<tr><th colspan="5">Industrial</th></tr>
<tr><th>BMP ID</th><th>HSG A (ac)</th><th>HSG B (ac)</th><th>HSG C (ac)</th><th>HSG D (ac)</th></tr>
<tr><td>306</td><td>-</td><td>-</td><td>-</td><td>0.0054</td></tr>
<tr><td>901</td><td>0.031</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>1101</td><td>-</td><td>0.043</td><td>0.018</td><td>-</td></tr>
<tr><td>1401</td><td>-</td><td>-</td><td>0.031</td><td>-</td></tr>
<tr><td>2201</td><td>-</td><td>0.35</td><td>-</td><td>-</td></tr>
<tr><td>3001</td><td>4.06</td><td>-</td><td>-</td><td>-</td></tr>
<tr><th colspan="5">Newly Graded Area</th></tr>
<tr><th>BMP ID</th><th>HSG A (ac)</th><th>HSG B (ac)</th><th>HSG C (ac)</th><th>HSG D (ac)</th></tr>
<tr><td>1603</td><td>-</td><td>0.006</td><td>0.007</td><td>-</td></tr>
</table>

Table 4.4: Best management practice identification number impervious area

Impervious Areas	
BMP Identification Number	**Hydrologic Soil Group D (ac)**
306	3.62
307	0.13
701	0.29
702	0.49
901	20.20
1001	3.40
1101	2.89
1301	10.06
1302	1.23
1303	2.10
1401	19.41
1402	0.44
1403	1.63
1404	18.81
1501	0.60
1502	0.35
1601	0.53
1602	0.43
1603	1.89
2201	31.33
2601	1.87
2602	0.80
2603	0.17
2604	-
3001	2.77
3101	3.14

Table 4.5: Best management practice identification number residential treatment groups

Residential District 1/8-Acre

BMP ID	HSG A (ac)	HSG B (ac)	HSG C (ac)	HSG D (ac)
306	-	-	-	1.13
901	1.09	12.33	0.19	0.09
1001	-	0.02	1.74	-
1101	-	0.70	-	-
1301	-	-	-	6.69
1302	-	-	-	0.95
1303	-	-	-	2.22
1401	-	-	10.78	-
1402	-	-	0.75	-
1403	0.02	-	2.07	-
1404	1.27	-	18.13	-
1601	-	-	0.03	-
1603	-	0.01	0.13	0.005
2201	-	16.14	-	0.002
3001	0.68	-	-	1.11
3101	-	-	-	0.0049

Residential District 1/4-Acre

BMP ID	HSG A (ac)	HSG B (ac)	HSG C (ac)	HSG D (ac)
306	-	-	-	1.64
901	-	2.91	-	-
1001	-	0.0005	0.37	-
1101	-	4.22	-	-
1301	-	-	-	2.75
1302	-	-	-	0.085
1303	-	-	-	0.233
1401	-	-	0.11	-
1404	0.12	-	1.45	-
1603	-	0.012	-	0.017
2201	-	6.04	0.0025	0.147
3001	0.28	-	-	0.126
3101	-	-	-	0.012

Table 4.5: Continued

Residential District 1/3-Acre				
BMP ID	**HSG A (ac)**	**HSG B (ac)**	**HSG C (ac)**	**HSG D (ac)**
306	-	-	-	0.20
901	-	0.72	-	-
1001	-	-	0.22	-
1101	-	1.22	-	-
1301	-	-	-	0.70
1404	-	-	0.42	-
2201	-	2.49	-	0.031
Residential District 1/2-Acre				
BMP ID	**HSG A (ac)**	**HSG B (ac)**	**HSG C (ac)**	**HSG D (ac)**
1603	-	-	0.12	-
2201	-	0.60	-	-
Residential District 1-Acre				
BMP ID	**HSG A (ac)**	**HSG B (ac)**	**HSG C (ac)**	**HSG D (ac)**
901	0.74	0.012	-	-
1601	-	-	0.15	-
1602	-	-	0.11	-
1603	-	-	0.74	-
2201	-	0.50	-	-
Residential District 2-Acre				
BMP ID	**HSG A (ac)**	**HSG B (ac)**	**HSG C (ac)**	**HSG D (ac)**
1601	-	-	0.083	-
1603	-	0.029	0.13	-
2201	-	1.39	-	-

4.2 The Watershed Resources Registry Rank Correlation

The Watershed Resources Registry ranks and their corresponding pre-treated pollutant loads were graphed to examine if higher ranks associated with higher loads. All of the BMP catchments graphed with pollutant loads (Figure 4.3) did not show a strong r-squared value, as they were 0.090 (TN), 0.089 (TP), and 0.122 (TSS). The BMP catchment areas separated from lowest to highest areas were graphed based on quartiles. The first quartile consisted of six data points. The r-squared value for both TN and TP versus Watershed Resources Registry rank was 0.009 and TSS versus Watershed Resources Registry rank was 0.012 (Figure 4.4). The second quartile (Figure 4.5) contained seven data points and the r-squared values were 0.332 (TN), 0.325 (TP), and 0.320 (TSS). The third quartile (Figure 4.6) contained seven data points and the r-squared values were 0.050 (TN), 0.055 (TP), and 0.051 (TSS). The fourth quartile (Figure 4.7) had six data points and r-squared values were 0.856 (TN), 0.857 (TP), and 0.853 (TSS). The r-squared values for each quartile graphed are listed in Table 4.6.

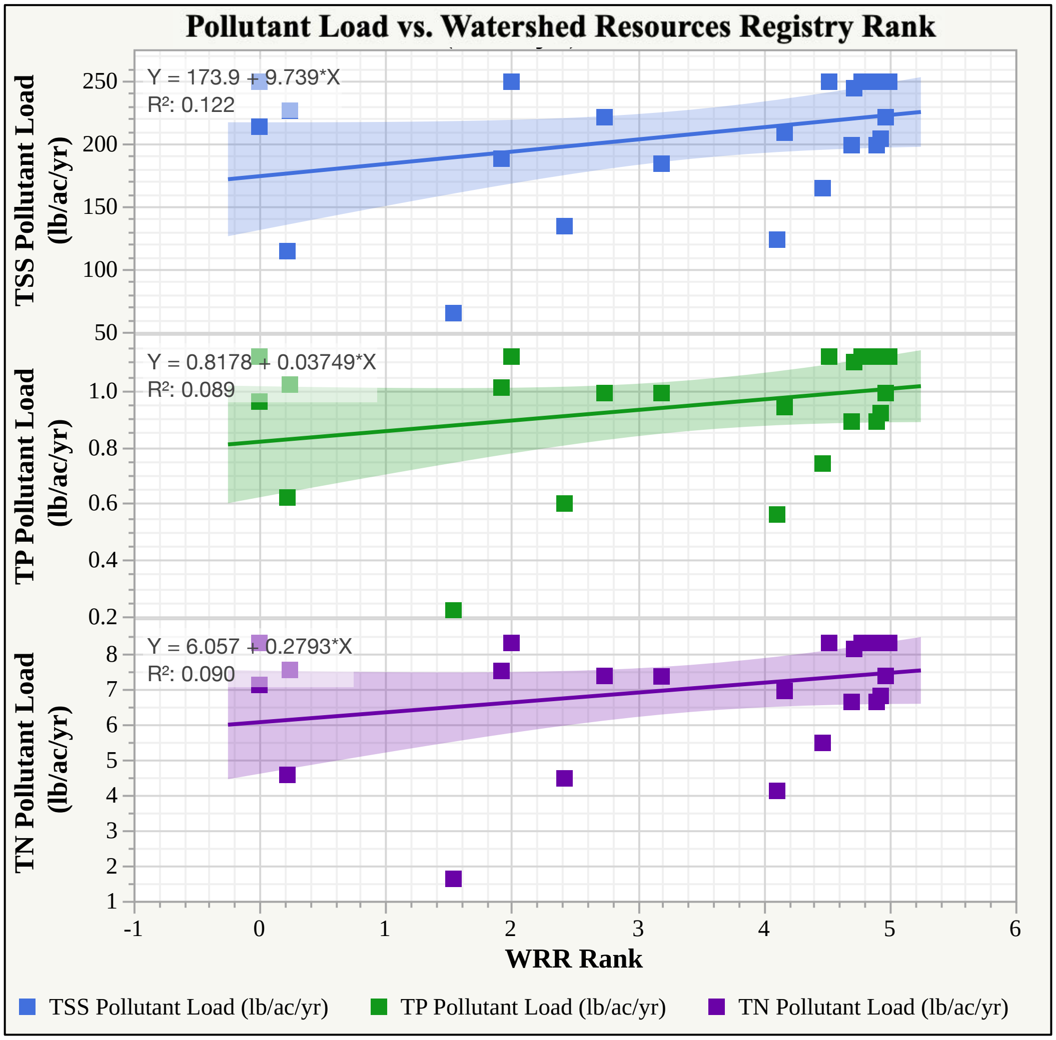


Figure 4.3: Correlation between all pollutant loads and Watershed Resources Registry rank

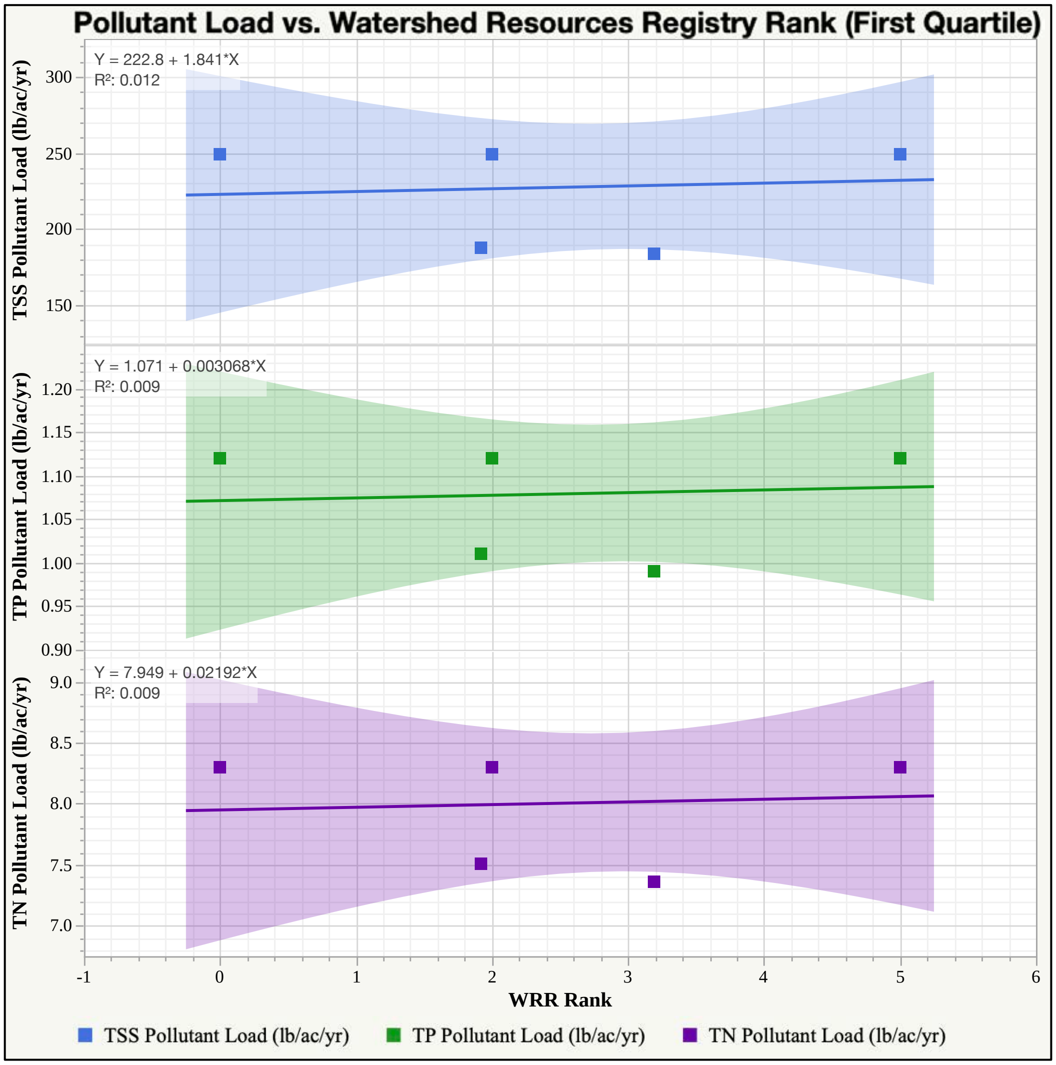


Figure 4.4: Correlation between pollutant loads and Watershed Resources Registry rank (first quartile)

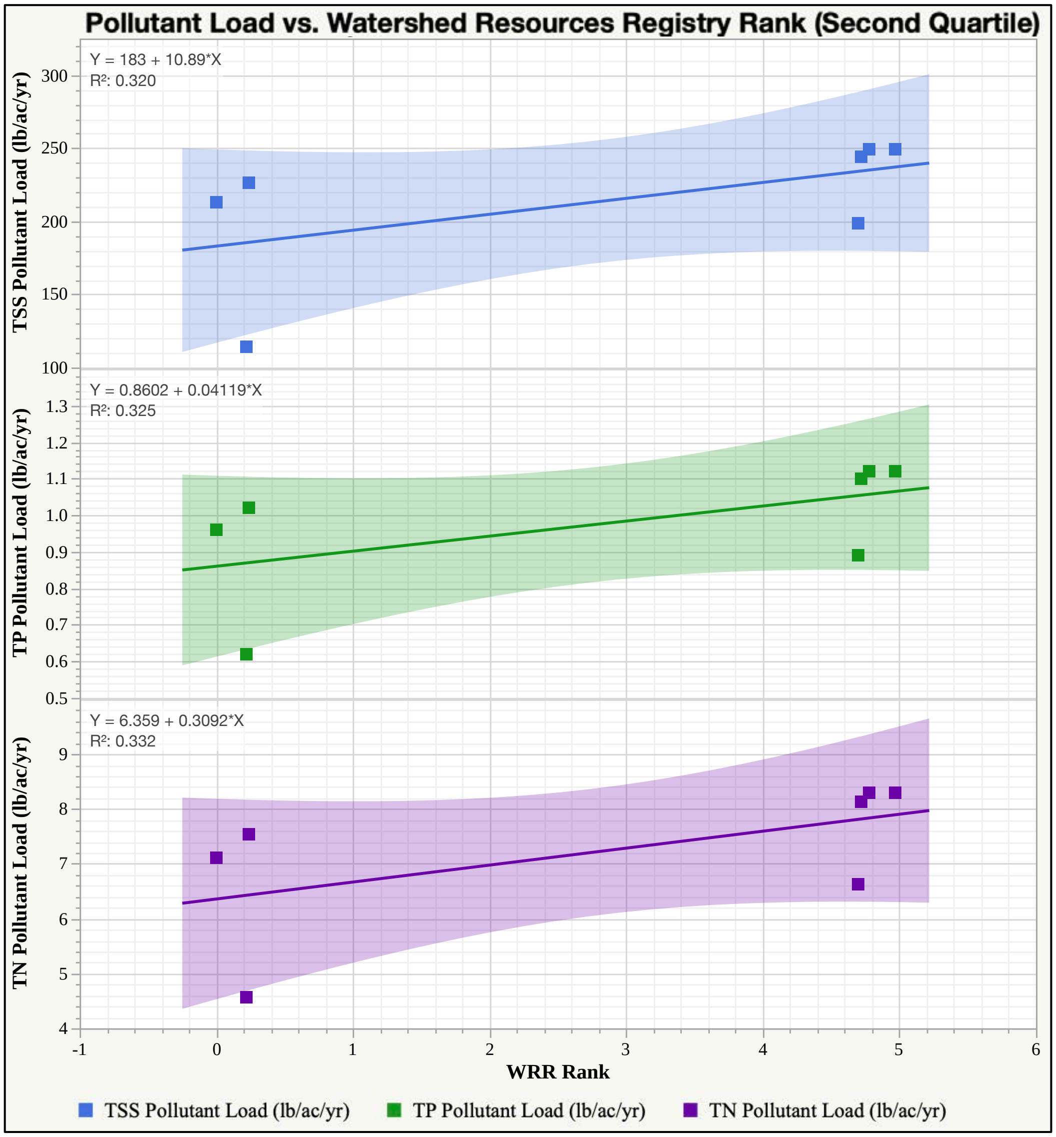


Figure 4.5: Correlation between pollutant loads and Watershed Resources Registry rank (second quartile)

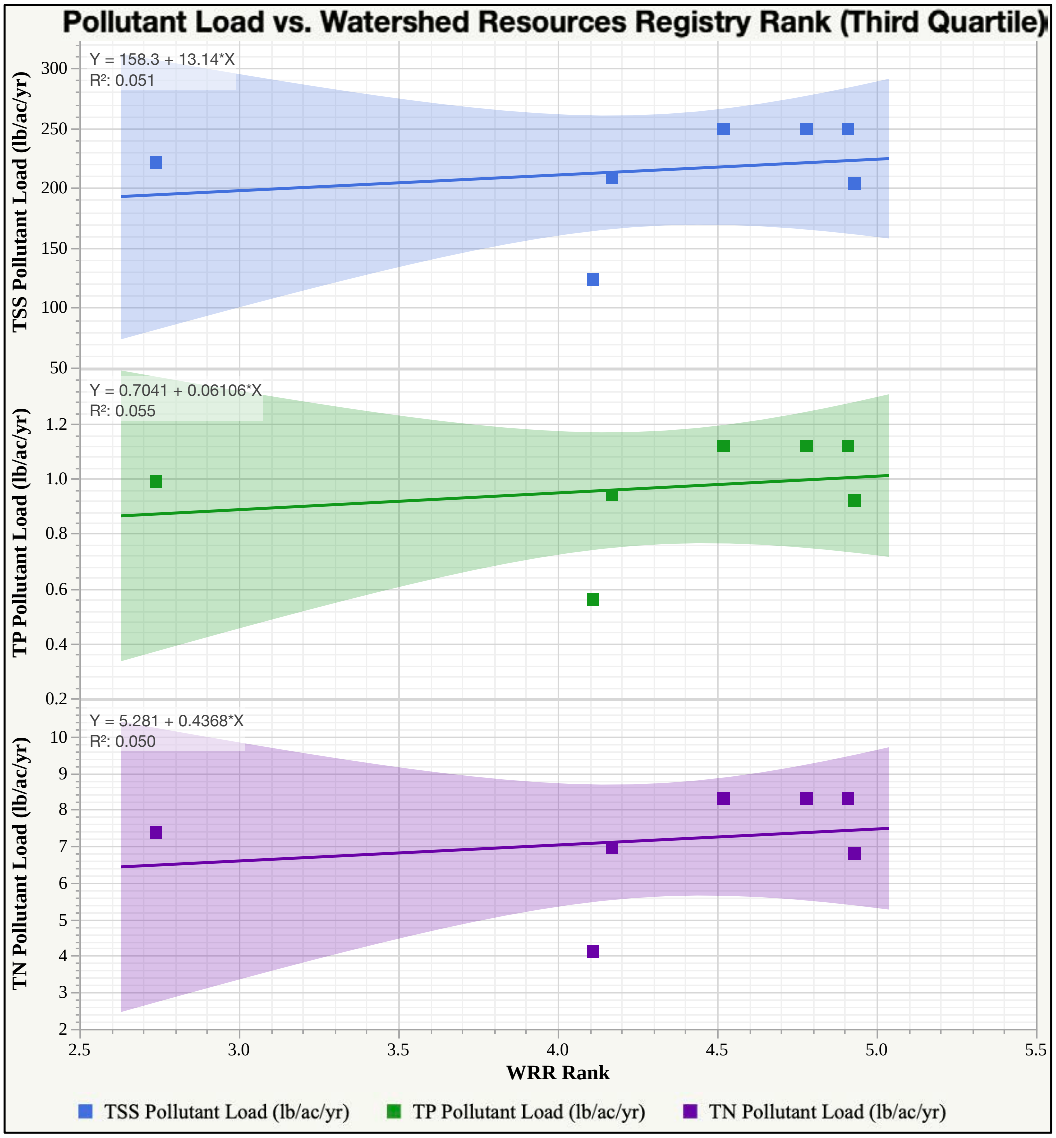


Figure 4.6: Correlation between pollutant loads and Watershed Resources Registry rank (third quartile)

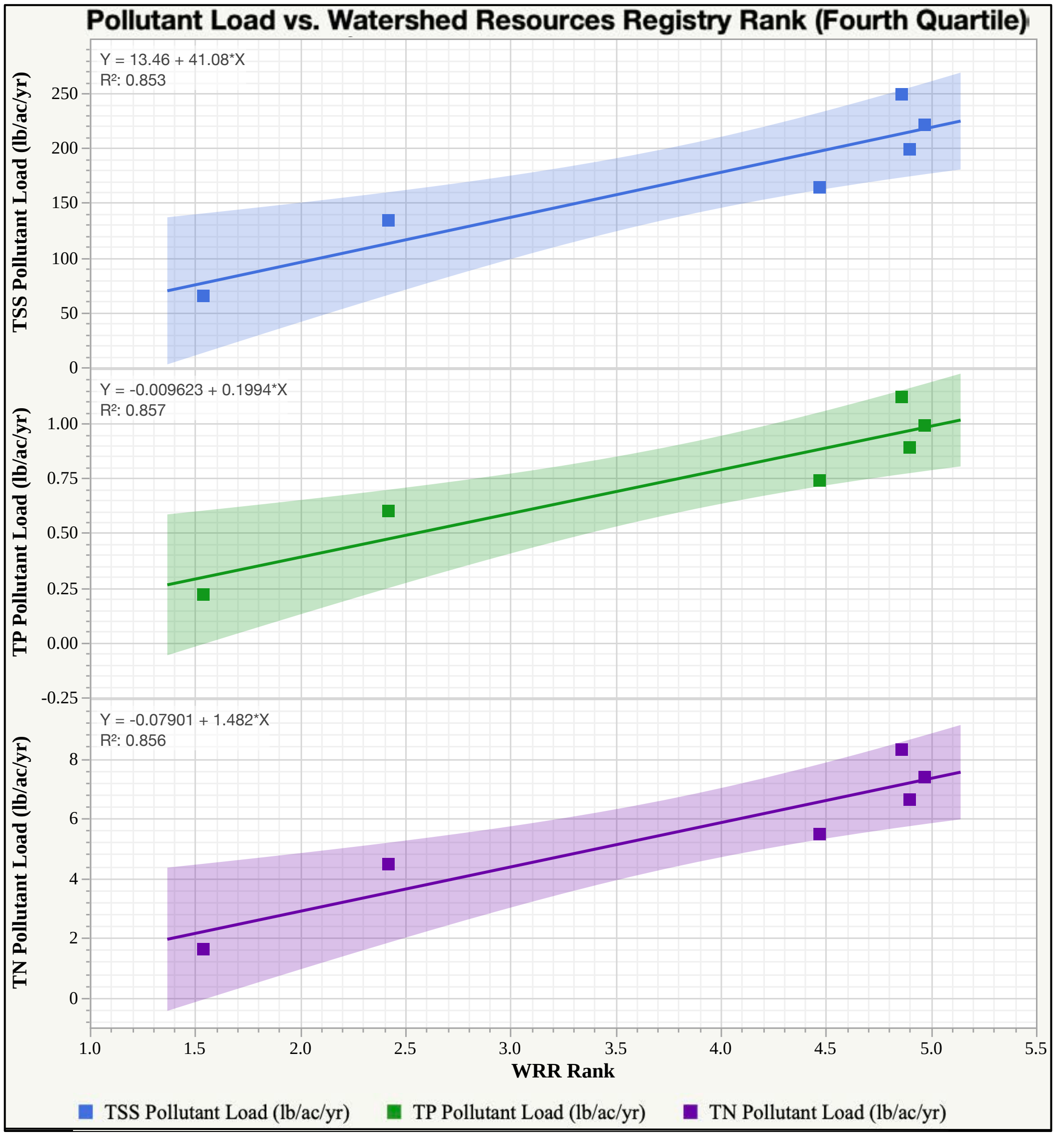


Figure 4.7: Correlation between pollutant loads and Watershed Resources Registry rank (fourth quartile)

Table 4.6: The coefficient of determination for each pollutant in each quartile

Pollutant	First Quartile	Second Quartile	Third Quartile	Fourth Quartile
TN	0.009	0.332	0.05	0.856
TP	0.009	0.325	0.055	0.857
TSS	0.012	0.32	0.051	0.853

4.3 The Best Resolution Suitable for the Watershed Resources Registry

The first, second, and third quartiles of data determined the most suitable resolution for the Watershed Resources Registry. All of the pollutant loads showed a measurable increase in their r-squared values at 1.03 acres (Figure 4.8). Both TP and TN had an r-squared value of 0.507 and TSS had 0.507, which all represented a moderately strong correlation. Another increase occurred at 4.34 acres for all pollutant loads, with r-squared values of 0.734 (TN), 0.735 (TP), and 0.711 (TSS), which represented a strong correlation. The Watershed Resources Registry seems to be suited for spatial resolution greater than 1 acre and best suited for 4.34 acres, which equals 16,187 square meters.

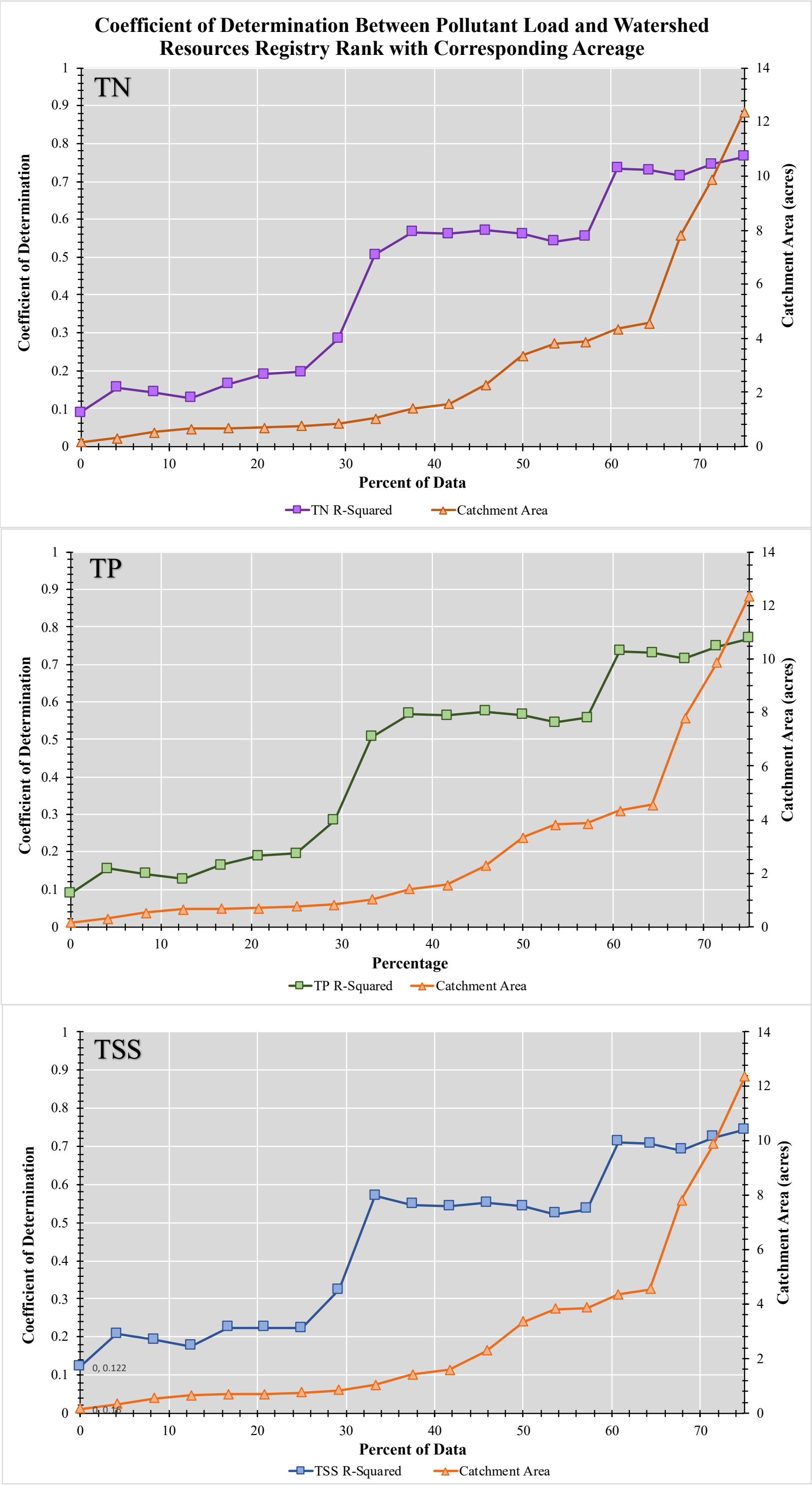


Figure 4.8: Coefficient of determination for pollutant loads and catchment areas

Chapter 5

DISCUSSION AND CONCLUSIONS

Results from this research provide insight to the applicational use of the Watershed Resources Registry. The r-squared values indicate varying relationship strengths between the Watershed Resources Registry ranks and catchment areas with their associated pollutant loads. The discussion below expands upon the results, explaining the catchment area compositions, the pollutant load correlations with the Watershed Resources Registry ranks, and the best suited resolution for the Watershed Resources Registry. The applicational use of the Watershed Resources Registry for WQIPs is further discussed to examine how this research could be applied in the future and the policy implications it could have. Lastly, recommendations for future work are given.

5.1 Best Management Practice Catchment Area Composition

It was typical to see higher amounts of urbanized land use in the catchments than agricultural or rural types because of urban clusters and NPDES coverage within the Christina River WQIP. The Christina River is also one of the more urbanized watersheds in the Brandywine-Christina watershed (Brandywine Conservancy et al. 2018). There was a large spread of data within the catchment areas. The smallest catchment was 0.16 acres while the largest was 59.95 acres. The catchment area was dependent upon the location of the BMP, as well as the purpose of implementing or retrofitting a BMP in that area, determined by Century Engineering, New Castle County, and DelDOT. It also depended on the amount of stormwater conveyances and flow direction in or around the catchment area.

The weighted average Watershed Resources Registry ranks corresponded to the amount of area from each rank within the delineated catchment. The average Watershed Resources Registry rank was 3.46-stars. Based on the data, the catchments as a whole were rated as suitable areas for stormwater BMP implementation. The lowest rank was 0-stars and the highest was 5-stars. For example, BMP ID 307 had a Watershed Resources Registry rank of 0 because none of the rankings overlapped with the catchment. There are two possible reasons for this. First, the Watershed Resources Registry provides ranks through absolute and relative criteria by surveying various types of land use data by a 30-meter resolution. If the area did not receive any rank, it may not have met any of the criteria or it could be a resolution error. BMP ID 307 is only 0.16 acres in size and with the Watershed Resources Registry measuring at a 30-meter scale, there is a chance it will not detect the criteria on that small of a scale. Some gaps in the Watershed Resources Registry ranks were detected, such as a 30-meter square not showing any ranks, and this could be due to one of the reasons listed above.

There were limitations to this research. First, the sample size was small. Considering the data are BMPs, 26 is a fair amount, but statistically, the sample size is small. Due to this, no probability tests or rank order tests were completed. The data seemed insufficient to determine if the relationships were significant, so instead this research focused on the coefficient of determination, or r-squared values. Another limitation is the inability to thoroughly understand each BMP site in the field. Analyzing the sites in the field could have narrowed the assumptions made about the length and width of each BMP. Fortunately, pictures were provided for each site, so the best judgement was made based on the data and tools available.

5.2 Rank Correlation between Pollutant Loads and Catchment Areas

First, all of the pollutant loads were graphed with the corresponding 26 BMP site's Watershed Resources Registry ranks. The purpose for this was to analyze whether any general relationship could be determined. With r-squared values less than 0.125, there was no prominent correlation with any of the pollutants. Because of this, the data were split by acreage value, from lowest to highest. This aided in the understanding of the Watershed Resources Registry ranks with corresponding loads.

The first, second, and third quartiles did not display any strong relationships, in fact they were only weak. This indicated there was not a reliable correlation between increasing pollutant load and Watershed Resources Registry rank. The fourth quartile showed a very strong relationship, with all three r-squared values greater than 0.85. The fourth quartile contained the higher acreage amounts with their associated loads. Since the Watershed Resources Registry rank showed a direct relationship with increasing load, it could be concluded that the higher ranks were associated with higher loads, but the specific spatial resolution was still to be determined.

Table 4.6 lists the r-squared values for each quartile. The first three quartiles all had weak correlations while the fourth quartile had a strong correlation. Each quartile either contained six or seven data points. When comparing each quartile's distribution, the third quartile was the only graph that contained the least spread in data, meaning there was better distribution of data in the other three graphs versus the third. If the sample size was greater, it would have been interesting to see if results varied or remained the same.

It is important to understand the inputs of both the DURMM and the Watershed Resources Registry criteria. The DURMM requires LULC within a HSG and the total acreage. The Watershed Resources Registry absolute and relative criteria vary for each category and were selected based on consensus from local, state, federal, and private partners. The stormwater compromised infrastructure restoration layer was the focus of this research so the two commonalities between the criteria and the DURMM inputs were land use and soil type. Land use could overlap between cropland, forest, open water, and urban while soil type overlapped when soils were poorly or very poorly drained. Knowing this, it would be interesting to see if there could be a stronger correlation between loads and ranks if more absolute and relative criteria were offered for the Watershed Resources Registry.

5.3 The Best Suited Resolution for the Watershed Resources Registry

This research concludes the Watershed Resources Registry ranks do increase with increasing pollutant loads, but the spatial scale was still undetermined. As noted in Chapter 4, the data were skewed towards smaller acreage, with a majority of values less than 10 acres. This actually benefited the research because the spatial resolution best suited for the Watershed Resources Registry was narrowed.

Figure 4.8 represents what it looks like to subtract one data point at each step from the overall sample size. The first square on the left side represents all 26 BMP sites, followed by the next square representing 25 BMP sites since the lowest BMP catchment was removed. The purpose for doing this was to determine if there was a specific value of area that started to show an increase in the r-squared value.

There are two noticeable increases throughout all three graphs. The first increase is at 1.03 acres, which is noted at 33 percent. This means that the data point at 1.03 acres represents the upper 67 percent of data. Essentially, there is a moderately strong correlation because the r-squared values for all graphs increased over 0.50 at 1.03 acres. The second increase is noted at 4.34 acres for all three graphs with r-squared values greater than 0.70, representing a strong correlation. It has been taken into consideration that naturally, as the amount of data points decreases, r-squared values may increase, but that was not the case in Figures 4.4, 4.5, and 4.6. The r-squared increases at 1.03 acres and 4.34 acres indicate the resolution the Watershed Resources Registry is best suited for. Based on these results, the Watershed Resources Registry can rank areas sufficiently down to a 4- to 5-acre scale, and possibly down to 1-acre.

The limitation in this result is the 30-meter resolution of the Watershed Resources Registry. The limitation was not the data inputted into the DURMM because the data was derived from LULC layers in GIS at 1-meter: the finest resolution possible given the datasets. If the Watershed Resources Registry were able to analyze criteria on a finer scale, lower than 30-meters, the 4-acre scale determined may be smaller. A sensitivity analysis in terms of appropriate results of the Watershed Resources Registry could be accomplished by rendering the Watershed Resources Registry resolution.

5.4 The Future of the Watershed Resources Registry

This research determines the Watershed Resources Registry can be used as a useful tool for New Castle County and DelDOT to use for their WQIPS. The Watershed Resources Registry should strictly be used as a planning tool in the first phase of WQIPs. Field verification is needed once the sites have been selected. When using this as a desktop tool, it is important to note that although the Watershed Resources Registry does not quantify its rankings, this research now proves that as long as the resolution is greater than 4 acres, the associated rankings can be representative of TN, TP, and TSS loads. This means increasing rank will most likely be associated with increasing loads that can be treated. Certain situations may prove this not to be true, such as if there are other BMPs in place upstream already, impacting the amount of loads reaching the proposed site. The Watershed Resources Registry can certainly be used to identify “hot spot” locations.

This research was only able to incorporate 26 BMP sites, but having more sites in the future would be extremely beneficial to see if the same results could be obtained. For example, this method of research could be applied to the White Clay Creek watershed. Using GIS, the Watershed Resources Registry ranks can be mapped out to identify areas to focus on, especially since the data suggest higher pre-treated loads are associated with higher ranks. Future work could analyze other categories the Watershed Resources Registry offers as well: upland preservation and restoration, wetland preservation and restoration, riparian preservation and restoration.

5.5 Policy Implications

The Watershed Resources Registry offers a new tool to use in the first phase of WQIPs. Depending on the spatial extent the user is looking for, the Watershed Resources Registry is suitable down to a 4-acre resolution, or 16,187 square meters. Granted, this is still a large area and BMP practices tend to be much smaller than this, but it does provide insight to a focus area.

If New Castle County and DelDOT decide to use the Watershed Resources Registry, it could potentially increase their efficiency and allow them to complete a screening process on their own, without hiring a company to do it. The Watershed Resources Registry offers opportunity for more sites to be analyzed because it identifies “hot spots” using the ranks. The more sites analyzed, the better chance there is to compare benefits and costs of each BMP project. It is important to select the most suitable areas to implement BMPs that typically correspond with the highest loads. Sometimes BMPs are designed to help flooding issues, but the overall goal still concludes with protecting water quality.

The Watershed Resources Registry is offered for five states: Delaware, Pennsylvania, Maryland, Virginia, and West Virginia. These states all contribute to the

Chesapeake Bay. The Watershed Resources Registry can be used to find the best suitable areas to implement BMPs within the Chesapeake Bay watershed. Each state has to meet a TMDL requirement and a tool like the Watershed Resources Registry can help attain this goal. The end goal of this research is to improve water quality. The purpose of implementing BMPs is to reduce the amount of pollutants entering a waterway which can deteriorate water quality health. Increasing site selection efficiency could accelerate the planning phase of the WQIP process, so over time more BMPs can be implemented, which in return has a positive impact on water quality health.

5.6 Conclusions and Recommendations

This research was the first of its kind in the State of Delaware. Using the Delaware Urban Runoff Management Model to calculate pre-treatment pollutant loads allowed for three results: The DURMM and Watershed Resources Registry can be used in tandem, a relationship was determined based on rankings and loads, and the Watershed Resources Registry's spatial scale appropriateness was analyzed.

Key conclusions from this study are:

(1) The DURMM is a model that can be used in tandem with the Watershed Resources Registry, which is beneficial to New Castle County and DelDOT who are required to use the DURMM to calculate nutrient loads. The Watershed Resources Registry now offers a new perspective when using the DURMM because loads can be associated

with Watershed Resources Registry ranks in different watersheds. It is beneficial to use the DURMM with the Watershed Resources Registry only after the site selection process has been made, such as the case for this research. Using this model and tool together can provide more opportunities for site selection as the Watershed Resources Registry provides the best suitable areas and the DURMM can confirm it by calculating loads.

(2) This research concluded that based on the data, the Watershed Resources Registry rank did increase with increasing pollutant loads. This was evident in the fourth quartile graph as the r-squared values indicated a strong correlation, meaning the utility of the Watershed Resources Registry is accentuated on larger scales. It was also proven in Figure 4.8 as r-squared values increased due to increasing catchment area sizes.

(3) The Watershed Resources Registry is best suited for at least a 4-acre resolution, or 16,187 square meters. This resolution will provide “hot spot” areas to focus on, rather than specific site locations. The Watershed Resources Registry should only be used for a screening tool because of this.

It is important to recognize two outcomes. First, the higher ranks associate with higher loads as long as the spatial scale is greater than 4 acres. Second, the Watershed Resources Registry can be used together with the DURMM to provide better insight to a location. Both the tool and model can help the user decide where to implement or retrofit the best BMP for the best use of funding as well.

Delaware's Watershed Resources Registry is a newer tool, designed in 2016, that has great opportunity to expand and be used elsewhere, specifically for WQIPs. It determines areas least to most suitable to implement BMPs and it even shows a strong relationship for pre-treated pollutant loads at lower spatial resolutions. Delaware is not the only state that implements WQIPs (Mikhail Ogawa Engineering 2016), so it is possible to use the Watershed Resources Registry in Maryland and Pennsylvania. WQIPs are not the only use for the Watershed Resources Registry. There are plenty of other entities that can use it to help determine their next stormwater BMP location. The end goal is the same for everyone, though, which is to improve water quality. Water is essential for life of all forms and it is an element that needs to be protected for generations to come.

This research has great potential to be translated and used by entities focused on stormwater restoration practices. It can be used in the Chesapeake Bay watershed or Delaware River watershed for states in Delaware, Maryland, Pennsylvania, Virginia, and West Virginia.

Key recommendations from this research include:

(1) The Watershed Resources Registry has upland, riparian, and wetland preservation and restoration categories, so an encompassed viewpoint can include all categories when selecting the best place to implement a BMP. Stormwater does not have to be the entire focus as it would be interesting to see if the same results can be produced.

(2) This research is recommended to be completed with a larger dataset. It has the potential to provide a better-defined spatial resolution the Watershed Resources Registry is suited for. All of the Watershed Resources Registry categories should be researched to see if the same resolution is prominent across all recommendations of BMPs.

(3) Better documentation of the Watershed Resources Registry rank selection process would be extremely beneficial for other states trying to create their own Watershed Resources Registry. There is no published documentation available for users, so providing insight on how to select absolute and relative criteria would be useful. It would also be helpful to understand the selection process of the two criteria groups and whether more criteria can be added for future work.

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