Brandywine-Christina Healthy Water Fund

Technical Analysis
June 2017

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UNIVERSITY OF DELAWARE

Brandywine-Christina Healthy Water Fund
Modeling and Technical Analysis
Final Report

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1. Introduction

This report represents modeling efforts in support of the development of a sustainable water fund (the Brandywine-Christina Healthy Water Fund, or the Water Fund) for the Brandywine-Christina basin. This effort was performed through a grant from the William Penn Foundation targeting the 13,000 square mile Delaware River Basin. The Water Fund is one of several projects undertaken in the 565 square-mile Brandywine-Christina basin, which is itself one of eight priority watersheds throughout the Delaware River Basin targeted for water quality improvements and watershed protections. The Water Fund was conceived to help return the waters of the Brandywine-Christina, the source of drinking water for over six hundred thousand residents of Pennsylvania and Delaware to fishable, swimmable, and potable status by 2025.

2. Overview of the watershed

The Brandywine-Christina basin is situated in the mid-Atlantic region, at the boundary between Delaware and Pennsylvania, see Figure 1.1. The basin comprises four watersheds defined by the major tributaries, Red Clay Creek, White Clay Creek, Brandywine Creek, and Christina River, with a total of over 1,200 miles of streams and rivers. Of the basin's 565 square mile area, the Red Clay watershed makes up 54 square miles, the White Clay, 107 square miles, the Brandywine 325 square miles, and the Christina 77 square miles. Table 2.1 presents the area of the Brandywine-Christina basin, by state, county and watershed.

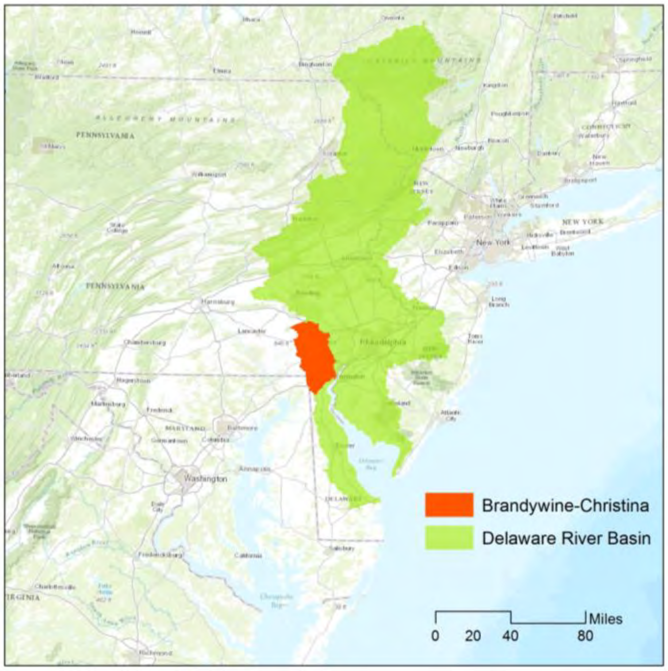


Figure 2.1 -- The Brandywine-Christina basin within the Delaware River Basin.

Table 2.1 -- Area (acres and square miles) of the watersheds of the Brandywine-Christina Basin, by state and county.

Watershed	State	County	Acres	Square Miles
Brandywine	DE	New Castle	14,753	23.1
Brandywine	PA	Chester	185,476	289.8
Brandywine	PA	Delaware	6,075	9.5
Brandywine	PA	Lancaster	2,106	3.3
Christina	DE	New Castle	42,567	66.5
Christina	MD	Cecil	5,395	8.4
Christina	PA	Chester	1,479	2.3
Red Clay	DE	New Castle	13,514	21.1
Red Clay	PA	Chester	21,084	32.9
White Clay	DE	New Castle	29,566	46.2
White Clay	MD	Cecil	10	0.02
White Clay	PA	Chester	39,112	61.1
Delaware Total	**DE**		**100,400**	**156.9**
Maryland Total	**MD**		**5,406**	**8.4**
Pennsylvania Total	**PA**		**69,856**	**109.2**
Basin Total			**361,138**	**564.3**

The Brandywine-Christina basin is characterized by high population density in the southern portions and the central Great Valley corridor. In total the basin contains over 615,000 inhabitants, and has seen significant population pressure in the past several decades. The majority of the population resides in Delaware, the largest portion of which receives its drinking water from surface water intakes on the major tributaries of the Brandywine-Christina. The City of Newark, the City of Wilmington, and Suez Delaware all take in water from streams, which then treated and distributed to consumers. In Pennsylvania a significant portion of the population also receives surface drinking water, including those served by PA American, Downingtown Borough, and Aqua PA. Table 2.2 presents the total population in each of the four watersheds of the basin, in 2000, 2010, and 2013.

Table 2.1 -- Population trends in the watersheds of the Brandywine-Christina Basin.

Watershed	2000	2010	2013
Brandywine Creek	221,413	246,702	257,313
Christina River	166,435	174,196	187,490
Red Clay Creek	42,630	46,893	45,877
White Clay Creek	118,577	123,504	124,480
Brandywine-Christina	**549,055**	**591,295**	**615,161**

The map in Figure 2.2 shows the population density in the basin as of 2013. Note the higher densities in the lower, Delaware portion of the basin and in the Great Valley corridor in central Chester County. Figure 2.3 shows the change in population across the same period.

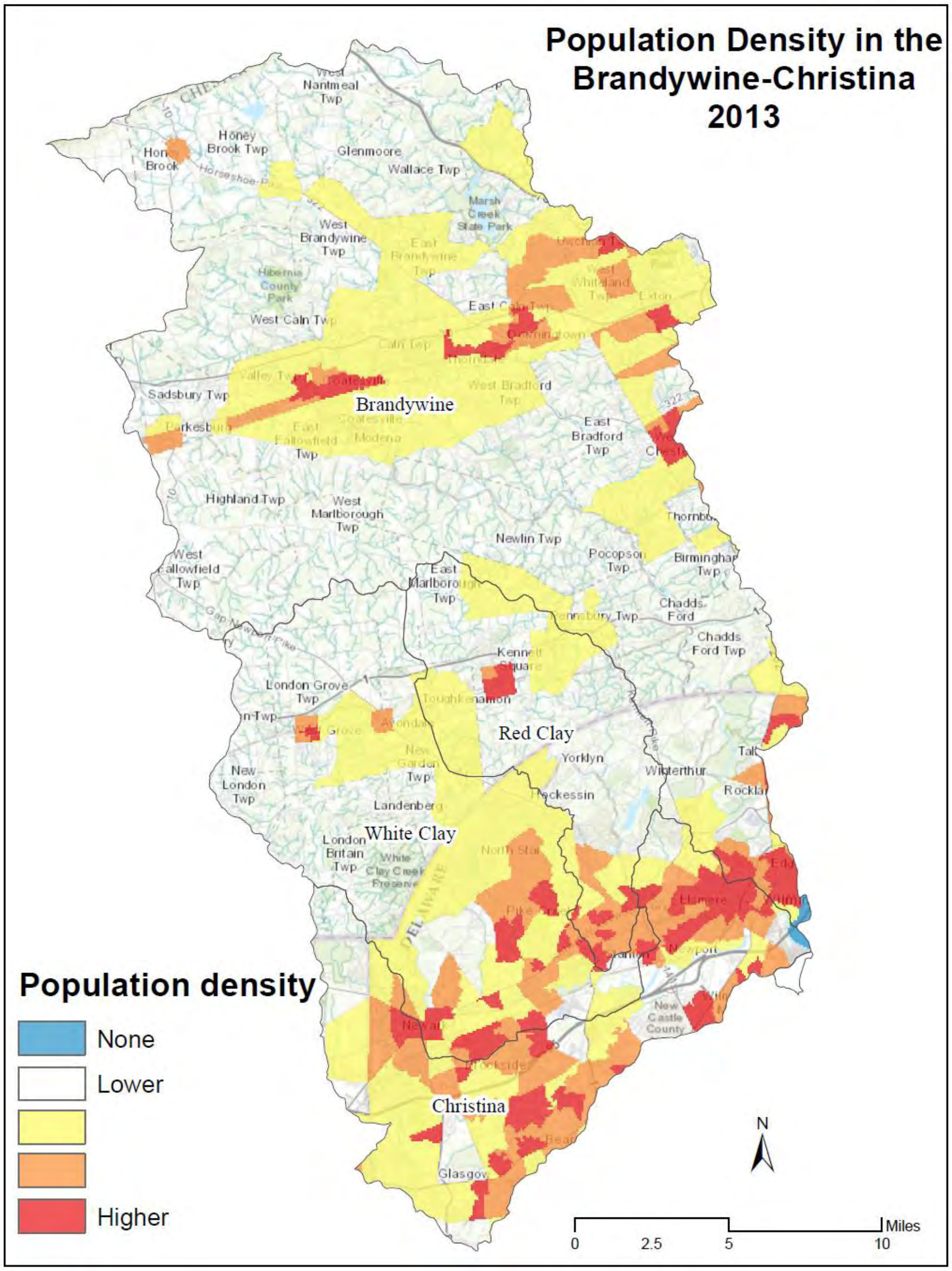


Figure 2.1 -- Population density in the Brandywine-Christina Basin, 2013 (based on the U.S. Census Bureau American Community Survey 5-year estimates).

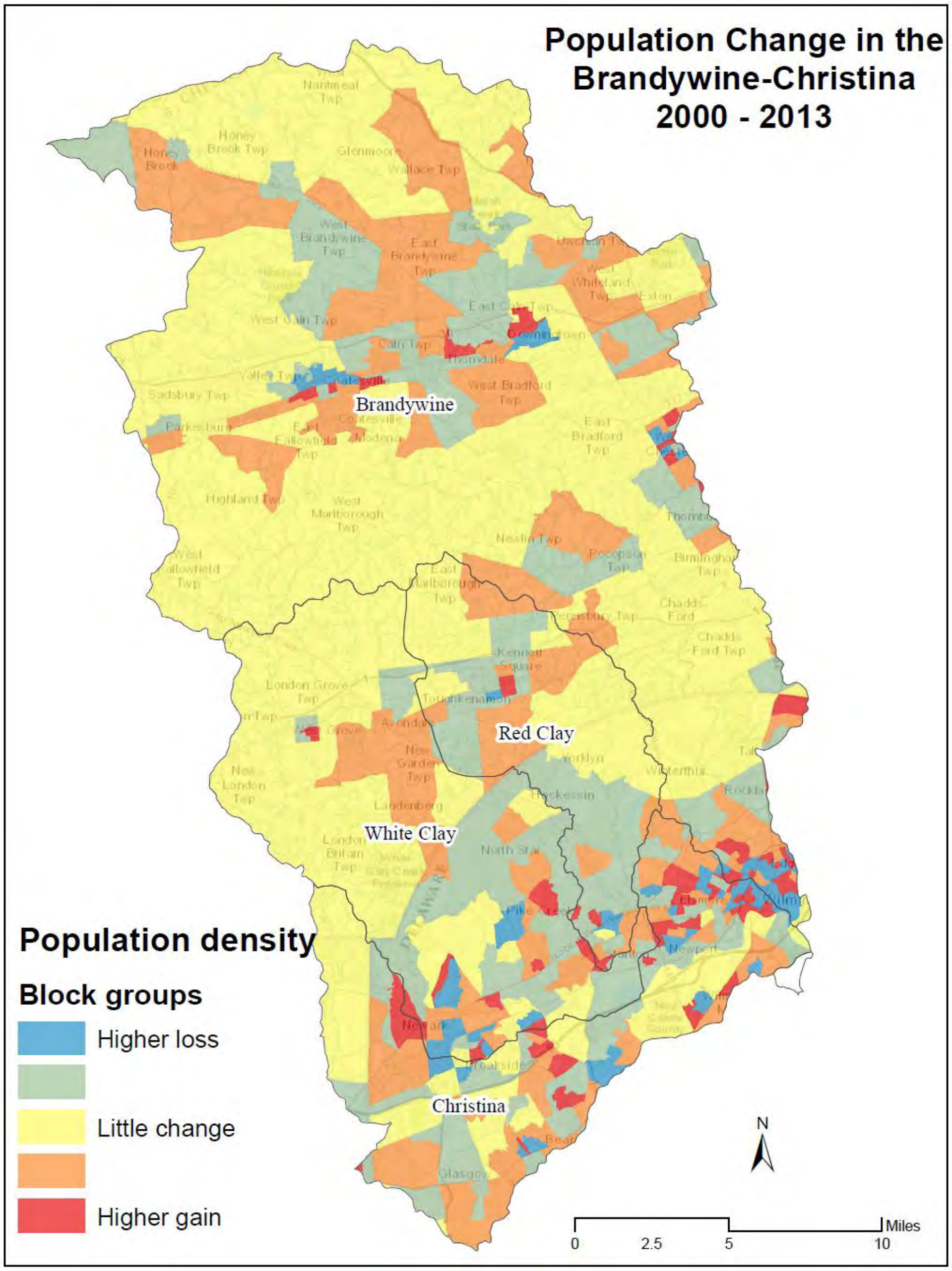


Figure 2.2 -- Population change in the Brandywine-Christina Basin, 2000-2013 (based on the U.S. Census Bureau Decennial Census and American Community Survey 5-year estimates).

Figures 2.4 and 2.5 show the population trends in the Brandywine-Christina, by state and by watershed.

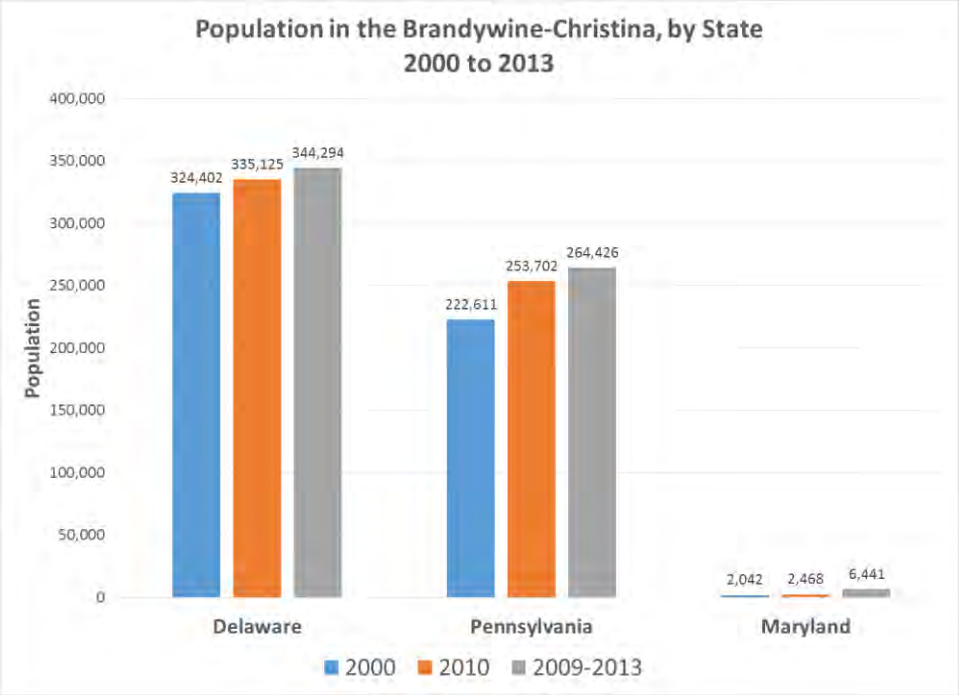


Figure 2.3 -- Population trends in the Brandywine-Christina Basin, 2000-2013, by state.

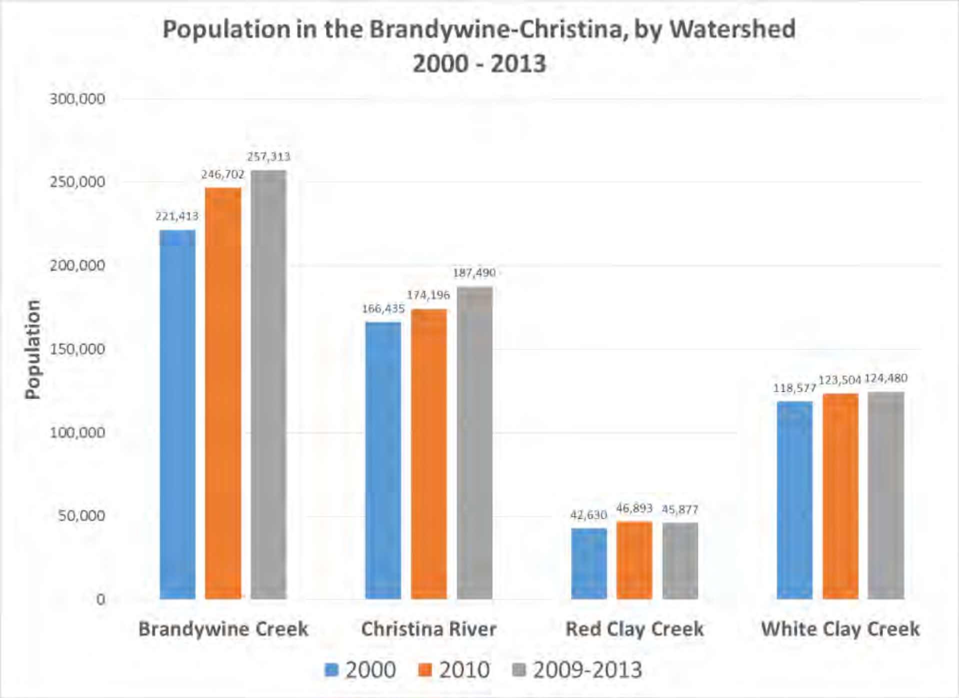


Figure 2.4 -- Population trends in the Brandywine-Christina Basin, 2000-2013, by watershed.

The watersheds of the Brandywine Christina are characterized by a mix of land cover, divided among developed land, agriculture, and natural land (forests and wetlands). The map in Figure 2.6 shows the distribution of land cover types across the Brandywine-Christina basin.

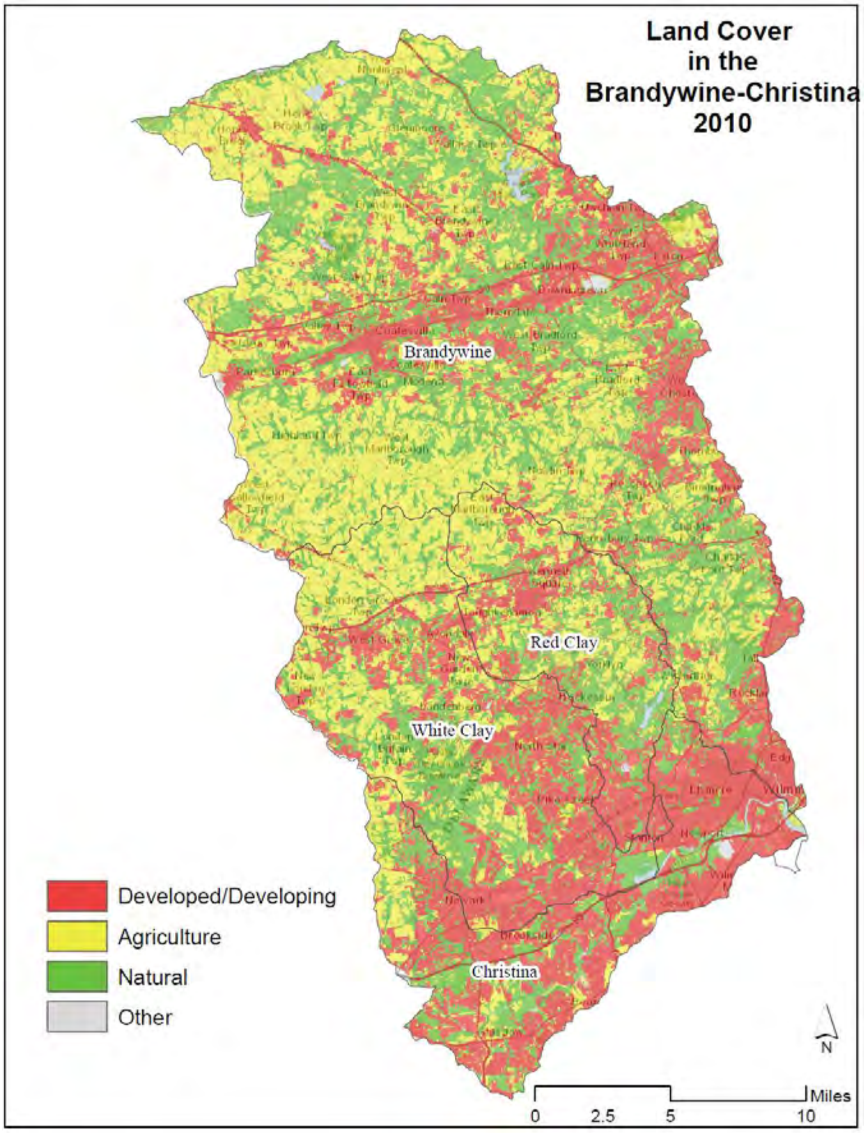


Figure 2.5 -- Land cover in the Brandywine-Christina Basin, 2010 (PA) and 2012 (DE).

Figure 2.7 shows the land cover breakdown into major categories. There is approximately the same amount of developed, agricultural, and natural land across the basin, but each type is focused in different areas. The southern, more populous areas of Delaware and the central portion along the Great Valley corridor are highly developed, with significant portions of agricultural land in Pennsylvania portions of the Red Clay, White Clay, and Brandywine watersheds.

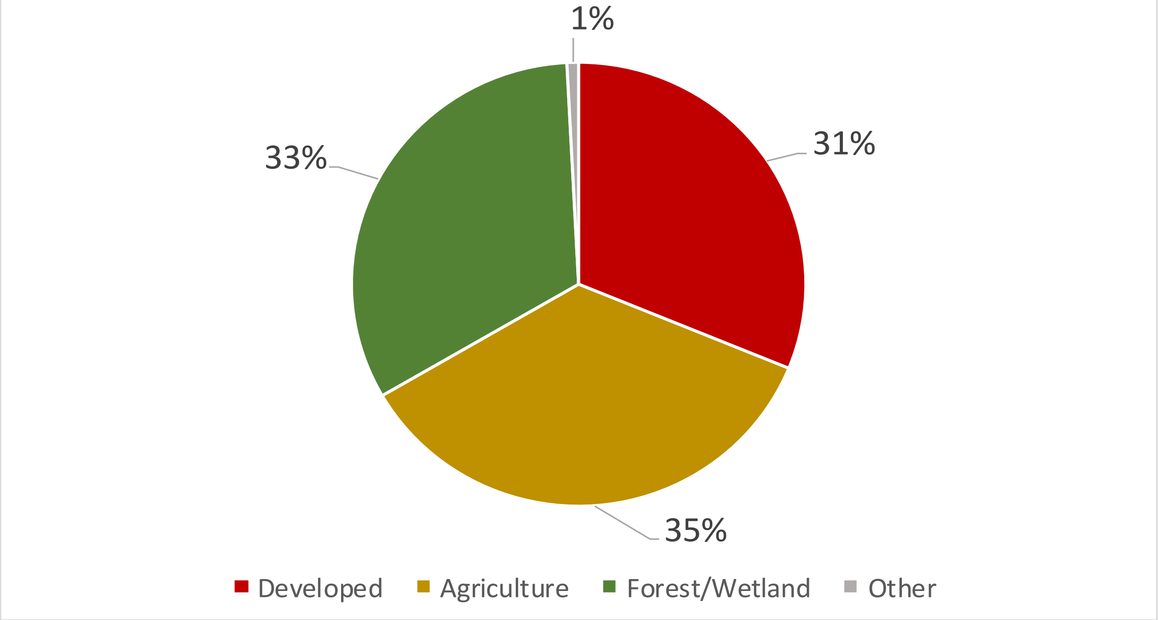


Figure 2.6 -- Land use distribution within the Brandywine-Christina Basin, 2010 (PA) and 2012 (DE).

Figure 2.8 presents the change in land cover from 1996 to 2010. During this time the Brandywine-Christina basin has seen a significant increase in developed land, along with a concomitant reduction in the amount of agricultural and natural (mostly forested) land in the same period.

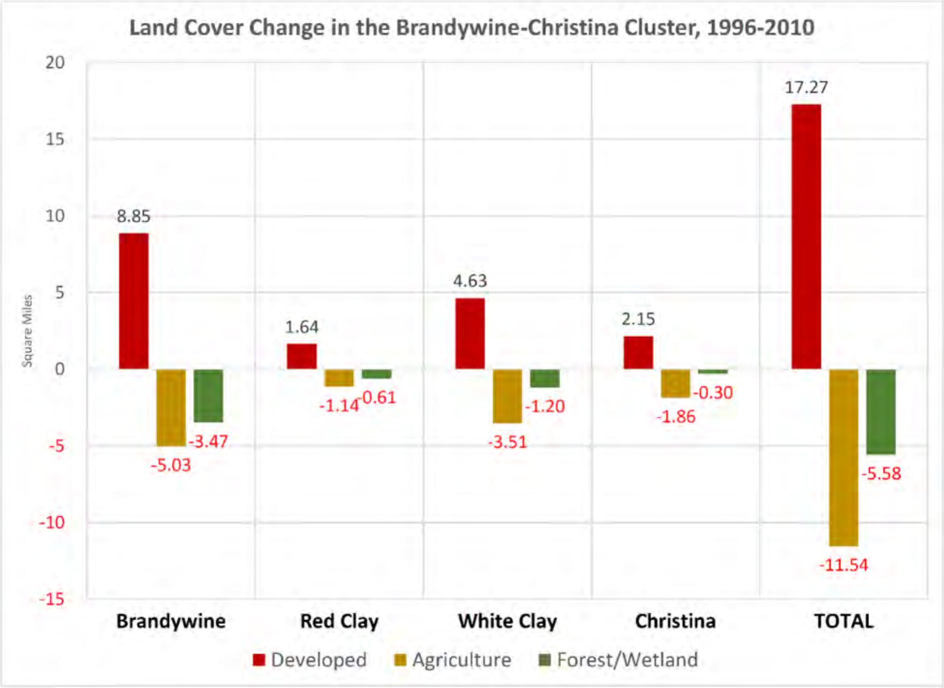


Figure 2.7 -- Land cover changes by watershed in the Brandywine-Christina Basin, 1996-2010 (NOAA C-CAP).

3. Existing planning and priorities

The Brandywine-Christina basin is one of the only bi-state watersheds in the Delaware Basin, and provides drinking water, recreation, and ecological habitat for residents of one of the most suburbanized and rapidly developing regions in the Delaware Basin. The Brandywine-Christina has seen high degree of watershed coordination and planning efforts over the past several decades. The many, often competing, interests in the waters of the Brandywine-Christina along with the complexities of laws and regulations governing their use and protection have led to many efforts to quantify watershed impacts from pollution, set limits or standards on contaminants entering the waterways, prioritize watersheds for protection and investment, and estimate costs of implementation of protection measures.

Christina Basin TMDL

The 2006 Christina Basin TMDL (Total Maximum Daily Load) (USEPA, 2006) for the watersheds of the Brandywine-Christina in Delaware and Pennsylvania was developed in accordance with Section 303(d) of the Federal Clean Water Act (CWA). The TMDL reports (for nutrients, sediment, and bacteria) represent a significant effort at modeling the loads within the watershed to determine the "pollution diet" of catchments and within municipalities in order to maintain acceptable water quality levels.

Loads and allocations were determined using the Hydrological Simulation Program—Fortran (HSPF) model implemented by the USGS, in collaboration with the Delaware River Basin Commission (DRBC), the Delaware Department of Natural Resources and Environmental Control (DNREC), and the Pennsylvania Department of Environmental Protection (DEP). The TMDL for the Brandywine-Christina serves as a *de facto* prioritization of the catchments of the watershed based on modeled pollutant loads.

The data for this effort were collected in the streams of the Brandywine-Christina in the years between 1994 and 1998, and therefore reflect conditions before many of the current water quality protections and Best Management Practices (BMPs) were implemented. Reductions in pollutants including nitrogen, phosphorus, and sediment (in the Pennsylvania portions of the watershed) required by the TMDL are reported on a catchment level and by municipality. These reductions, as expressed by percentage reductions from baseline levels, form the basis for determining reduction and cost estimates to guide the Water Fund in prioritizing areas and techniques to achieve water quality goals. The map in Figure 3.1 shows the basin with use designations used in the Christina Basin water quality modeling process.

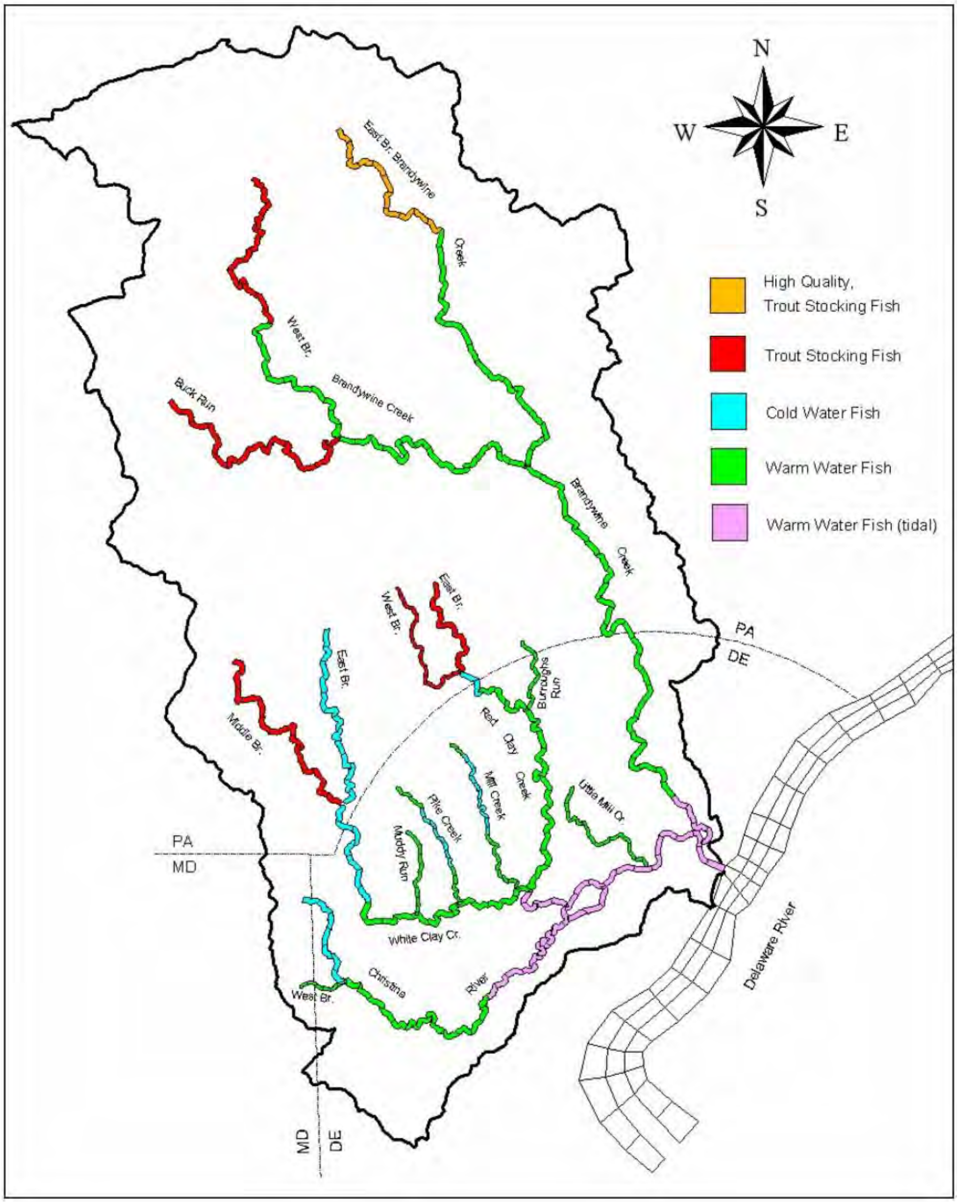


Figure 3.1 – Designated use of streams in the Brandywine-Christina Basin used for water quality modeling.

Christina Basin Watershed Restoration Action Strategy

A watershed action plan to restore the waters of the Christina Basin, developed by the University of Delaware Water Resources Agency (now the Water Resources Center) focused on establishing a report card on the waters and watersheds of the basin, outlining strategies to address each specific threat (Kauffman, et al., 2003).

See the full report at http://www.wrc.udel.edu/wp-content/uploads/2013/02/Christina-Basin-Watershed-Restoration-Action-Strategy-Executive-Summary.pdf

Christina Basin Pollution Control Strategy

An approach to addressing water quality issues in the watersheds of Delaware is the development of Pollution Control Strategies (PCS), through which a team of stakeholders is engaged to identify existing problems and potential solutions, along with funding approaches and cost estimates (Delaware Tributary Action Teams 2011). Delaware has promulgated several such strategies, including one for the Christina Basin (i.e., the Brandywine-Christina Basin). According to USEPA there are four main steps in developing a PCS:

1) determine priority pollutants,
2) identify control measures,
3) incorporate the control measures into a plan, and
4) involve the public in development and implementation of the plan.

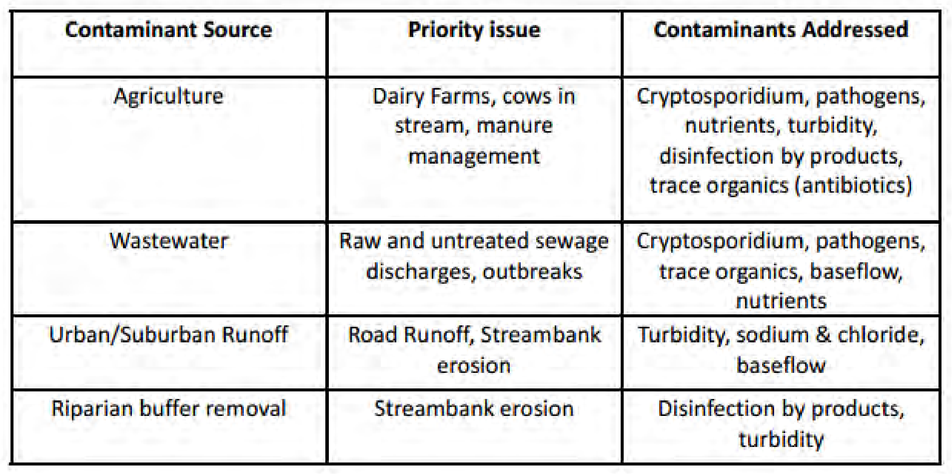
The Christina Basin Pollution Control Strategy recommended 40 strategies in five broad program areas:

- Stormwater (eight strategies)
- Open Space (seven strategies)
- Wastewater (seven strategies)
- Agriculture (seven strategies)
- Education (eleven strategies)

Wilmington Source Water Protection Plan

In 2010 Wilmington produced a plan to protect source waters of the Brandywine Creek upstream in Pennsylvania as part of their effort to reduce pollutant loads, particularly sediment, at their drinking water intake (Crockett Consulting 2010). The City recognized the importance of protecting the headwaters of their drinking water source watershed, and that spending money on protective measures could produce cost-effective benefits on the water quality of all waters downstream. This innovative approach is considered a model regionally and nationally. The following table (Table 3.1) defines the watershed priorities identified by the plan.

Table 3.1 -- Contaminants of concern as defined in the City of Wilmington Source Water Protection Plan.



Contaminant Source	Priority issue	Contaminants Addressed
Agriculture	Dairy Farms, cows in stream, manure management	Cryptosporidium, pathogens, nutrients, turbidity, disinfection by products, trace organics (antibiotics)
Wastewater	Raw and untreated sewage discharges, outbreaks	Cryptosporidium, pathogens, trace organics, baseflow, nutrients
Urban/Suburban Runoff	Road Runoff, Streambank erosion	Turbidity, sodium & chloride, baseflow
Riparian buffer removal	Streambank erosion	Disinfection by products, turbidity

BVA Red Streams Blue restoration plans

Red Streams Blue is a program of the Brandywine Red Clay Alliance (BRC, formerly the Brandywine Valley Association and the Red Clay Valley Association) which aims to restore water quality to the streams of the Brandywine and Red Clay watersheds by implementing water quality planning, laying out measures to protect and restore streams. In the mapping for the EPA's Impaired Waters program as described in the CWA, streams that are impaired for one or more constituents based on EPA's criteria are displayed in red, while streams that are unimpaired are displayed in blue. This symbolization, and the listing of the streams based on impairment status, forms the rationale for the BRC's program, and its name.

Tributaries included in the Red Streams Blue program include the Upper West Branch of the Brandywine, Buck Run, Plum Run, Valley Run, Radley Run, and Shamona Creek. Plans to restore these streams can be found on-line at: http://www.brandywineredclay.org/watershed-conservation/red-streams-blue/.

According to the BRC, the "goal of the Red Streams Blue Program is to ensure that all streams in the Brandywine and Red Clay Watersheds meet Pennsylvania and Delaware water quality standards."[1], using the following steps:

- Identify the impaired segments and reasons for impairment
- Develop a Restoration Plan to identify possible area for improvements
- Select projects to be undertaken based on cost, impact and priority
- Build partnerships within the restoration area
- Identify funding sources

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[1] http://www.brandywineredclay.org/watershed-conservation/red-streams-blue/

- Complete restoration projects

Christina Basin TMDL Implementation Plan

The Christina Basin TMDL Implementation Plan was produced by the Christina TMDL Implementation Plan Municipal Partnership (CTIP, now known as Christina Watersheds Municipal Partnership, or CWMP), is a document summarizing the water quality and quantity issues facing Chester County, Pennsylvania municipalities which have a regulatory obligation to the Pennsylvania DEP to reduce stormwater pollutants and runoff according to TMDL limits (Brandywine Valley Association 2013).

Traditionally stormwater has been treated at the very local (municipal or site) level, without much consideration of overall watershed or basin impacts. CTIP was an effort (led mainly by the Chester County Water Resources Authority, or CCWRA, and the BRC) to enable coordination among municipalities toward meeting regulatory requirements in a cost effective and efficient manner with the idea that such coordinated efforts would also benefit the watershed as a whole. Figure 3.2 shows the CTIP planning priority areas and an overview of the regulated townships and boroughs in Chester County, along with the inventory of impaired streams (in red) for the county.

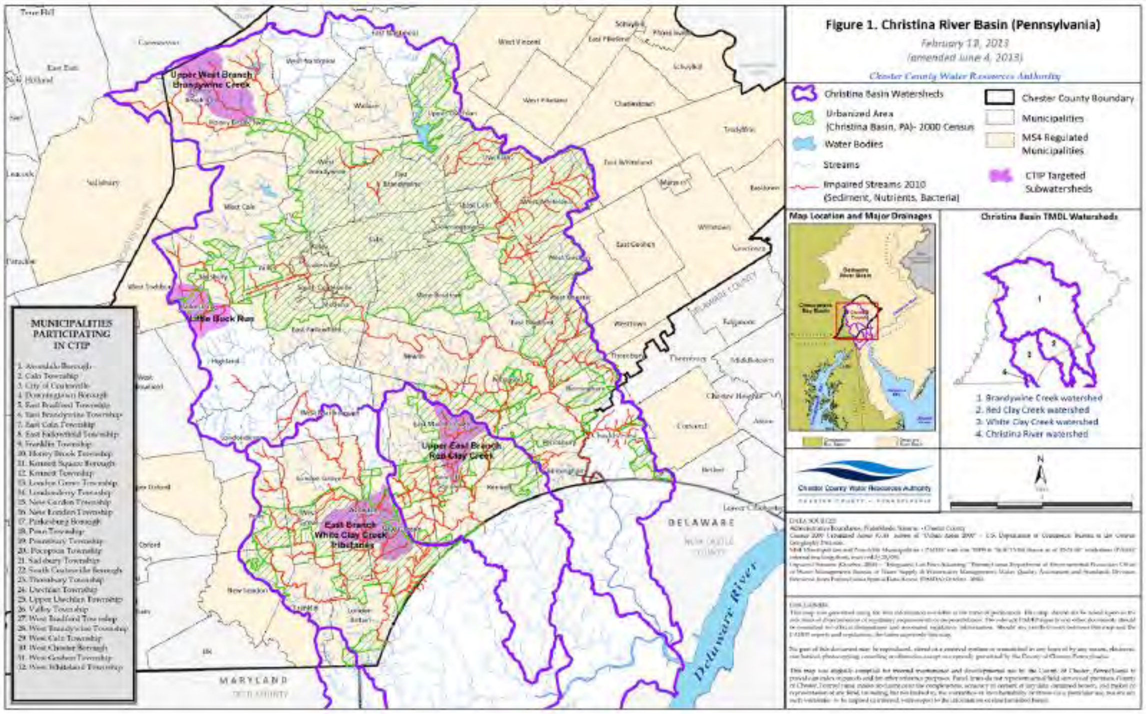

Figure 3.2 -- Christina TMDL Implementation Plan map of priority areas and regulated municipalities in Chester County, PA.

Christina Basin PA watershed plans

Chester County (through the Chester County Water Resources Authority, or CCWRA) has developed several plans for watersheds of the county, both at the basin and smaller watershed scales. A listing of these plans is available on-line at:

http://pa-chestercounty2.civicplus.com/2025/Watershed-Action-Plans

The document *Watershed Plans For Watersheds That Are Within Chester County*, also developed at the CCWRA can be found at:
http://www.chesco.org/DocumentCenter/View/31587.

White Clay Creek Wild and Scenic Watershed

The White Clay Creek has been designated a national Wild and Scenic river system by the Department of the Interior, National Park Service, the first such designation for a waterway on a watershed basis. As a part of the nomination process the White Clay Creek Watershed Management Committee developed a Management Plan (White Clay Watershed Association 1998) to lay out strategies and policies for maintaining and enhancing the high quality of the watershed's waters and habitats. Periodic updates to the plan, as well as documentation of the state of the watershed has occurred since then. See the website www.whiteclay.org for more information. The following objectives were developed to address the mission of the White Clay Creek as set forth in the Management Plan:

1. Maintain stream flow and maintain or improve water quality to revitalize fisheries and enhance recreational and scenic qualities, while accommodating legitimate demands for water supply, waste assimilation, commercial, industrial and agricultural uses.
2. Foster the protection, enhancement and stewardship of the natural, cultural and recreational resources of the watershed for the benefit and enjoyment of present and future generations.
3. Encourage coordination and consistency among existing levels of government, businesses, organizations and individuals to facilitate implementation of the management plan, without creating a new regulatory agency.
4. Promote public recognition of the White Clay Creek watershed as a place with its own identity, continuing history and a future to be shaped by its residents.
5. Manage growth to protect the watershed's special qualities, while emphasizing the rights of property owners and existing local control.

4. Existing modeling approaches

HSPF/TMDL

The map in Figure 4.1 illustrates the catchment structure that the TMDL is based on, and that is also used in modeling for the Water Fund.

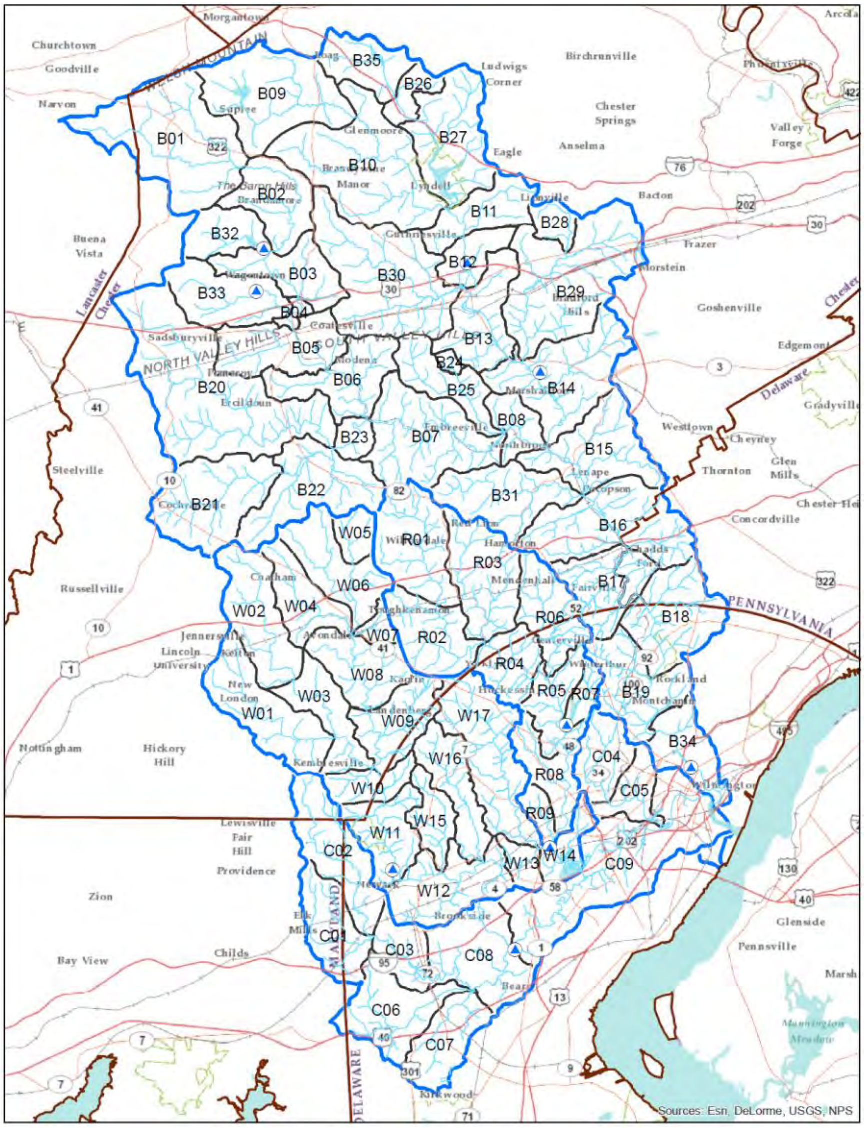

Figure 4.1 -- TMDL catchments of the Brandywine-Christina Basin.

There are 70 catchments divided among the four watersheds of the Brandywine-Christina Basin (Red Clay Creek, White Clay Creek, Brandywine Creek, and Christina River). Table 4.1 presents the acreage and square miles for each of the 70 catchments in the basin.

Table 4.1 -- Catchments showing area in the Brandywine-Christina Basin.

Watershed	Catchment ID	Acreage	Square Miles	Catchment ID	Acreage	Square Miles
Brandywine	B01	11,785	18.4	B19	5,535	8.6
Brandywine	B02	4,721	7.4	B20	16,350	25.5
Brandywine	B03	4,335	6.8	B21	7,425	11.6

Brandywine	B04	520	0.8	B22	7,014	11.0
Brandywine	B05	5,644	8.8	B23	1,246	1.9
Brandywine	B06	5,160	8.1	B24	393	0.6
Brandywine	B07	8,617	13.5	B25	3,734	5.8
Brandywine	B08	2,314	3.6	B26	1,673	2.6
Brandywine	B09	9,398	14.7	B27	7,388	11.5
Brandywine	B10	11,722	18.3	B28	1,552	2.4
Brandywine	B11	4,040	6.3	B29	11,654	18.2
Brandywine	B12	2,370	3.7	B30	11,568	18.1
Brandywine	B13	5,114	8.0	B31	5,884	9.2
Brandywine	B14	8,268	12.9	B32	3,063	4.8
Brandywine	B15	6,631	10.4	B33	5,120	8.0
Brandywine	B16	8,996	14.1	B34	3,874	6.1
Brandywine	B17	4,805	7.5	B35	3,714	5.8
Brandywine	B18	6,637	10.4			
Christina	C01	4,298	6.7	C06	5,544	8.7
Christina	C02	6,243	9.8	C07	4,113	6.4
Christina	C03	2,906	4.5	C08	6,826	10.7
Christina	C04	3,443	5.4	C09	14,040	21.9
Christina	C05	2,462	3.8			
Red Clay	R01	6,452	10.1	R06	4,544	7.1
Red Clay	R02	4,727	7.4	R07	1,344	2.1
Red Clay	R03	6,334	9.9	R08	3,443	5.4
Red Clay	R04	3,272	5.1	R09	1,103	1.7
Red Clay	R05	3,353	5.2			
White Clay	W01	6,538	10.2	W10	2,304	3.6
White Clay	W02	6,089	9.5	W11	4,175	6.5
White Clay	W03	4,061	6.3	W12	5,786	9.0
White Clay	W04	3,971	6.2	W13	1,339	2.1
White Clay	W05	1,706	2.7	W14	2,185	3.4
White Clay	W06	5,369	8.4	W15	2,490	3.9
White Clay	W07	941	1.5	W16	4,250	6.6
White Clay	W08	4,773	7.5	W17	8,285	12.9
White Clay	W09	4,387	6.9			

For the Water Fund, three constituents of concern were selected: total nitrogen (TN), total phosphorus (TP), and total suspended sediment (TSS) (see section on MapShed modeling below for a discussion of constituents of concern). The maps in Figure 4.2 illustrate the reductions, as a percentage, for the constituents of concern. As will be discussed later, these percentage reductions form the basis for determining total load reductions required, based on baseline loads calculated through more recent (MapShed) modeling efforts.

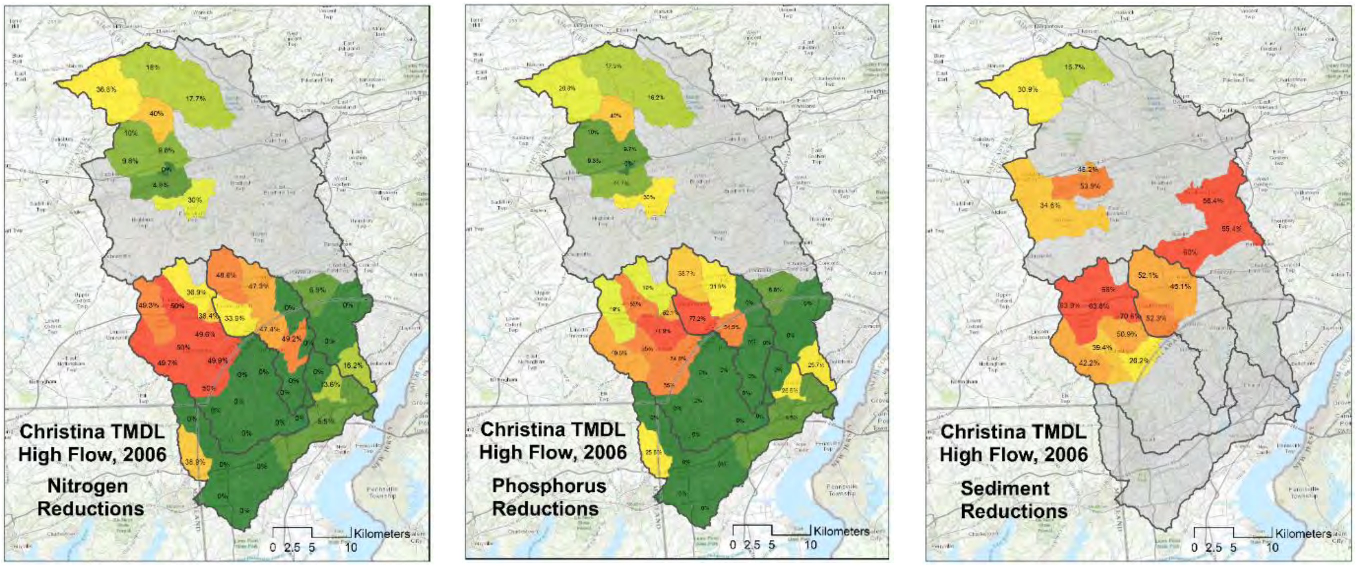

Figure 4.2 -- TMDL specified reductions for the catchments within the watersheds of the Brandywine-Christina Basin, for nitrogen, phosphorus, and sediment.

The following table (Table 4.2) summarizes the TMDL reductions, as a percentage, based on the 2006 Christina Basin TMDL, for total nitrogen (TN), total phosphorus (TP), and total suspended sediment (TSS). "NA" indicates that a catchment does not have a TMDL for that constituent.

Table 4.2 -- TMDL reductions for catchments in the watersheds of the Brandywine-Christina Basin.

Watershed	Catchment ID	TN	TP	TSS	Catchment ID	TN	TP	TSS
Brandywine	B01	37%	21%	31%	B19	0%	0%	NA
Brandywine	B02	40%	40%	NA	B20	NA	NA	35%
Brandywine	B03	10%	10%	NA	B21	NA	NA	NA
Brandywine	B04	0%	0%	46%	B22	NA	NA	NA
Brandywine	B05	5%	12%	54%	B23	NA	NA	NA
Brandywine	B06	30%	30%	0%	B24	NA	NA	NA
Brandywine	B07	NA	NA	NA	B25	NA	NA	NA
Brandywine	B08	NA	NA	NA	B26	NA	NA	NA
Brandywine	B09	18%	18%	16%	B27	NA	NA	NA
Brandywine	B10	18%	16%	NA	B28	NA	NA	NA
Brandywine	B11	NA	NA	NA	B29	NA	NA	NA
Brandywine	B12	NA	NA	NA	B30	NA	NA	NA
Brandywine	B13	NA	NA	NA	B31	NA	NA	60%
Brandywine	B14	NA	NA	56%	B32	10%	10%	NA
Brandywine	B15	NA	NA	55%	B33	10%	9%	NA

Brandywine	B16	NA	NA	NA	B34	16%	26%	NA
Brandywine	B17	7%	7%	NA	B35	NA	NA	NA
Brandywine	B18	0%	0%	NA				
Christina	C01	39%	26%		C06	0%	0%	
Christina	C02	0%	0%		C07	0%	0%	
Christina	C03	0%	0%		C08	0%	0%	
Christina	C04	0%	0%		C09	6%	10%	
Christina	C05	14%	27%				%	
Red Clay	R01	49%	36%	52%	R06	0%	0%	NA
Red Clay	R02	34%	77%	52%	R07	0%	0%	NA
Red Clay	R03	47%	32%	45%	R08	0%	0%	NA
Red Clay	R04	47%	55%	NA	R09	0%	0%	NA
Red Clay	R05	49%	0%	NA				
White Clay	W01	50%	50%	42%	W10	50%	55%	
White Clay	W02	49%	19%	64%	W11	0%	0%	
White Clay	W03	50%	55%	39%	W12	0%	0%	
White Clay	W04	50%	55%	64%	W13	0%	0%	
White Clay	W05	NA	NA	NA	W14	0%	0%	
White Clay	W06	37%	19%	68%	W15	0%	0%	
White Clay	W07	38%	52%	71%	W16	0%	0%	
White Clay	W08	50%	72%	51%	W17	0%	0%	
White Clay	W09	50%	55%	26%				

SPARROW

SPARROW (SPAtially-Referenced Regression On Watershed attributes) is a regional modeling tool created by the United States Geological Service (USGS) that tracks sources of pollution and models expected contaminant loads on a stream reach basis (Preston, *et al*. 2009). The models track a variety of parameters, and predict loads from terrestrial, point-source, and airborne sources. There are national and regional models for several parameters of interest. The models are calibrated using extensive monitoring data. See https://water.usgs.gov/nawqa/sparrow/ to access the model.

Limitations to SPARROW include the restricted number of constituents modeled and the fixed time-frame in which the models were calibrated to real-world data. Due to these limitations, assessment of SPARROW to inform the subsequent modeling process was limited to nutrients in the Brandywine-Christina basin, based on a 2002 base year. This assessment provided a verification of the general overall trends and order of magnitude of contaminant loads and their sources.

Figure 4.3 shows the graphic map output for the total nitrogen loads in the Red Clay Creek watershed. Figure 4.4 illustrates the sample graphic output showing sources and percentages attributed to each.

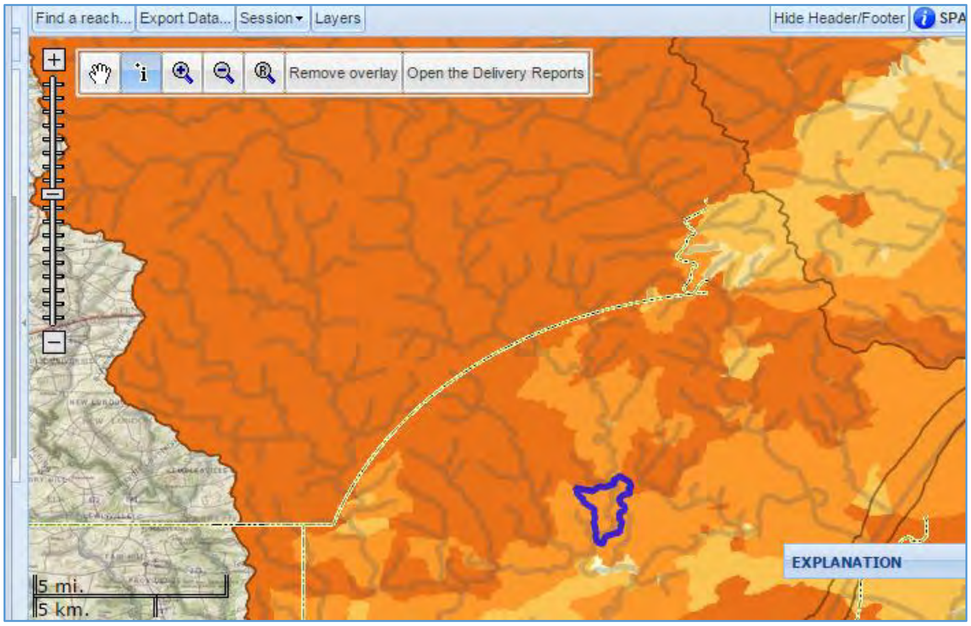

Figure 4.3 -- Example web mapping interface showing nitrogen loads in the Brandywine-Christina Basin. Blue outline indicates terminal catchment of the Red Clay Creek Watershed.

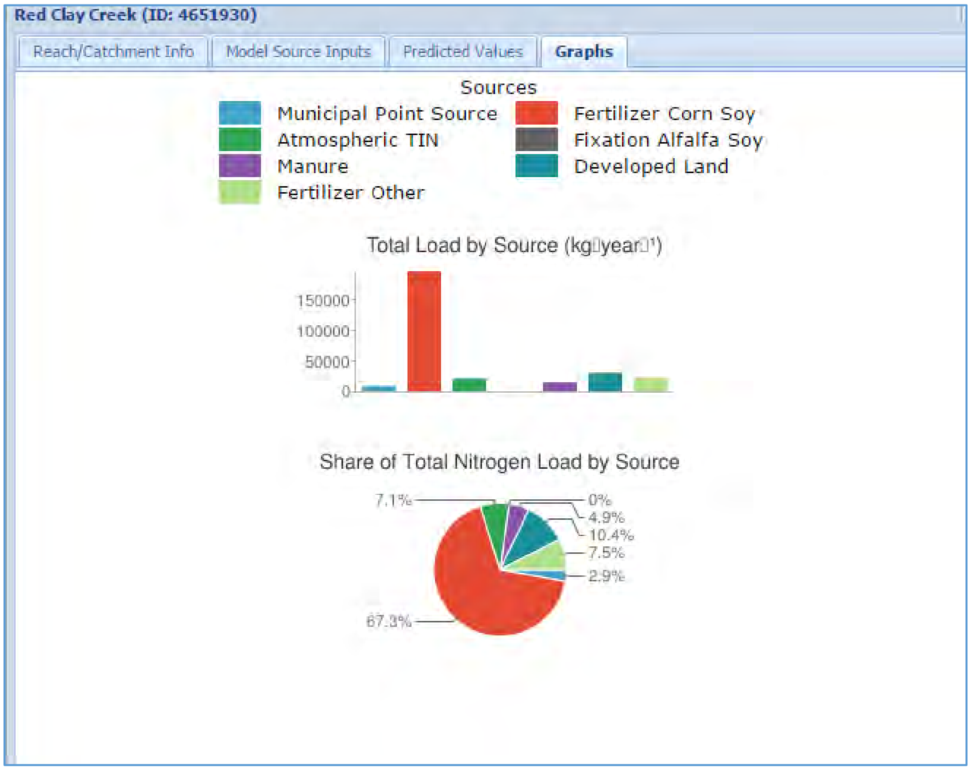

Figure 4.4 -- Example predicted nitrogen loading in the Red Clay Creek watershed produced in the SPARROW web mapping interface.

A summary of the predicted loads of TN, TP, and TSS for the Brandywine, Red Clay, and White Clay Creek watersheds is shown in Table 4.3. Note that the values differ significantly from those used in subsequent modeling and analysis. Dates of each model parameter are shown parentheses.

Table 4.3 -- Loading rates for the watersheds of the Brandywine-Christina Basin produced by SPARROW based on the 2002 model for the Mid-Atlantic region.

Watershed	Upstream Area (sq. km)	Upstream Area (sq. mi.)	Annual Load (kg/year)		
			TN (2002)	TP (2002)	TSS (1992)
Brandywine Creek	839.1	324.0	2,272,981	122,902	284,667,934
Red Clay Creek	140.8	54.3	292,519	14,838	65,783,481
White Clay Creek	276.4	106.7	602,791	29,949	68,045,420

5. Role of modeling and technical analysis

In order to establish a rational and transparent framework for decisions driving the functioning of the Water Fund it is useful to use modeling techniques in conjunction with the best available data to identify priorities and plan for implementation of watershed protection practices.

Prerequisites for a successful Water Fund include a clear statement of the goals of the fund, a scope and mission, including geographic area of focus, and a set of strategies to accomplish the goals in a realistic time-frame. For instance, decisions need to be made regarding the constituents or watershed problems (such as water quality and flow volumes) of most concern, the appropriate approaches to address these concerns, specific numeric or non-numeric goals, such as reduction in stream loads or de-listing of streams from the USEPA 303(d) list of impaired streams, mechanisms to ensure proper operation and maintenance of any installed measures (or other, non-structural approaches such as municipal riparian ordinances), and design of long-term monitoring programs so that progress can be tracked.

Modeling can provide a scientifically valid and defensible way of identifying watershed parameters of interest that the Water Fund will address, as well as quantifying potential costs of implementation and the resulting expected reductions of stream loads from those efforts. By understanding the expected outcomes (e.g., in terms of reduced pounds of nitrogen, phosphorus, and sediment in streams) and the potential benefit in monetary value to downstream users, a cost-benefit analysis becomes possible. While some benefits, such as reduced cost of water treatment at water treatment plants may have a clear direct cost (in chemicals, electricity, personnel, etc.) others are less directly quantifiable, but nonetheless important, such as habitat benefits, recreational value, and economic effects (jobs, tourism, publicity).

Finally, validation with measured stream quality and flow data are important to calibrate predictive models to address loads and reductions, and also to ascertain that the expected improvements to stream quality and watershed health are being achieved.

The following section ("6. Modeling and technical analysis methods and results") presents models that allow the Water Fund to clarify these questions. Some decisions, such as which catchments and stream segments are the most appropriate areas of focus and what the potential costs and benefits (i.e., from water quality improvements) may result from the modeling outcomes, while others are more dependent on either policy considerations, such as which parameters are regulated under the provisions of the Clean Water Act in each state, or external factors, such as directives from larger, regional initiatives (e.g., the William Penn-funded Delaware River Watershed Initiative, of which the Water Fund is one component).

Many of the priorities and decisions regarding the focus and scope of the goals of the Water Fund were explored in the previous phase of this project, and summarized in the resultant feasibility study (The Nature Conservancy and the University of Delaware Water Resources Center 2015). Much of the dialog that informed these decisions were made through a collaborative process in which stakeholders, including watershed partners and an Advisory Panel (see the feasibility study for details), helped guide the outcomes and drive priorities. The modeling work associated with the subsequent stage of the project (in years two and three of the William Penn Foundation grant) largely began with those guidelines and priorities.

Watershed priorities

A successful Water Fund will focus on a fairly limited set of priorities. Since there is a limited amount of funding for projects within the watersheds of the Brandywine-Christina Basin (as elsewhere), understanding where money and effort is best spent, and on what sorts of practices, is critical. Various approaches to watershed protection through BMPs (Best Management Practices) or other tools are possible, depending on budget, local conditions, regulatory requirements, and localized factors such as at-risk populations or infrastructure. The following list summarizes some of the common priorities.

- **Water quality**
  This goal is important to both water purveyors who incur costs to treat water to potable status, and MS4 communities, which are bound by regulation to act toward reducing pollutants to specified targets. Constituents of concern for purveyors (see also below) include those which are most costly to remove to meet regulatory standards and aesthetic/taste thresholds, and those constituents of specific regulatory concern, such as cryptosporidium. For MS4 communities state and

federal regulatory agencies identify constituents causing various impairments by stream segment, and in some cases establish TMDLs specifying target reductions required to meet those regulatory standards.

- **Volume and velocity control**
  Volume and velocity is a major concern for purveyors and regulators, as well as for the overall health of a watershed. Water quality constituents are often highly correlated with increased volumes (e.g., bacteria, sediment, and nutrients), and floodplain and property protection is a major regulatory and cost driver. Recent initiatives by the PADEP have created an increased focus on volume and velocity control as part of localities Pollution Reduction Plans (PRPs) under NPDES permitting.
- **Habitat and biodiversity**
  Protection and restoration of habitat and biodiversity (a measure of the biotic richness of an ecosystem) is an important component of watershed protection, and one which constitutes a large percentage of protection efforts currently. This goal also relates directly to many other, often less quantifiable, benefits within a watershed. These ancillary benefits include water quality and volume/velocity reductions, ecosystem service provision, active and passive recreational value, and even human health and wellness-related benefits.
  Habitat and biodiversity projects can be divided into either preservation priority or restoration priority types. Preservation priority projects focus on protecting and conserving (or augmenting) existing high-value habitats, such as riparian corridors, forests, grasslands, etc. These occur in watersheds not already significantly degraded. Examples of preservation strategies include tree planning along streams and conservation easements. Restoration strategies occur in areas where there is potential for habitat and other benefits by restoring properties to more natural and ecologically balanced states. Example strategies might include brownfield development, wetland restoration, and urban greenway development.

As stated in the Water Fund Feasibility Study, the overarching aim of the Water Fund is to restore the waters of the Brandywine-Christina to fishable, swimmable, and potable status by 2025. Achievement of this goal would also have larger ancillary benefits in terms of habitat, diversity, and economic sustainability. However, the first item in the list above, water quality, relates most directly to that stated top-level goal, and has therefore been the primary focus of modeling efforts.

Beneficiaries of and stakeholders in these efforts were identified and invited to participate on the Advisory Panel. This initial group consisted of the water purveyors who are downstream of impaired streams in the Brandywine-Christina Basin, municipalities and other local governmental (or quasi-governmental) entities (counties, universities, transportation departments), that have a regulatory requirement to reduce contaminant loads, as well as a variety of watershed and conservation groups (public, private, and non-profit) active in the basin.

The beneficiaries (water purveyors and MS4 municipalities) will be the potential initial funders of the Water Fund. To procure support it is necessary to provide a business case which demonstrates 1) the level of the contamination or stream impact, 2) the cost of efforts to ameliorate the contamination or impact, 3) the monetary or other benefits accruing to investors following from watershed investments. To make a business case for the Water Fund it is also critical to demonstrate that the benefits to individual investors in the Water Fund are greater than those realized by investors acting individually to address water quality issues. The prioritization possible through watershed-wide predictive modeling provides the basis for the justification. See the Water Fund Business Plan for details on this the advantages of pooled versus individual efforts.

The following table summarizes the common stressors, their metrics, which goal they relate to, the potential direct beneficiary of improving, and whether there is a governing regulation.

Table 5.1-- Constituents of concern, metrics, goals, potential beneficiaries of reductions, and applicable regulation(s).

Stressor	Metric	Goal	Beneficiary	Regulation
Nutrients (TN)	Concentration & load	Water quality	Purveyors, MS4	TMDL (PA, DE)
Nutrients (TP)	Concentration & load	Water quality	Purveyors	TMDL (PA, DE)
Sediment and TSS	Concentration & load	Water quality	Purveyors, MS4, public	TMDL (PA)
Bacteria	Concentration & load	Water quality	Purveyors, MS4, public	TMDL (PA, DE)
Runoff: Volume and velocity	Flow exceedances, flood insurance claims, Average/median flows, impervious cover surrogates	Volume and velocity	MS4, purveyors (clarity), public, private landowners, gov't., insurers	NA

Habitat degradation	Land use change, forest and wetland cover, species metrics	Habitat and biodiversity	Multiple	NA but listed as impairment under section 303(d) of the CWA.

Constituents (stressors) of focus for the Water Fund

For the purposes of the Water Fund, through the initial feasibility phase, it has been determined that the constituents of concern (see Table 5.1, above) are nutrients (total nitrogen, TN, and total phosphorus, TP), and total suspended sediment (TSS). While bacteria is also a major problem in many streams and other waters, it is fairly ubiquitous and can come from a wide variety of "natural" sources, such as wildlife, particularly geese. Further, treating primary pollutants such as nutrients and sediment has co-benefits in dealing with others. For example, infiltration basins or constructed wetlands will slow stormwater runoff and provide habitat, in addition to providing reductions in nutrients and sediment. Recent work has identified nutrients and sediment as key indicators of chemical and physical water quality. (see, for example, Sweeney and Newbold 2014, Sweeney and Blaine 2016, U.S. Environmental Protection Agency 2016).

Suite of potential BMPs

There are a wide variety of strategies, or BMPs that may be employed to target improvements to stream water quality. Which strategy, or suite of approaches is taken depends on factors including existing watershed priorities and goals, available funding, and direct beneficiaries. The modeling and technical analysis can help quantify the costs and the benefits, defined broadly, to each approach. The following table summarizes potential strategies, what goals they typically address

Table 5.2 -- Potential BMPs, goals, beneficiaries, relative cost, and relative benefits.

Strategy	Goal addressed[2]	Beneficiaries	Cost	Benefits
Agricultural BMPs	A	Purveyors, MS4s	$ - $$	++ - +++
These will focus on nutrient and sediment reductions, and may represent a significant and cost-effective strategy to meet goals downstream. Many of these are low cost and easily implemented, but are non-permanent. For example, while flow control measures such as level-lip spreaders are long-term strategies, the use				

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[2] A = Water quality; B = Volume and velocity; C = Habitat, preservation; D = Habitat, restoration

<table>
<tr><td colspan="5">of cover crops, contour plowing, no-till planting, or filter strips need to be renewed each year (or maintained on an ongoing basis). Additionally, agricultural BMPs can last only as long as the land remains agricultural. If it is developed, for instance, the benefits of these practices will disappear with the farm. As with other practices, long-term maintenance and upkeep is an issue, particularly as land changes hands, and prior agreements potentially are forgotten.</td></tr>
<tr><td>Riparian buffers</td><td>A, B, C</td><td>Purveyors, MS4s</td><td>$$</td><td>++</td></tr>
<tr><td colspan="5">Multiple benefits for water quality and watershed health, but it is important to differentiate buffers based on local situation—i.e., there will be differing widths required according to factors such as watershed position, soils, slopes, local land cover, and landowner willingness. Agricultural users will seek compensation for taking potentially productive land out of service. Strategies will be most effective in headwaters and in areas where large land owners interested in stewardship occur.</td></tr>
<tr><td>Stormwater BMPs</td><td>A</td><td>MS4s</td><td>$$$</td><td>+ - ++</td></tr>
<tr><td colspan="5">These are often in urbanized areas, and tend to be higher-cost, gray infrastructure projects. It is necessary to quantify costs and benefits to water quality and volume/velocity to focus on the highest benefit projects, and identify potential lower-cost options which may require investments outside the political jurisdiction.</td></tr>
<tr><td>Floodplain protection/ enhancement</td><td>B, C, D</td><td>Purveyors, landowners, gov’t</td><td>$$ - $$$</td><td>+++</td></tr>
<tr><td colspan="5">This is a potentially high-value strategy in terms of flood protection, downstream volume and velocity reduction. This can be presented as a risk-reduction strategy, which could make investments from downstream stakeholders more attractive.</td></tr>
<tr><td>Wetland protection/creation</td><td>A, B, C, D</td><td>Multiple</td><td>$ - $$$</td><td>+++</td></tr>
<tr><td colspan="5">Provides habitat, water quality, resiliency, and recreational/aesthetic benefits. However, these tend to be costly from a strictly water quality improvement standpoint. Issues with identifying suitable potential sites can be problematic.</td></tr>
<tr><td>Avoided loss (protecting what’s there)</td><td>A, B, C, D</td><td>Multiple</td><td>$ - $$</td><td>+ - +++</td></tr>
</table>

<table>
<tr><td colspan="5">These strategies can give potentially a high cost to benefit ratio, since they do not involve construction costs, but do involve potential resistance due to property rights concerns.</td></tr>
<tr><td>Risk management</td><td>A, B, C, D</td><td>Purveyors, landowners, gov’t</td><td>$</td><td>+++</td></tr>
<tr><td colspan="5">Private water purveyors have indicated that focusing on strategies that avoid potential costly risks are more palatable to management and investors. Damage to brand and negative publicity arising from high-profile negative exposure (e.g., contamination requiring a disruption of service or a threat to public health) are of particular concern for publicly traded water companies.</td></tr>
<tr><td>Non-structural BMPs (e.g., street sweeping, LID ordinances)</td><td>A, B</td><td>Purveyors, MS4s</td><td>$</td><td>+</td></tr>
<tr><td colspan="5"></td></tr>
</table>

The *Pennsylvania Stormwater Best Management Practices Manual, Chapter 8: Stormwater Calculations and Methodology* has a comprehensive list of potential BMPs and their pollution reduction benefits.

As has been explored in the Water Fund Feasibility Study, it was determined that a water quality priority will favor lower cost agricultural practices providing maximal benefits, particularly transient, non-structural practices (e.g., cover crops, no-till, and contour plowing). It should be noted that whole-farm plans are a good proxy for the implementation of such practices, as well as for other approaches to nutrient and sediment control such as manure management and nutrient management. These plans, therefore can be very cost-effective in that they encompass several best practices for agricultural pollution and runoff control.

The Pennsylvania DEP has identified the most effective suite of agricultural BMPs recommended for implementation in the Chesapeake Bay basin, and which also can apply to targeted reductions for nutrients and sediment in the Delaware River basin (Pennsylvania Department of Environmental Protection 2016):

1. Cover crops
2. Tillage (no-till & conservation till)
3. Manure Transport
4. Streambank fencing
5. Buffers

Table 5.3 summarizes a selected suite of agricultural practices, including estimated reduction efficiencies (Simpson and Weammert 2009). Note that reduction efficiencies are approximate and are highly variable based on individual conditions. Values are provided for illustration only, and do not necessarily reflect numbers used for modeling analysis, below.

Table 5.3 -- Selected BMPs and reduction efficiencies from the Chesapeake Bay Foundation.

BMP	BMP Effectiveness Estimate (%)		
	TN	TP	TSS
Conservation Plans			
Conventional tillage	8	15	25
Conservation tillage	3	5	8
Hayland	3	5	8
Pastureland	5	10	14
Conservation Tillage	8	22	30
Forest Buffer			
Inner Coastal Plain	65	42	56
Tidal Influenced	19	45	60
Piedmont Scnist/Gneiss	46	36	48
Valley and Ridge - marble/limestone	34	30	40
Grass Buffer			
Inner Coastal Plain	46	42	56
Tidal Influenced	13	45	60
Piedmont Schist/Gneiss	32	36	48
Piedmont Sandstone	39	42	56
Valley and Ridge - marble/limestone	24	30	40
Wetland Restoration and Creation			
Appalachian (1% of Watershed in wetlands)	7	12	15
Piedmont and Valley (2% of watershed in wetlands)	14	26	15
Coastal Plain (4% of watershed in wetlands)	25	50	15
Cover Crops			
Coastal Plain/Piedmont/Crystalline/Karst Settings:			
Drilled Rye early	45	15	20
Off-Stream Watering With Fencing	25	30	40

Off-Stream Watering Without Fencing	15	22	30

PA DEP has also recently established updated guidelines for practices targeting NPDES MS4 regulated entities (Pennsylvania Department of Environmental Protection 2016). A selected list of practices and their associated reduction efficiencies (for calculating water quality benefits as required by regulation) is found in Table 5.4, below.

Table 5.4 -- PADEP BMP reduction effectiveness values.

BMP Name	**BMP Effectiveness Values**			**BMP Description**
	TN	**TP**	**Sediment**	
Wet Ponds and Wetlands	20%	45%	60%	A water impoundment structure that intercepts stormwater runoff then releases it to an open water system at a specified flow rate. These structures retain a permanent pool and usually have retention times sufficient to allow settlement of some portion of the intercepted sediments and attached nutrients/toxics. Until recently, these practices were designed specifically to meet water quantity, not water quality objectives. There is little or no vegetation living within the pooled area nor are outfalls directed through vegetated areas prior to open water release. Nitrogen reduction is minimal.
Dry Detention Basins and Hydrodynamic Structures	5%	10%	10%	Dry Detention Ponds are depressions or basins created by excavation or berm construction that temporarily store runoff and release it slowly via surface flow or groundwater infiltration following storms. Hydrodynamic Structures are devices designed to improve quality of stormwater using features such as swirl concentrators, grit chambers, oil barriers, baffles, micropools, and absorbent pads that are designed to remove sediments, nutrients, metals, organic chemicals, or oil and grease from urban runoff.
Dry Extended Detention Basins	20%	20%	60%	Dry extended detention (ED) basins are depressions created by excavation or berm construction that temporarily store runoff and release it slowly via surface flow or groundwater infiltration following storms. Dry ED basins are designed to dry out between storm events, in contrast with wet ponds, which contain standing water permanently. As such, they are similar in construction and function to dry detention basins, except that the duration of detention of stormwater is designed to be longer, theoretically improving treatment effectiveness.
Infiltration Practices w/ Sand, Veg.	85%	85%	95%	A depression to form an infiltration basin where sediment is trapped and water infiltrates the soil. No underdrains are associated with infiltration basins and trenches, because by definition these systems provide complete infiltration. Design specifications require infiltration basins and trenches to be built in good soil, they are not constructed on poor soils, such as C and D soil types. Engineers are required to test the soil before approval to build is issued. To receive credit over the longer term, jurisdictions must conduct yearly inspections to determine if the basin or trench is still infiltrating runoff.

Filtering Practices	40%	60%	80%	Practices that capture and temporarily store runoff and pass it through a filter bed of either sand or an organic media. There are various sand filter designs, such as above ground, below ground, perimeter, etc. An organic media filter uses another medium besides sand to enhance pollutant removal for many compounds due to the increased cation exchange capacity achieved by increasing the organic matter. These systems require yearly inspection and maintenance to receive pollutant reduction credit.
Filter Strip Runoff Reduction	20%	54%	56%	Urban filter strips are stable areas with vegetated cover on flat or gently sloping land. Runoff entering the filter strip must be in the form of sheet-flow and must enter at a non-erosive rate for the site-specific soil conditions. A 0.4 design ratio of filter strip length to impervious flow length is recommended for runoff reduction urban filter strips.
Filter Strip Stormwater Treatment	0%	0%	22%	Urban filter strips are stable areas with vegetated cover on flat or gently sloping land. Runoff entering the filter strip must be in the form of sheet-flow and must enter at a non-erosive rate for the site-specific soil conditions. A 0.2 design ratio of filter strip length to impervious flow length is recommended for stormwater treatment urban filter strips.
Bioretention / Raingarden (A/B soils w/o underdrain)	80%	85%	90%	An excavated pit backfilled with engineered media, topsoil, mulch, and vegetation. These are planting areas installed in shallow basins in which the storm water runoff is temporarily ponded and then treated by filtering through the bed components, and through biological and biochemical reactions within the soil matrix and around the root zones of the plants. This BMP has no underdrain and is in A or B soil.
Vegetated Open Channels (C/D Soils)	10%	10%	50%	Open channels are practices that convey stormwater runoff and provide treatment as the water is conveyed, includes bioswales. Runoff passes through either vegetation in the channel, subsoil matrix, and/or is infiltrated into the underlying soils. This BMP has no underdrain and is in C or D soil.
Bioswale	70%	75%	80%	With a bioswale, the load is reduced because, unlike other open channel designs, there is now treatment through the soil. A bioswale is designed to function as a bioretention area.
Permeable Pavement w/o Sand or Veg.	10%	20%	55%	Pavement or pavers that reduce runoff volume and treat water quality through both infiltration and filtration mechanisms. Water filters through open voids in the pavement surface to a washed gravel subsurface storage reservoir, where it is then slowly infiltrated into the underlying soils or exits via an underdrain. This BMP has an underdrain, no sand or vegetation and is in C or D soil.
Stream Restoration	0.075 lb/ft/yr	0.068 lb/ft/yr	44.88 lb/ft/yr	An annual mass nutrient and sediment reduction credit for qualifying stream restoration practices that prevent channel or bank erosion that otherwise would be delivered downstream from an actively enlarging or incising urban stream. Applies to 0 to 3rd order streams that are not tidally influenced. If one of the protocols is cited and pounds are reported, then the mass reduction is received for the protocol.
Forest Buffers	25%	50%	50%	An area of trees at least 35 feet wide on one side of a stream, usually accompanied by trees, shrubs and other vegetation that is adjacent to a body of water. The riparian area is managed to maintain the integrity of stream channels and shorelines, to reduce the impacts of upland sources of pollution by trapping, filtering, and converting sediments, nutrients, and other chemicals. (Note – the values represent pollutant load reductions from stormwater draining through buffers).

Tree Planting	10%	15%	20%	The BMP effectiveness values for tree planting are estimated by DEP. DEP estimates that 100 fully mature trees of mixed species (both deciduous and non-deciduous) provide pollutant load reductions for the equivalent of one acre (i.e., one mature tree = 0.01 acre). The BMP effectiveness values given are based on immature trees (seedlings or saplings); the effectiveness values are expected to increase as the trees mature. To determine the amount of pollutant load reduction that can credited for tree planting efforts: 1) multiply the number of trees planted by 0.01; 2) multiply the acreage determined in step 1 by the pollutant loading rate for the land prior to planting the trees (in lbs/acre/year); and 3) multiply the result of step 2 by the BMP effectiveness values given.
Street Sweeping	3%	3%	9%	Street sweeping must be conducted 25 times annually. Only count those streets that have been swept at least 25 times in a year. The acres associated with all streets that have been swept at least 25 times in a year would be eligible for pollutant reductions consistent with the given BMP effectiveness values.

Modeling and the Water Fund

Once implemented the fund will need to define a methodology to rank projects that come up for funding consideration. A transparent and defensible scoring system will allow applicants to tailor projects toward the aims of the fund, and will allow beneficiaries and funders to become comfortable with the manner in which funds are spent. This protocol needs to be congruent with the overall goals of the fund and its guiding partners.

The modeling process established should inform decisions made by the Water Fund in terms of determining priority areas, selecting projects based on their expected return on investment, and predicted outcomes in terms of improving water quality.

The flowchart in Figure 5.1 presents a schematic illustration of the Water Fund and the role of the modeling and technical analysis in it.

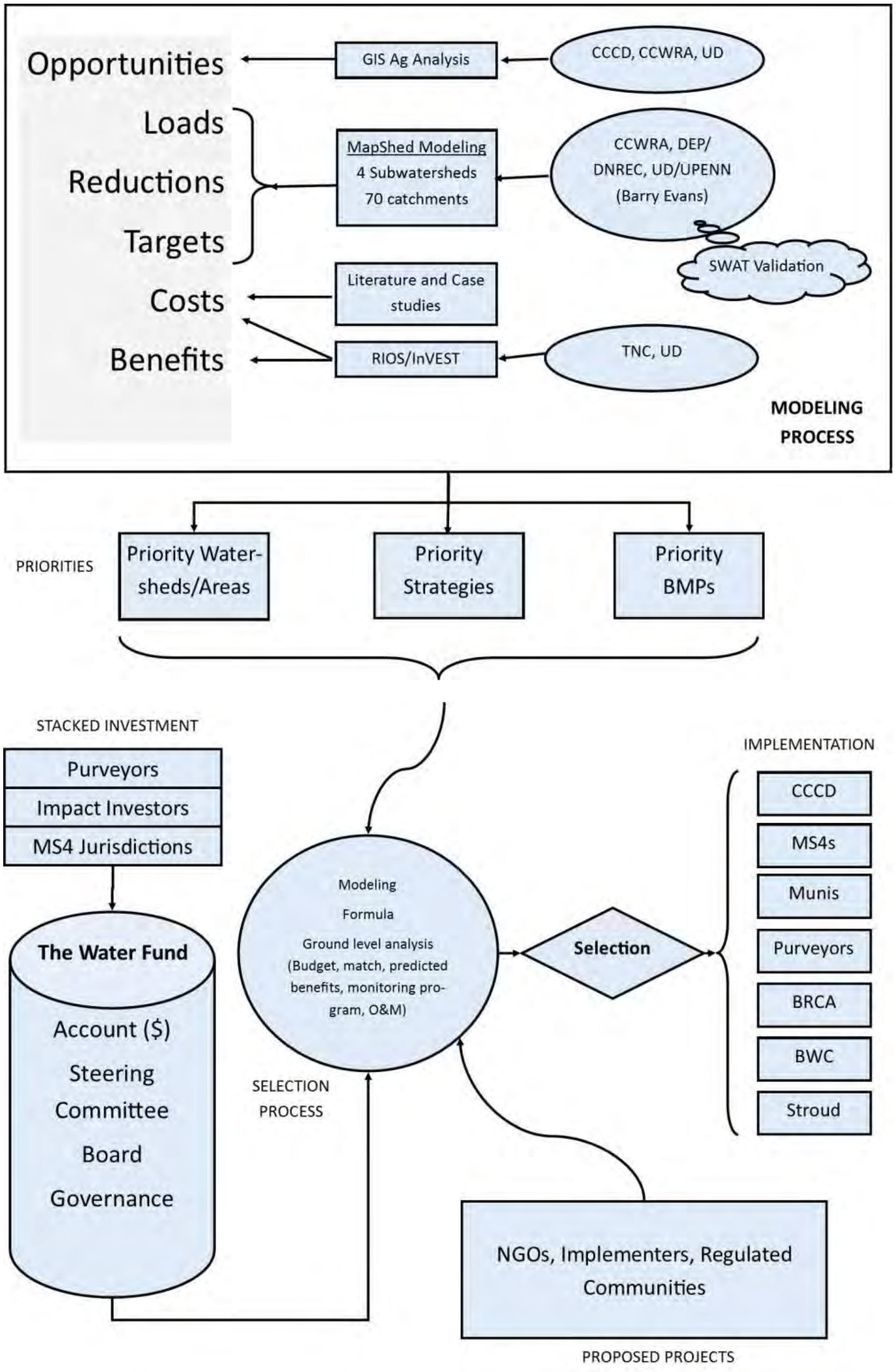


Figure 5.1 -- Conceptual model of the Water Fund and the role of modeling and technical analysis.

The following sections summarizes the efforts made using various modeling and analysis techniques to understand the loads, required reductions, and costs involved to meet water quality goals as enumerated above.

6. Modeling and technical analysis methods and results

SWAT

The William Penn Foundation has engaged the Center for Naval Analyses (CNA) to undertake a watershed-wide modeling analysis of the four watersheds in the Brandywine-Christina basin (Brandywine Creek, Red Clay Creek, White Clay Creek, and the Christina River) using the Soil and Water Assessment Tool (SWAT) model, developed and supported by Texas A&M University and the NRCS Agricultural Research Service. Loads for nitrogen (total Kjeldahl and inorganic), phosphorus (as orthophosphate), and suspended sediment were modeled using flow-weighted methods for the USGS stream gages (see map in Appendix A) near Newark (for the White Clay), at Stanton (for the Red Clay), at Wilmington (for the Brandywine), and at Cooch's Bridge (for the Christina). Predicted loads for each of the basins was extrapolated from those values. The results of this modeling effort are presented in Table 6.1.

Table 6.1 -- SWAT model results for the watersheds of the Brandywine Christina Basin.

	Annual Load (kg/year), 1995-2009		
Watershed	**TN (Inorganic + TKN)**	**P as Orthophosphate**	**TSS**
Brandywine Creek	1,557,676	31,446	34,007,699
Red Clay Creek	258,439	5,992	7,937,416
White Clay Creek	502,112	7,683	14,585,240
Christina River	76,045	905	2,070,800

A comparison of selected results of the SWAT analysis with MapShed and other modeling results (in the same area and for the same years) is presented below.

See Appendix A for a scope of work for the SWAT modeling process in the Brandywine-Christina watersheds.

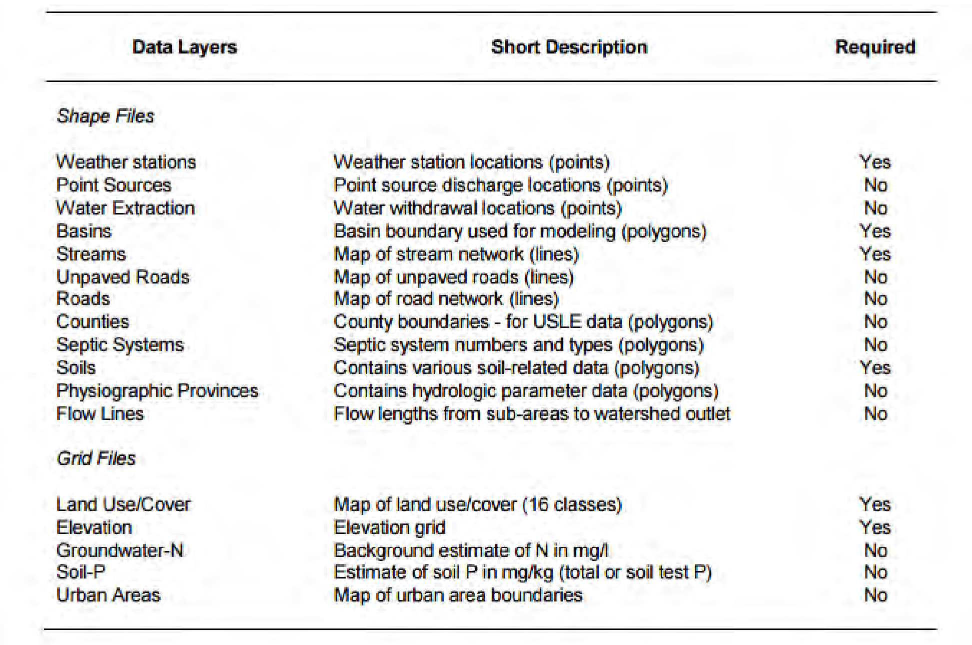
MapShed

Introduction

MapShed is a catchment-based water quality modeling tool developed by Barry Evans at Penn State University (Evans and Corradini 2012 and 2016). MapShed combines the watershed simulation model GWLF (Generalized Watershed Loading Function) created by Haith and Shoemaker (Haith and Shoemaker 1987) with a mapping front-end implemented with the MapWindow software (see http://www.mapwindow.org). The model can simulate runoff, and sediment, phosphorus, and nitrogen loads from various sources. MapShed is not a flow-routing model, but aggregates output (loads) at the catchment level. MapShed can incorporate a suite of Best Management Practices (BMPs) to allow planners to assess the effects of water quality improvement strategies.

MapShed uses many spatial data layers as input, and outputs simulated land-cover based loads, in-stream sediment erosion, groundwater nitrogen contributions, and point-source and septic inputs. Table 6.2 shows the input files MapShed uses to generate input files to the GWLF modeling process.

Table 6.2 -- MapShed model input files.



Data Layers	Short Description	Required
Shape Files		
Weather stations	Weather station locations (points)	Yes
Point Sources	Point source discharge locations (points)	No
Water Extraction	Water withdrawal locations (points)	No
Basins	Basin boundary used for modeling (polygons)	Yes
Streams	Map of stream network (lines)	Yes
Unpaved Roads	Map of unpaved roads (lines)	No
Roads	Map of road network (lines)	No
Counties	County boundaries - for USLE data (polygons)	No
Septic Systems	Septic system numbers and types (polygons)	No
Soils	Contains various soil-related data (polygons)	Yes
Physiographic Provinces	Contains hydrologic parameter data (polygons)	No
Flow Lines	Flow lengths from sub-areas to watershed outlet	No
Grid Files		
Land Use/Cover	Map of land use/cover (16 classes)	Yes
Elevation	Elevation grid	Yes
Groundwater-N	Background estimate of N in mg/l	No
Soil-P	Estimate of soil P in mg/kg (total or soil test P)	No
Urban Areas	Map of urban area boundaries	No

Once the input files have been loaded and verified, the user selects one or more catchments on which to perform the modeling. An input file based on the selection is produced, using calculated default parameters. Before running the model it is generally necessary to calibrate the inputs for the local conditions. For example, animal inputs (e.g., pigs, cows, and horses) are not calculated by default, so need to be compiled (or estimated) in the calibration process.

Rationale

The MapShed model was evaluated for use in determining the loads and required reductions, as well as estimates of existing investment and future costs of strategies (i.e., BMPs), to achieve the water quality goals of the fund. Several factors led to the decision to use MapShed for this purpose.

MapShed has been widely implemented in Pennsylvania and beyond. It has been developed in conjunction with the PA DEP for use in the Chesapeake Bay watershed portion of the state. It has also been recently extended into the eastern portion of the state and is currently being implemented across the entire Delaware River Basin (through the DRWI, funded in large part by the William Penn Foundation).

The tool is fairly easy to implement using a desktop application, and is also being developed as an on-line tool. Currently, under the aegis of the DRWI and in collaboration with The Academy of Natural Sciences of Drexel University, Stroud Water Research Center, and others, the model is being implemented across the Delaware River Basin at the stream reach level, through the Stream Reach Assessment Tool (SRAT). The model is also being incorporated in the on-line, interactive planning tool, "Model My Watershed", being developed at Stroud, and available through the WikiWatershed project.

The Chester County Water Resources Authority (CCWRA), a close partner in the work being undertaken in the Brandywine-Christina cluster has worked extensively with Barry Evans to develop a fully-calibrated version of the model for the Brandywine Christina Basin portion of Chester County, Pennsylvania, specifically to assist Municipal Separate Storm Sewer System (MS4) jurisdictions in fulfilling their regulatory requirements to address water quality and quantity issues within their stormwater systems under the National Pollutant Discharge Elimination System (NPDES) permitting process. The CCWRA provided calibrated model input files for the 1995 baseline loads, as well as for 2012 (i.e., based on 2012 land cover data), both without and with BMPs included.

There are a few drawbacks to the MapShed model for use with the Water Fund. First, the model does not fully implement flow routing (though this also makes the model easier to implement). Also, the input parameters for calibration apply only at the catchment scale. In particular, the input of BMPs is not spatially explicit, but instead implemented through specification of the percentage of the catchment treated by a particular measure. For this reason the tool is not appropriate at the site or parcel level, and should not take the place of load and reduction modeling for current and proposed BMPs (e.g., when calculating loads and reductions for specific sites or projects). This aspect of the model does not impair its utility to calculate catchment-level loads to serve as a baseline, and to approximate the scale of measures required to achieve water quality goals. In the future it is anticipated that much of the functionality of the desktop will be enhanced and extended through online tools such as SRAT and Model My Watershed.

Methodology

Model suitability

To determine the suitability of MapShed to assist in the development of the Water Fund, a proof-of-concept study was undertaken in the Red Clay Creek watershed. The following graphs (Figures 5.2-5.4) show typical annual predicted loads (in kilograms) by source for nitrogen, phosphorus, and sediment. They illustrate the relative impact of inputs of nutrients and sediment from various sources. The Water Fund will focus on agricultural practices since they provide greater reduction potential for lower cost than practices in more urbanized, stormwater-influenced areas. These figures illustrate the rationale for the emphasis on agriculture as a source of water quality impairment.

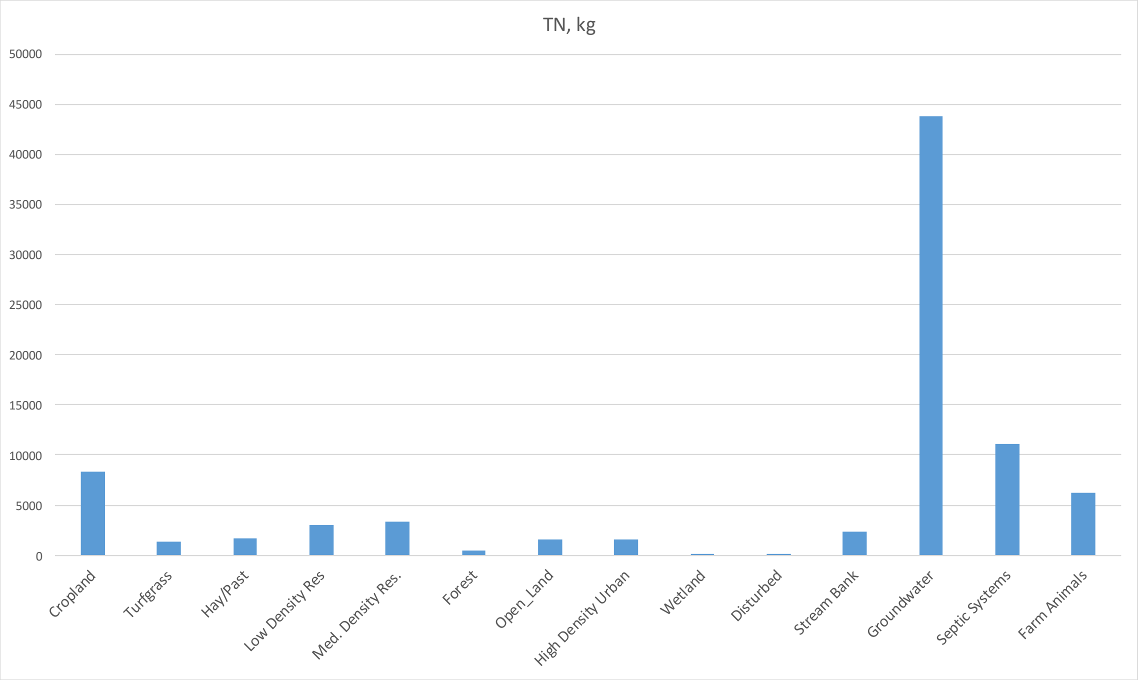


Figure 6.2 -- Relative importance of sources of total nitrogen, as determined by MapShed modeling.

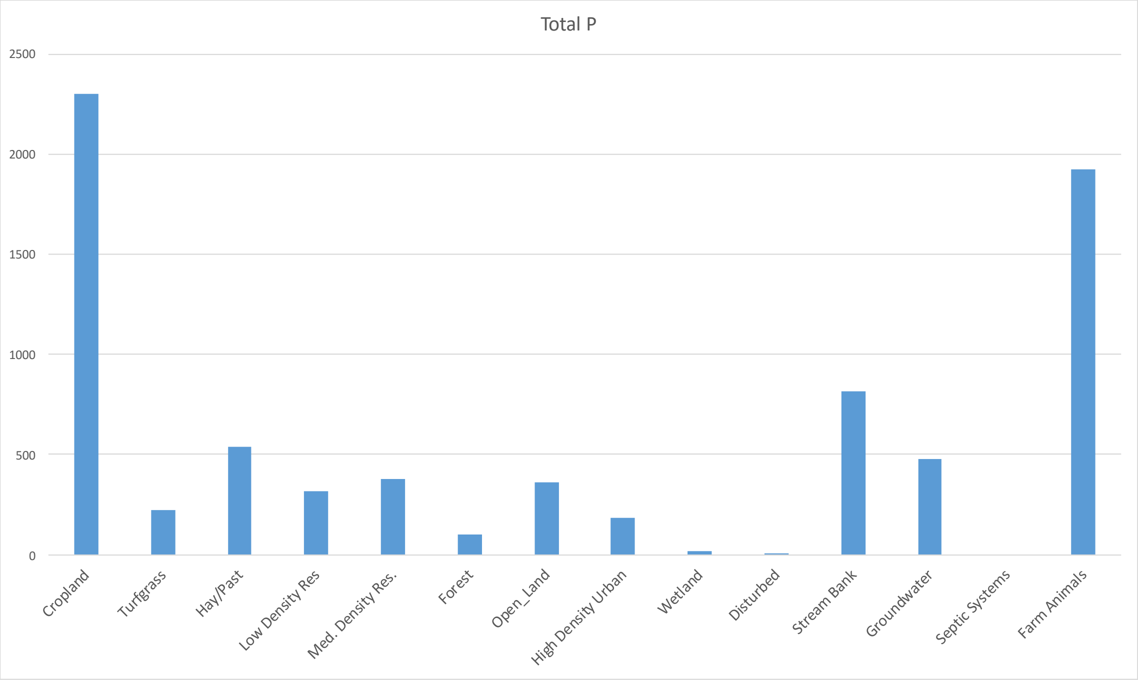


Figure 6.3 -- Relative importance of sources of total phosphorus, as determined by MapShed modeling.

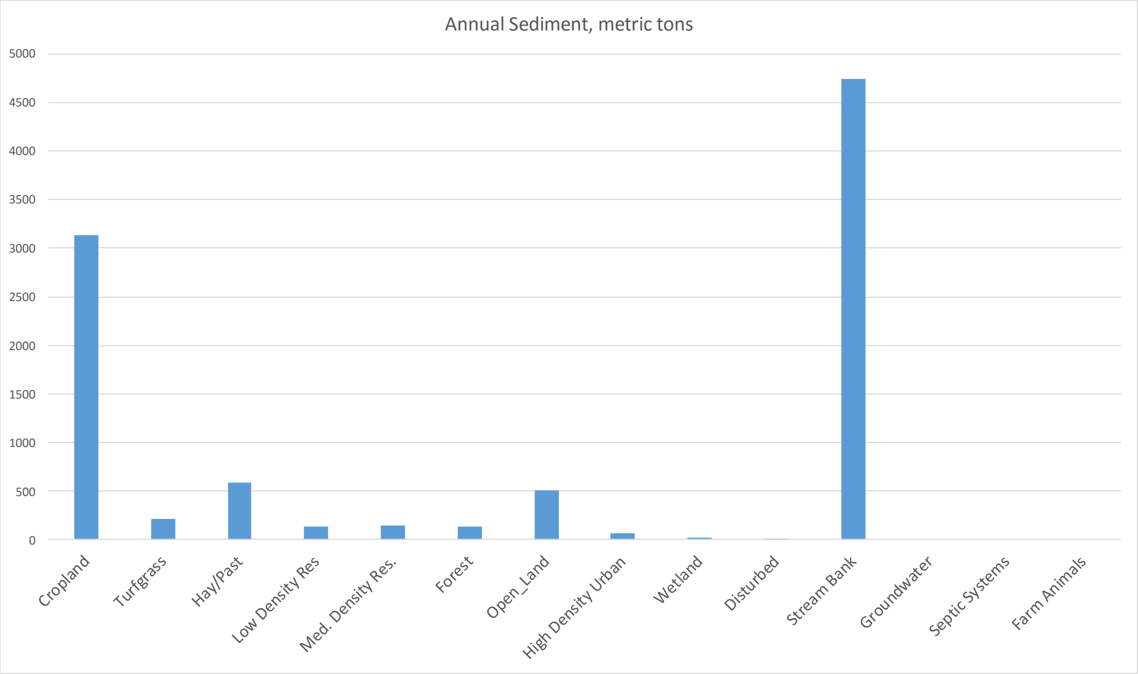


Figure 6.4 -- Relative importance of sources of total suspended sediment, as determined by MapShed modeling.

Nutrients (TP and TN) enter the watershed primarily through agricultural practices (e.g., “Cropland” and “Farm Animals” in the graphs). In the case of nitrogen, it is evident that groundwater is the major contributor; however, addressing groundwater input to nitrogen in streams is complicated by the long travel time of that nutrient through the ground. Addressing groundwater nitrogen levels requires long-term strategies of reducing infiltration from agricultural practices on the ground. Even though the effects might not be seen for years, or perhaps decades, reducing surface input is critical to longer term improvements. Septic inputs are also a concern, but are often addressed by other factors, including increasing provision of central sewer service, which is occurring rapidly throughout the Brandywine-Christina Basin.

For suspended sediment, cropland is also the major land cover input in the watershed. Streambank erosion is clearly a very significant factor as well, and is highly correlated with runoff volume. While important, runoff volume tends to be most affected by developed areas in which there is a high percentage of impervious cover. Remediation of those issues is also relatively expensive compared to agricultural practices, so are seen as a secondary approach for the Water Fund in the initial phase of implementation. Note that the high level of phosphorus from streambank erosion will also be addressed by reductions in sediment erosion.

Figures 6.5-6.7 show the estimated yield from various land cover types. In the case of nitrogen, cropland and other agricultural land cover types produce the highest yields. For phosphorus developed land covers also produce significant impacts to water quality, while sediment input is dominated by cropland.

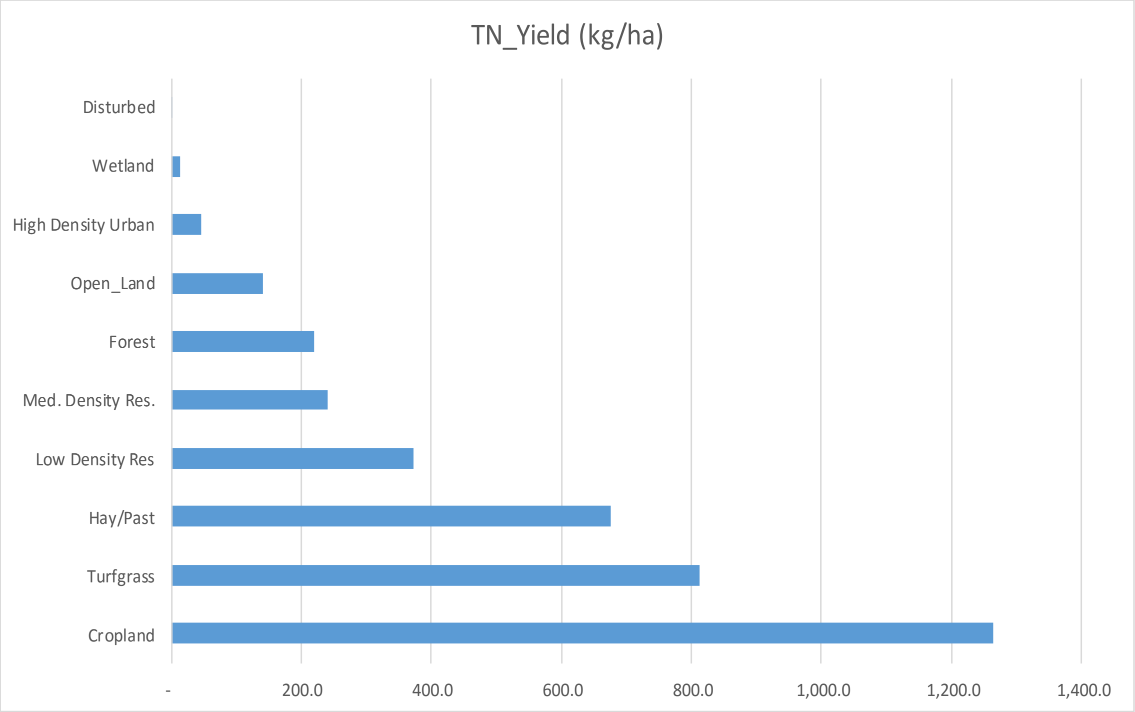


Figure 6.5 -- Yield, in kilograms per hectare per year, of total nitrogen, for various land cover types, from MapShed.

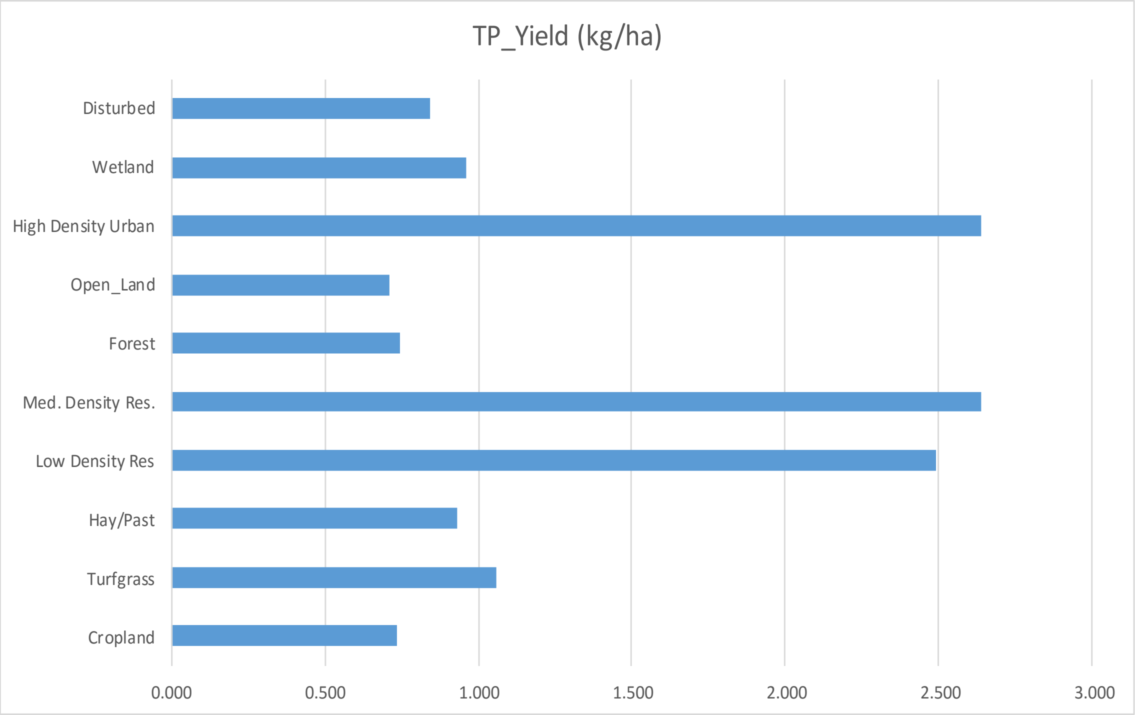


Figure 6.6 -- Yield, in kilograms per hectare per year, of total phosphorus, for various land cover types, from MapShed.

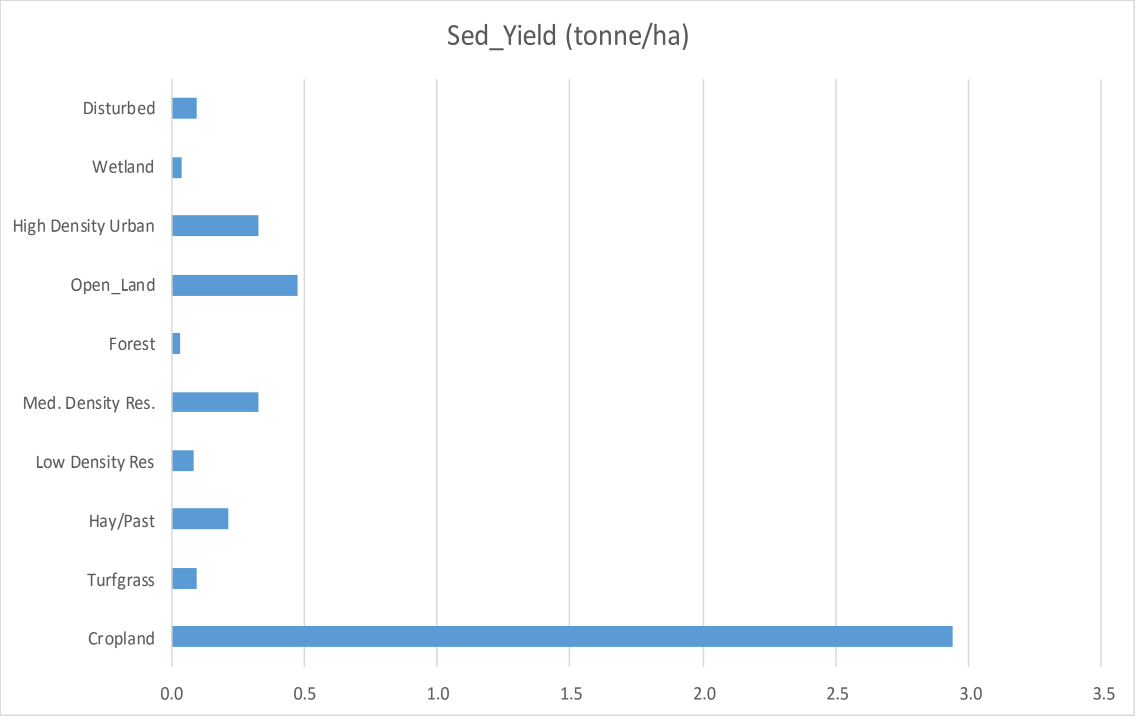


Figure 6.7 -- Yield, in metric tons per hectare per year, of total suspended sediment, for various land cover types, from MapShed.

MapShed model development in the Brandywine-Christina

To create a calibrated MapShed model for the Brandywine-Christina based on the watersheds as defined by the TMDL (see above) the Water Fund technical team worked with the CCWRA and Barry Evans to compile model input files in the Pennsylvania portion of the watershed, then extend those calibration files into Delaware. The CCWRA has expended considerable time and effort in developing the calibrated model for the Chester County portion of the Brandywine-Christina Basin. The Water Fund was able to work with them toward development of a comprehensive model for use in the Water Fund.

Three versions of the model were calibrated at the TMDL catchment scale: 1) a set of input files reflecting the 1995 situation in the basin based on land cover data from that date, 2) a similar calibration for 2012, without the inclusion of any water quality BMP strategies, and 3) a version of the 2012 calibration with BMPs compiled by the CCWRA in collaboration with Barry Evans.

This approach allowed the development of a baseline load (i.e., based on 1995 land cover) for nitrogen, phosphorus, and sediment, which were used to determine, for each catchment in the four watersheds of the Brandywine-Christina basin—the Red Clay, White Clay, Brandywine, and Christina—the load reductions required to meet water quality goals. The team was also able to determine the loads in each catchment based on 2012 land cover information and the amount of reduction achieved through BMPs implemented through 2012.

Tables 6.3 to 6.7 show the results of modeled loads for the Red Clay, White Clay, and the Brandywine (Main Stem, West Branch, and East Branch) showing the calculated 1995 MapShed baseline, TMDL reduction requirements, and resultant allocation (this is different than the TMDL allocation as published). A dash (-) indicates there is no TMDL for that sub-watershed.

Table 6.3 -- MapShed and TMDL baseline and TMDL percentage reduction requirements, Red Clay Creek watershed.

	TN (kg)			TP (kg)			TSS (kgx1000)		
Sub-shed	MapShed baseline	TMDL reduction	TMDL allocation	MapShed baseline	TMDL reduction	TMDL allocation	MapShed baseline	TMDL reduction	TMDL allocation
R01	63,187	49%	32,478	6,736	36%	4,331	2,404	52%	1,152
R02	48,016	34%	31,739	4,987	77%	1,137	1,579	52%	753
R03	47,280	47%	24,916	4,326	32%	2,946	1,556	45%	854
R04	18,462	47%	9,711	1,206	55%	549	1,148	-	-
R05	14,102	49%	7,164	704	0%	704	622	-	-
R06	16,132	0%	16,132	1,526	0%	1,526	1,325	-	-
R07	3,245	0%	3,245	161	0%	161	131	-	-
R08	12,401	0%	12,401	1,031	0%	1,031	668	-	-
R09	4,587	0%	4,587	209	0%	209	156	-	-
Totals	**227,412**		**142,373**	**20,887**		**12,594**	**9,590**		**2,759**

Table 6.4 -- MapShed and TMDL baseline and TMDL percentage reduction requirements, White Clay Creek watershed.

	TN (kg)			TP (kg)			TSS (kgx1000)		
Sub-shed	MapShed baseline	TMDL reduction	TMDL allocation	MapShed baseline	TMDL reduction	TMDL allocation	MapShed baseline	TMDL reduction	TMDL allocation
W01	56,554	50%	28,447	3,983	50%	2,011	1,827	42%	1,056
W02	63,954	49%	32,425	4,226	19%	3,423	1,462	64%	528
W03	30,007	50%	15,004	2,009	55%	904	1,138	39%	689
W04	43,713	50%	21,857	3,041	55%	1,368	952	64%	345
W05	21,560	-	-	1,647	-	-	656	-	-
W06	59,060	37%	37,267	4,220	19%	3,418	1,677	68%	537
W07	6,843	38%	4,215	358	52%	172	106	71%	31
W08	37,197	50%	18,747	2,117	72%	595	1,112	51%	546
W09	32,219	50%	16,142	1,575	55%	712	1,222	26%	902
W10	14,249	50%	7,124	594	55%	267	401	-	-
W11	22,402	0%	22,402	756	0%	756	545	-	-
W12	33,647	0%	33,647	770	0%	770	710	-	-
W13	3,793	0%	3,793	201	0%	201	52	-	-
W14	3,726	0%	3,726	158	0%	158	149	-	-
W15	14,010	0%	14,010	811	0%	811	481	-	-
W16	14,601	0%	14,601	467	0%	467	490	-	-
W17	29,146	0%	29,146	1,065	0%	1,065	1,519	-	-
Totals	**486,682**		**302,553**	**27,997**		**17,099**	**14,500**		**4,634**

Table 6.5 -- MapShed and TMDL baseline and TMDL percentage reduction requirements, Brandywine Creek, Main Stem watershed.

	TN (kg)			TP (kg)			TSS (kgx1000)		
Sub-shed	**MapShed baseline**	**TMDL reduction**	**TMDL allocation**	**MapShed baseline**	**TMDL reduction**	**TMDL allocation**	**MapShed baseline**	**TMDL reduction**	**TMDL allocation**
B15	48,736	-	-	1,930	-	-	764	55%	341
B16	50,809	-	-	1,792	-	-	865	-	-
B17	20,537	7%	19,120	1,111	7%	1,035	599	-	-
B18	1,446	0%	1,446	118	0%	118	5	-	-
B19	21,921	0%	21,921	1,166	0%	1,166	695	-	-
B31	53,001	-	-	2,646	-	-	826	60%	330
B34	12,955	16%	10,856	568	26%	422	391	-	-
Totals	**209,405**		**53,343**	**9,332**		**2,742**	**4,145**		**671**

Table 6.6 -- MapShed and TMDL baseline and TMDL percentage reduction requirements, Brandywine Creek, West Branch watershed.

	TN (kg)			TP (kg)			TSS (kgx1000)		
Sub-shed	**MapShed baseline**	**TMDL reduction**	**TMDL allocation**	**MapShed baseline**	**TMDL reduction**	**TMDL allocation**	**MapShed baseline**	**TMDL reduction**	**TMDL allocation**
B01	124,541	37%	78,710	7,451	21%	5,901	1,399	31%	967
B02	29,516	40%	17,709	1,535	40%	921	412	-	-
B03	27,656	10%	24,946	1,302	10%	1,175	326	-	-
B04	1,564	0%	1,564	62	-	-	10	46%	5
B05	104,839	5%	99,702	5,381	12%	4,751	422	54%	195
B06	40,699	30%	28,489	2,043	30%	1,430	577	32%	392
B07	77,273	-	-	5,886	-	-	2,220	-	-
B08	25,251	-	-	2,006	-	-	631	-	-
B20	152,553	-	-	8,874	-	-	2,434	35%	1,592
B21	87,585	-	-	5,869	-	-	1,403	-	-
B22	90,985	-	-	7,621	-	-	2,022	-	-
B23	10,598	-	-	853	-	-	276	-	-
B24	1,995	-	-	49	-	-	8	-	-
B25	28,403	-	-	1,510	-	-	531	-	-
B32	17,156	10%	15,441	791	10%	712	138	-	-
B33	38,572	10%	34,792	1,932	9%	1,752	501	-	-
Totals	**859,185**		**301,352**	**53,162**		**16,643**	**13,312**		**3,150**

Table 6.7 -- MapShed and TMDL baseline and TMDL percentage reduction requirements, Brandywine Creek, East Branch watershed.

	TN (kg)			TP (kg)			TSS (kgx1000)		
Sub-shed	MapShed baseline	TMDL reduction	TMDL allocation	MapShed baseline	TMDL reduction	TMDL allocation	MapShed baseline	TMDL reduction	TMDL allocation
B09	81,522	18%	66,848	4,671	18%	3,835	1,164	16%	981
B10	78,498	18%	64,604	3,582	16%	3,002	1,112	-	-
B11	26,573	-	-	1,090	-	-	302	-	-
B12	11,465	-	-	479	-	-	76	-	-
B13	140,623	-	-	9,582	-	-	405	-	-
B14	81,118	-	-	5,189	-	-	1,530	56%	667
B26	8,680	-	-	450	-	-	136	-	-
B27	43,191	-	-	1,913	-	-	793	-	-
B28	6,639	-	-	176	-	-	39	-	-
B29	81,097	-	-	2,795	-	-	1,260	-	-
B30	80,041	-	-	2,735	-	-	1,110	-	-
B35	29,693	-	-	1,211	-	-	304	-	-
Totals	**669,140**		**131,452**	**33,873**		**6,837**	**8,231**		**1,648**

Tables 6.8 to 6.12 present the total agricultural acreage (as used in the MapShed Modeling process) by sub-watershed, the estimated degree of implementation for the six selected BMPs (in either total acreage or stream miles), and the reduction in load for the principal constituents, nitrogen, phosphorus, and suspended sediment. This last value represents the difference between modeled current (2012) loads including agricultural BMPs, and the modeled loads with no agricultural BMPs (the load reductions are applied to agricultural lands only)

Table 6.8 -- Acreage of selected agricultural BMPs and MapShed calculated reductions, Red Clay Creek watershed.

	Acreage						Annual Ag BMP Reductions (kg)		
Sub-shed	All Agriculture	Cover crops	No till	Nutrient management	Riparian Buffer (km)	Fencing (km)	TN	TP	TSS (kgX1000)
R01	3,308.7	330.9	1,654.4	66.2	8.7	0.1	1,507	509	418
R02	1,732.2	173.2	866.1	34.6	8.7	0.1	1,184	388	337
R03	1,944.7	194.5	972.4	38.9	6.7	-	1,693	432	365
R04	580.7	58.1	290.3	-	2.5	-	1,520	476	527
R05	388.0	38.8	194.0	-	1.7	-	734	212	217
R06	1,191.0	119.1	595.5	11.9	9.9	-	1,745	501	456
R07	106.3	10.6	53.1	-	2.2	-	162	43	38
R08	89.0	8.9	44.5	-	0.2	-	105	108	34
R09	-	-	-	-	-	-	-	-	-
Totals	**9,340.6**	**934.1**	**4,670.3**	**151.6**	**40.6**	**0.2**	**8,649**	**2,667**	**2,391**

Table 6.9 -- Acreage of selected agricultural BMPs and MapShed calculated reductions, White Clay Creek watershed.

	Acreage						Annual Ag BMP Reductions (kg)		
Sub-shed	All Agriculture	Cover crops	No till	Nutrient management	Riparian Buffer (km)	Fencing (km)	TN	TP	TSS (kgX1000)
W01	2,863.9	286.4	1,432.0	57.3	9.6	-	3,934	860	327
W02	3,145.6	314.6	1,572.8	62.9	9.6	-	4,595	826	282
W03	1,270.1	127.0	635.1	25.4	4.7	-	1,835	459	242
W04	1,939.8	194.0	969.9	-	6.2	-	2,538	476	177
W05	1,257.8	125.8	628.9	-	-	-	293	178	226
W06	3,588.0	358.8	1,794.0	35.9	8.2	-	3,758	701	393
W07	202.6	20.3	101.3	-	1.2	-	295	49	5
W08	1,282.5	128.2	641.2	-	5.9	-	2,299	552	62
W09	1,008.2	100.8	504.1	-	6.4	4.9	1,001	325	205
W10	509.0	50.9	254.5	-	2.2	-	811	227	24
W11	565.9	56.6	282.9	-	1.2	-	855	230	26
W12	323.7	32.4	161.9	-	3.5	-	324	65	9
W13	19.8	2.0	9.9	-	-	-	4	2	1
W14	-	-	-	-	-	-	-	-	-
W15	783.3	78.3	391.7	-	0.5	-	1,011	314	27
W16	185.3	18.5	92.7	-	1.0	-	212	53	5
W17	402.8	40.3	201.4	-	2.0	-	494	126	13
Totals	**19,348.3**	**1,934.8**	**9,674.2**	**181.5**	**62.3**	**4.9**	**24,256**	**5,442**	**2,024**

Table 6.10 -- Acreage of selected agricultural BMPs and MapShed calculated reductions, Brandywine Creek, Main Stem watershed.

	Acreage						Annual Ag BMP Reductions (kg)		
Sub-shed	All Agriculture	Cover crops	No till	Nutrient management	Riparian Buffer (km)	Fencing (km)	TN	TP	TSS (kgX1000)
B15	1,373.9	137.4	687.0	13.7	6.2	-	1,216	260	141
B16	1,534.5	153.5	767.3	15.3	6.2	-	359	148	91
B17	914.3	91.4	457.1	9.1	4.4	-	1,537	359	255
B18	46.9	4.7	23.5	-	25.2	-	94	12	1
B19	412.7	41.3	206.3	-	10.9	-	511	133	84
B31	1,949.7	195.0	974.8	19.5	5.4	-	1,368	354	158
B34	-	-	-	-	-	-	-	-	-
Totals	**6,232.0**	**623.2**	**3,116.0**	**57.7**	**58.3**	**-**	**5,085**	**1,267**	**731**

Table 6.11 -- Acreage of selected agricultural BMPs and MapShed calculated reductions, Brandywine Creek, West Branch watershed.

	Acreage						Annual Ag BMP Reductions (kg)		
Sub-shed	All Agriculture	Cover crops	No till	Nutrient management	Riparian Buffer (km)	Fencing (km)	TN	TP	TSS (kgX1000)
B01	6,115.8	611.6	3,057.9	61.2	15.2	0.1	9,829	1,440	476
B02	1,030.4	103.0	515.2	10.3	5.4	0.0	2,154	425	184
B03	859.9	86.0	430.0	8.6	4.9	0.0	1,728	340	137
B04	14.8	1.5	7.4	0.1	-	-	3	1	1
B05	622.7	62.3	311.4	6.2	7.9	0.0	1,673	308	122
B06	1,230.6	123.1	615.3	12.3	5.8	0.0	1,748	392	163
B07	3,753.5	375.4	1,876.8	37.5	16.1	0.1	6,101	1,606	817
B08	1,386.3	138.6	693.1	13.9	4.2	0.0	1,863	454	202
B20	8,774.7	877.5	4,387.3	87.7	30.8	0.2	12,380	2,102	849
B21	5,426.4	542.6	2,713.2	54.3	19.6	0.1	9,760	1,488	524
B22	5,589.5	559.0	2,794.8	55.9	17.4	0.1	8,264	1,589	583
B23	568.3	56.8	284.2	5.7	1.6	0.0	1,233	345	166
B24	9.9	1.0	4.9	0.1	0.8	-	21	3	1
B25	1,018.1	101.8	509.0	10.2	6.6	0.0	1,416	324	169
B32	729.0	72.9	364.5	7.3	3.3	0.0	1,150	189	61
B33	1,705.0	170.5	852.5	17.1	5.8	0.0	3,009	594	255
Totals	**38,835.0**	**3,883.5**	**19,417.5**	**388.4**	**145.5**	**1.0**	**62,330**	**11,600**	**4,709**

Table 2.12 -- Acreage of selected agricultural BMPs and MapShed calculated reductions, Brandywine Creek, East Branch watershed.

	Acreage						Annual Ag BMP Reductions (kg)		
Sub-shed	All Agriculture	Cover crops	No till	Nutrient management	Riparian Buffer (km)	Fencing (km)	TN	TP	TSS (kgX1000)
B09	4,487.4	448.7	2,243.7	44.9	7.0	0.1	5,182	1,125	458
B10	2,819.5	281.9	1,409.7	28.2	8.6	0.1	4,567	968	421
B11	602.9	60.3	301.5	6.0	1.3	-	540	121	54
B12	93.9	9.4	46.9	0.9	0.8	-	53	12	5
B13	358.3	35.8	179.2	3.6	3.2	-	521	91	67
B14	2,112.7	211.3	1,056.4	21.1	5.2	-	1,636	486	295
B26	353.4	35.3	176.7	3.5	1.6	-	611	124	75
B27	1,418.4	141.8	709.2	14.2	6.9	-	2,399	494	294
B28	9.9	1.0	4.9	0.1	0.6	-	12	1	0
B29	1,430.7	143.1	715.4	14.3	4.1	-	1,102	252	158
B30	2,270.9	227.1	1,135.4	22.7	7.9	-	2,575	441	247
B35	1,658.1	165.8	829.0	16.6	3.6	-	1,859	331	142
Totals	**17,616**	**1,762**	**8,808**	**176**	**50.7**	**0.2**	**21,057**	**4,447**	**2,216**

Using values from the literature for the implementation costs for various BMPs used by MapShed we could estimate the cost (based on existing BMPs) for the reductions realized between 1995 and 2012. Using those numbers to estimate the return, in terms of load reductions, from the approximated costs of the BMPs implemented in that time frame, we extrapolated the total cost to achieve water quality goals for each constituent of concern. While this approach makes certain assumptions, such as that future pollution control efforts will be as effective as previous approaches in reducing pollutants, and that there is minimal co-benefits from implementation, for instance, the benefits in terms of phosphorus reduction that sediment control measures will afford (this is certainly not the case, and could reduce the total costs toward reaching water quality goals). The approach, however, provides an approximation of the level of cost and effort to reach goals; while specific performance will vary based on the particular situation in each catchment. Once areas of concern are identified and loads and potential reductions are estimated, progress toward water quality goals is still dependent on the ability to find sufficient and appropriate project sites and willing landowners.

MapShed presents a limited but significant suite of BMPs, both agricultural and urban-based. While there are a wide range of potential BMPs that the Water Fund could implement (to address both agricultural and urban stormwater water quality impacts) those considered here have been identified as the principal approaches appropriate in MapShed (Barry Evans, personal conversation). Table 6.13 presents the BMPs considered in the modeling process for agricultural pollution load reduction, along with the estimated range in unit cost for each practice.

Table 6.13-- MapShed BMPs with unit cost range.

Type	Unit	Unit Cost Low	Unit Cost High
Cover crops	ha	$ 86.49	$ 128.49
No till	ha	$ 6.72	$ 98.84
Contouring	ha	$ 12.36	$ 24.71
Nutrient management	ha	$ 7.41	$ 24.71
Riparian forest buffer	km	$ 40.36	$ 371.89
Animal fencing	km	$ 2,405.11	$ 2,405.11

Agricultural BMPs are generally significantly lower cost than urban BMPs, which are usually highly engineered and occur in areas where land rent is at a premium. Using calculations based on the results of a recent stormwater cost pilot study of the Pike Creek (a sub-watershed of White Clay Creek) (Duffield Associates, Inc. and Water Resources Agency at the University of Delaware 2012), it was estimated that the total cost for targeted stormwater BMPs (i.e., for urbanized MS4 communties) in the Pike Creek was approximately \$3.5 million, or an annualized rate of \$240,000 (including 3% debt service). Extrapolating to the entire White Clay Creek watershed, using the reduction values for nitrogen from the Pike Creek study and the total load reduction requirements provided by MapShed, this would translate to an annual cost (over 20 years) of \$236 million (without debt load). The estimated annual cost for targeted reduction of total nitrogen using agricultural BMPs (see below) is approximately \$2.3 million per year, or approximately two orders of magnitude less (see Figure 6.8).

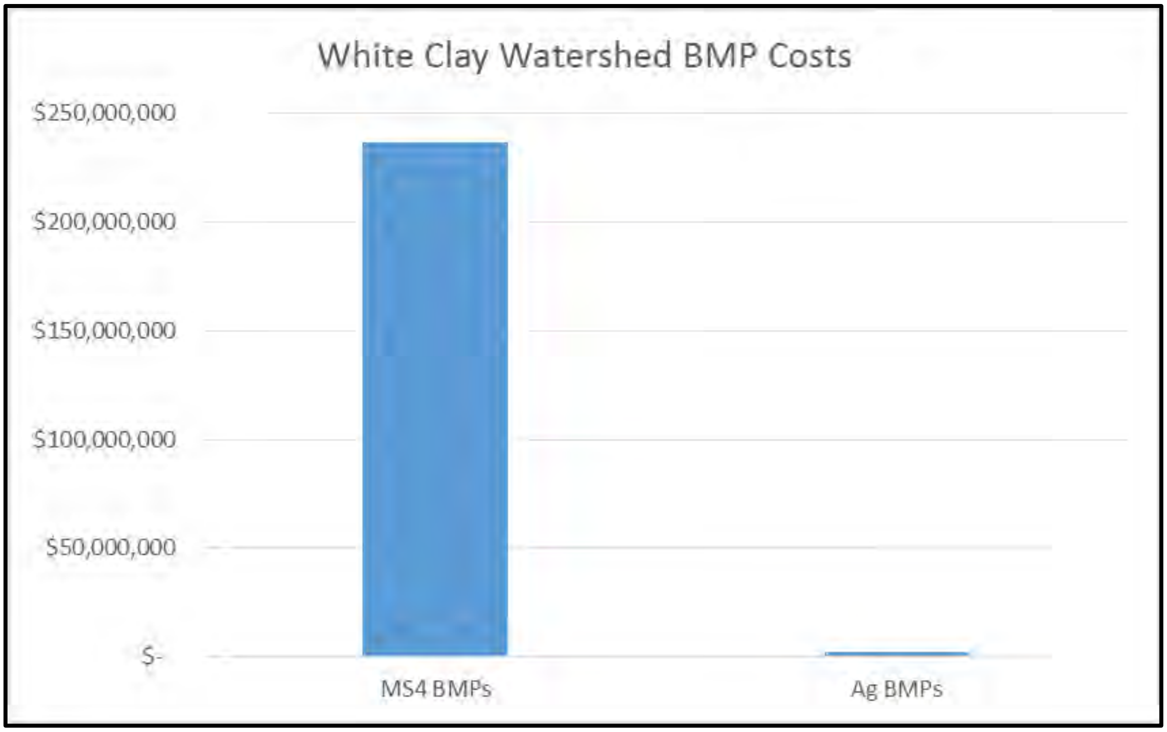
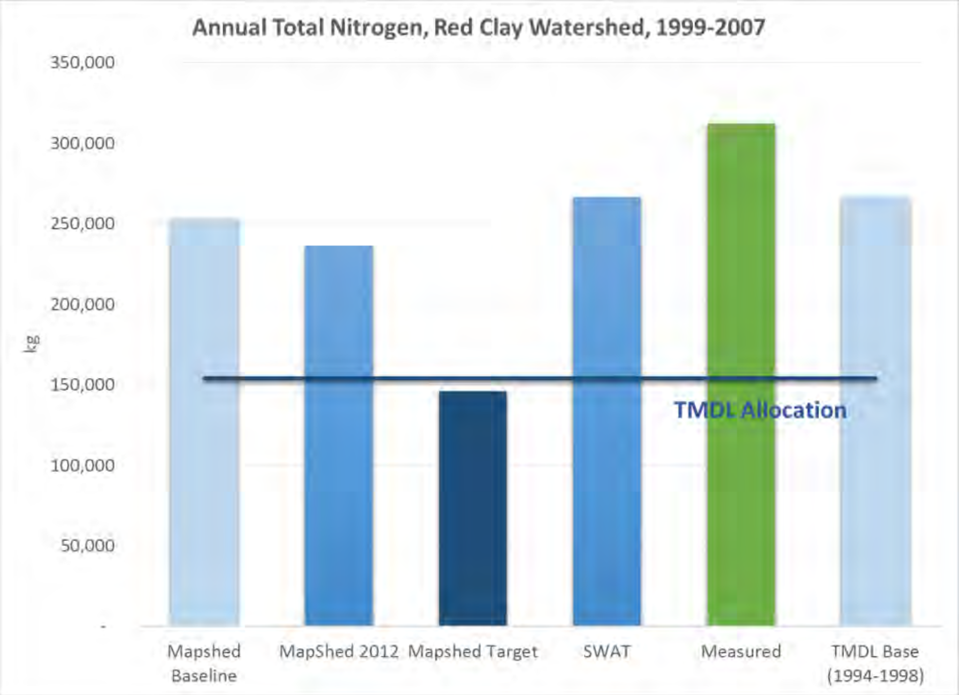


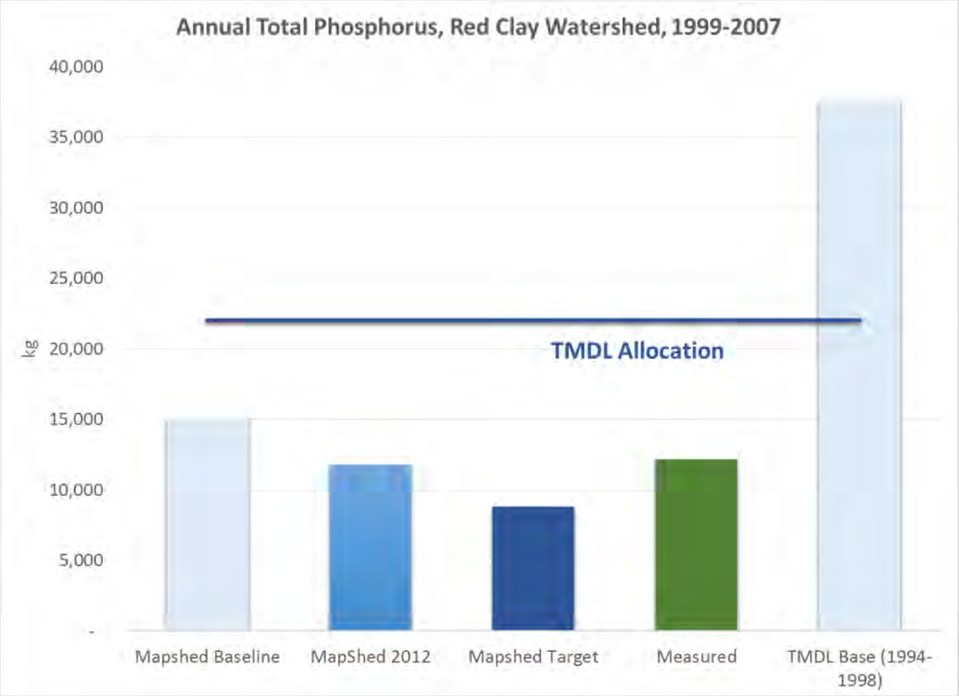
Figure 6.8 -- Comparison of non-agricultural v. agricultural BMPs to achieve required nitrogen reductions in the White Clay, extrapolated from Pike Creek Water Quality Improvement Plan.

Comparison with other models

A comparison of modeled loads in the watersheds of the Brandywine-Christina was undertaken to determine the concurrence of several approaches. We looked at the baseline allocations as defined in the TMDL, from the SWAT modeling process (see above), the MapShed baseline from 1995, and the MapShed load for 2012 with existing BMPs (i.e., pollution control strategies that were implemented between 1995 and 2012). This analysis was undertaken for both the Red Clay Creek, the watershed chosen as a proof-of-concept in the initial phase of the project, and for White Clay Creek, which was selected as a pilot test-case for the Water Fund. Because of the need for a comparison across the same period, given the limited time span for the models considered and data availability constraints in the measured stream gage data, the period from 1999 to 2007 was used in the comparison. The results of that analysis is summarized in the graphs shown in Figures 6.9 (Red Clay) and 6.10 (White Clay).


Annual Total Nitrogen, Red Clay Watershed, 1999-2007
350,000
300,000
250,000
200,000
150,000
100,000
50,000
-
kg
TMDL Allocation
Mapshed Baseline
MapShed 2012
Mapshed Target
SWAT
Measured
TMDL Base (1994-1998)

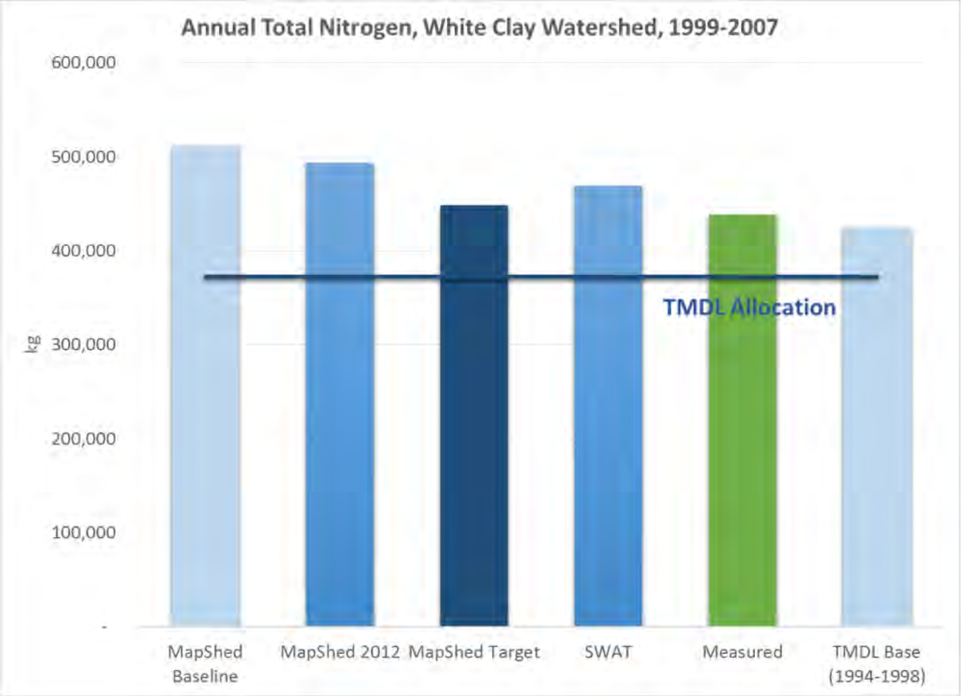
(a)

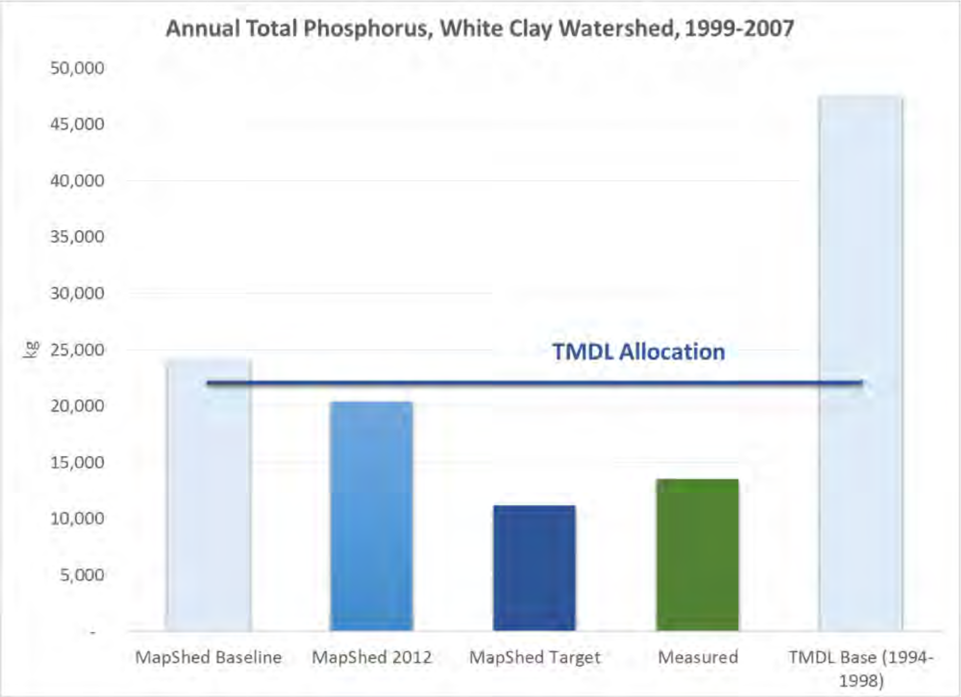

Annual Total Phosphorus, Red Clay Watershed, 1999-2007
40,000
35,000
30,000
25,000
20,000
15,000
10,000
5,000
-
kg
TMDL Allocation
Mapshed Baseline
MapShed 2012
Mapshed Target
Measured
TMDL Base (1994-1998)

(b)

(c)

Figure 6.9 -- Comparison of models and measured values in the Red Clay Creek watershed for the period 1999-2007, for nitrogen (a), phosphorus (b), and suspended sediment (c).





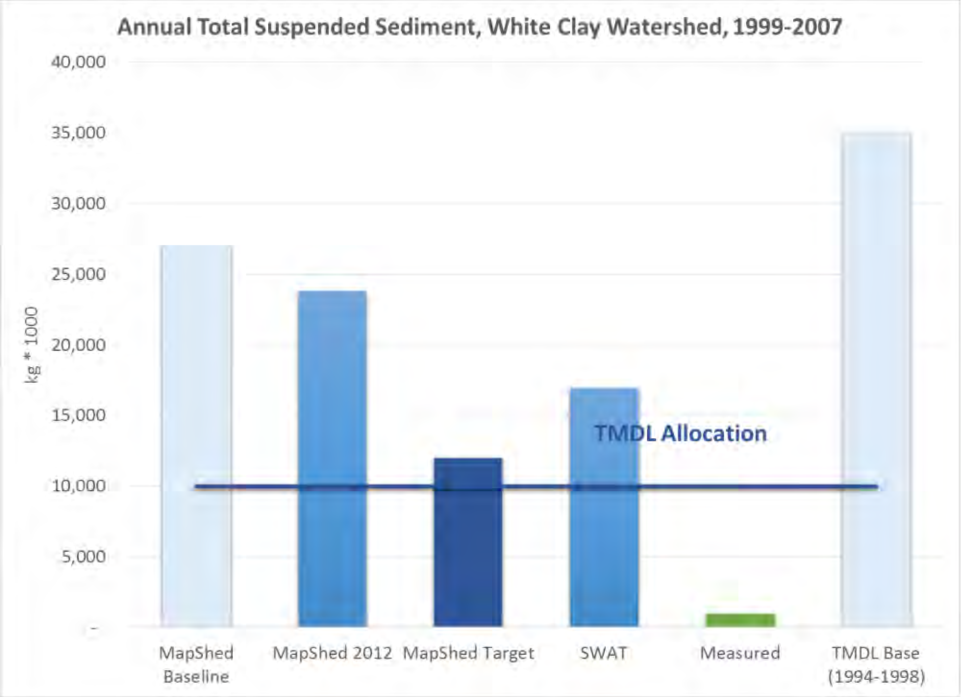


Figure 6.10 -- Comparison of models and measured values in the White Clay Creek watershed for the period 1999-2007, for nitrogen (a), phosphorus (b), and suspended sediment (c).

The bars in light blue represent the baseline values (either from MapShed, 1995, or the TMDL) showing the pre-condition, before any pollution control measures were implemented, and against which percentage reduction requirements are applied. The medium blue bars show the modeled values based on "current" (i.e., 2012) conditions, including any pollution control measures (BMPs) that have been implemented. The dark blue bar shows the target load that should be achieved to return the watershed to healthy status based on the newer MapShed-based calculations, while the dark blue line shows the allocation (target) as defined in the TMDL. The green bars illustrate the measured values over the period at monitoring stations. The difference in height of the bars represents the difference in loads among the modeled and measured values.

There is a general concurrence in the modeled values, with some variation, in particular, SWAT indicates a somewhat lower load that MapShed for most constituents (note that there are no values for total phosphorus from SWAT, as that parameter is not modeled by SWAT). In general baseline loads based on the TMDL are higher than those modeled by MapShed. Measured values at the monitoring stations/stream gages are generally mirrored by the modeled values, with the exception of sediment, which shows much lower measured values. This discrepancy is a result of the periodic nature of the data collection at monitoring stations. Sediment in particular is extremely variable and proportional to stream flows. Sediment levels during a storm event can be several orders of magnitude higher than background levels; sampling for sediment generally occurs at most several times per month, which results in a high likelihood of high sediment loads not being captured by the monitoring protocol. Attempts are currently underway to establish continuous monitoring of turbidity at stream gages, which can be used to accurately derive sediment loads, which will result in a much more realistic understanding of actual sediment loads.

To determine "Mapshed Target" values in these graphs, baseline loads from MapShed (i.e., from the 1995, "pre-BMP" scenario) were used, instead of those calculated in the TMDL. Percentage reductions derived from the TMDL were then applied to the values modeled in MapShed to determine reduction targets. This approach to calculating baseline loads and required reductions is the method approved by the PA DEP for determining TMDL and MS4 required reductions.

Results

Agricultural contribution

Based on calibrated MapShed model runs for the watersheds of the Brandywine-Christina basin, the total contribution for the constituents of concern (total nitrogen, total phosphorus, and suspended sediment) is primarily from agricultural land cover while less comes from other land cover types. The proportions of loads from agricultural sources is higher in the upper portions of each watershed (or sub-watershed), which is expected, since the proportion of agricultural land is generally higher in upstream catchments.

For this analysis the watersheds of the Brandywine portion of the Brandywine-Christina were divided into three branches, the Main Stem, from Wilmington to the confluence of the East and West Branches, and the East and West Branches, above the confluence. For the purposes of modeling and assessment, the Christina River watershed was not considered, since it is almost entirely urbanized, and has relatively little agricultural load or opportunities for load reductions from farm-based practices.

Figures 6.11 through 6.25 illustrate the proportion of load for nitrogen, phosphorus, and sediment from agricultural (brown bars) versus all other sources (gray bars) for the Brandywine-Christina basin.

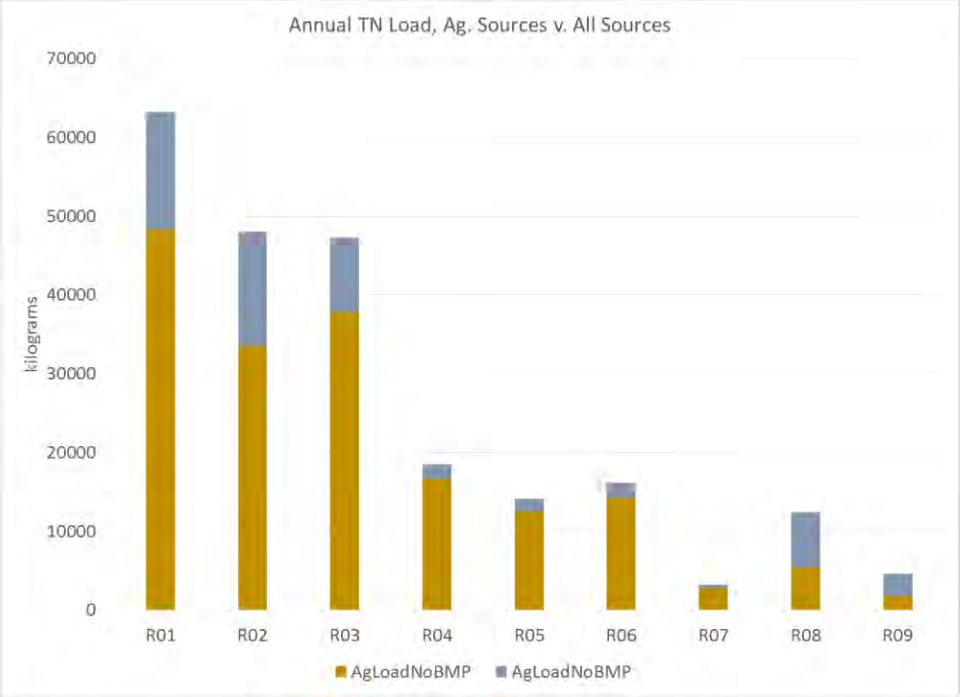


Figure 6.11 – Total nitrogen loads in the Red Clay Creek watershed by catchment, comparing loads from agricultural and non-agricultural sources, with no BMPs.

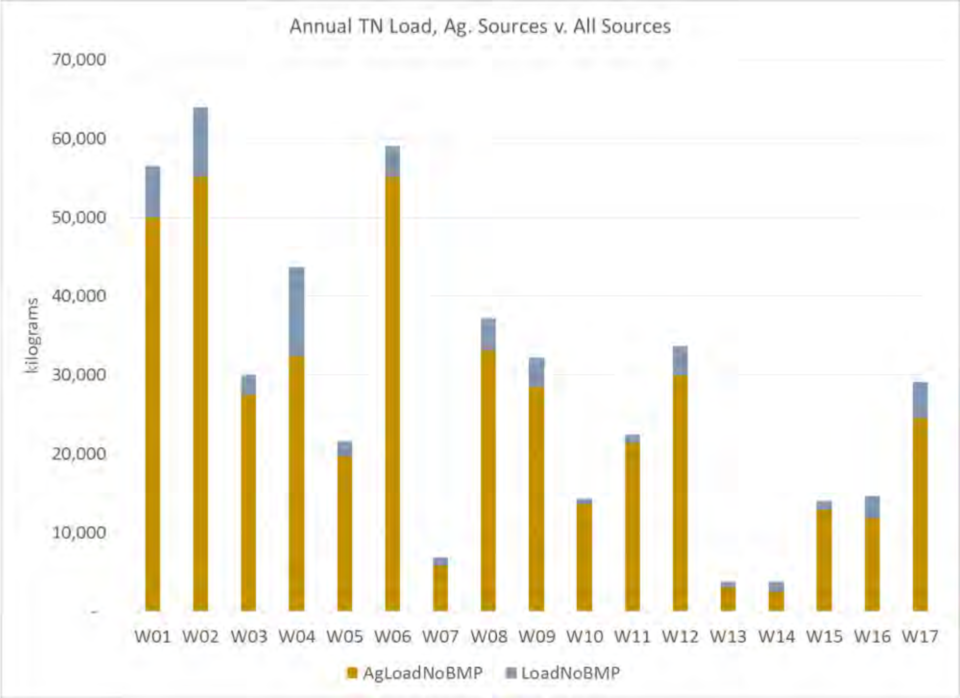


Figure 6.12 – Total nitrogen loads in the White Clay Creek watershed by catchment, comparing loads from agricultural and non-agricultural sources, with no BMPs.

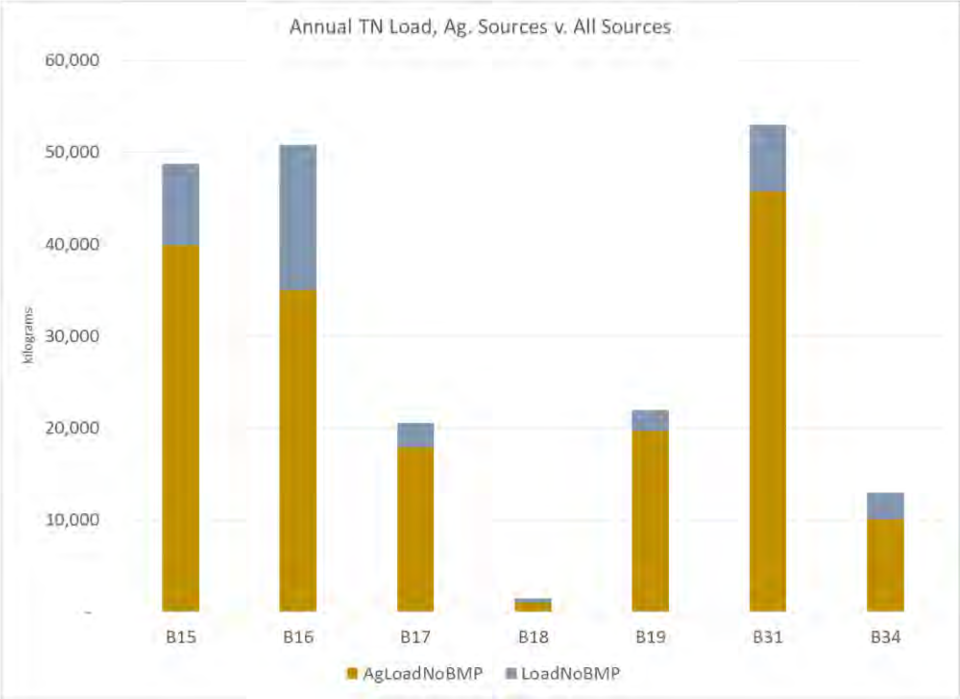


Figure 6.13 – Total nitrogen loads in the Brandywine Creek, Main Stem watershed by catchment, comparing loads from agricultural and non-agricultural sources, with no BMPs.

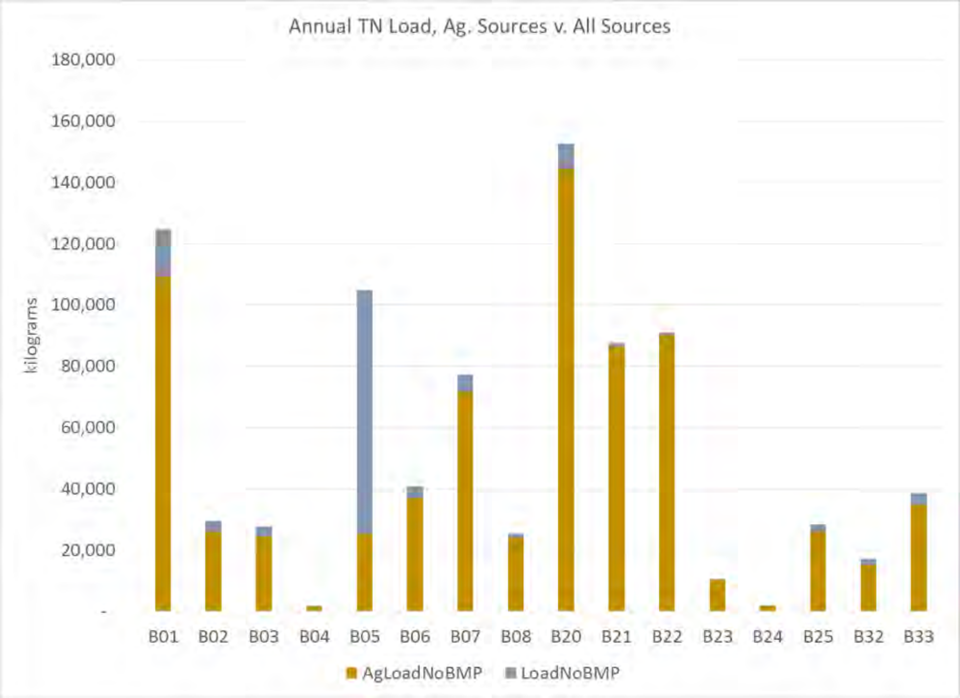


Figure 6.14 – Total nitrogen loads in the Brandywine Creek, West Branch watershed by catchment, comparing loads from agricultural and non-agricultural sources, with no BMPs.

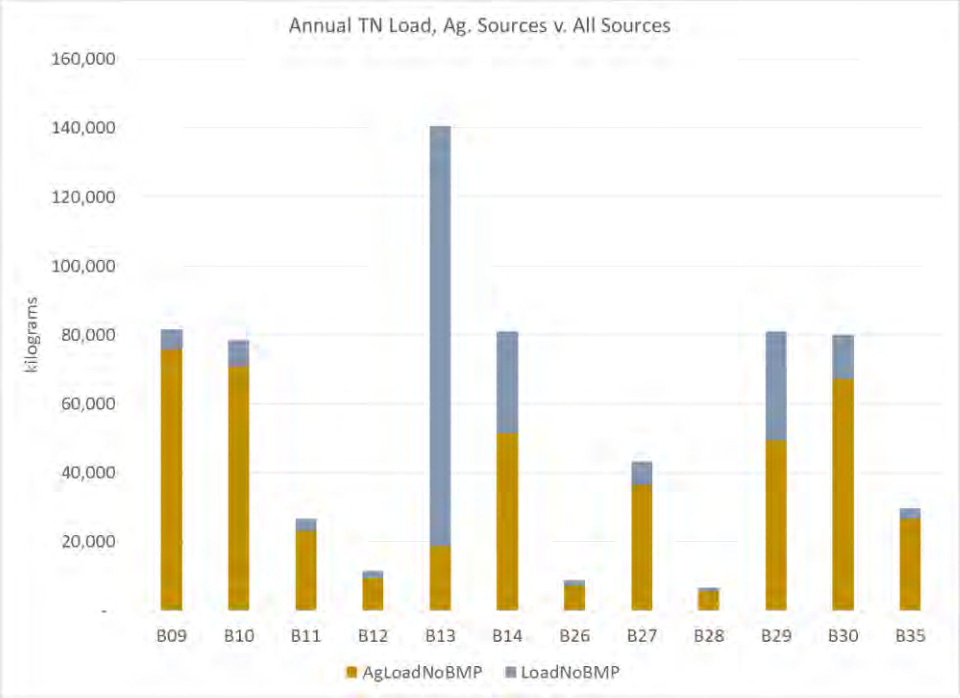


Figure 6.15 – Total nitrogen loads in the Brandywine Creek, East Branch watershed by catchment, comparing loads from agricultural and non-agricultural sources, with no BMPs.

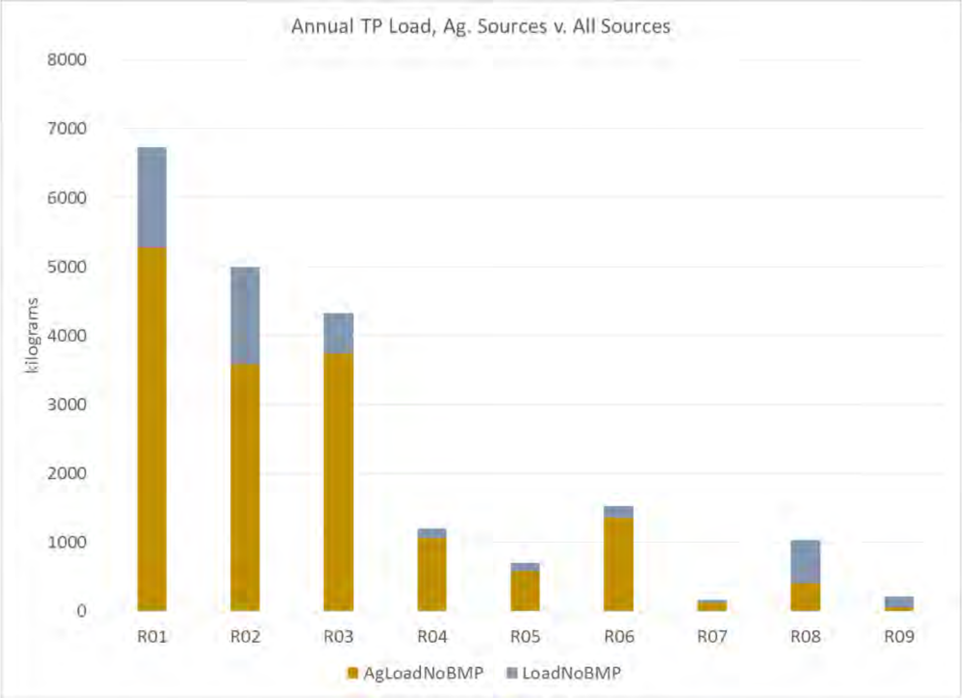


Figure 6.16 – Total phosphorus loads in the Red Clay Creek watershed by catchment, comparing loads from agricultural and non-agricultural sources, with no BMPs.

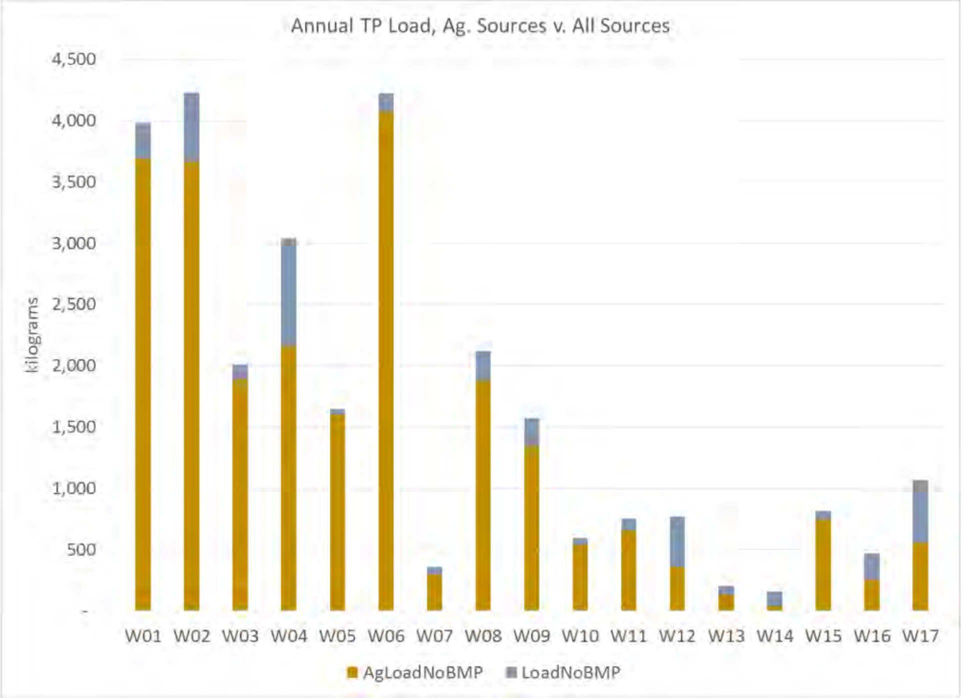


Figure 6.17 – Total phosphorus loads in the White Clay Creek watershed by catchment, comparing loads from agricultural and non-agricultural sources, with no BMPs.

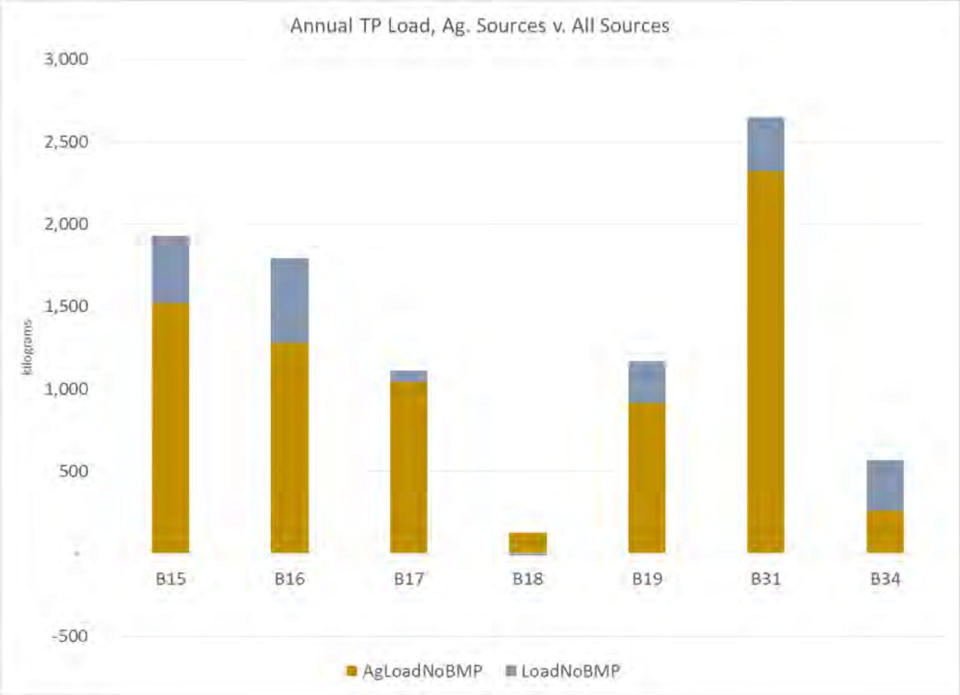


Figure 6.18 – Total phosphorus loads in the Brandywine Creek, main Stem watershed by catchment, comparing loads from agricultural and non-agricultural sources, with no BMPs.

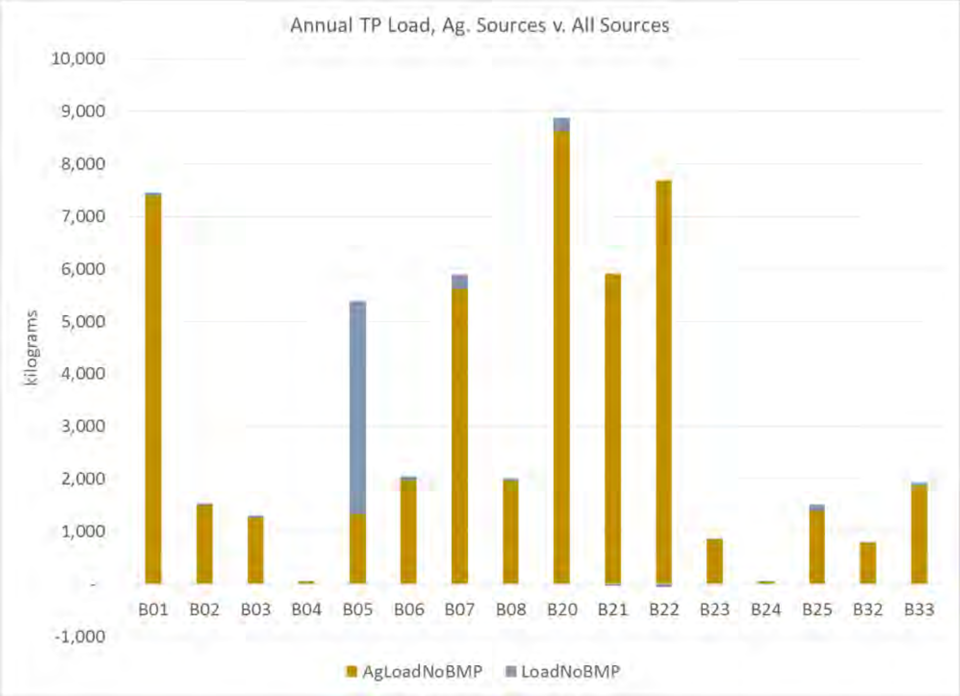


Figure 6.19 – Total phosphorus loads in the Brandywine Creek, West Branch watershed by catchment, comparing loads from agricultural and non-agricultural sources, with no BMPs.

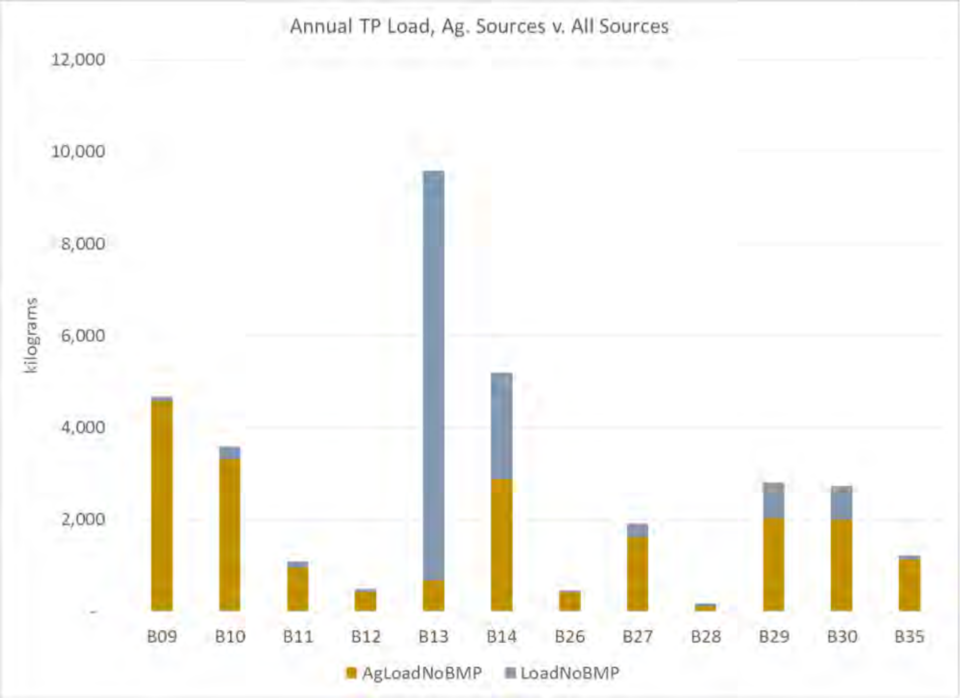


Figure 6.20 – Total phosphorus loads in the Brandywine Creek, East Branch watershed by catchment, comparing loads from agricultural and non-agricultural sources, with no BMPs.

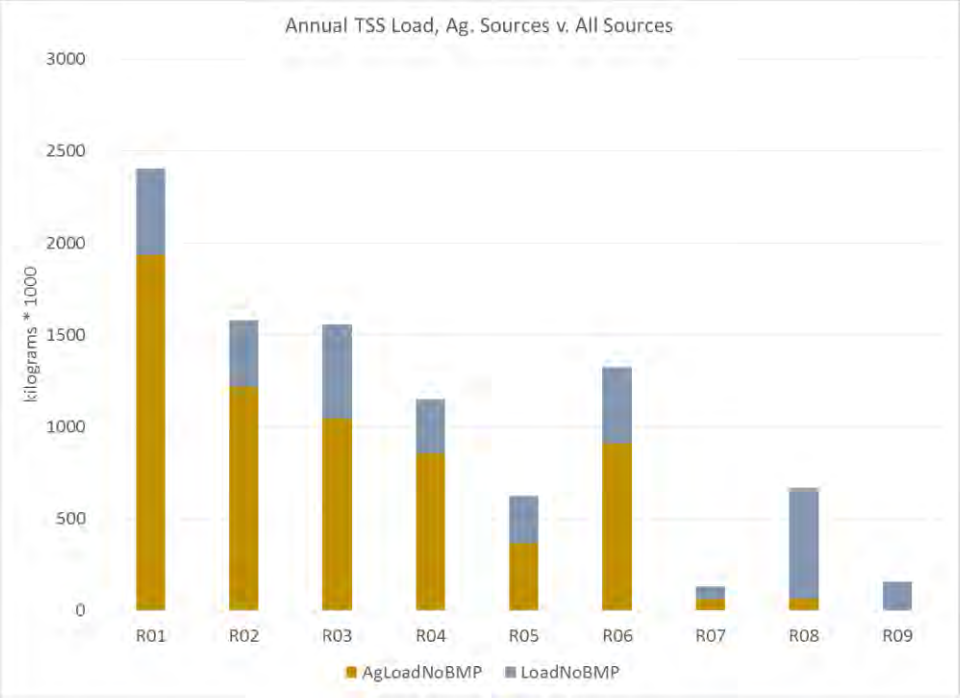


Figure 6.21 – Total phosphorus loads in the Red Clay Creek watershed by catchment, comparing loads from agricultural and non-agricultural sources, with no BMPs.

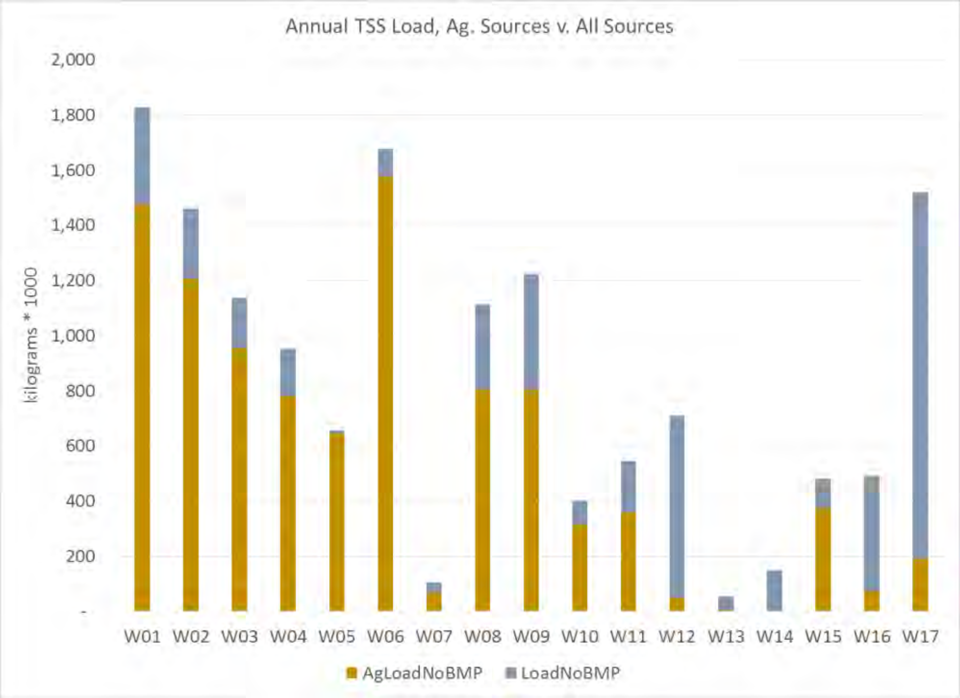


Figure 6.22 – Total phosphorus loads in the White Clay Creek watershed by catchment, comparing loads from agricultural and non-agricultural sources, with no BMPs.

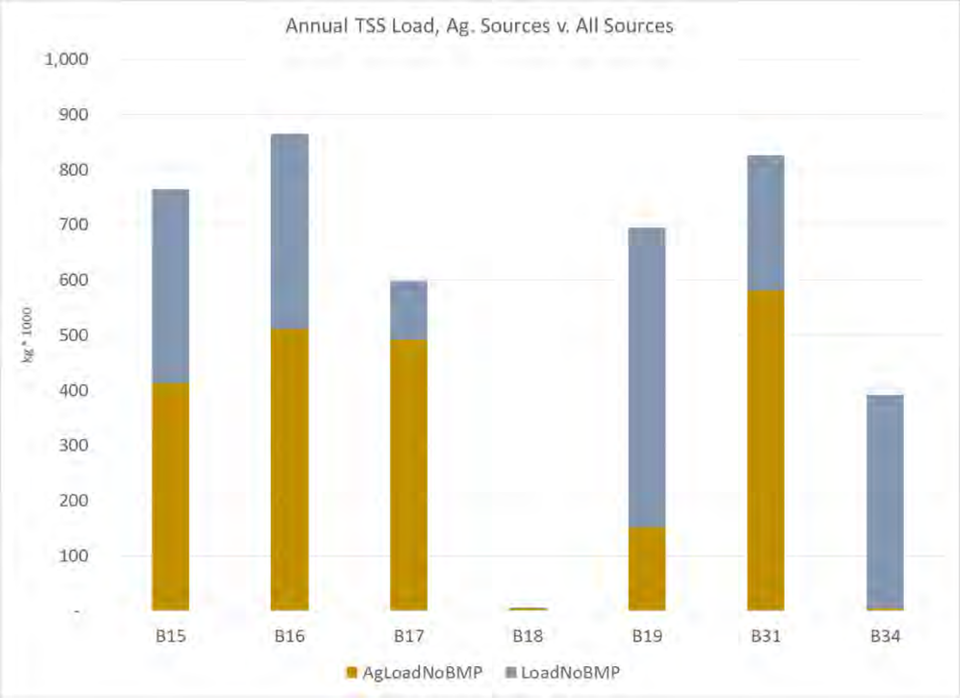


Figure 6.23 – Total phosphorus loads in the Brandywine Creek, Main Stem watershed by catchment, comparing loads from agricultural and non-agricultural sources, with no BMPs.

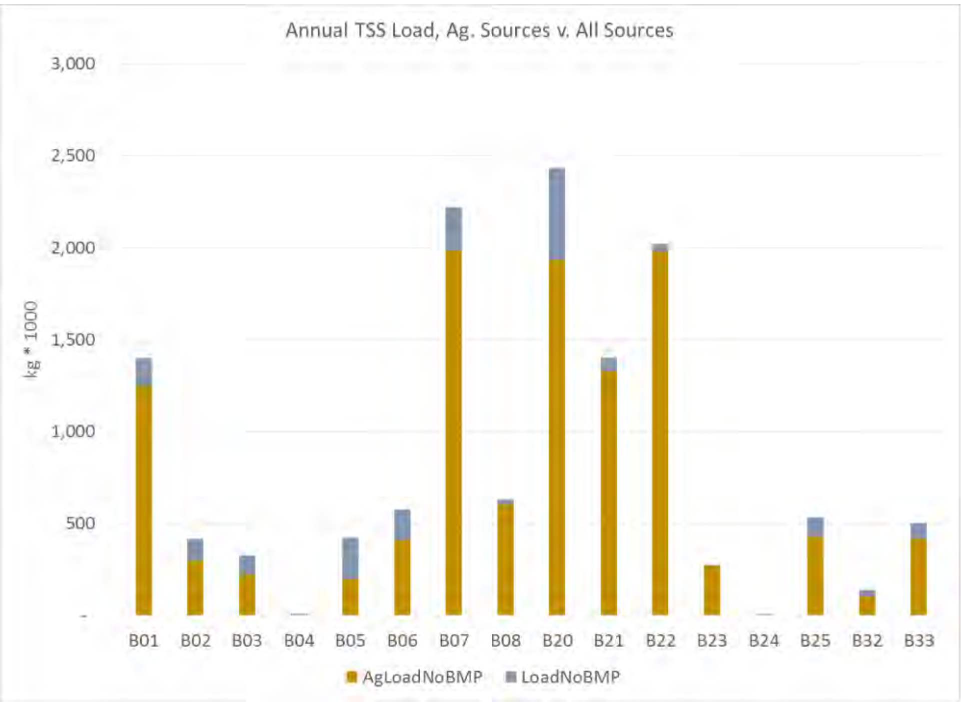


Figure 6.24 – Total suspended sediment loads in the Brandywine Creek, West Branch watershed by catchment, comparing loads from agricultural and non-agricultural sources, with no BMPs.

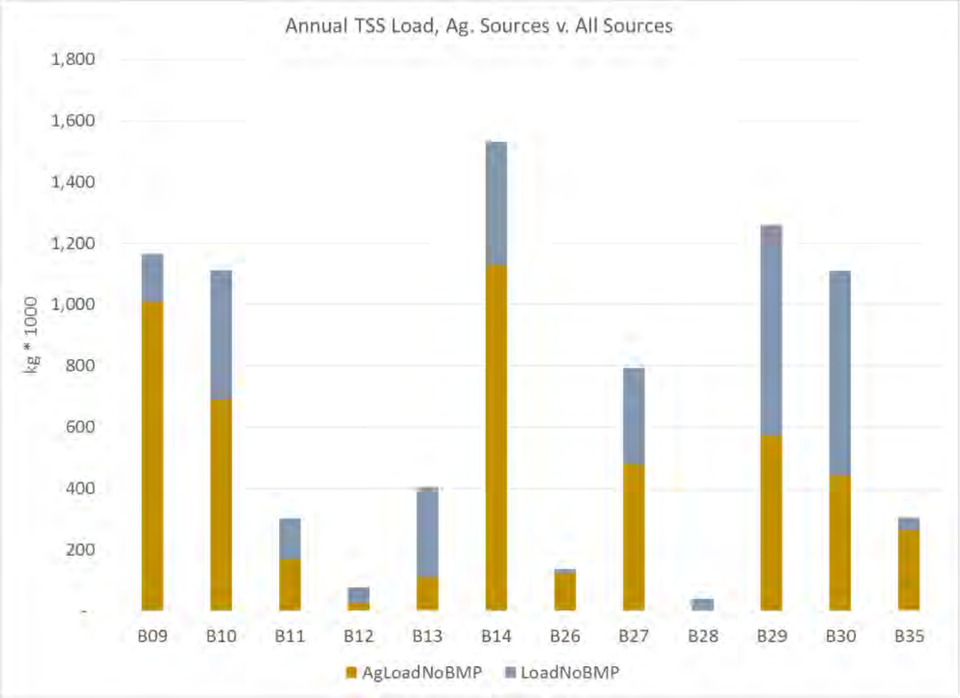


Figure 6.25 – Total suspended sediment loads in the Brandywine Creek, East Branch watershed by catchment, comparing loads from agricultural and non-agricultural sources, with no BMPs.

Total implemented agricultural BMP costs

To determine the total cost of agricultural BMPs currently implement (as of 2012) in the Brandywine-Christina Basin, the total area and/or stream mileage treated with agricultural BMPs as determined through the MapShed calibration process was multiplied by the average unit cost for that BMP to determine total estimated annual cost for currently implemented BMPs in the basin.

The map in Figure 6.26 illustrates the approximate total annual current cost for agricultural BMPs the 70 catchments in the Brandywine-Christina basin based on the MapShed analysis. Also shown on the map are the impaired streams in the basin (for nitrogen, phosphorus, and sediment), as well as the focus areas (outlined in purple) where the DRWI Cluster Partners for the Brandywine-Christina are implementing their strategies.

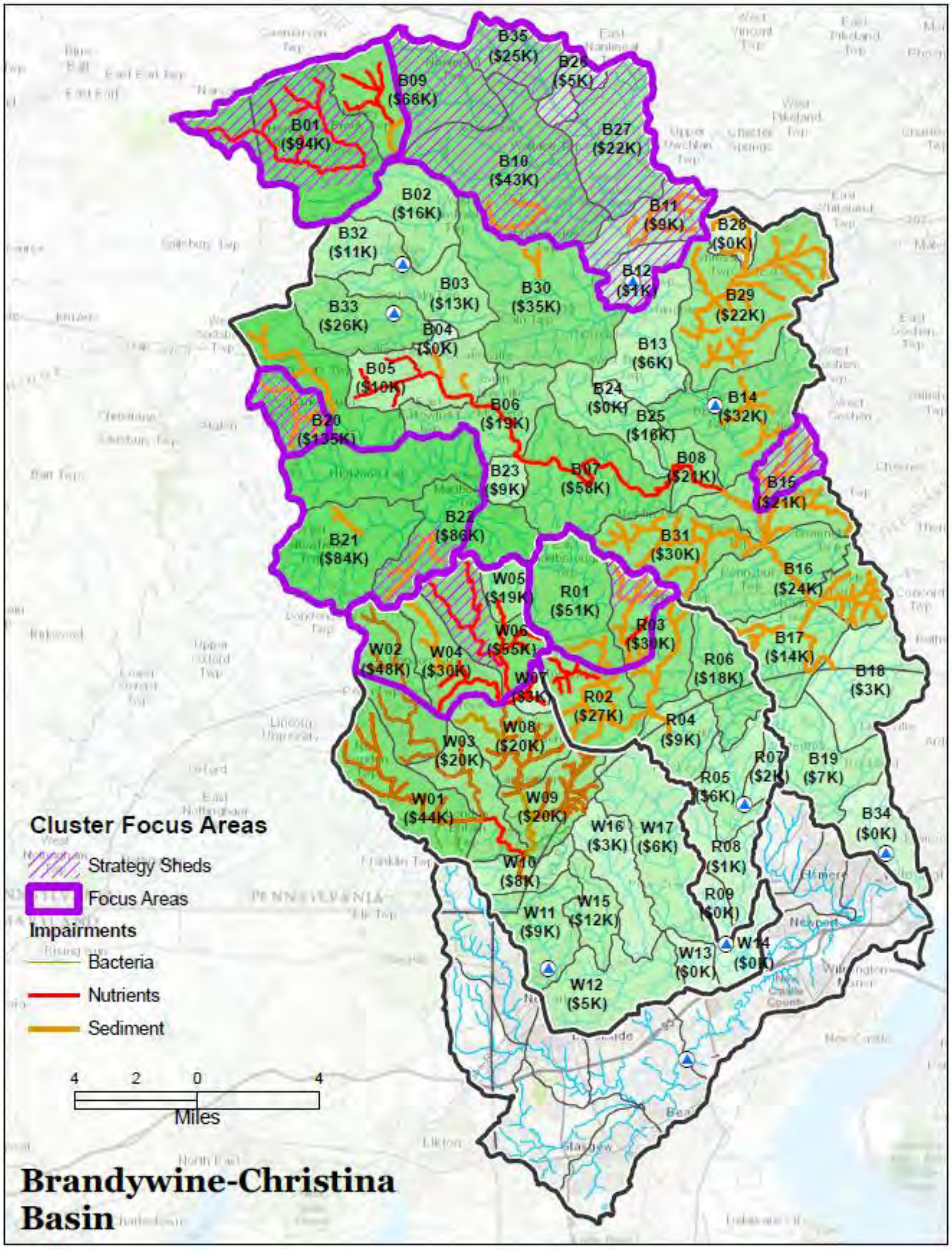


Figure 6.26 – Approximate current investment in agricultural BMPs in the Brandywine-Christina Basin, as determined by MapShed analysis.

Tables 6.14 to 6.18 summarize the costs, by catchment area, for currently (as of 2012) implemented agricultural BMPs by each watershed or branch. Six principal BMPs were considered.

Table 6.14 -- Total implemented cost of agricultural BMPs as of 2012 in the Red Clay Creek watershed.

Sub-shed	Cover crops	No till/conservation till	Nutrient management	Riparian buffer	Stream fencing	TOTAL
R01	$ 14,393	$ 35,337	$ 1,413	$ 185	$ 3	$ 51,331
R02	$ 7,535	$ 18,500	$ 740	$ 185	$ 3	$ 26,962
R03	$ 8,459	$ 20,769	$ 831	$ 143	$ -	$ 30,202
R04	$ 2,526	$ 6,202	$ -	$ 53	$ -	$ 8,780
R05	$ 1,688	$ 4,143	$ -	$ 37	$ -	$ 5,868
R06	$ 5,181	$ 12,720	$ 254	$ 211	$ -	$ 18,367
R07	$ 462	$ 1,135	$ -	$ 48	$ -	$ 1,644
R08	$ 387	$ 950	$ -	$ 5	$ -	$ 1,342
R09	$ -	$ -	$ -	$ -	$ -	$ -
Totals	**$ 40,631**	**$ 99,755**	**$ 3,239**	**$ 867**	**$ 5**	**$ 144,496**

Table 6.15 -- Total implemented cost of agricultural BMPs as of 2012 in the White Clay Creek watershed.

Sub-shed	Cover crops	No till/conservation	Nutrient management	Riparian buffer	Stream fencing	TOTAL
W01	$ 12,458	$ 30,586	$ 372	$ 804	$ -	$ 44,220
W02	$ 13,683	$ 33,595	$ 409	$ 804	$ -	$ 48,491
W03	$ 5,525	$ 13,565	$ 165	$ 392	$ -	$ 19,646
W04	$ 8,438	$ 20,716	$ -	$ 515	$ -	$ 29,670
W05	$ 5,471	$ 13,433	$ -	$ -	$ -	$ 18,904
W06	$ 15,607	$ 38,319	$ 233	$ 680	$ -	$ 54,839
W07	$ 881	$ 2,164	$ -	$ 103	$ -	$ 3,148
W08	$ 5,579	$ 13,697	$ -	$ 495	$ -	$ 19,770
W09	$ 4,386	$ 10,767	$ -	$ 536	$ 4,810	$ 20,499
W10	$ 2,214	$ 5,436	$ -	$ 186	$ -	$ 7,836
W11	$ 2,461	$ 6,043	$ -	$ 103	$ -	$ 8,608
W12	$ 1,408	$ 3,457	$ -	$ 289	$ -	$ 5,154
W13	$ 86	$ 211	$ -	$ -	$ -	$ 297
W14	$ -	$ -	$ -	$ -	$ -	$ -
W15	$ 3,407	$ 8,366	$ -	$ 41	$ -	$ 11,814
W16	$ 806	$ 1,979	$ -	$ 82	$ -	$ 2,868
W17	$ 1,752	$ 4,302	$ -	$ 165	$ -	$ 6,219
Totals	**$ 84,163**	**$ 206,636**	**$ 1,180**	**$ 5,194**	**$ 4,810**	**$ 301,983**

Table 6.16-- Total implemented cost of agricultural BMPs as of 2012 in the Brandywine Creek, Main Stem watershed.

Sub-shed	Cover crops	No till/conservation	Nutrient management	Riparian buffer	Stream fencing	TOTAL
B15	$ 5,976	$ 14,673	$ 89	$ 515	$ -	$ 21,254
B16	$ 6,675	$ 16,388	$ 100	$ 515	$ -	$ 23,678
B17	$ 3,977	$ 9,764	$ 59	$ 371	$ -	$ 14,172
B18	$ 204	$ 501	$ -	$ 2,102	$ -	$ 2,808
B19	$ 1,795	$ 4,407	$ -	$ 907	$ -	$ 7,109
B31	$ 8,481	$ 20,822	$ 127	$ 453	$ -	$ 29,883
B34	$ -	$ -	$ -	$ -	$ -	$ -
Totals	**$ 27,109**	**$ 66,556**	**$ 375**	**$ 4,864**	**$ -**	**$ 98,905**

Table 6.17-- Total implemented cost of agricultural BMPs as of 2012 in the Brandywine Creek, West Branch watershed.

Sub-shed	Cover crops	No till/conservation	Nutrient management	Riparian buffer	Stream fencing	TOTAL
B01	$ 26,603	$ 65,316	$ 398	$ 1,270	$ 72	$ 93,659
B02	$ 4,482	$ 11,005	$ 67	$ 447	$ 24	$ 16,025
B03	$ 3,741	$ 9,184	$ 56	$ 412	$ 24	$ 13,417
B04	$ 64	$ 158	$ 1	$ -	$ -	$ 224
B05	$ 2,709	$ 6,650	$ 40	$ 662	$ 48	$ 10,109
B06	$ 5,353	$ 13,142	$ 80	$ 482	$ 24	$ 19,082
B07	$ 16,328	$ 40,087	$ 244	$ 1,340	$ 144	$ 58,142
B08	$ 6,030	$ 14,805	$ 90	$ 346	$ 48	$ 21,320
B20	$ 38,169	$ 93,712	$ 570	$ 2,566	$ 241	$ 135,258
B21	$ 23,604	$ 57,953	$ 353	$ 1,639	$ 120	$ 83,669
B22	$ 24,314	$ 59,695	$ 363	$ 1,453	$ 120	$ 85,945
B23	$ 2,472	$ 6,070	$ 37	$ 136	$ 24	$ 8,739
B24	$ 43	$ 106	$ 1	$ 70	$ -	$ 219
B25	$ 4,429	$ 10,873	$ 66	$ 554	$ 48	$ 15,970
B32	$ 3,171	$ 7,785	$ 47	$ 276	$ 24	$ 11,304
B33	$ 7,417	$ 18,209	$ 111	$ 482	$ 24	$ 26,243
Totals	**$ 168,929**	**$ 414,750**	**$ 2,524**	**$ 12,136**	**$ 986**	**$ 599,325**

Table 6.18 -- Total implemented cost of agricultural BMPs as of 2012 in the Brandywine Creek, East Branch watershed.

Sub-shed	Cover crops	No till/conservation	Nutrient management	Riparian buffer	Stream fencing	TOTAL
B09	$ 19,520	$ 47,925	$ 292	$ 581	$ 72	$ 68,390
B10	$ 12,264	$ 30,111	$ 183	$ 719	$ 96	$ 43,375
B11	$ 2,623	$ 6,439	$ 39	$ 105	$ -	$ 9,206
B12	$ 408	$ 1,003	$ 6	$ 64	$ -	$ 1,481
B13	$ 1,559	$ 3,827	$ 23	$ 266	$ -	$ 5,674
B14	$ 9,190	$ 22,564	$ 137	$ 435	$ -	$ 32,326
B26	$ 1,537	$ 3,774	$ 23	$ 132	$ -	$ 5,466
B27	$ 6,170	$ 15,148	$ 92	$ 575	$ -	$ 21,985
B28	$ 43	$ 106	$ 1	$ 47	$ -	$ 197
B29	$ 6,224	$ 15,280	$ 93	$ 344	$ -	$ 21,941
B30	$ 9,878	$ 24,253	$ 148	$ 660	$ -	$ 34,938
B35	$ 7,212	$ 17,708	$ 108	$ 303	$ -	$ 25,331
Totals	**$ 76,629**	**$ 188,136**	**$ 1,145**	**$ 4,232**	**$ 168**	**$ 270,310**

The following charts (Figures 6.27 to 6.31) present a comparison of the estimated total annual investments in agricultural BMPs in the Brandywine-Christina basin, based on MapShed estimates of the current (as of 2012) level of implementation.

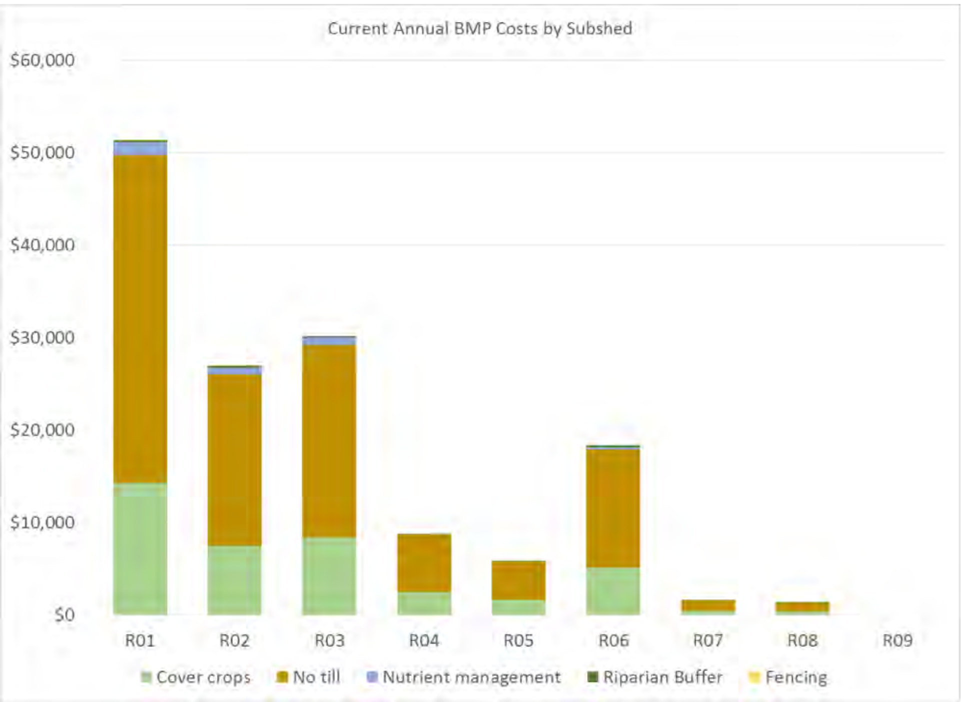


Figure 6.27 -- Total agricultural BMP investments in 2012 by catchment in the Red Clay Creek watershed.

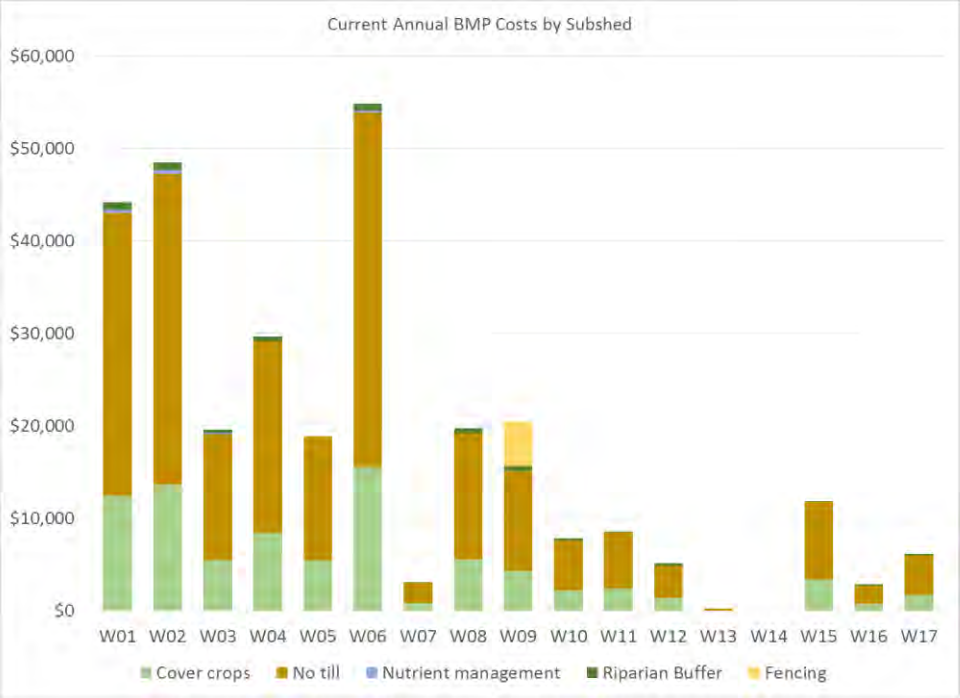


Figure 6.28 -- Total agricultural BMP investments in 2012 by catchment in the White Clay Creek watershed.

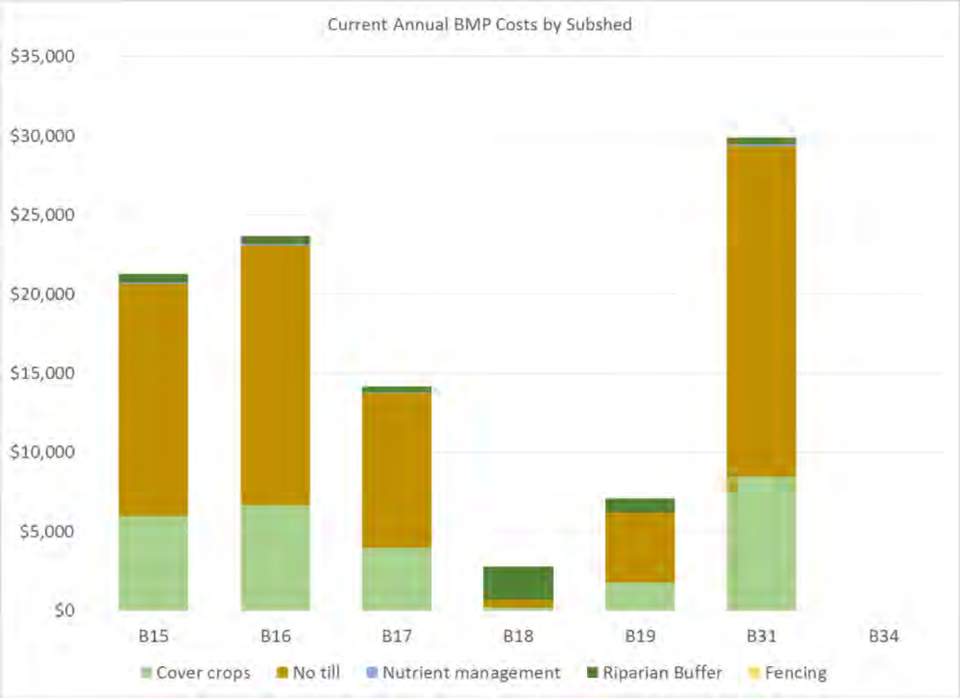


Figure 6.29 -- Total agricultural BMP investments in 2012 by catchment in the Brandywine Creek, Main Stem watershed.

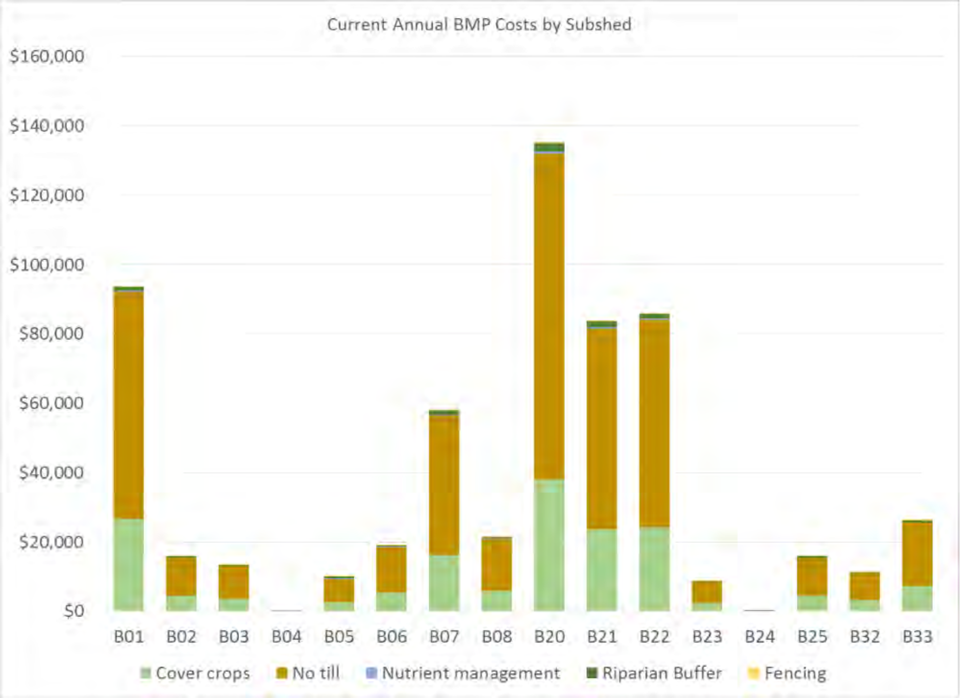


Figure 6.30 -- Total agricultural BMP investments in 2012 by catchment in the Brandywine Creek, West Branch watershed.

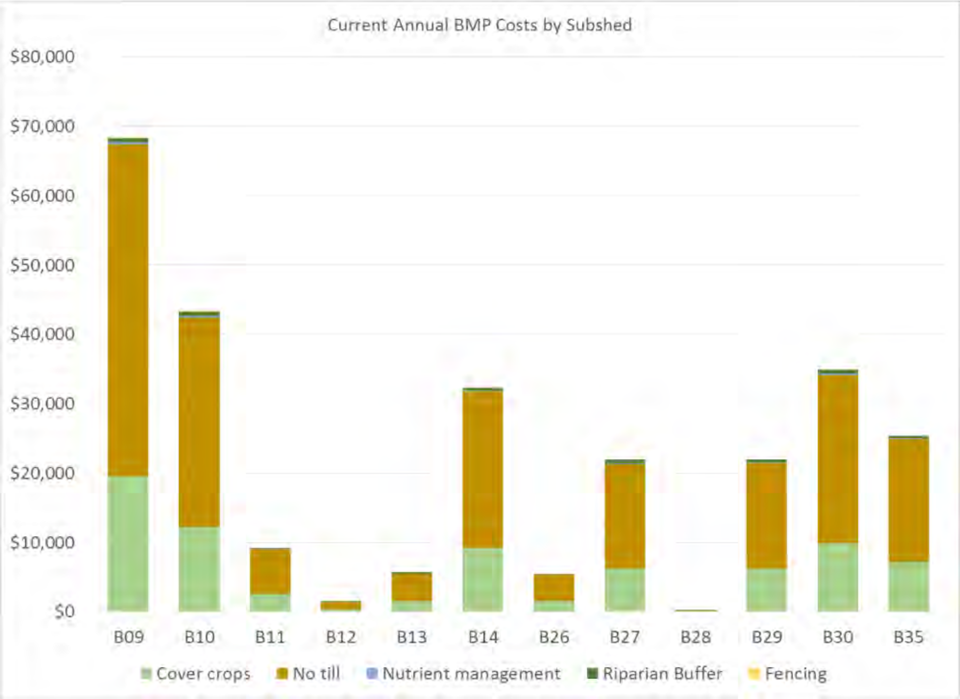


Figure 6.31 -- Total agricultural BMP investments in 2012 by catchment in the Brandywine Creek, East Branch watershed.

The following table (Table 6.19) summarizes the total approximate annual cost for existing agricultural BMPs in the Brandywine-Christina basin. In all there are approximately $1.4 million of annual investment in implementation of agricultural BMPs in the Brandywine-Christina basin.

Table 6.19 -- Summary of agricultural BMP investment as of 2012 in the watersheds of the Brandywine-Christina Basin.

Watershed	**Ag BMP Cost**
Red Clay	$144,496
White Clay	$301,983
Main Stem Brandywine	$98,905
West Branch Brandywine	$599,325
East Branch Brandywine	$270,310
Brandywine-Christina Total	**$1,415,020**

Total costs to achieve water quality targets

To determine the estimated additional annual cost for implementation of agricultural BMPs a similar approach is taken to that described for estimating the current annual investment. First, the total level of implementation is derived through the MapShed calibration process, then, given a known approximate cost range for implementing these BMPs (the unit cost times the farm acreage or stream mileage) the total of existing agricultural BMP implementation costs is calculated. Next, the required target reductions for each constituent is derived. These figures are calculated by applying the TMDL percentage reduction requirement to the modeled baseline (1995) loads and subtracting the modeled current (2012) loads, including implemented BMPs. The unit cost (e.g., dollars per kilogram) to reduce nitrogen, phosphorus, and sediment levels is calculated by dividing the modeled reduction from the 1995 baseline levels by the estimated total cost of agricultural implementation. This unit cost for reduction is then applied to the current modeled load reduction required to meet clean water targets (i.e., based on the TMDL).

This approach assumes that current rates of reductions will continue given the same level of investment. These costs are estimated over a 20 year time horizon, and include the costs of land acquisition, where appropriate. There is a difference among BMPs in terms of longevity, maintenance costs, and whether they are permanent or annual (i.e., some BMPs, such as conservation till are implemented each year, while others, such as riparian buffer planting have a high initial cost, but cost less in subsequent years as trees and plantings mature).

The following maps summarize the approximate annual costs to achieve and maintain water quality goals in the Brandywine-Christina basin. Sub-sheds that are not shaded green but that have a label are those in which water quality goals for that particular constituent have been met; sub-sheds with no label do not have a TMDL. Impaired streams (based on the 303(d) list of impaired streams for Pennsylvania) are shown color coded by constituent. The areas outlined in purple indicate project Focus Areas as defined by the Brandywine-Christina Cluster partners.

Figure 6.32 shows the estimated cost to reduce nitrogen to target levels, Figure 6.33 shows the estimated cost to target for phosphorus, and Figure 6.34shows estimated cost for sediment.

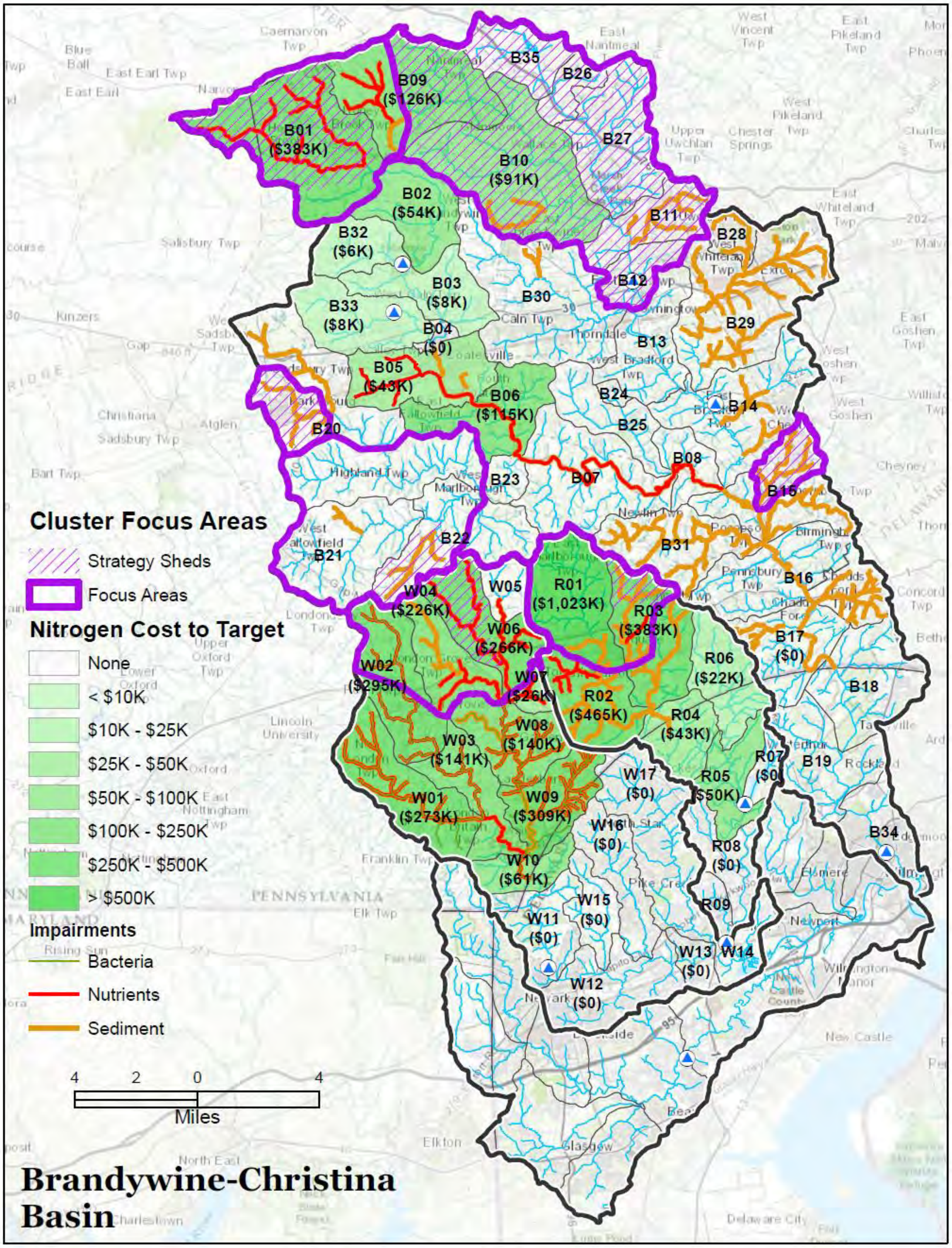


Figure 6.32 -- Estimated total annual costs to achieve water quality goals for nitrogen reduction by catchment, based on MapShed derived estimates.

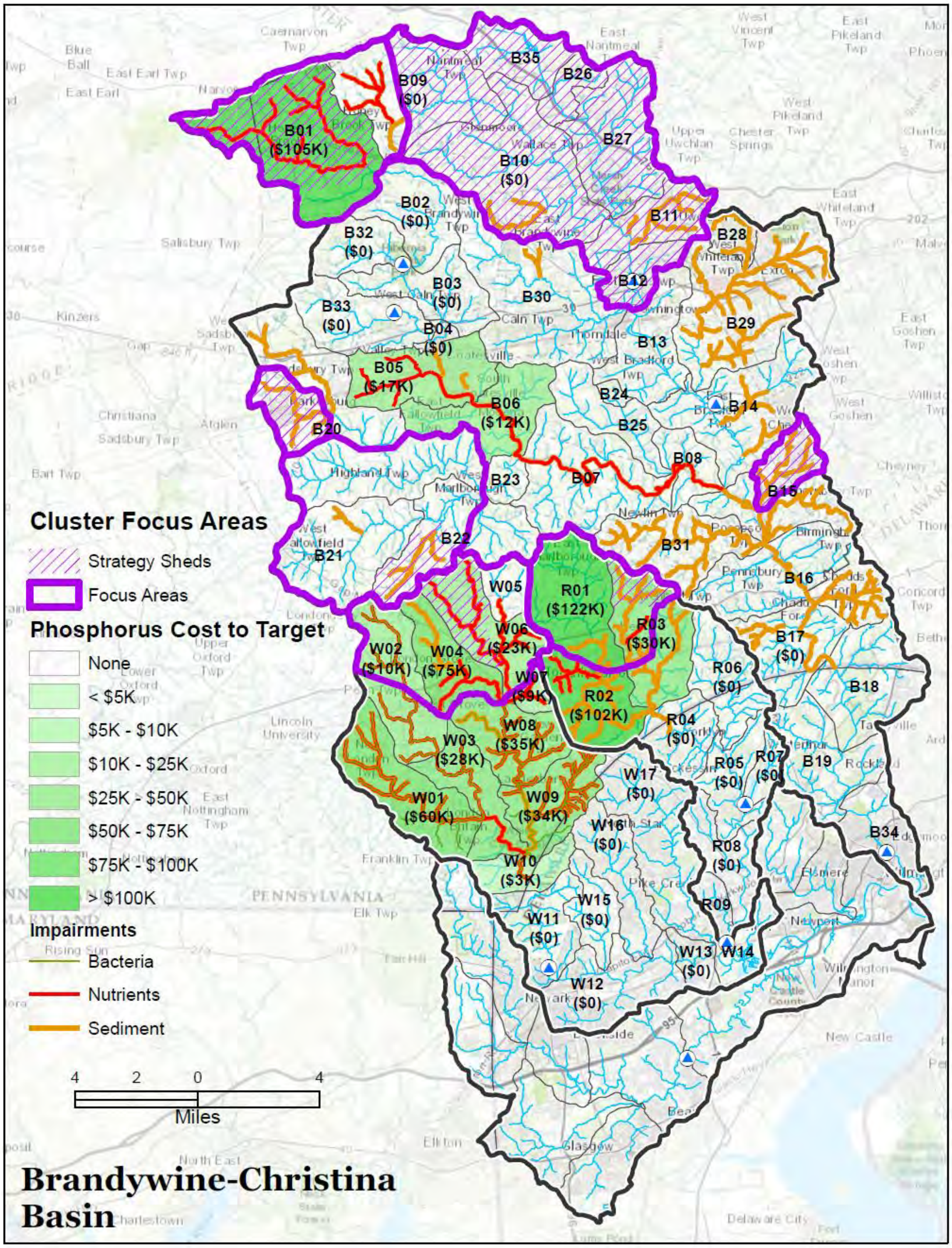


Figure 6.33 -- Estimated total annual costs to achieve water quality goals for phosphorus reduction by catchment, based on MapShed derived estimates.

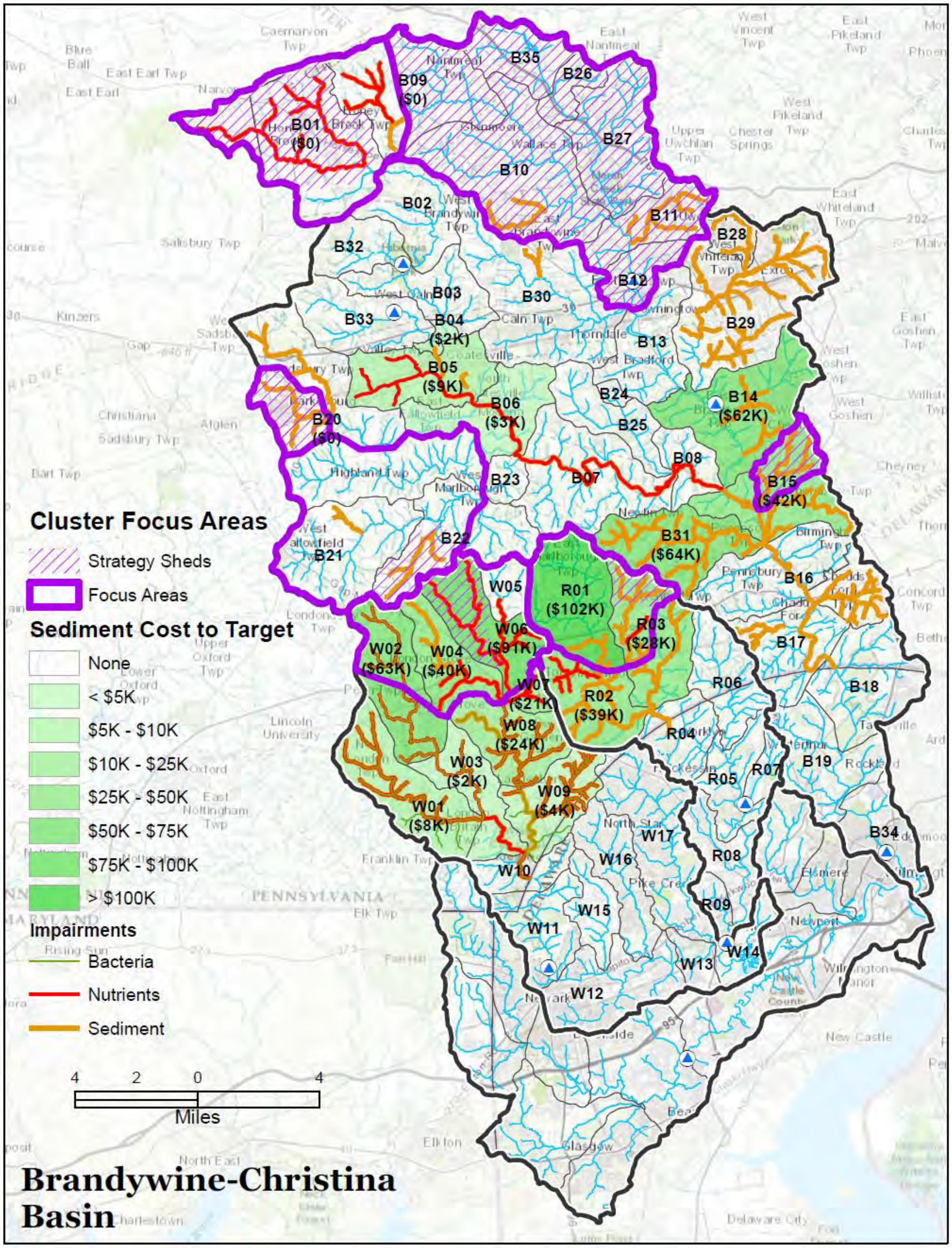


Figure 6.34 -- Estimated total annual costs to achieve water quality goals for sediment reduction by catchment, based on MapShed derived estimates.

Tables 6.20 to 6.24 present the estimated annual costs to meet target loads for nitrogen, phosphorus, and sediment, by watershed or branch. The target reduction represents the difference between the calculated allocation and the current (2012) load including all BMPs.

Table 6.20 -- Summary of reduction unit costs, target reductions and estimated annual cost to reduction targets for nitrogen, phosphorus, and suspended sediment, based on MapShed analysis, for the Red Clay Creek watershed.

Sub-shed	TN			TP			TSS		
	Cost per kg	Target reduction (kg)	Total cost to target	Cost per kg	Target reduction (kg)	Total cost to target	Cost per kg	Target reduction (kgx1000)	Total cost to target
R01	$ 34	30,036	$ 1,023,029	$ 47	2,572	$ 121,947	$ 123	834	$ 102,482
R02	$ 23	20,443	$ 465,448	$ 32	3,190	$ 102,372	$ 80	488	$ 39,070
R03	$ 18	21,464	$ 382,950	$ 48	627	$ 29,928	$ 83	336	$ 27,836
R04	$ 6	7,453	$ 43,067	$ 51	-	$ -	$ 17	-	-
R05	$ 8	6,296	$ 50,362	$ 172	-	$ -	$ 27	-	-
R06	$ 11	2,125	$ 22,357	$ 55	-	$ -	$ 40	-	-
R07	$ 10	-	$ -	$ 110	-	$ -	$ 43	-	-
R08	$ 13	-	$ -	$ 35	-	$ -	$ 40	-	-
R09	$ -	-	$ -	$ -	-	$ -	-	-	-
Totals		**87,818**	**$ 1,987,212**		**6,388**	**$ 254,247**		**1,658**	**$ 169,388**

Table 6.21 -- Summary of reduction unit costs, target reductions and estimated annual cost to reduction targets for nitrogen, phosphorus, and suspended sediment, based on MapShed analysis, for the White Clay Creek watershed.

	TN			TP			TSS		
Sub-shed	**Cost per kg**	**Target reduction (kg)**	**Total cost to target**	**Cost per kg**	**Target reduction (kg)**	**Total cost to target**	**Cost per kg**	**Target reduction (kgx1000)**	**Total cost to target**
W01	$ 11	24,249	$ 272,599	$ 51	1,173	$ 60,283	$ 135	63	$ 8,462
W02	$ 11	27,921	$ 294,679	$ 59	177	$ 10,377	$ 172	368	$ 63,295
W03	$ 11	13,174	$ 141,032	$ 43	649	$ 27,769	$ 81	24	$ 1,967
W04	$ 12	19,320	$ 225,839	$ 62	1,198	$ 74,734	$ 167	240	$ 40,173
W05	$ 65	-	$ -	$ 106	-	$ -	$ 84	-	$ -
W06	$ 15	18,199	$ 265,600	$ 78	295	$ 23,033	$ 140	650	$ 90,650
W07	$ 11	2,397	$ 25,622	$ 64	141	$ 9,079	$ 615	34	$ 20,871
W08	$ 9	16,303	$ 140,219	$ 36	973	$ 34,845	$ 320	74	$ 23,843
W09	$ 20	15,088	$ 308,877	$ 63	535	$ 33,724	$ 100	37	$ 3,694
W10	$ 10	6,315	$ 61,050	$ 35	100	$ 3,457	$ 328	-	$ -
W11	$ 10	-	$ -	$ 37	-	$ -	$ 335	-	$ -
W12	$ 16	-	$ -	$ 79	-	$ -	$ 577	-	$ -
W13	$ 85	-	$ -	$ 192	-	$ -	$ 437	-	$ -
W14	$ -	-	$ -	$ -	-	$ -	$ -	-	$ -
W15	$ 12	-	$ -	$ 38	-	$ -	$ 434	-	$ -
W16	$ 14	-	$ -	$ 54	-	$ -	$ 574	-	$ -
W17	$ 13	-	$ -	$ 49	-	$ -	$ 468	-	$ -
Totals		**142,965**	**$ 1,735,518**		**5,239**	**$ 277,301**		**1,491**	**$ 252,954**

Table 6.22 -- Summary of reduction unit costs, target reductions and estimated annual cost to reduction targets for nitrogen, phosphorus, and suspended sediment, based on MapShed analysis, for the Brandywine Creek, Main Stem watershed.

	TN			TP			TSS		
Sub-shed	**Cost per kg**	**Target reduction (kg)**	**Total cost to target**	**Cost per kg**	**Target reduction (kg)**	**Total cost to target**	**Cost per kg**	**Target reduction (kgx1000)**	**Total cost to target**
B15	$ 17	-	$ -	$ 82	-	$ -	$ 151	282	$ 42,452
B16	$ 66	-	$ -	$ 160	-	$ -	$ 259	-	$ -
B17	$ 9	-	$ -	$ 39	-	$ -	$ 55	-	$ -
B18	$ 30	-	$ -	$ 228	-	$ -	$ 2,035	-	$ -
B19	$ 14	-	$ -	$ 53	-	$ -	$ 84	-	$ -
B31	$ 22	-	$ -	$ 84	-	$ -	$ 190	338	$ 63,995
B34	$ -	-	$ -	$ -	-	$ -	$ -	-	$ -
Totals		**-**	**$ -**		**-**	**$ -**		**619**	**$ 106,447**

Table 6.23 -- Summary of reduction unit costs, target reductions and estimated annual cost to reduction targets for nitrogen, phosphorus, and suspended sediment, based on MapShed analysis, for the Brandywine Creek, West Branch watershed.

	TN			TP			TSS		
Sub-shed	**Cost per kg**	**Target reduction (kg)**	**Total cost to target**	**Cost per kg**	**Target reduction (kg)**	**Total cost to target**	**Cost per kg**	**Target reduction (kgx1000)**	**Total cost to target**
B01	$ 10	40,151	$ 382,592	$ 65	1,621	$ 105,432	$ 197	-	$ -
B02	$ 7	7,309	$ 54,385	$ 38	-	$ -	$ 87	-	$ -
B03	$ 8	1,083	$ 8,413	$ 39	-	$ -	$ 98	-	$ -
B04	$ 89	-	$ -	$ 249	-	$ -	$ 393	4	$ 1,546
B05	$ 6	7,060	$ 42,661	$ 33	524	$ 17,213	$ 83	105	$ 8,777
B06	$ 11	10,500	$ 114,648	$ 49	241	$ 11,733	$ 117	22	$ 2,590
B07	$ 10	-	$ -	$ 36	-	$ -	$ 71	-	$ -
B08	$ 11	-	$ -	$ 47	-	$ -	$ 105	-	$ -
B20	$ 11	-	$ -	$ 64	-	$ -	$ 159	-	$ -
B21	$ 9	-	$ -	$ 56	-	$ -	$ 160	-	$ -
B22	$ 10	-	$ -	$ 54	-	$ -	$ 147	-	$ -
B23	$ 7	-	$ -	$ 25	-	$ -	$ 53	-	$ -
B24	$ 10	-	$ -	$ 65	-	$ -	$ 264	-	$ -
B25	$ 11	-	$ -	$ 49	-	$ -	$ 95	-	$ -
B32	$ 10	605	$ 5,943	$ 60	-	$ -	$ 185	-	$ -
B33	$ 9	906	$ 7,905	$ 44	-	$ -	$ 103	-	$ -
Totals		**67,614**	**$ 616,547**		**2,386**	**$ 134,377**		**132**	**$ 12,912**

Table 6.24 -- Summary of reduction unit costs, target reductions and estimated annual cost to reduction targets for nitrogen, phosphorus, and suspended sediment, based on MapShed analysis, for the Brandywine Creek, East Branch watershed.

	TN			TP			TSS		
Sub-shed	**Cost per kg**	**Target reduction (kg)**	**Total cost to target**	**Cost per kg**	**Target reduction (kg)**	**Total cost to target**	**Cost per kg**	**Target reduction (kgx1000)**	**Total cost to target**
B09	$ 13	9,543	$ 125,954	$ 61	-	$ -	$ 149	-	$ -
B10	$ 9	9,621	$ 91,371	$ 45	-	$ -	$ 103	-	$ -
B11	$ 17	-	$ -	$ 76	-	$ -	$ 170	-	$ -
B12	$ 28	-	$ -	$ 121	-	$ -	$ 319	-	$ -
B13	$ 11	-	$ -	$ 62	-	$ -	$ 85	-	$ -
B14	$ 20	-	$ -	$ 67	-	$ -	$ 110	567	$ 62,098
B26	$ 9	-	$ -	$ 44	-	$ -	$ 73	-	$ -
B27	$ 9	-	$ -	$ 45	-	$ -	$ 75	-	$ -
B28	$ 17	-	$ -	$ 194	-	$ -	$ 3,932	-	$ -
B29	$ 20	-	$ -	$ 87	-	$ -	$ 139	-	$ -
B30	$ 14	-	$ -	$ 79	-	$ -	$ 141	-	$ -
B35	$ 14	-	$ -	$ 76	-	$ -	$ 178	-	$ -
Totals		**19,165**	**$ 217,325**		**-**	**$ -**		**567**	**$ 62,098**

Figures 6.35 to 6.39 present the estimated annual costs to meet target loads for the constituents of concern by watershed or branch. Nitrogen is generally represents the most costly pollutant to target, with higher costs further up in the watershed. This reflects the variable nature of the load across the watershed, and in particular the prevalence of agricultural land cover in the upper portions of each watershed. Note that sediment is not considered for sub-watersheds (or portions thereof) within the state of Delaware, which does not have a TMDL for sediment. The maps in Appendix B show the unit cost and total estimate cost to target for each constituent in all watersheds branches.

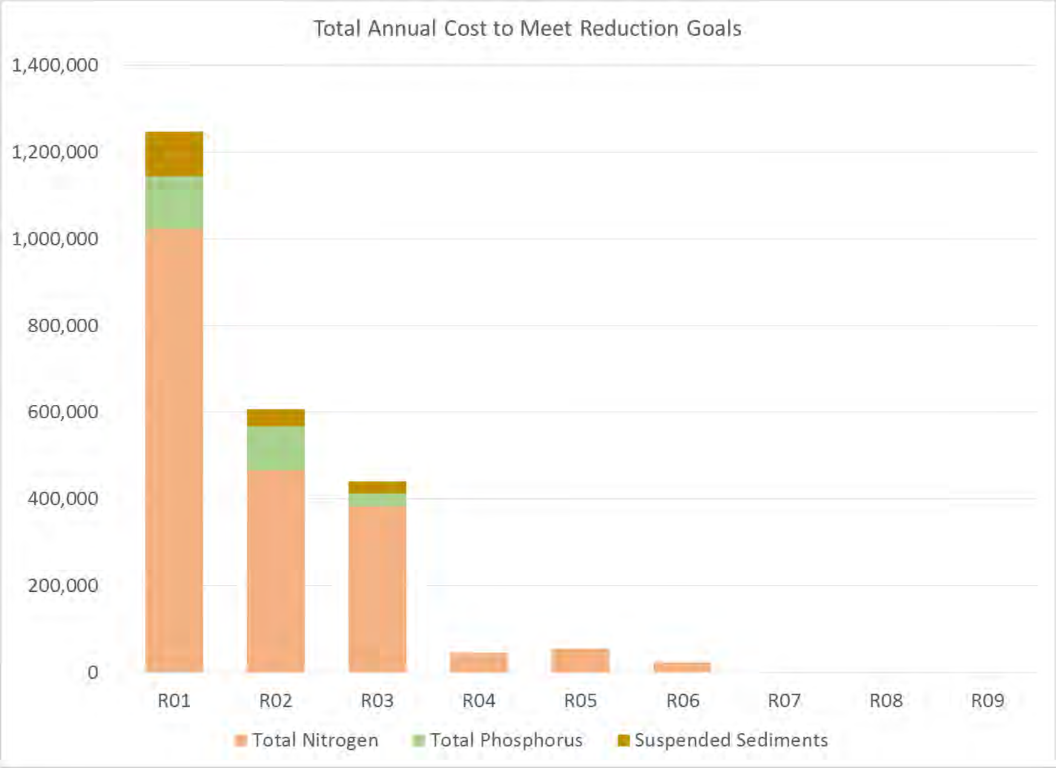


Figure 6.35 -- Total estimated annual cost to meet reduction goals for nitrogen, phosphorus, and suspended sediment, based on MapShed analysis for the Red Clay Creek watershed.

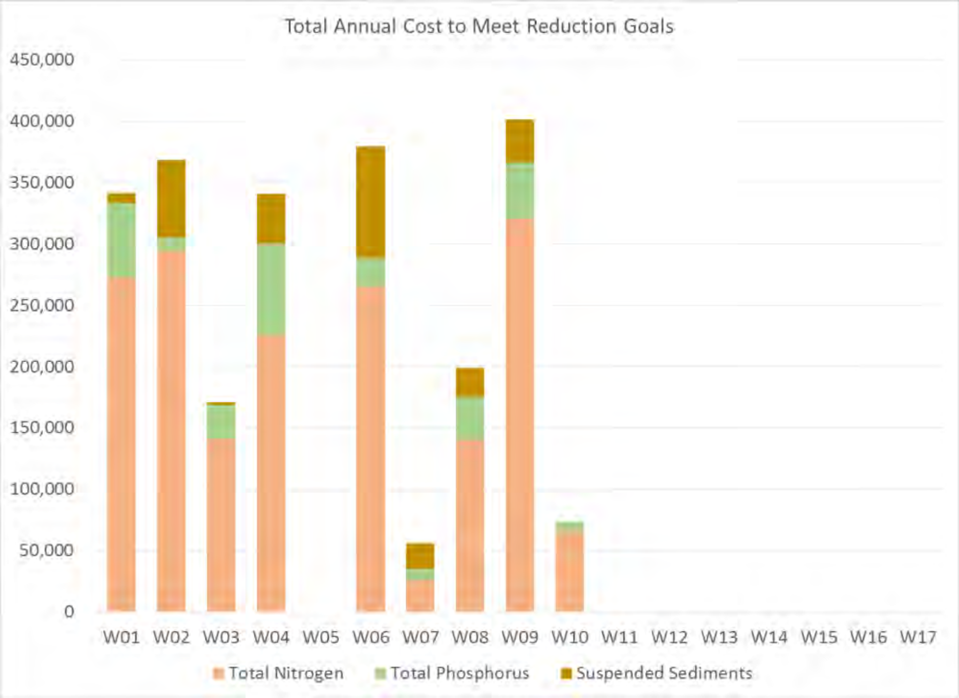


Figure 6.36 -- Total estimated annual cost to meet reduction goals for nitrogen, phosphorus, and suspended sediment, based on MapShed analysis for the White Clay Creek watershed.

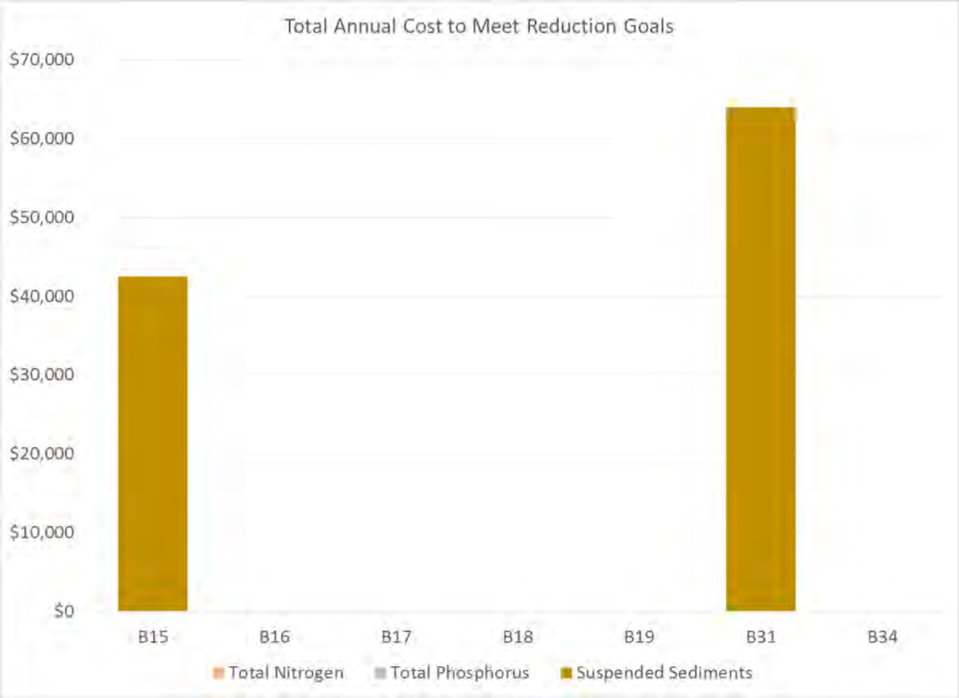


Figure 6.37 -- Total estimated annual cost to meet reduction goals for nitrogen, phosphorus, and suspended sediment, based on MapShed analysis for the Brandywine Creek, Main Stem watershed.

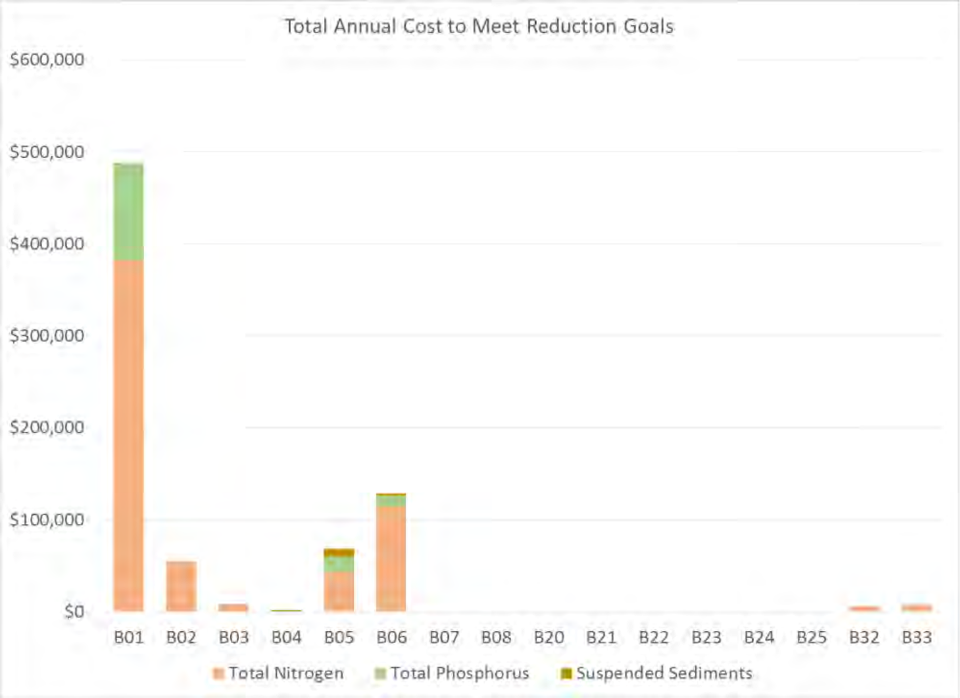


Figure 6.38 -- Total estimated annual cost to meet reduction goals for nitrogen, phosphorus, and suspended sediment, based on MapShed analysis for the Brandywine Creek, West Branch watershed.

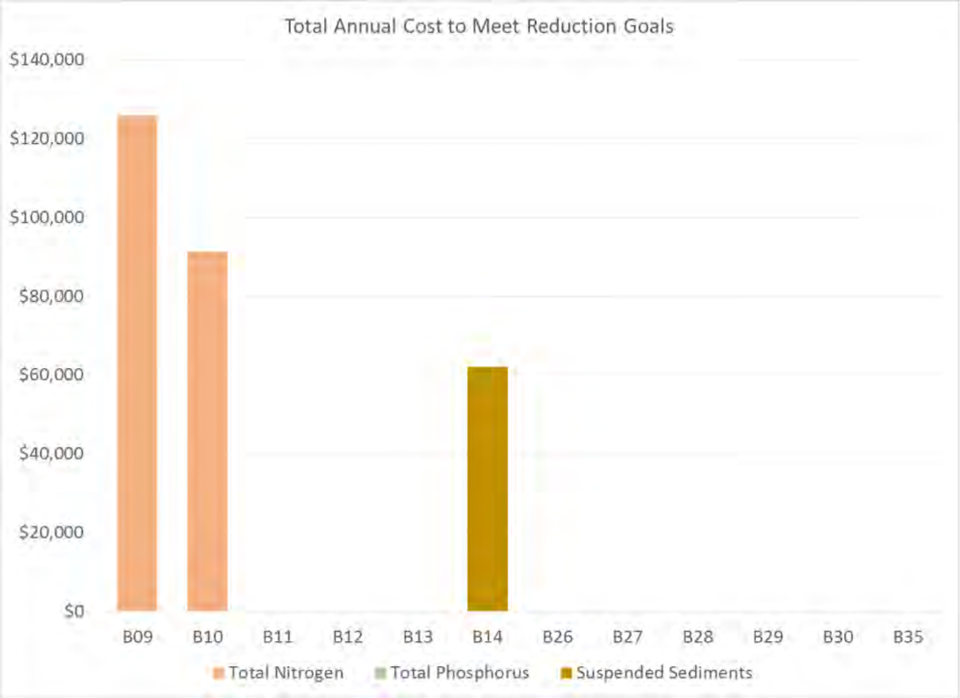


Figure 6.39 -- Total estimated annual cost to meet reduction goals for nitrogen, phosphorus, and suspended sediment, based on MapShed analysis for the Brandywine Creek, East Branch watershed.

Tables 6.25 to 6.29 summarize the estimated target reductions by constituent and the estimated annual costs to meet those targets, on a 20 year time-frame.

Table 6.25 -- Summary of target reductions and estimated cost to targets, based on MapShed analysis for the Red Clay Creek watershed.

Red Clay Creek

Constituent	Target reduction	Unit	Cost to target
Nitrogen	87,818	kg	$1,987,212
Phosphorus	6,388	kg	$254,247
Sediment	1,658	kgx1000	$169,388
			$2,410,847

Table 6.26 -- Summary of target reductions and estimated cost to targets, based on MapShed analysis for the White Clay Creek watershed.

White Clay Creek

Constituent	Target reduction	Unit	Cost to target
Nitrogen	142,965	kg	$1,735,518
Phosphorus	5,239	kg	$277,301
Sediment	1,491	kgx1000	$252,954
			$2,265,773

Table 6.27 -- Summary of target reductions and estimated cost to targets, based on MapShed analysis for the Brandywine Creek, Main Stem watershed.

Brandywine, Main Stem

Constituent	Target reduction	Unit	Cost to target
Nitrogen	0	kg	$-
Phosphorus	0	kg	$-
Sediment	619	kgx1000	$106,447
			$106,447

Table 6.28 -- Summary of target reductions and estimated cost to targets, based on MapShed analysis for the Brandywine Creek, West Branch watershed.

Brandywine, West Branch

Constituent	Target reduction	Unit	Cost to target
Nitrogen	67,614	kg	$616,547
Phosphorus	2,386	kg	$134,377
Sediment	132	kgx1000	$12,912
			$763,836

Table 6.29 -- Summary of target reductions and estimated cost to targets, based on MapShed analysis for the Brandywine Creek, East Branch watershed.

Brandywine, East Branch

Constituent	Target reduction	Unit	Cost to target
Nitrogen	19,165	kg	$217,325
Phosphorus	0	kg	$-
Sediment	567	kgx1000	$62,098
			$279,423

RIOS/InVEST

The Resource Investment Optimization System (RIOS) (Vogel, et al. 2015) is a suite of modeling tools developed by the Natural Capital Project, a collaboration among Stanford University, the University of Minnesota, The Nature Conservancy, and the World Wildlife Fund to provide water fund managers answers to questions about the most efficient use of resources to meet specific water quality goals at the least cost.

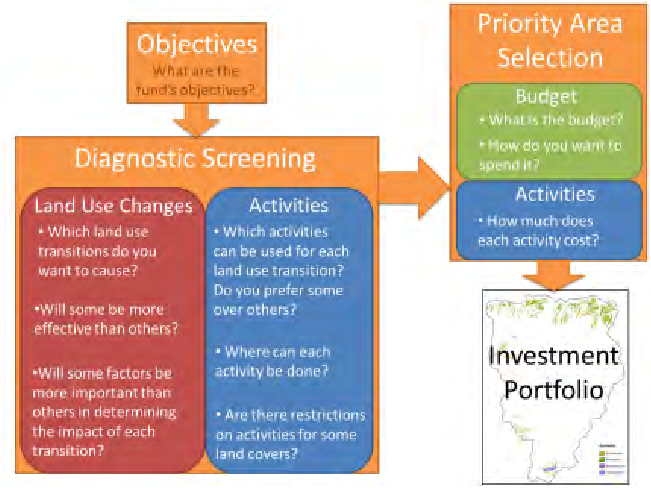


Figure 6.40 -- RIOS schematic design (http://www.naturalcapitalproject.org/pubs/RIOS_brief.pdf).

The modeling tools allow the definition of multiple objectives (e.g., nutrient reduction, habitat protection, erosion control, etc.) and a suite of strategies (e.g., BMPs or land use policies) to determine the most cost effective use of the strategies to meet the objectives. In concert with the Integrated Valuation of Environmental Services and Tradeoffs (InVEST) (Sharp, et al. 2016) tool, the effectiveness of the strategies identified can be evaluated. Water managers can therefore determine 1) what the best suite of approaches is to address particular objectives (taking into account bio-physical, socio-cultural, and legal situations), 2) what the expected return is on investment (in terms of either monetary or natural capital), and 3) whether the outcomes from the expenditure of resources offer improvement from the status quo.

This modeling approach has been applied to the Brandywine-Christina basin to help understand the optimal allocation of agricultural strategies (erosion control for sediment, and nutrients) within the watersheds of the Brandywine-Christina. Given a fixed level of funding across a 30 year time horizon, several scenarios were considered: a fixed budget for each strategy (so that all strategy is represented), and a fixed area, so that each approach is allocated equivalent level of implementation.

The full report on the outcomes of the RIOS/InVEST modeling process is presented in Appendix C.

Agricultural parcels inventory

Collaboration with the Chester County Conservation District

Ultimately, when applying agricultural water quality improvement strategies on the ground, there must be available farms (and willing farmers) on which to implement projects. Compiling an inventory of farms in the Brandywine-Christina is not straightforward, however, since the information is often not publicly available (i.e., through the USDA's Natural Resources Conservation Service, or NRCS, the responsible agency).

Through a close collaboration with the Chester County Conservation District (CCCD), the Water Fund team assessed the potential for inventorying the current status and level of implementation for BMPs and Conservation Plans on farms in Chester County (most of the agricultural land in the Brandywine-Christina basin lies in Chester County). The CCCD provided a list of standard, approved BMPs that they implement, see Table 6.30.

Table 6.30 -- Suite of BMPs typically implemented by the CCCD.

BMP Type
Conservation Plan/MFEMP*
Nutrient Management Plan (DEP)
Cover Crops
Conservation Tillage
Contour Plowing
Riparian Buffers
Stream Fencing
Vegetated Buffer
Terracing

Tree Planting
Sprayfields
Constructed Wetlands
Collection and Storage System
Animal Waste System
Nutrient Transport
Training & Outreach
10 year O&M

* Mushroom farm environmental management plan

Currently, the Water Fund is working to compile data on the level of implementation and average or overall costs of these practices. The Water Fund team plans to continue the collaboration with the CCCD to identify farms with the potential to provide water quality benefits by implementing cost effective strategies.

Additionally, based on work by the University of Delaware Geography Department, the locations of mushroom farms were compiled in a spatial file. However, while all mushroom farms in the county have a management plan that is publically available, non-mushroom farm plans are protected from public access. This makes assessment of in-ground BMP implementation problematic, and means that the precise locations of farm parcels is not readily available.

GIS Processing

To overcome the limitations of ascertaining farm locations from an inventory of plans or from other direct sources, it was determined possible to infer the location of farm parcels using GIS processing techniques.

Using tax parcel information for Pennsylvania (Chester County) and Delaware (New Castle County), it is possible to overlay independent land use data (compiled by the Delaware Valley Regional Planning Commission (Delaware Valley Region Planning Commission 2010) and the State of Delaware (State of Delaware 2012) and thereby determine which parcels are likely to be farms. See Appendix D for a description of this methodology.

The data for farms was further divided into mushroom farms, non-mushroom farms, and wooded portions of farm parcels by using both the GIS layer of mushroom farms (see above) and land cover information plus aerial photography. Finding the intersection of these data with streams (from the USGS National Hydrography Dataset, or NHD) it was further possible to determine which farms contained stream segments (both wooded and non-wooded) that could provide the opportunity for water quality projects. This information can then be used to identify sub-watersheds most suitable to target for agricultural BMP implementations through the Water Fund to maximize impact on water quality.

The map in Figure 6.41 shows the farmland in the Brandywine-Christina basin categorized using this methodology. Mushroom farms, non-mushroom farms, and wooded portions of farms. Mushroom and non-mushroom are color-coded. Blue triangles indicate the locations of surface drinking water intakes. Intakes downstream from areas of intensive farm activity will be most highly affected by water quality impacts (high nitrogen, phosphorus, and sediment levels). Reductions on these farms will have a direct positive effect on water quality at those intakes, and a potential cost savings in terms of cost of treatment and avoided costs such as service disruptions and energy costs to pump from off-stream sources (e.g., reservoirs).

Figure 6.42 shows a more detailed version of the data, for the White Clay Creek watershed above the City of Newark drinking water intake. In addition to farmland and intakes, this map also shows focus areas for the DRWI Brandywine-Christina cluster partnership, and stream segments on the 303(d) list of impaired streams that pass through farm parcels. Those streams are of particular concern in reducing pollutant levels and achieving clean water goals.

The maps in Figures 6.43 and 6.44 show the total number of farms and the farm acreage within each sub-watershed in the Brandywine-Christina basin. The maps in Figures 6.45 and 6.46 show the total stream miles in farms of the Brandywine-Christina basin, by streams that flow through the non-wooded and wooded portions of farms. The darker the color in these maps the higher the value of the parameter being mapped (number of farms, acreage of farms, stream miles).

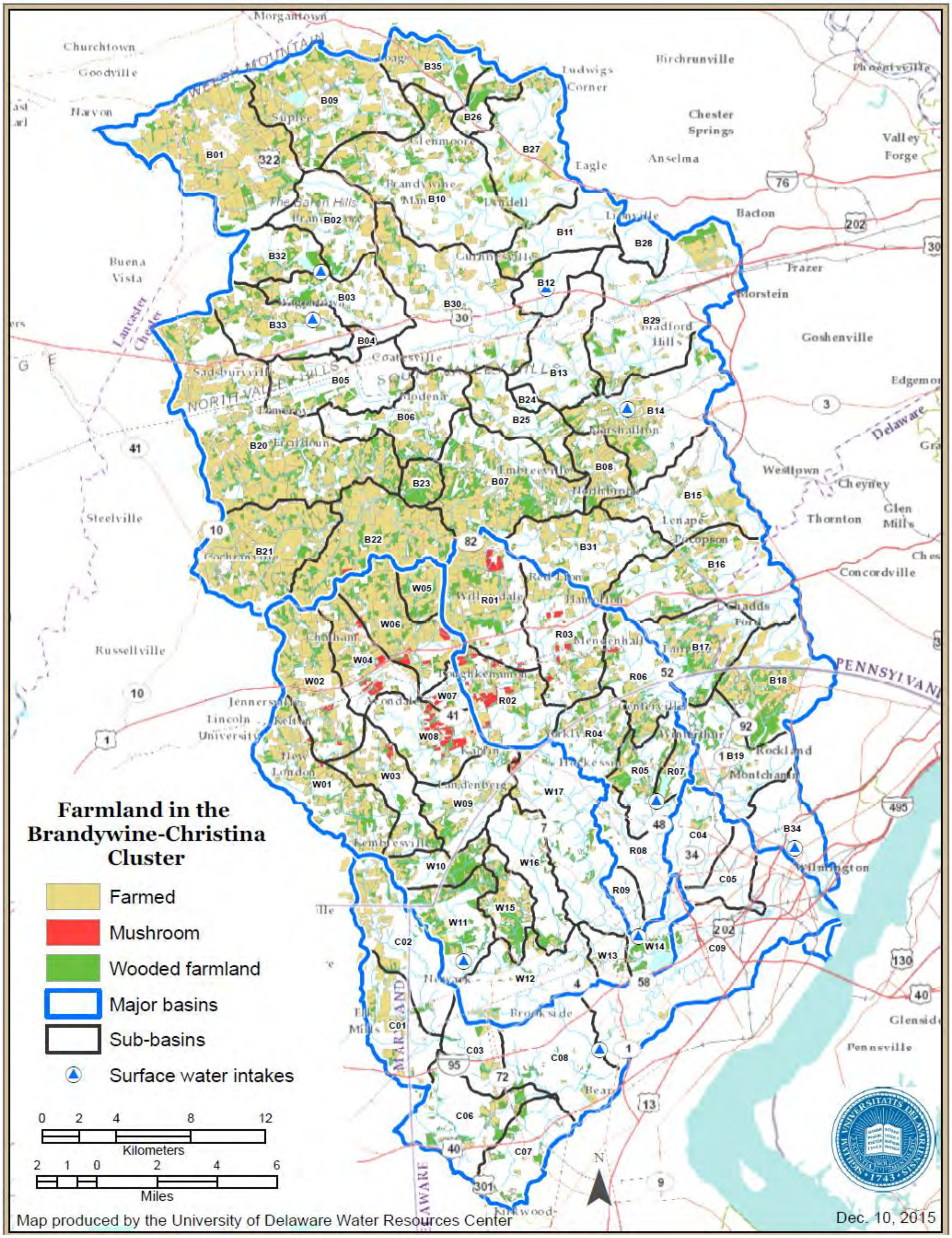
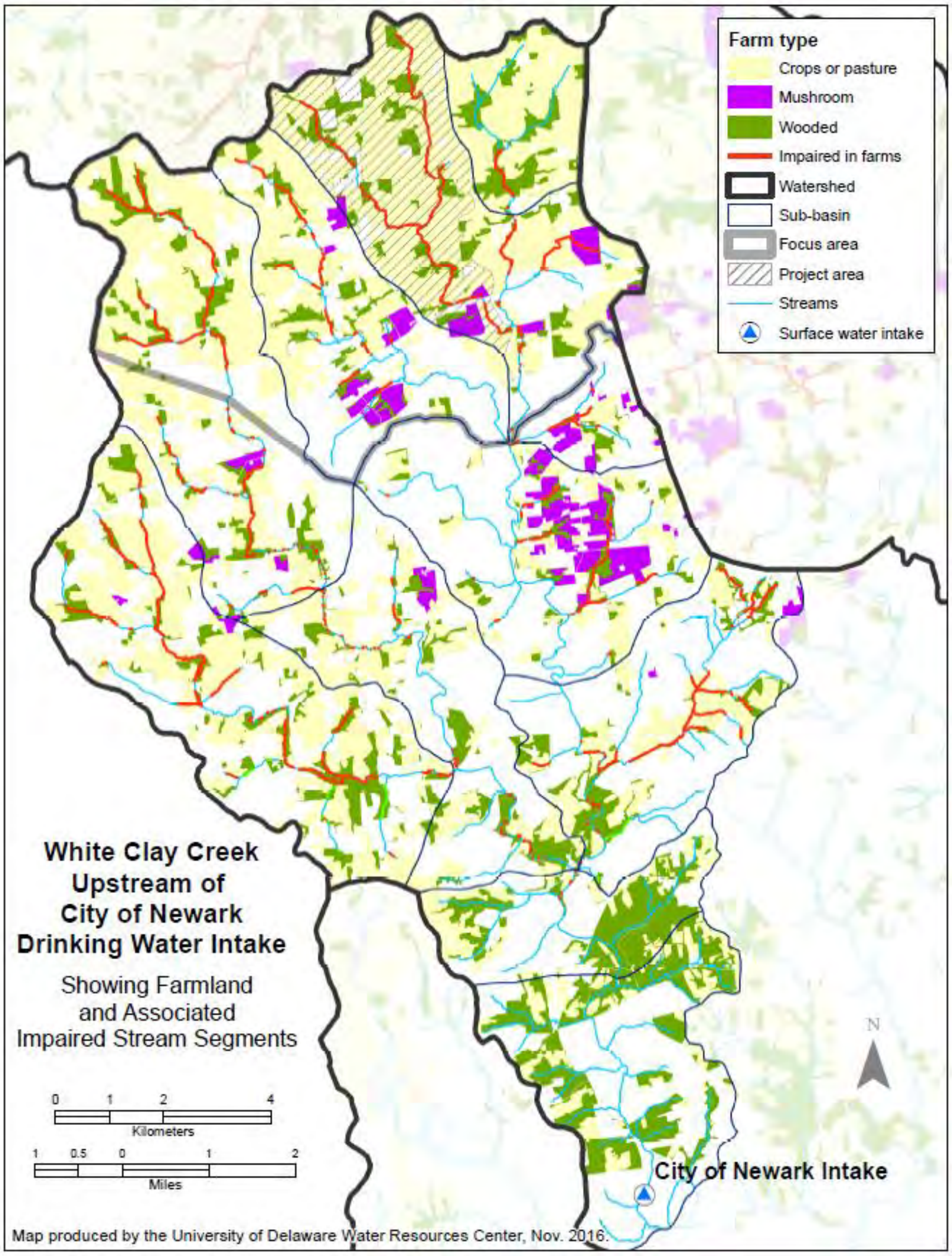


Figure 6.41 -- Farms in the Brandywine-Christina Basin, showing surface drinking water intakes, watersheds, and catchments.



Map produced by the University of Delaware Water Resources Center, Nov. 2016.

Figure 6.42 -- Detail of farms (wooded and non-wooded portions) in the White Clay Creek watershed upstream of the City of Newark surface drinking water intake, showing impaired stream segments within farm parcels.

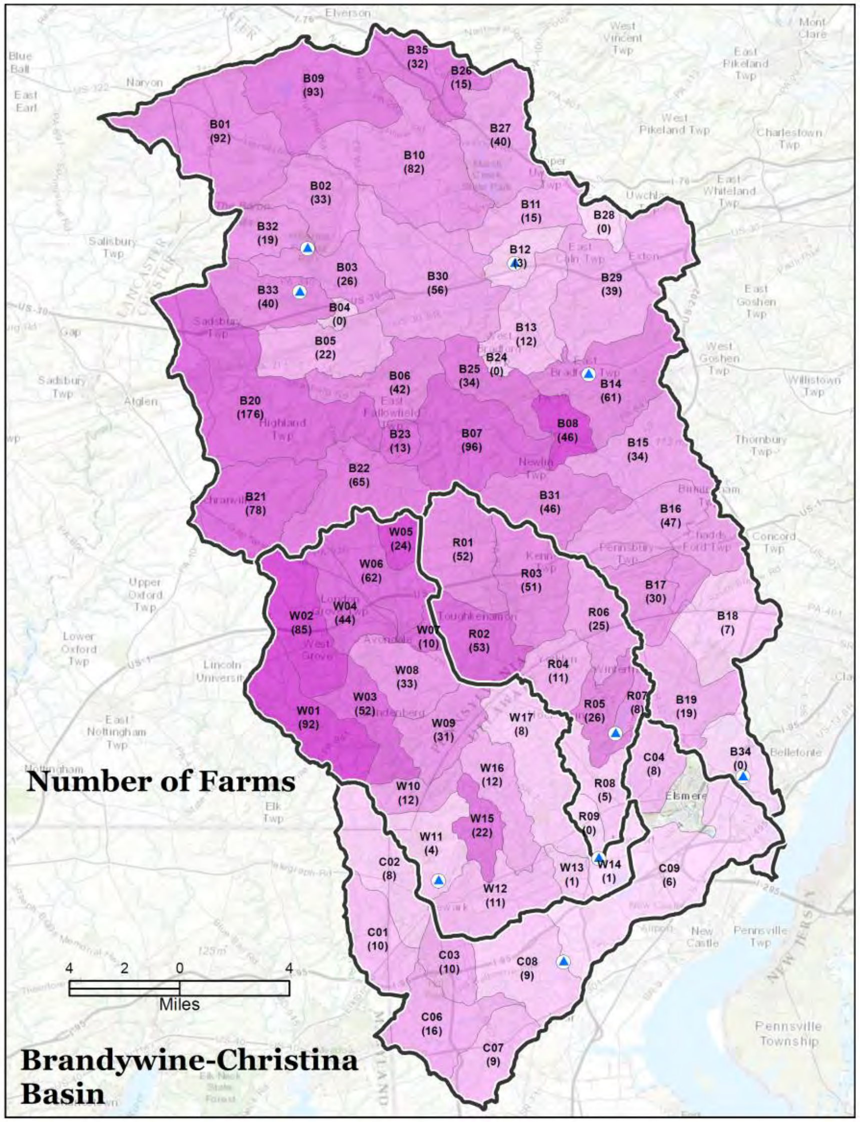


Figure 6.43 -- Number of farms in the Brandywine-Christina Basin, by catchment. Colors are normalized by area, darker colors indicate more farms per unit area.

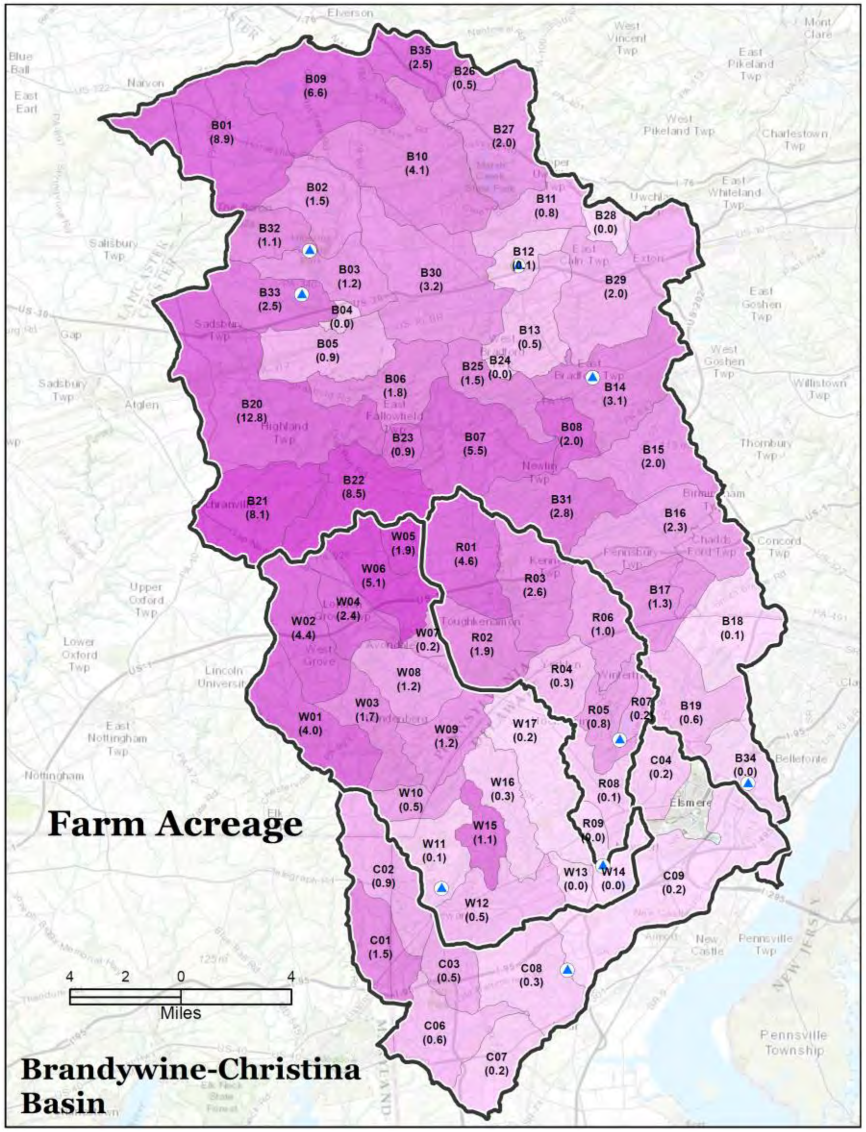


Figure 6.44 – Area of farms in the Brandywine-Christina Basin, by catchment. Colors are normalized by area, darker colors indicate more farm acreage per unit area.

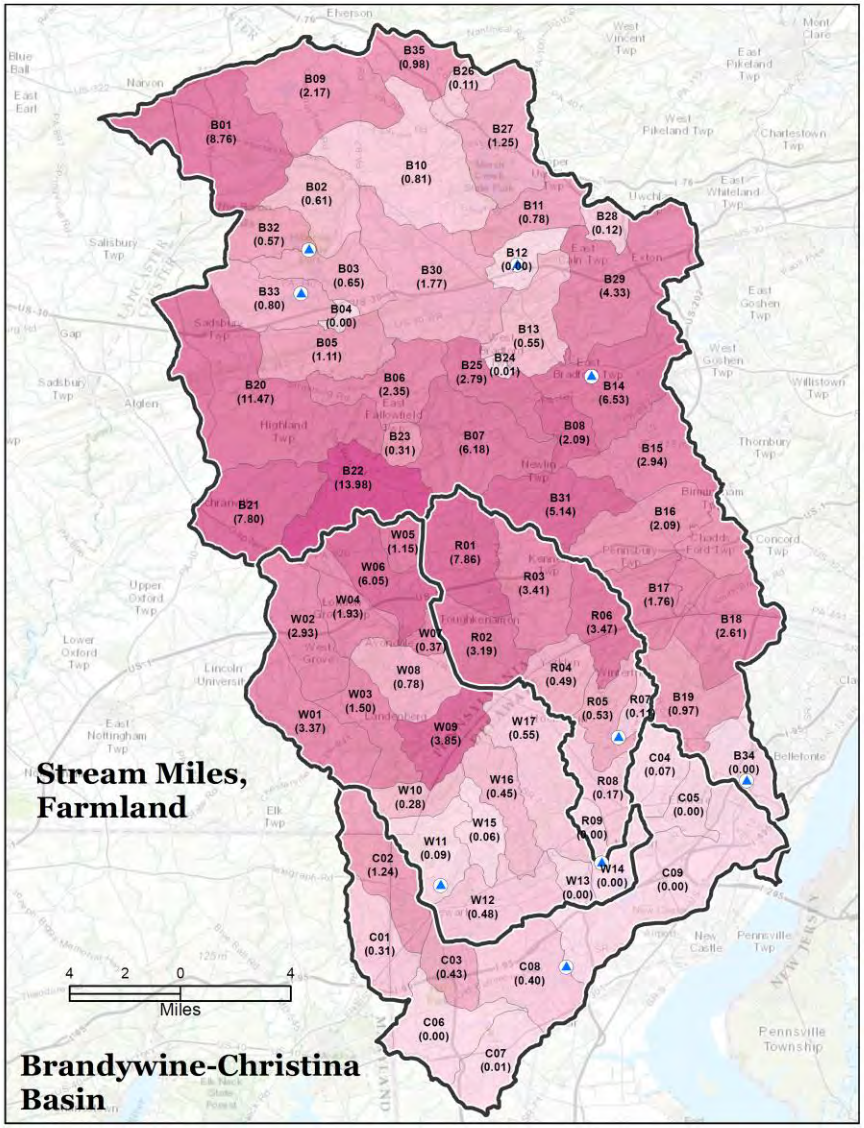


Figure 6.45 – Stream miles in farms in the Brandywine-Christina Basin, by catchment. Colors are normalized by area, darker colors indicate more streams per unit area of non-wooded portions of farms.

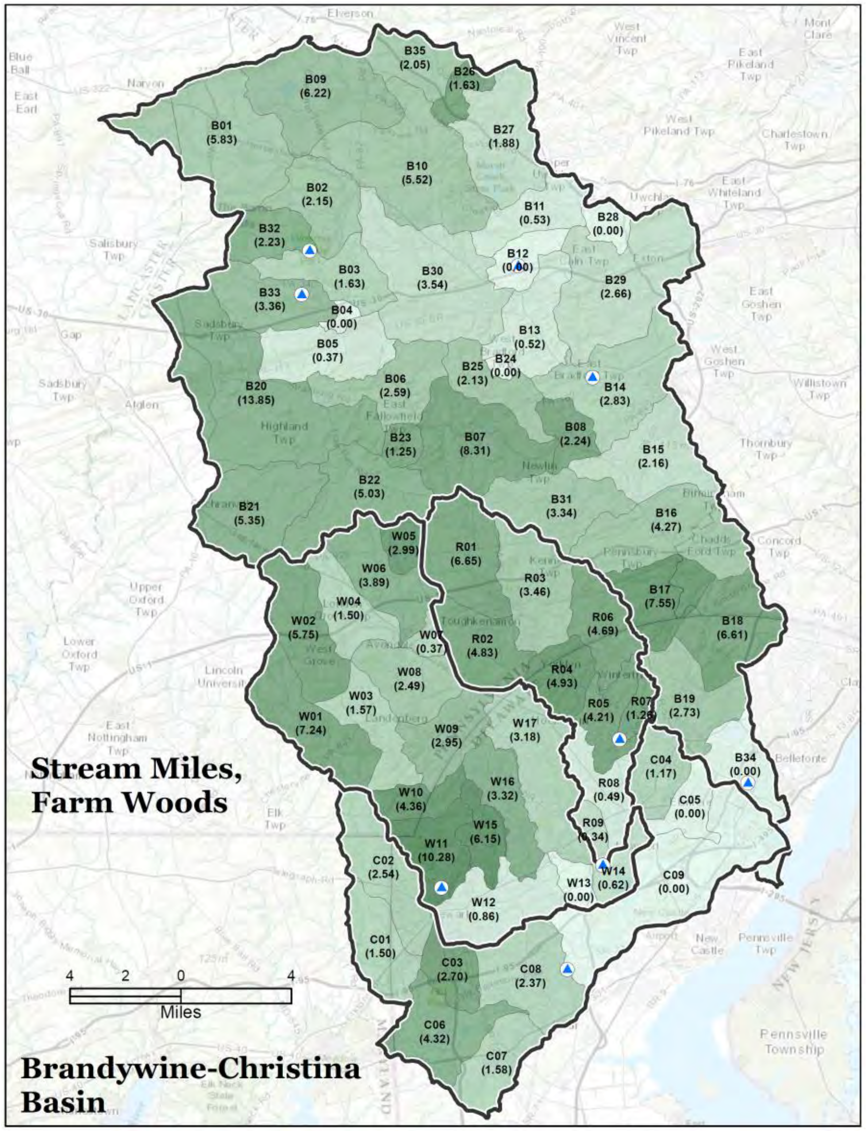


Figure 6.46 -- Stream miles in farms in the Brandywine-Christina Basin, by catchment. Colors are normalized by area, darker colors indicate more streams per unit area of wooded portions of farms.

Figure 6.47 shows the number of farms, by watershed within the Brandywine-Christina basin, and Figure 6.48 shows the total farm acreage, categorized by type (mushroom, non-mushroom, and wooded portions of farms). Figures 6.49 and 6.50 present the stream mileage within farmland, including the wooded and non-wooded portions of farms, by watershed and by county.

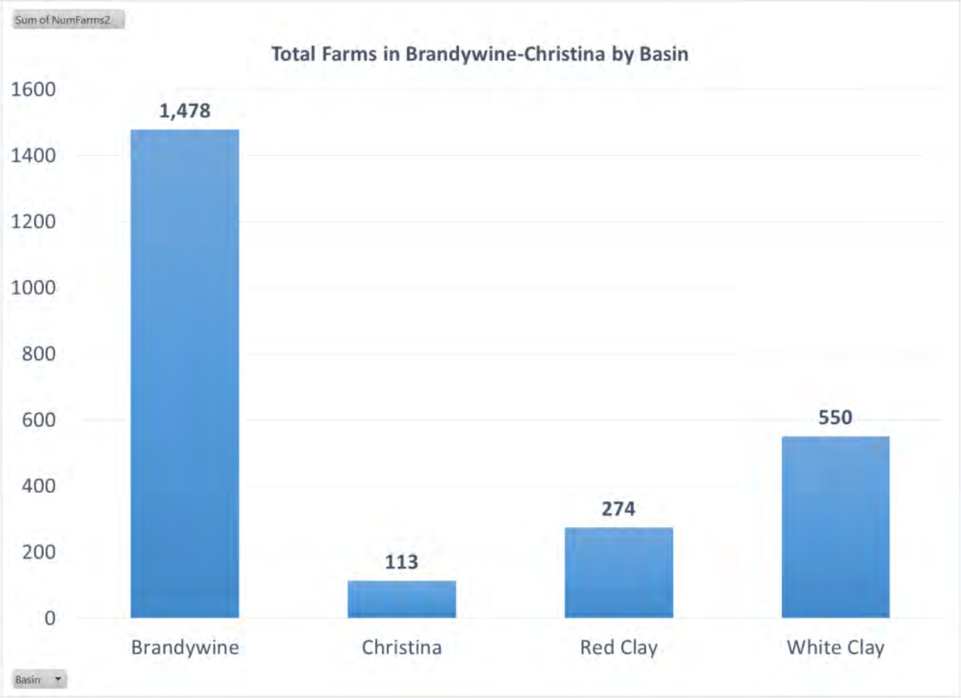


Figure 6.47 -- Number of farms, by watershed, in the Brandywine-Christina Basin.

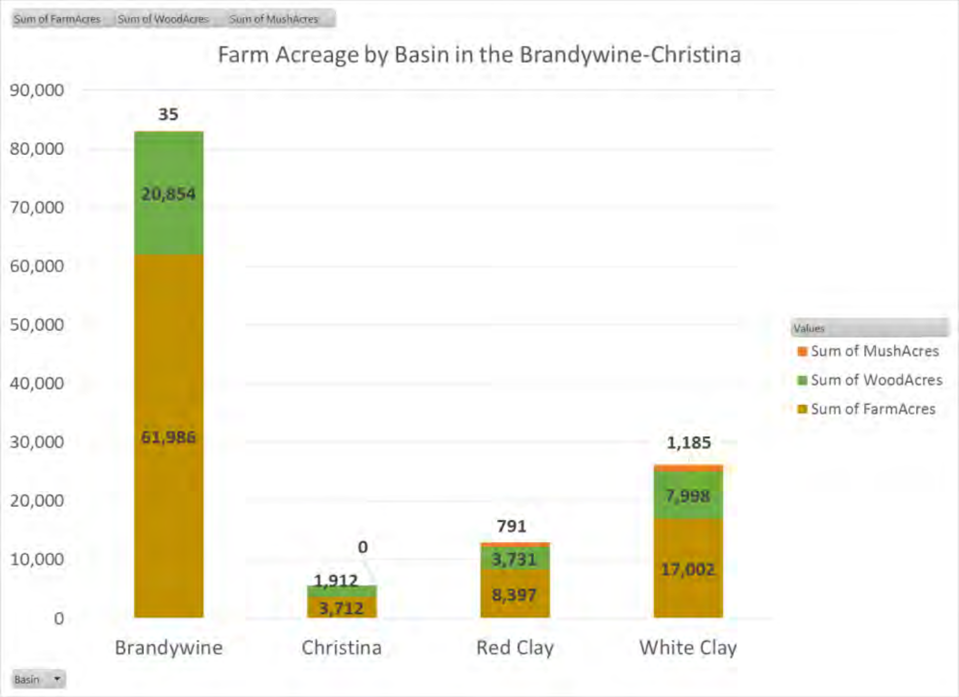


Figure 6.48 – Farm acreage, by watershed, in the Brandywine-Christina Basin.

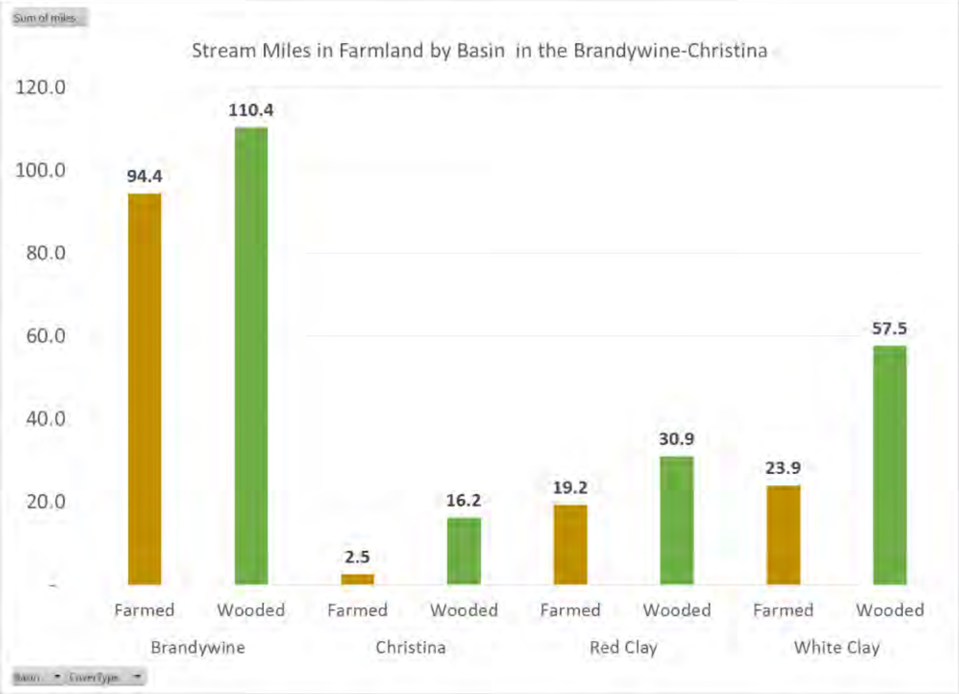


Figure 6.49 – Stream miles, by watershed, in the Brandywine-Christina Basin, in wooded and non-wooded portions of farms.

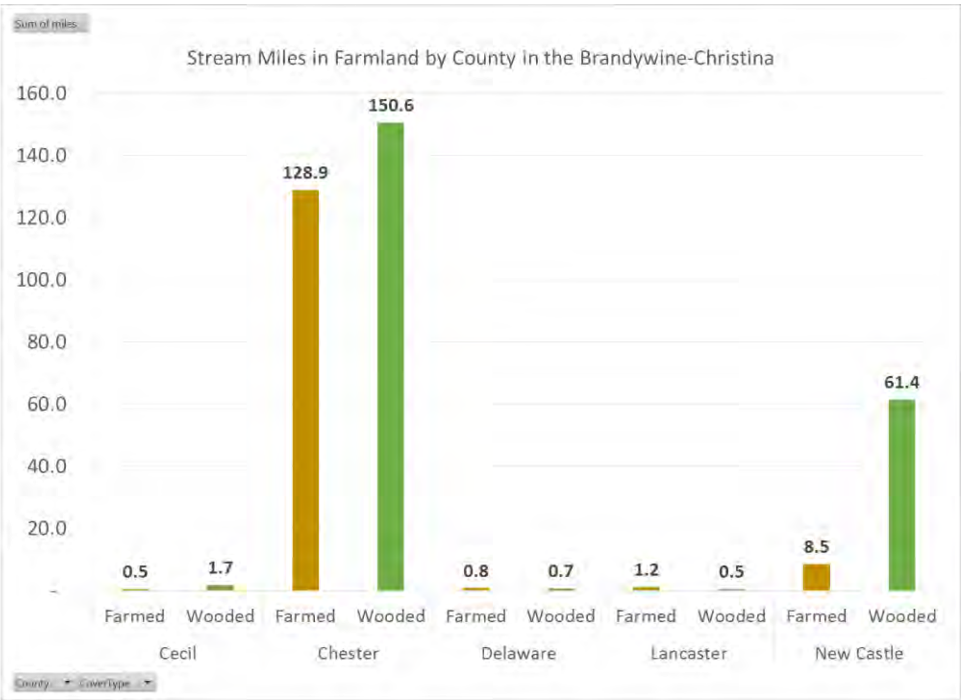


Figure 6.50 – Stream miles, by county, in the Brandywine-Christina Basin, in wooded and non-wooded portions of farms.

Figure 6.51 represents the total number of farms and acreage of farms (wooded and non-wooded portions) containing stream miles impaired for sediment in the White Clay Creek watershed. These farms would be of particular importance in addressing water quality goals in the watersheds of the Brandywine-Christina basin.

This example is presented to guide efforts at prioritizing pilot projects to address water quality at the City of Newark surface drinking water intake. Focusing effort on high-priority farms contributing the highest levels of nutrients and sediments will determine if targeted inputs of capital in a limited number of farms can be an effective tool in making substantive improvements to water quality downstream. If such improvement is achievable the economics related to water purveyors' targeted investments upstream through the Water Fund become more persuasive. Monitoring and measurement becomes critical to making this economic argument for investments in high priority farms upstream of surface water intakes.

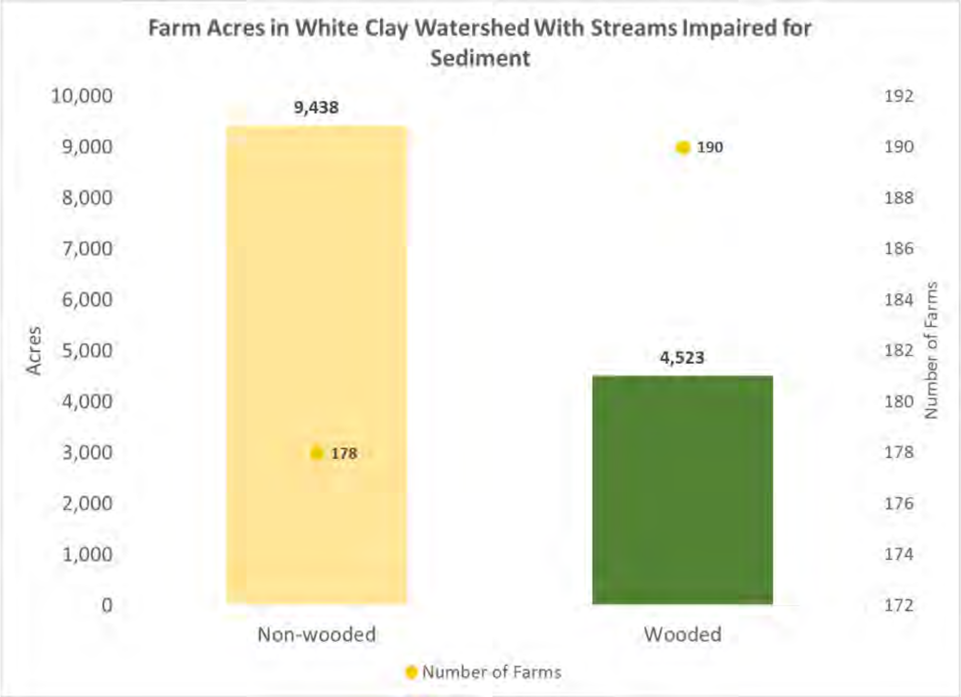


Figure 6.51 – Farm acres and number of farms, or portion of farms by land cover (wooded or non-wooded) in the White Clay Creek watershed upstream of the City of Newark surface drinking water intake..

Partnerships

Final implementation of the Water Fund will require an independent body to review potential projects, set priorities, and monitor progress. This group will be composed of partner members from within the watersheds of the Brandywine-Christina Basin with a stake in clean water. This body, or board, will be responsible for evaluating projects, guiding the functioning of the Water Fund, setting and reviewing priorities, and overseeing the monitoring program to assess the Water Fund's performance in terms of meeting water quality goals. The following list represents component members of the Water Fund stakeholder group.

- *Steering Committee* – The Steering Committee was formed to provide feedback in the modeling and technical analysis and to help guide the Water Fund Business Plan. The group is composed of water purveyors (representatives from the City of Wilmington, City of Newark, Suez Delaware, Aqua PA, Pennsylvania American, Downingtown Borough, and Honey Brook Borough), jurisdictions regulated under NPDES stormwater permitting requirements (New Castle County, Delaware Department of Transportation, the City of Wilmington, the City of Newark, and the University of Delaware in Delaware, and a representative of the municipalities in Pennsylvania through the Christina Watersheds Municipal Partnership, or CWMP, formerly Christina TMDL Implementation Partnership, or CTIP). This group has met four times—September 22nd, 2015, March 3rd, 2016, November 30th, 2016, and May 4th, 2017. Individual meetings with the Delaware and the Pennsylvania water purveyors were also conducted on May 5th, 2016 (Delaware) and July 14th, 2016 (Pennsylvania).

- *Select Advisory Panel Members* – In the course of the Water Fund Feasibility Study a group of stakeholders was engaged to help guide the process, serving as an Advisory Panel. Several key members of this group could also be engaged in the process of prioritizing strategies and locations for project implementation. These partners should include representatives from the Chester County Conservation District (CCCD), the Chester County Water Resources Authority (CCWRA), the New Castle County Conservation District (NCCCD), and the Delaware Department of Natural Resources and Environmental Control (DNREC).
- *Cluster Partners* – The members of the Brandywine-Christina DRWI cluster are critical to help coordinate and direct the development and implementation of the Water Fund. Cluster partners include the Brandywine Conservancy, Stroud Water Research Center, Brandywine Red Clay Alliance, and Natural Lands Trust. These entities will be implementing and monitoring the progress of projects funded through the Water Fund. It is therefore important that these organizations continue in their partnership role throughout the development and maturation of the Water Fund.

7. Discussion and implications

The modeling effort undertaken for the Water Fund included many components over several years. The Technical and Modeling team considered literature on methods for determining baseline loads and required reductions, and drew on many past modeling efforts and monitoring programs to determine realistic values. It is never possible to predict the precise level of loading in streams, nor the reductions achieved and total costs of implementing BMPs. There are simply too many variables and unknowns involved to arrive at exact numbers. However, by looking at past predictions and analyses, and comparing these to observed values in the field, it is possible to arrive at predictive values that are useful for planning purposes, and to be able to assess the overall cost effectiveness of proposed water quality strategies.

The Team looked at work performed in the basin over the past several decades, including the TMDL-based methods for determining waste load allocation standards, USGS modeling work through SPARROW, work sponsored by the William Penn Foundation for calibrated predictive models using SWAT, as well as a project siting and cost-benefit analysis through the RIOs/InVEST modeling process.

Based on the fact that the PADEP and other agencies were committed to using the MapShed model for determining TMDL compliance, that model was chosen to analyze pollutant loads (of sediment, phosphorus, and nitrogen) in the basin, and calculate the reduction potential along with predicted costs for implementing agriculturally-based BMPs to achieve water quality goals set forth by the USEPA. Much of the effort in calibrating the model to the Brandywine-Christina basin was supported by the William Penn Foundation (including its extension in the subsequent phase of the DRWI effort through development of the Stream Reach Assessment Tool, SRAT, and the Model My Watershed suite of online tools), and implemented by Penn State, the PADEP, and the CCWRA.

Baseline loads

The MapShed model was implemented on a small catchment scale across the Brandywine-Christina basin. The first step in using this model was to determine the "pre-BMP" baseline loads predicted using land cover data and other related information. Each catchment within the four watersheds of the basin were assessed to predict levels of nitrogen, phosphorus, and sediment in streams before any treatment by BMPs had occurred.

Next, by modeling the level of pollution in streams as of 2012, and applying the percentage reductions specified in the TMDL for each catchment, it was possible to determine how far from achieving clean water standards each catchment was. This enabled ranking of each catchment based on both its total load as well as its potential to reach water quality goals.

This effort reinforced the findings of the TMDL process, that there were considerable impacts from the upper reaches, in the most highly agricultural areas of the basin.

Targeted reductions

To determine how far a catchment was from achieving its water quality goals defined in the TMDL document, required reductions expressed as a percentage were applied to the baseline ("pre-BMP") loads. By using the calibrated values for "current" (2012) loads, including all BMPs installed since the baseline calculation, the remaining load reduction required to meet water quality goals was determined.

The highest level of required reductions for nitrogen, phosphorus, and sediment were in those agricultural areas where the opportunity for BMP implementation is greatest due to the availability of land and the relatively low cost of strategies.

Costs to achieve targets

Determining the costs to achieve clean water is among the most important component of the modeling and technical analysis for the Water Fund. In order to determine the level of funding required to make a difference in the watershed, it is necessary to know that the money that might become available will be sufficient to achieve water quality improvement goals.

Based on the analysis, annual funding levels of between $2 and $2.5 million in White and Red Clay Creek watersheds, and approximately $1 million in the Brandywine Creek watershed will be required. These numbers are based on the assumption that future reductions, given a modeled reduction based on known levels of agricultural BMP implementation, will be commensurate with the equivalent implementation of additional agricultural BMPs.

Focusing on agriculturally-based BMPs is a key component of the Water Fund in its initial stages, since the costs for achieving similar reductions with “grey-infrastructure”, or traditional urban BMPs, can be two orders of magnitude higher. Increased capitalization of the Water Fund, including through large-scale impact investing will likely make urbanized stormwater control efforts a more viable alternative strategy for the Water Fund in the future.

Targeting farms

Based on experience and research, the focus on farms as the basis for BMP implementation has guided both the Water Fund’s development and the modeling and technical analysis underlying the Water Fund.

Collaboration with on-the-ground partners such as the Chester County Conservation District, along with in-house GIS and remote sensing analysis has enabled the development of a robust database of farm properties in the Delaware and Pennsylvania portions of the Brandywine-Christina Basin. Assistance in determining the location and ownership of farm parcels was also provided by the CCWRA. These efforts, along with knowledge and personal contacts cultivated over years and decades by cluster partners such as the Brandywine Conservancy, Brandywine Red Clay Alliance, Stroud Water Research Center, and Natural Lands Trust will provide the basis for developing a focused, farm-based strategy to target specific land owners and properties in critical areas.

The Fund will undertake a pilot project in the White Clay Creek watershed to determine the feasibility of targeted project implementation to impact downstream water quality in a meaningful and measureable way. This tactic will then be expanded to other key areas across the watersheds of the basin.

Providing value to stakeholders

Initially, the capitalization for the Water Fund will rely on both traditional water quality grants (this is the model the Water Fund seeks to move away from, in favor of a more sustainable model), and on input from direct and immediate beneficiaries of projects undertaken by the Water Fund. Those initial stakeholders are the water purveyors, who rely on clean and abundant surface water in streams to serve their customers, and the municipal MS4 communities, who have an unfunded mandate to implement stormwater BMPs and achieve specific, quantified water quality goals.

Both sets of stakeholders have been engaged through the Water Fund creation and have been instrumental in helping to guide the modeling and technical analysis process. The water purveyors recognize an immediate benefit to clean water. As we have seen, several are already investing money upstream to effect cleaner water at their intakes, which helps lower their processing costs. By providing a conduit for these annual funds to be channeled to the most cost-effective use, the Water Fund will help leverage and pool those investments along with others to expeditiously and efficiently reduce pollution in streams. It is critical that the Water Fund can provide demonstrably favorable cost to benefit for these water purveyors in order that they will continue to help capitalize the Water Fund.

The municipalities and other entities in Delaware and Pennsylvania who are required to develop plans and implement projects to achieve water quality targets are also key stakeholders in the initial stages of the Water Fund. Modeling has shown that urban BMPs, while effective at reducing pollution and controlling flow volumes, are often costly in comparison to agricultural measures. Current trends in the regulatory frameworks may allow funds to support BMPs in non-urbanized (i.e., agricultural) portions of regulated areas. In that case the argument both for the use of Fund capital to be invested in MS4 municipalities, as well as the capitalization of the Water Fund by those regulated entities becomes more compelling.

Complementing Cluster partners

A key element of the Water Fund's implementation is its close alignment with the Brandywine-Christina Cluster partners. These partners are co-grantees in the William Penn Foundation DRWI grant, therefore all priorities related to Water Fund efforts in the Brandywine-Christina Basin must align precisely with those of the Cluster partners.

All aspects of the Water Funds activities have been developed in close cooperation with the Cluster. The Cluster's members are the organizations that will be funded with capital from the Water Fund to implement projects both within the scope of the William Penn Foundation grant and beyond. Existing Cluster partner relationships with land owners, communities, and regulators will be critical to ensuring the Water Fund's viability. Cluster partners will be coordinating strategies, implementing BMPs, and monitoring the results.

As part of the Phase II planning process within the Cluster the initial "Focus Areas", or areas of interest within which it has been determined that projects will have the most impact for the lowest cost were refined. The Water Fund team has been an integral participant in the planning process. The revised Focus Areas will determine where the initial capital outlays of the Water Fund can be allocated. By leveraging capital through the Water Fund and focusing projects in a relatively limited geographic region, this partnership will establish a dynamic that uses science-based analysis and state-of-the art BMPs and monitoring protocols to "move the needle" on pollution within the basin.

Through the Water Fund mechanism, this system of financing and implementation of water quality projects will become sustainable in the future. Such insulation from the typical grant-funding driven project cycles will mean a more certain funding stream for important projects, and will ultimately lead to cleaner streams and healthier watersheds.

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APPENDIX A – SWAT Analysis Scope of Work (Center for Naval Analyses, CNA)

Brandywine-Christina SWAT update

Overview

As a scenario for the William Penn Delaware River Basin (DRB) Soil and Water Assessment Tool (SWAT) modeling project, CNA will perform a local, improved calibration of the DRB SWAT model focused on the five subbasins the Brandywine-Christina watershed area at the HUC-10 scale. CNA will collaborate with fellow William Penn grantees at the University of Delaware and The Nature Conservancy who are developing a water fund for the Brandywine-Christina sub-watershed cluster. The Brandywine-Christina Water Fund will rely on hydrologic models and outputs to develop an understanding of the watershed and to assess the impact of different practices on the watershed to maximize return on investment. Our local SWAT model will produce improved loading values that can be used by the water fund researchers to inform their benefit/cost analyses and better assess the value and impact of different practices within the watershed. Further, this scenario will demonstrate for William Penn the potential for local use of the basin-wide SWAT model, should similar scenarios arise in some of the foundation's other focus subwatershed clusters.

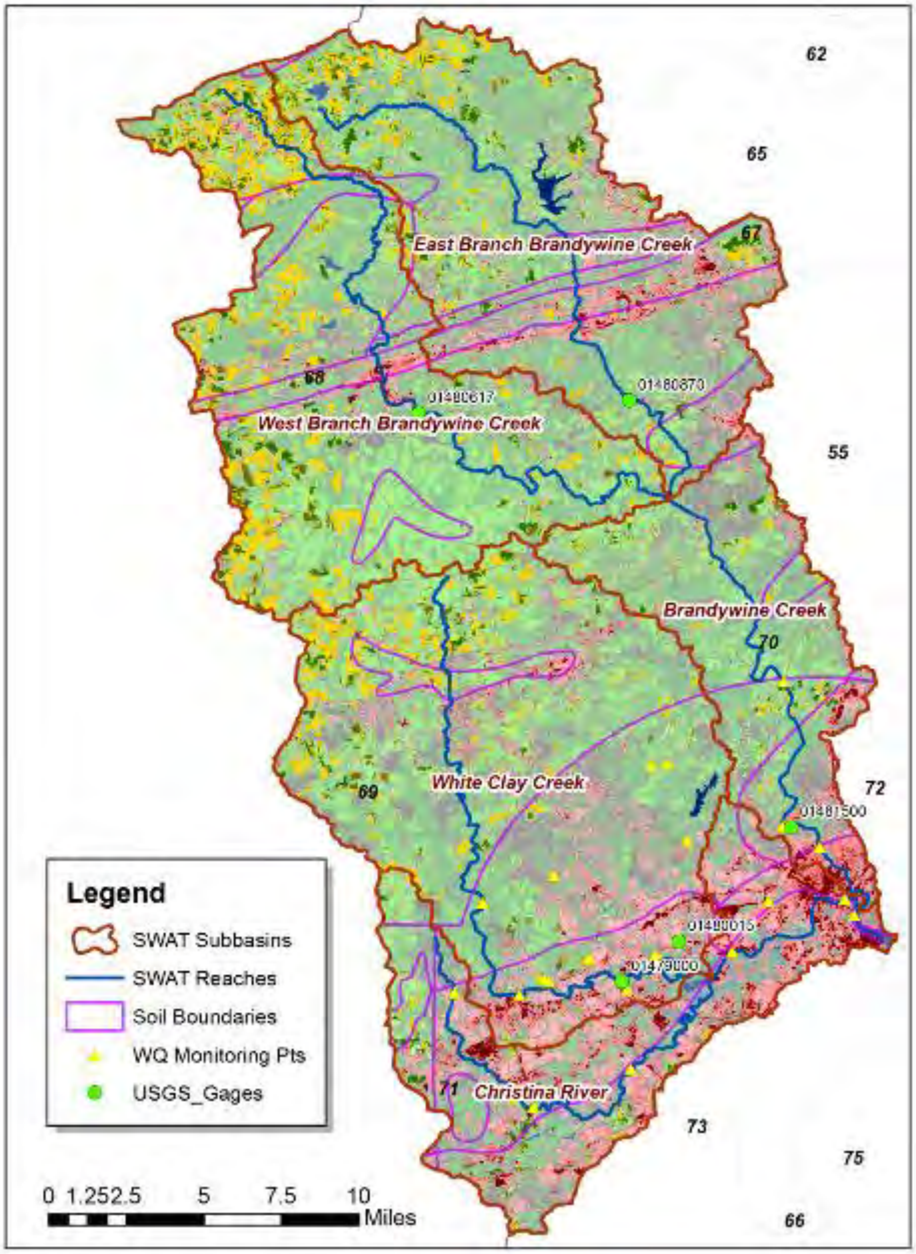
Scope of Work

1. Complete baseline calibration of HUC-10 model of Brandywine basin
    - Hydrologic calibration (monthly, Brandywine outlet)
    - SPARROW: sediment, TN, TP loadings by subbasin (HUC-10)
2. Split off 3 (or 5) subbasin model of the Brandywine (/ Brandywine-Christina) basin.
3. Verify/improve parameterization, and check for new data sources to use (with help from UDel).
    - Additional hydrologic calibration, daily
    - Improve agricultural operations/ fertilization parameters, irrigation
    - Manure management
    - Other data sources (GW N&P, atmo deposition)
    - Improve point source load estimates
    - Improve modeling of ponds, water withdrawals
4. Calibrate model with time-series data where available.
    - STORET (N, P, Sediment)
5. Output results in desired formats
    - At subbasin outlets
    - By land cover/land use, e.g. Forest/ Agricultural (pasture, row crop)/ Developed
    - By Soil/Location
    - Time (yearly vs monthly/ average vs peak or range)
    - Variables Formats
        i. Yield by HRU (land use/soil combination)

ii. Total delivered load at reach pour point
iii. In-stream change (delivery ratio)
iv. Nutrient types
    - N (NO_3, NO_2, NH_4, Org N, TN)
    - P (Org P, Mineral P, TP)

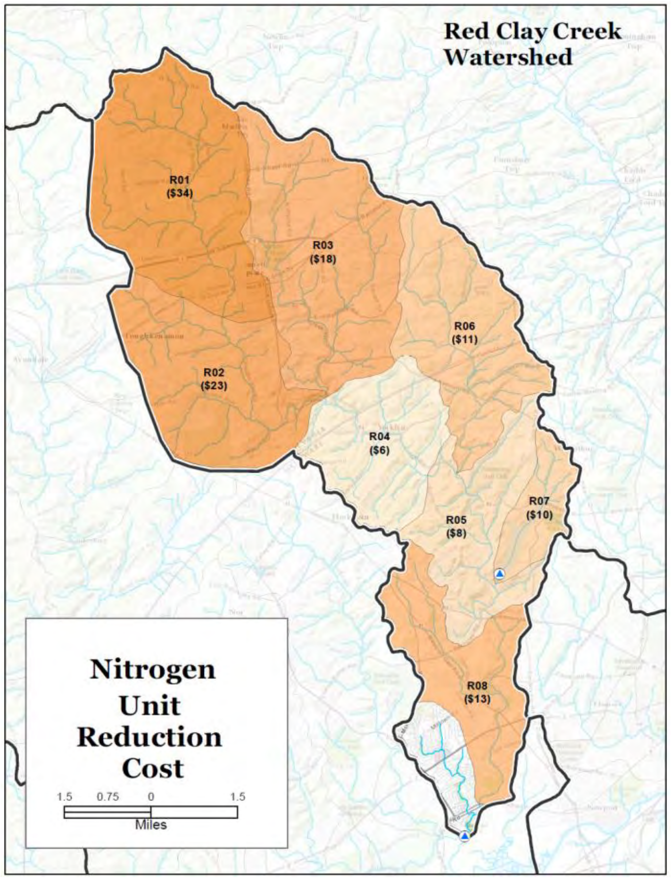
Study Area

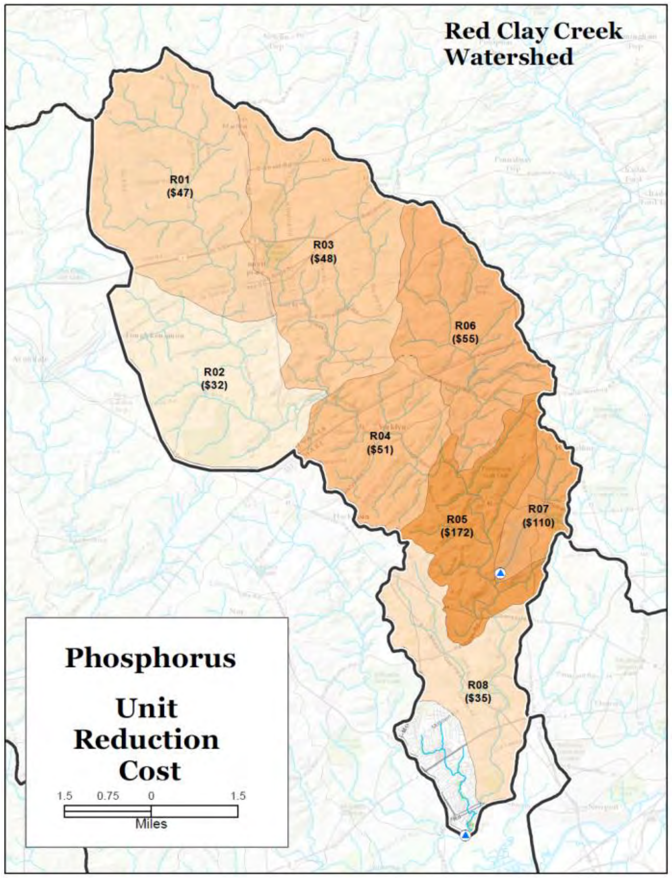
The land cover/land use map below depicts the study area for this work.

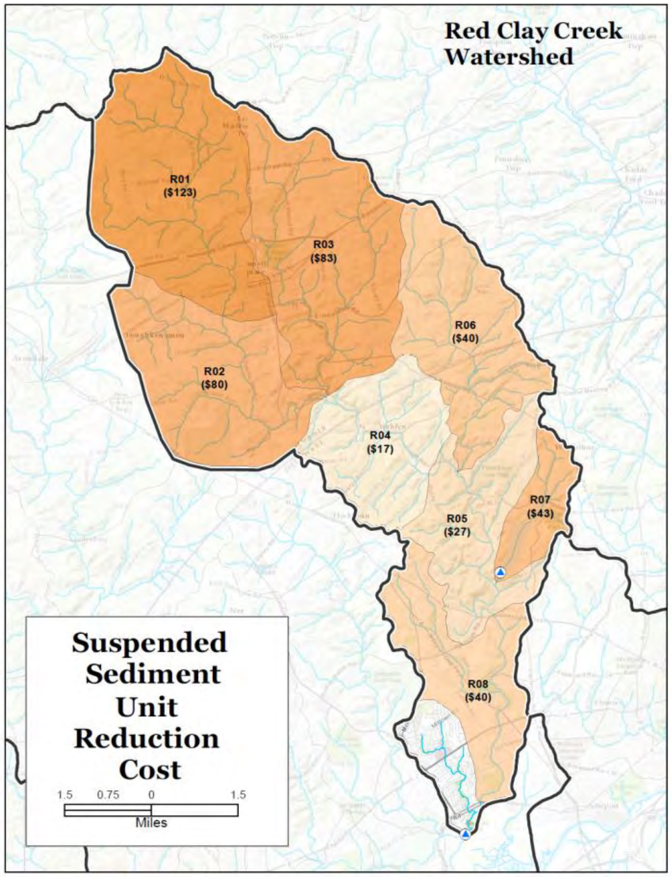


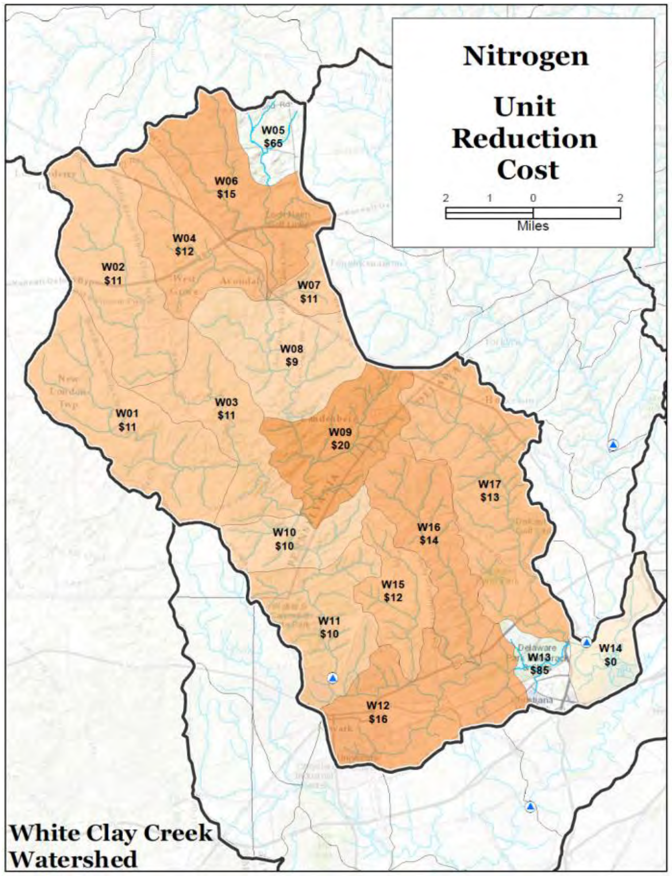
APPENDIX B – Cost Scenario Mapping by Watershed

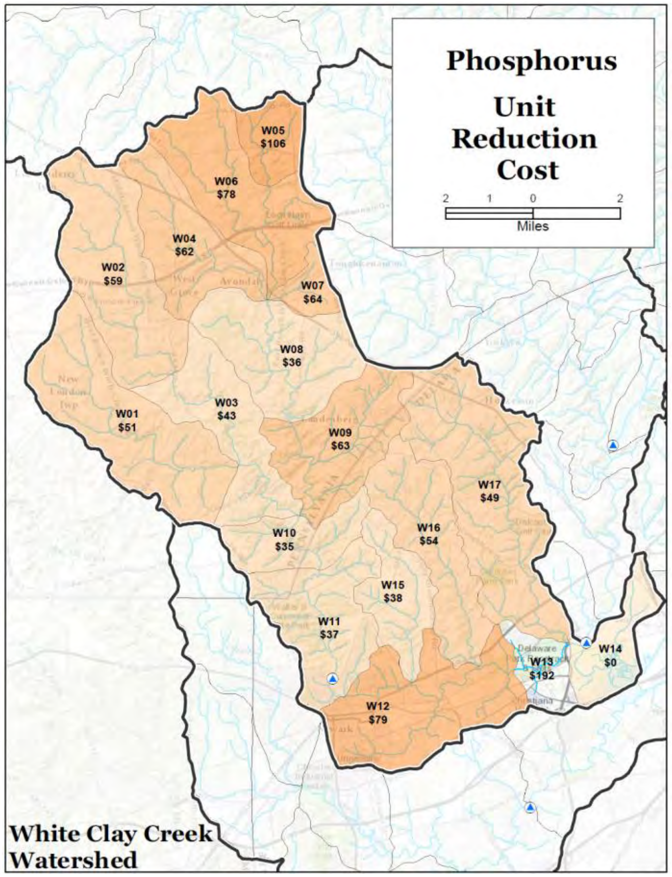
These maps show unit costs for reductions of nitrogen and phosphorus (per kilogram), and sediment (per 1000 kilograms) for the Red Clay, White Clay, and Brandywine (Main Stem, West Branch, and East Branch). Darker colors indicate higher relative unit reduction costs.

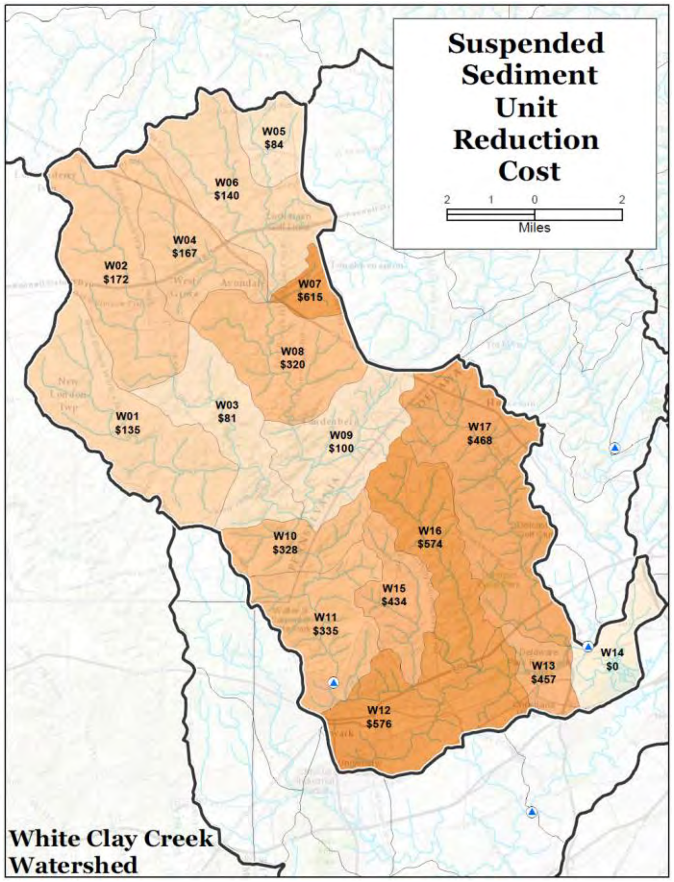


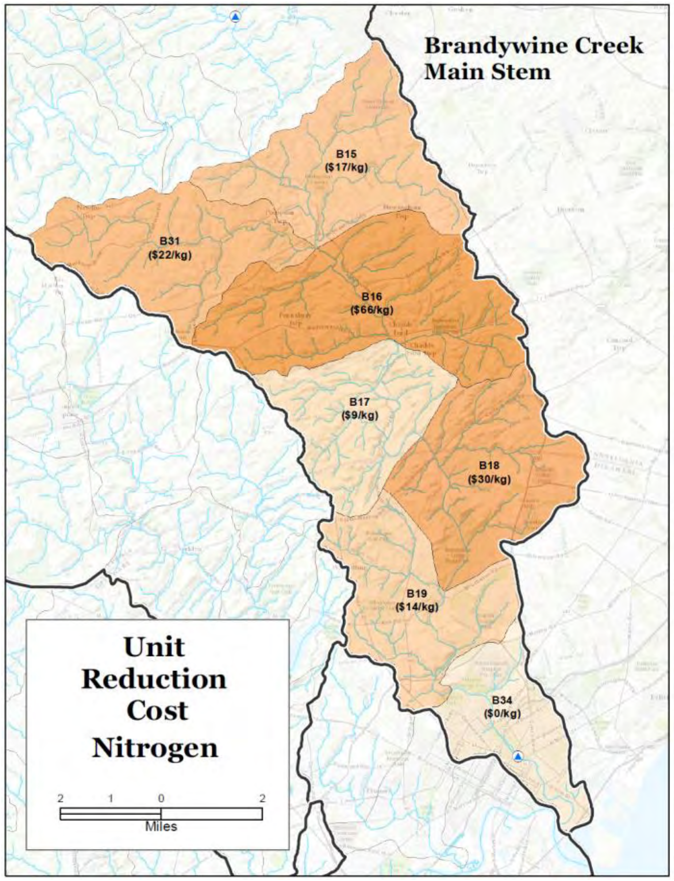


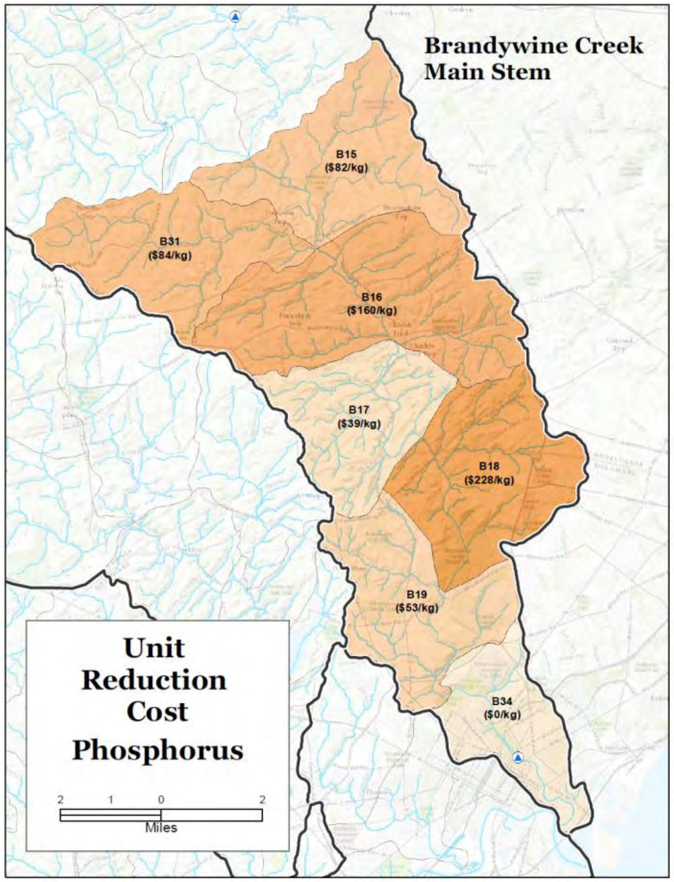


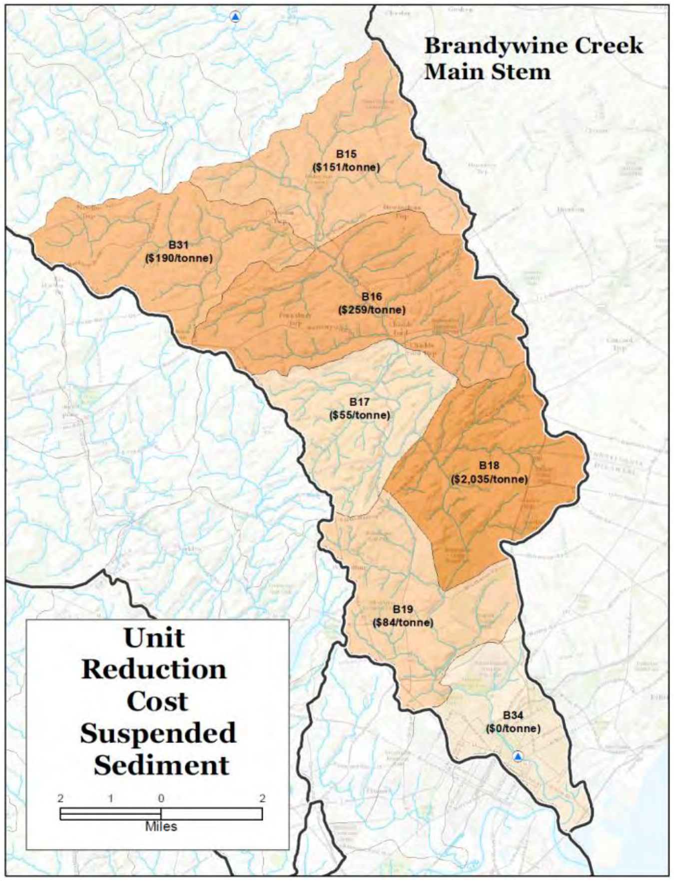

Nitrogen
Unit Reduction Cost
2 1 0 2
Miles
W05 $65
W06 $15
W04 $12
W02 $11
W07 $11
W08 $9
W01 $11
W03 $11
W09 $20
W17 $13
W16 $14
W10 $10
W15 $12
W11 $10
W14 $0
W13 $85
W12 $16
White Clay Creek Watershed


Phosphorus
Unit Reduction Cost
2 1 0 2
Miles
W05 $106
W06 $78
W04 $62
W02 $59
W07 $64
W08 $36
W01 $51
W03 $43
W09 $63
W17 $49
W16 $54
W10 $35
W15 $38
W11 $37
W14 $0
W13 $192
W12 $79
White Clay Creek Watershed

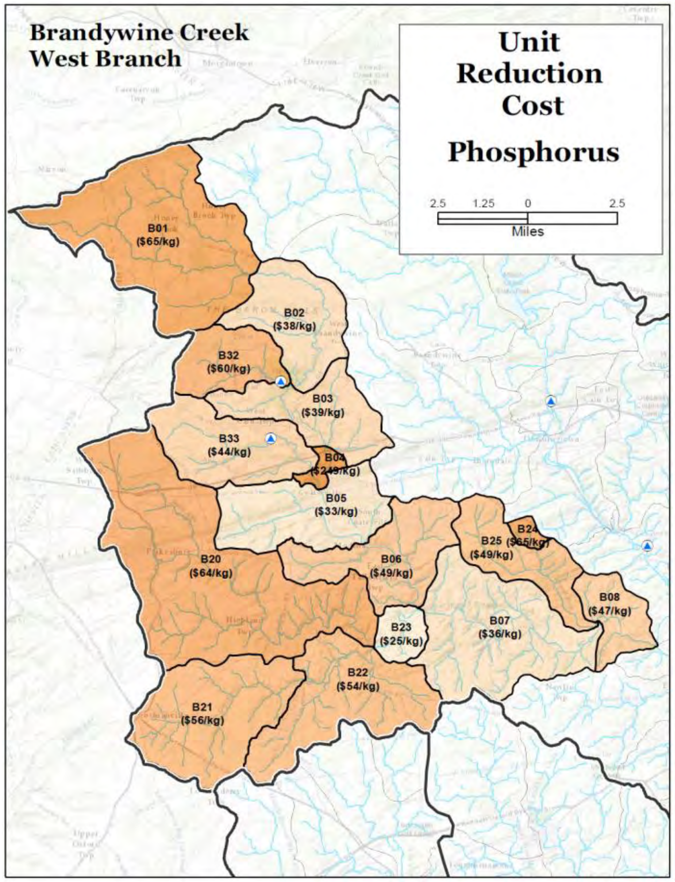

Suspended Sediment Unit Reduction Cost
2 1 0 2
Miles
W05 $84
W06 $140
W04 $167
W02 $172
W07 $615
W08 $320
W01 $135
W03 $81
W09 $100
W17 $468
W16 $574
W10 $328
W15 $434
W11 $335
W14 $0
W13 $457
W12 $576
White Clay Creek Watershed

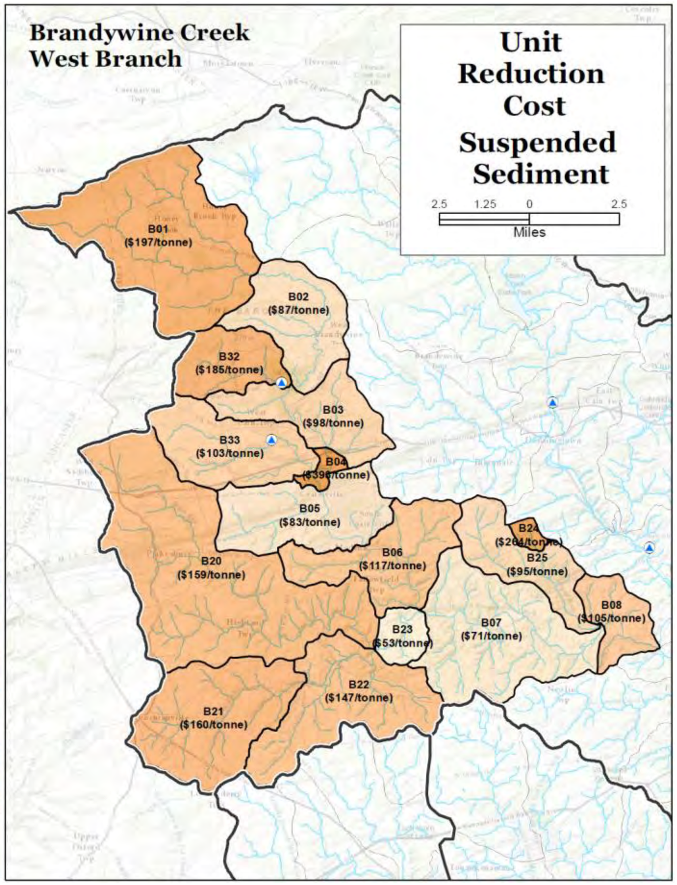

Brandywine Creek
Main Stem
B15
($17/kg)
B31
($22/kg)
B16
($66/kg)
B17
($9/kg)
B18
($30/kg)
B19
($14/kg)
B34
($0/kg)
Unit
Reduction
Cost
Nitrogen
2 1 0 2
Miles

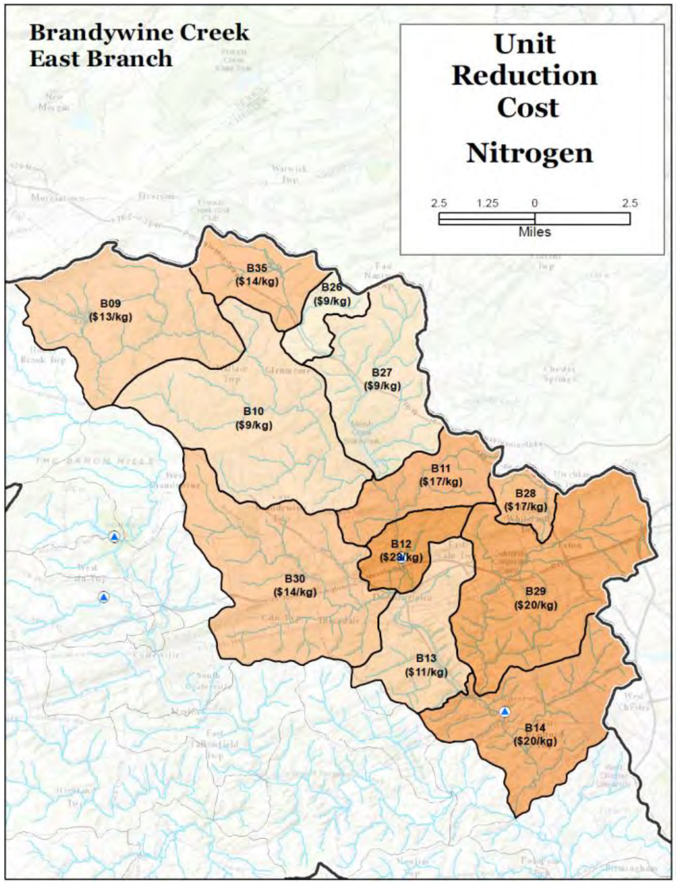

Brandywine Creek
Main Stem
B15
($82/kg)
B31
($84/kg)
B16
($160/kg)
B17
($39/kg)
B18
($228/kg)
B19
($53/kg)
B34
($0/kg)
Unit
Reduction
Cost
Phosphorus
2 1 0 2
Miles

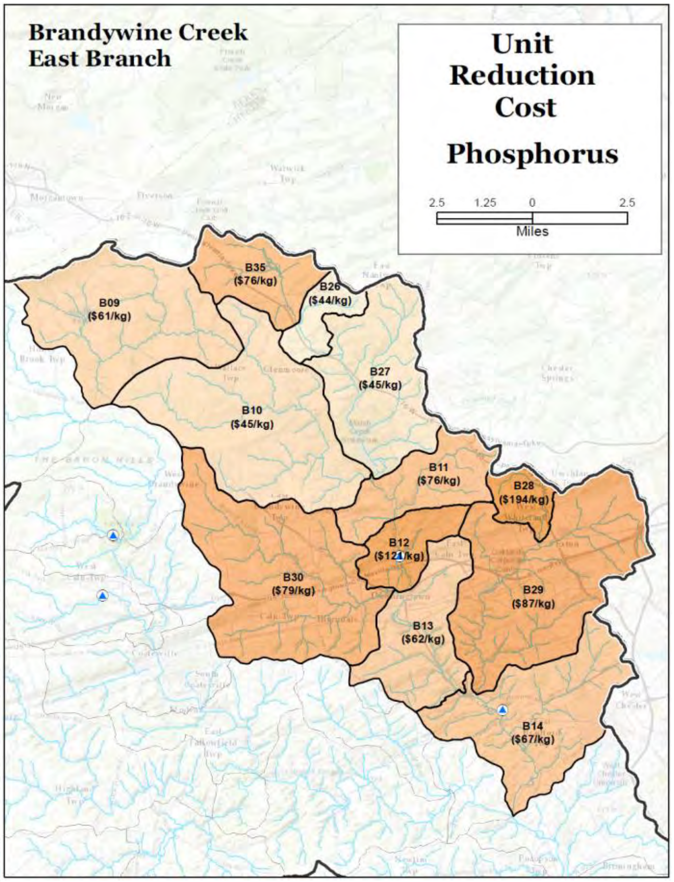

Brandywine Creek
Main Stem
B15
($151/tonne)
B31
($190/tonne)
B16
($259/tonne)
B17
($55/tonne)
B18
($2,035/tonne)
B19
($84/tonne)
B34
($0/tonne)
Unit
Reduction
Cost
Suspended
Sediment
2 1 0 2
Miles

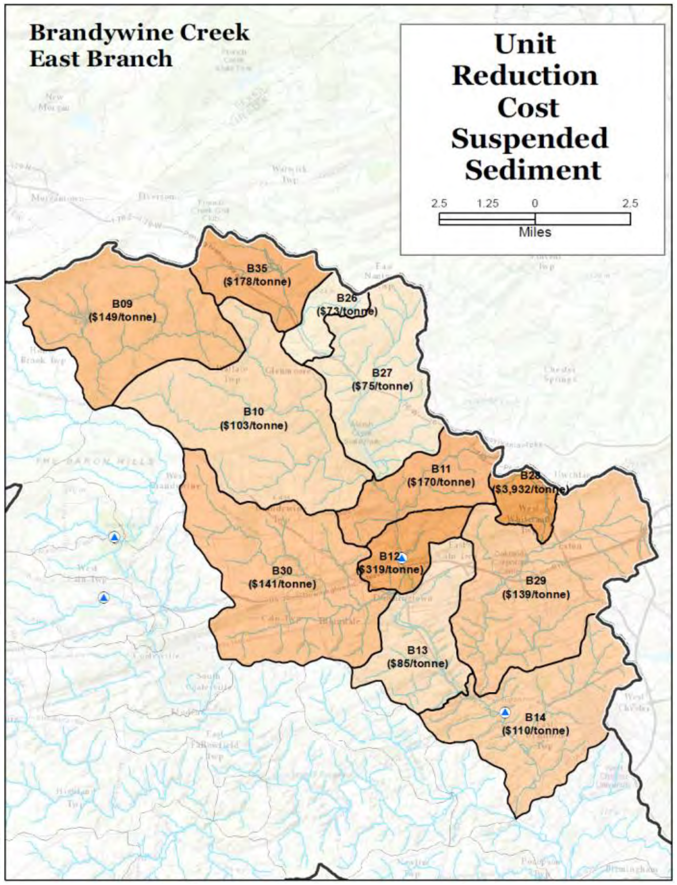

Brandywine Creek
West Branch
Unit
Reduction
Cost
Nitrogen
2.5 1.25 0 2.5
Miles
B01
($10/kg)
B02
($7/kg)
B32
($10/kg)
B03
($8/kg)
B33
($9/kg)
B04
($89/kg)
B05
($6/kg)
B24
($10/kg)
B25
($11/kg)
B20
($11/kg)
B06
($11/kg)
B08
($11/kg)
B23
($7/kg)
B07
($10/kg)
B22
($10/kg)
B21
($9/kg)


Brandywine Creek
West Branch
Unit
Reduction
Cost
Phosphorus
2.5 1.25 0 2.5
Miles
B01
($65/kg)
B02
($38/kg)
B32
($60/kg)
B03
($39/kg)
B33
($44/kg)
B04
($249/kg)
B05
($33/kg)
B24
B25
($65/kg)
($49/kg)
B20
($64/kg)
B06
($49/kg)
B08
($47/kg)
B23
($25/kg)
B07
($36/kg)
B22
($54/kg)
B21
($56/kg)

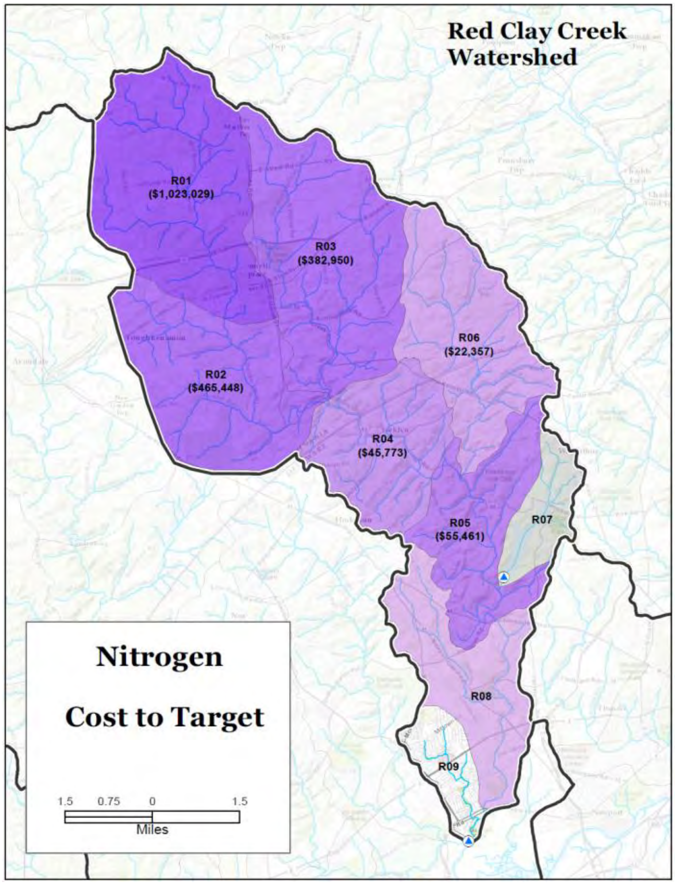

Brandywine Creek
West Branch
Unit
Reduction
Cost
Suspended
Sediment
2.5 1.25 0 2.5
Miles
B01
($197/tonne)
B02
($87/tonne)
B32
($185/tonne)
B03
($98/tonne)
B33
($103/tonne)
B04
($396/tonne)
B05
($83/tonne)
B24
($264/tonne)
B25
($95/tonne)
B20
($159/tonne)
B06
($117/tonne)
B08
($105/tonne)
B23
($53/tonne)
B07
($71/tonne)
B22
($147/tonne)
B21
($160/tonne)

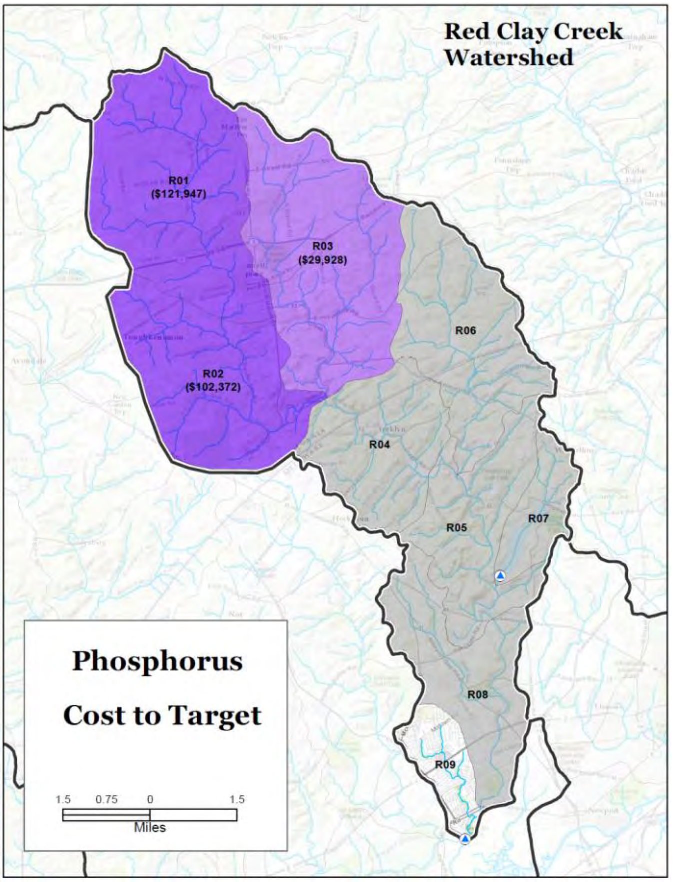

Brandywine Creek
East Branch
Unit Reduction Cost
Nitrogen
2.5 1.25 0 2.5
Miles
B35 ($14/kg)
B26 ($9/kg)
B09 ($13/kg)
B27 ($9/kg)
B10 ($9/kg)
B11 ($17/kg)
B28 ($17/kg)
B12 ($28/kg)
B30 ($14/kg)
B29 ($20/kg)
B13 ($11/kg)
B14 ($20/kg)

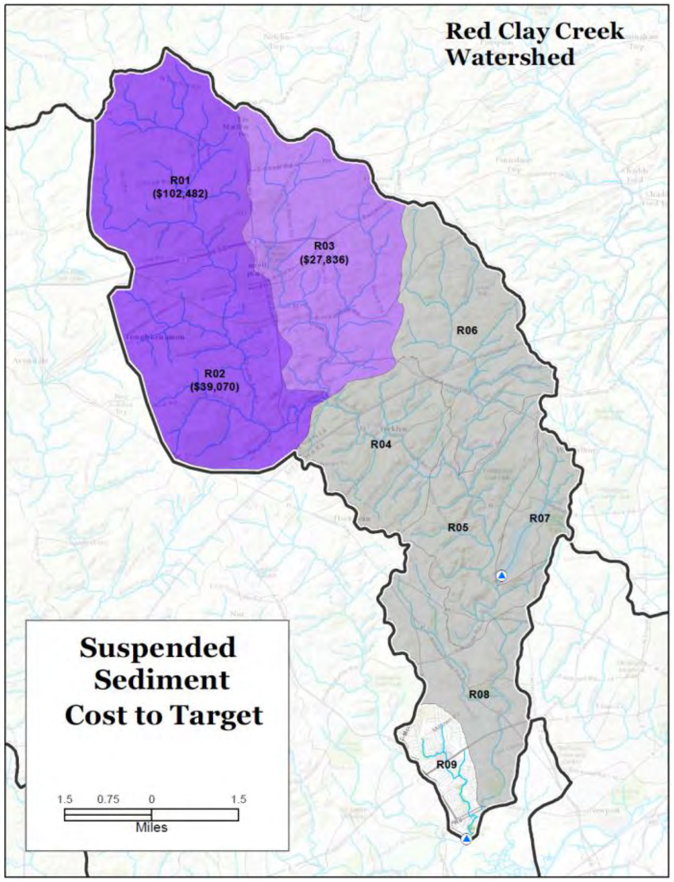

Brandywine Creek
East Branch
Unit Reduction Cost
Phosphorus
2.5 1.25 0 2.5
Miles
B35 ($76/kg)
B26 ($44/kg)
B09 ($61/kg)
B27 ($45/kg)
B10 ($45/kg)
B11 ($76/kg)
B28 ($194/kg)
B12 ($124/kg)
B30 ($79/kg)
B29 ($87/kg)
B13 ($62/kg)
B14 ($67/kg)

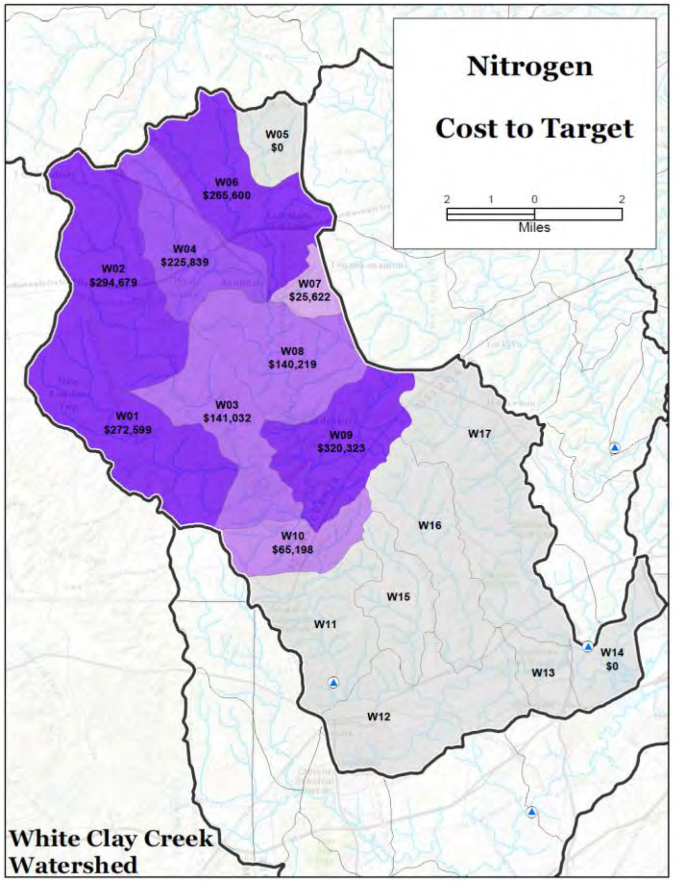

Brandywine Creek
East Branch
Unit Reduction Cost
Suspended Sediment
2.5 1.25 0 2.5
Miles
B35 ($178/tonne)
B26 ($73/tonne)
B09 ($149/tonne)
B27 ($75/tonne)
B10 ($103/tonne)
B11 ($170/tonne)
B28 ($3,932/tonne)
B12 ($319/tonne)
B30 ($141/tonne)
B29 ($139/tonne)
B13 ($85/tonne)
B14 ($110/tonne)

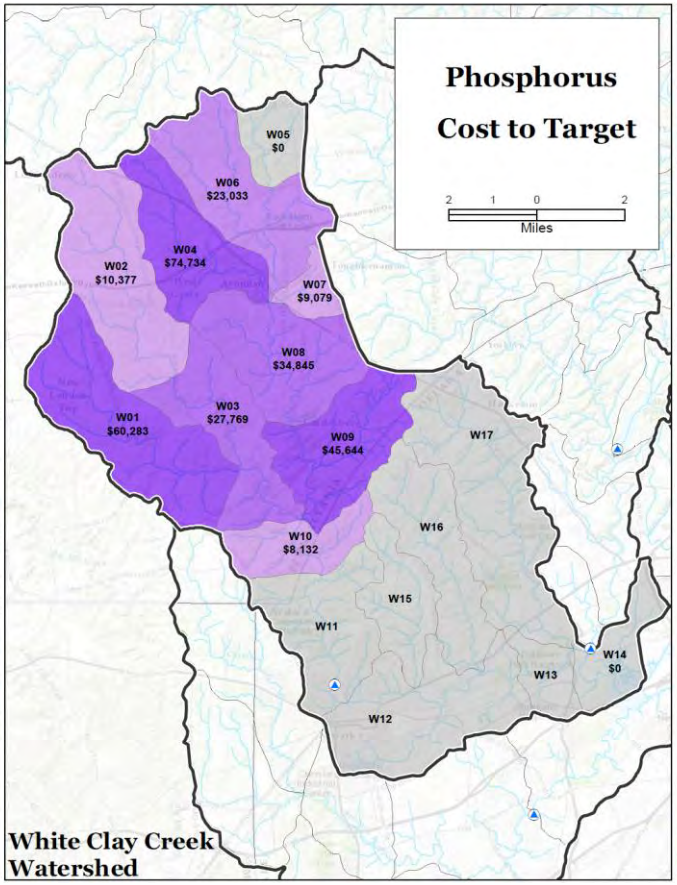
These maps show the estimated total annual costs to achieve water quality goals for nitrogen, phosphorus, and suspended sediment for the Red Clay, White Clay, and Brandywine (Main Stem, West Branch, and East Branch). Darker colors indicate higher total cost; gray tone indicates the TMDL is met or there is no TMDL for that sub-watershed.

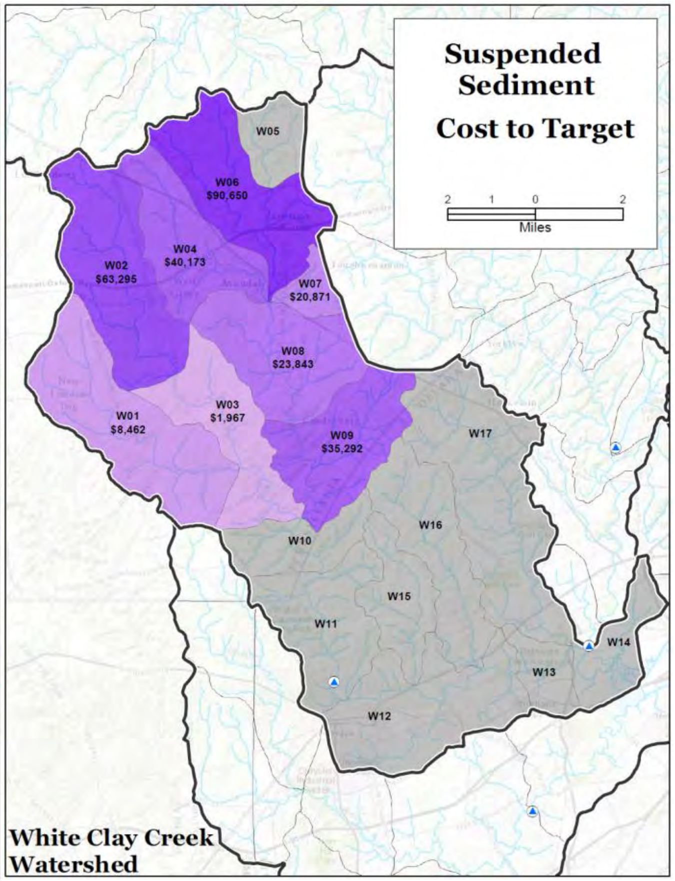


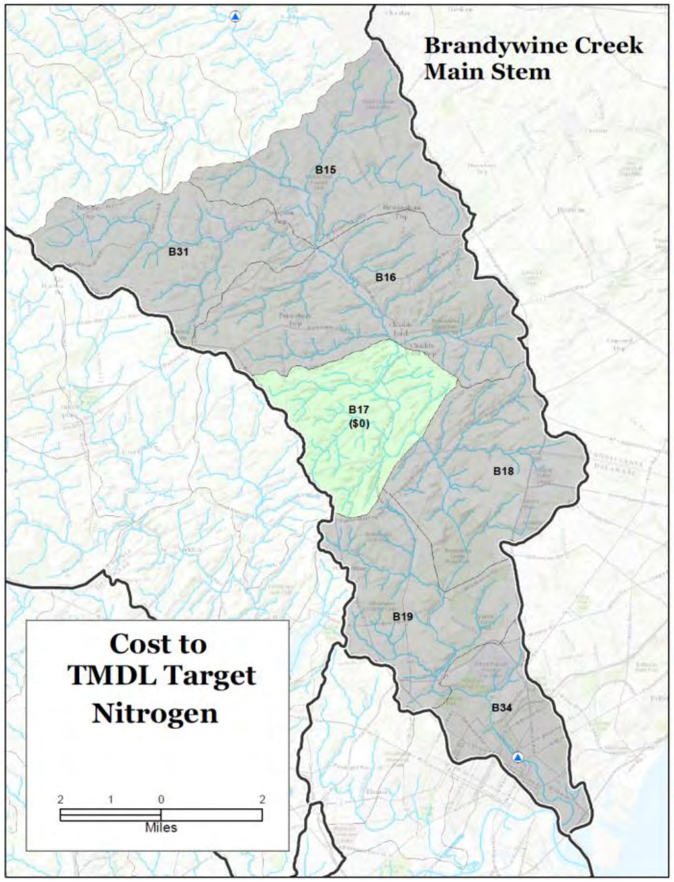


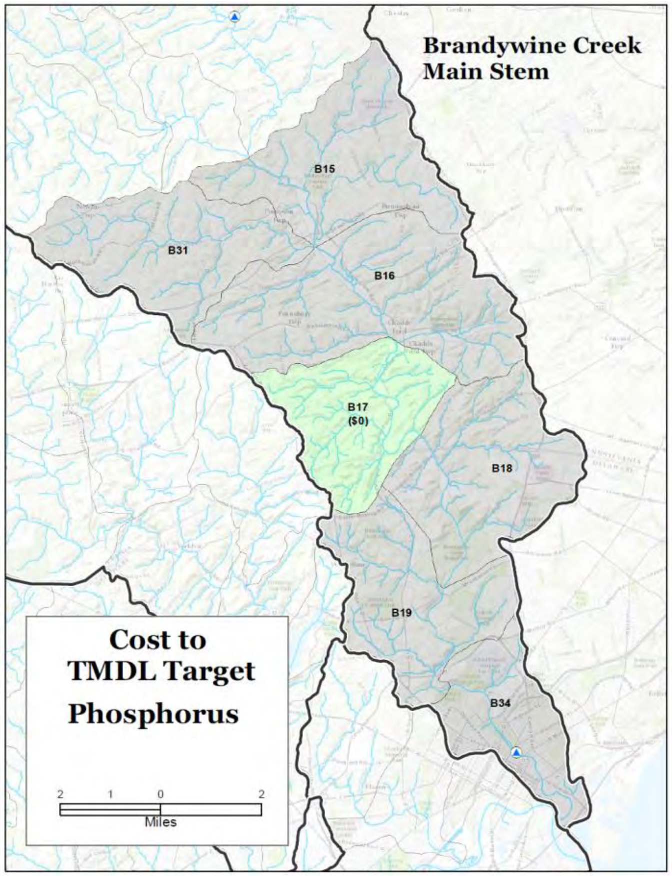


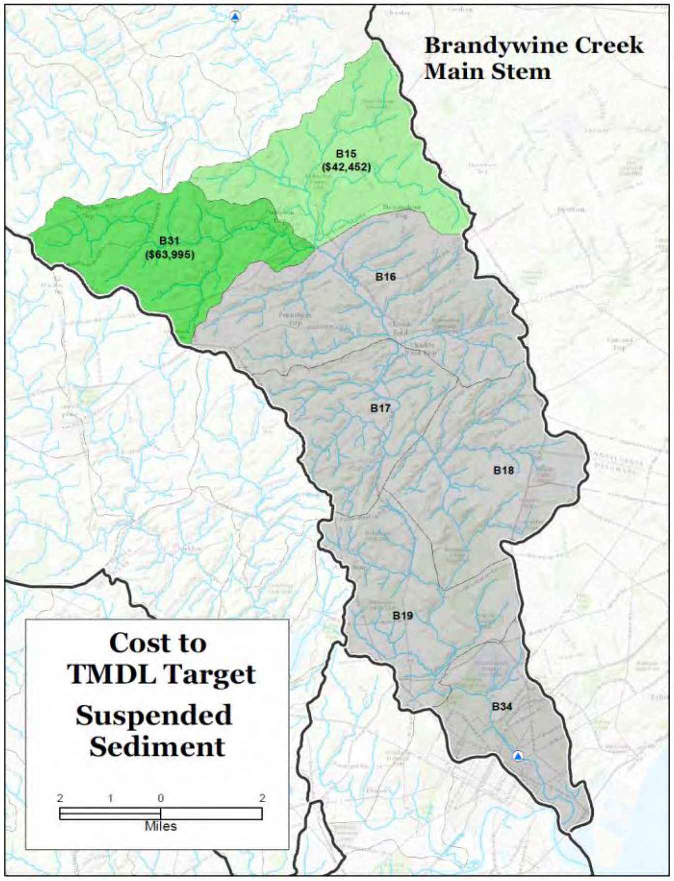

Nitrogen
Cost to Target
2 1 0 2
Miles
W05
$0
W06
$265,600
W04
$225,839
W02
$294,679
W07
$25,622
W08
$140,219
W03
$141,032
W01
$272,599
W09
$320,323
W17
W10
$65,198
W16
W15
W11
W14
$0
W13
W12
White Clay Creek
Watershed

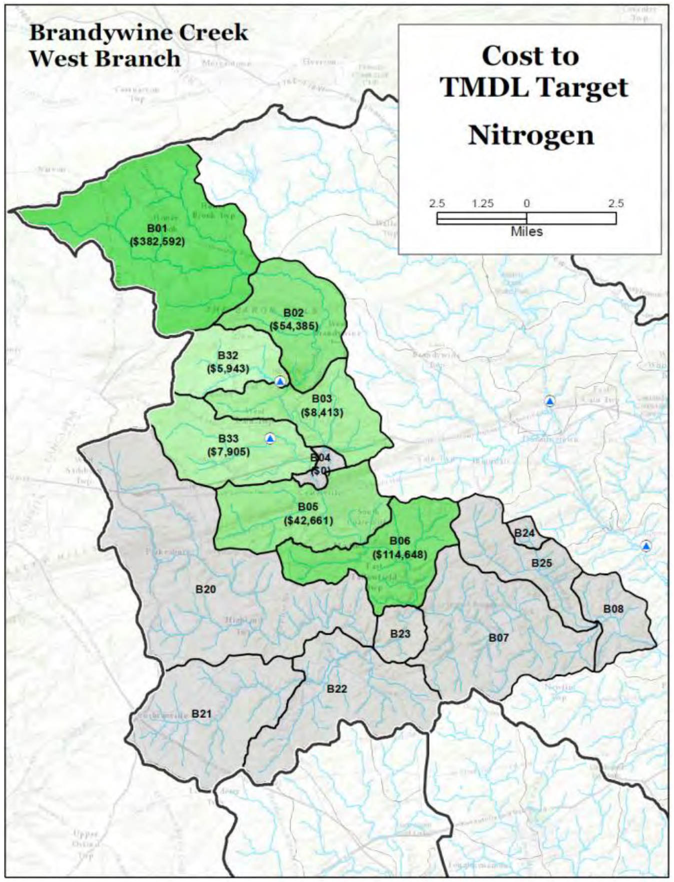

Phosphorus
Cost to Target
2 1 0 2
Miles
W05
$0
W06
$23,033
W04
$74,734
W02
$10,377
W07
$9,079
W08
$34,845
W03
$27,769
W01
$60,283
W09
$45,644
W17
W10
$8,132
W16
W15
W11
W14
$0
W13
W12
White Clay Creek
Watershed

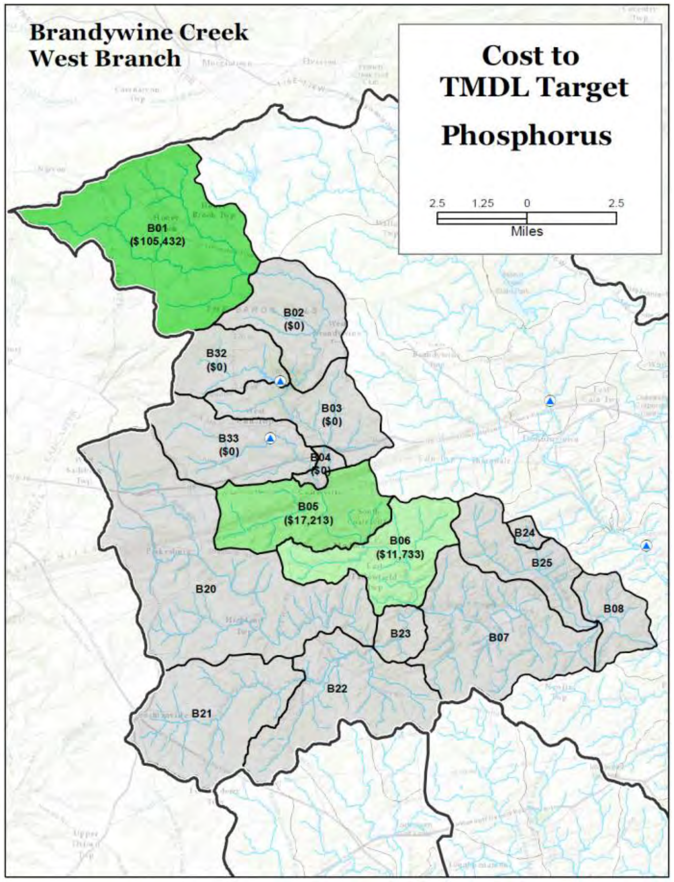

Suspended
Sediment
Cost to Target
2 1 0 2
Miles
W05
W06
$90,650
W04
$40,173
W02
$63,295
W07
$20,871
W08
$23,843
W03
$1,967
W01
$8,462
W09
$35,292
W17
W10
W16
W15
W11
W14
W13
W12
White Clay Creek
Watershed

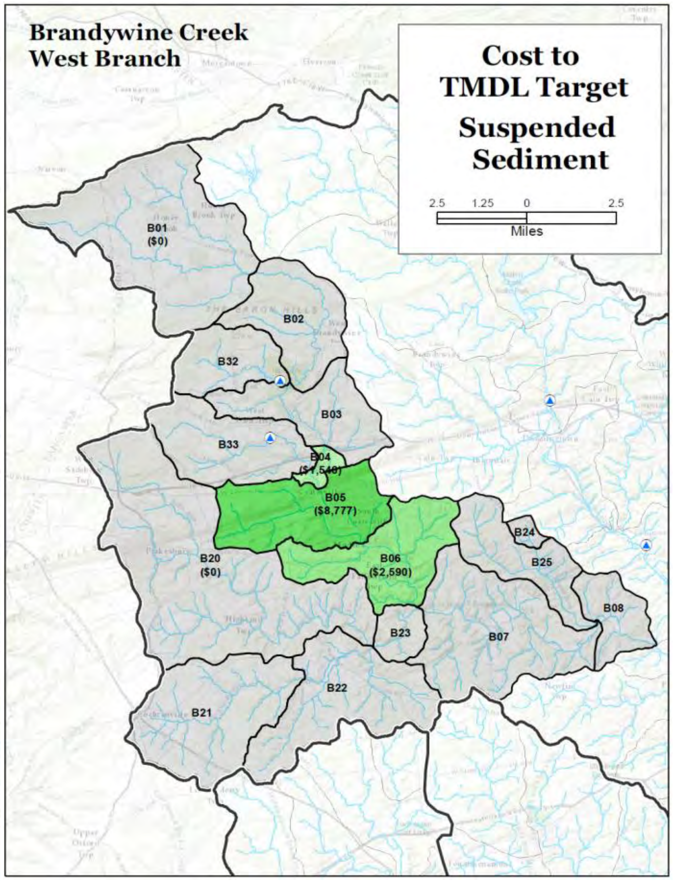

Cost to TMDL Target Nitrogen


Cost to TMDL Target Phosphorus

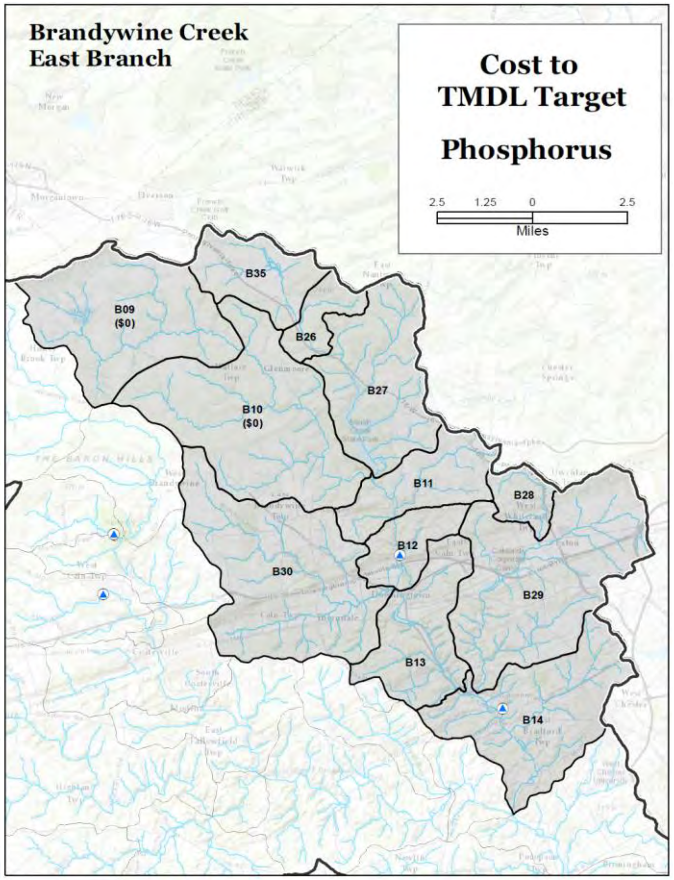

Cost to TMDL Target Suspended Sediment

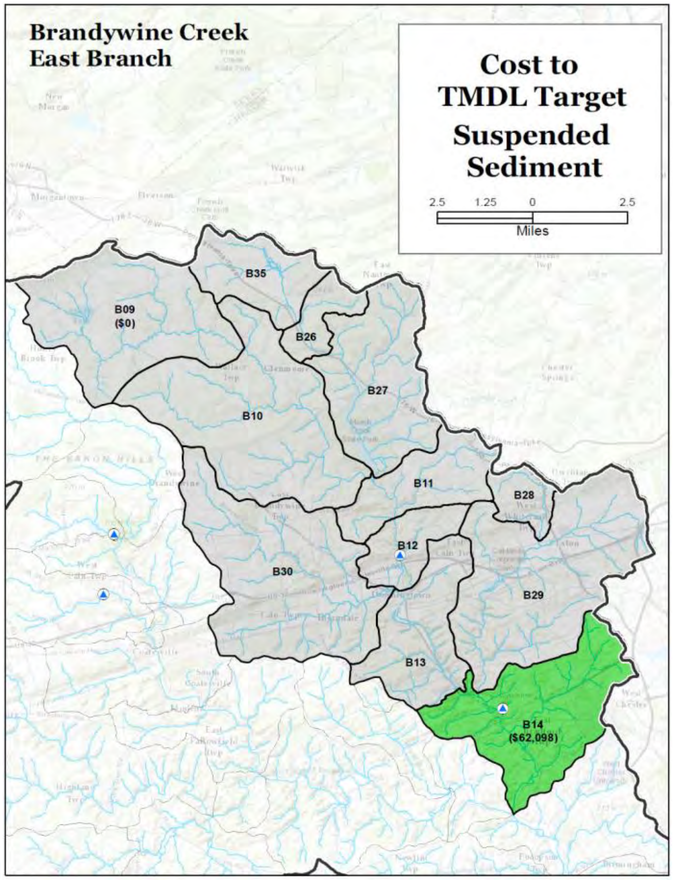

Brandywine Creek
West Branch
Cost to
TMDL Target
Nitrogen
2.5 1.25 0 2.5
Miles
B01
($382,592)
B02
($54,385)
B32
($5,943)
B03
($8,413)
B33
($7,905)
B04
($0)
B05
($42,661)
B06
($114,648)
B24
B25
B08
B20
B23
B07
B22
B21


Brandywine Creek
West Branch
Cost to
TMDL Target
Phosphorus
2.5 1.25 0 2.5
Miles
B01
($105,432)
B02
($0)
B32
($0)
B03
($0)
B33
($0)
B04
($0)
B05
($17,213)
B06
($11,733)
B24
B25
B08
B20
B23
B07
B22
B21


Brandywine Creek
West Branch
Cost to
TMDL Target
Suspended
Sediment
2.5 1.25 0 2.5
Miles
B01
($0)
B02
B32
B03
B33
B04
($1,540)
B05
($8,777)
B06
($2,590)
B20
($0)
B24
B25
B08
B23
B07
B22
B21


Brandywine Creek
East Branch
Cost to
TMDL Target
Nitrogen
2.5 1.25 0 2.5
Miles
B09
($125,954)
B10
($91,371)
B35
B26
B27
B11
B28
B12
B30
B29
B13
B14


Brandywine Creek
East Branch
Cost to
TMDL Target
Phosphorus
2.5 1.25 0 2.5
Miles
B09
($0)
B10
($0)
B35
B26
B27
B11
B28
B12
B30
B29
B13
B14


Brandywine Creek
East Branch
Cost to
TMDL Target
Suspended
Sediment
2.5 1.25 0 2.5
Miles
B09
($0)
B10
B35
B26
B27
B11
B28
B12
B30
B29
B13
B14
($62,098)

APPENDIX C – RIOs/InVEST Modeling Overview and Results

Optimizing the selection of conservation areas and the provision of hydrological ecosystem services: The Brandywine-Christina Healthy Water Fund.

September 2016

Juan Sebastián Lozano V.

Contents

Executive summary

The Brandywine-Christina watershed is part of the Delaware River Basin, and valuable for providing drinking water, recreation, biological diversity and agricultural production. Impairments to its water quality has resulted in the establishment of TMDL reduction goals for the watershed to comply with the federal Clean Water Act. In order to achieve these goals, the Brandywine-Christina Healthy Water Fund was created as a novel way to find funding alternatives to establish natural infrastructure as a mechanism to deliver watershed services for people and nature.

The purpose of this study is to create hypothetical scenarios of future land use as a result of the implementation of conservation activities, in order to characterize the change in the provision of hydrological ecosystem services on the four subwatersheds that are part of the Brandywine-Christina watershed (Brandywine, Red Clay Creek, White Clay Creek and Christina), through spatial modelling tools. The scenarios were produced using RIOS, a tool that creates ‘conservation portfolios’; maps that show the distribution of conservation practices based on a given budget and ecological priorities.

We modelled conservation portfolios at a 30-year timeline for each subwatershed, investing a total USD $45,000,000, distributed in the following way:

Brandywine Creek:	USD $10,000,000
Red Clay Creek:	USD $10,000,000
White Clay Creek:	USD $15,000,000
Christina River:	UDS $10,000,000

We took 6 annual portfolios to assess the change in ecosystem services provision, in each subwatershed. The baseline sediment export runs showed that higher values are found in the catchments with high erosivity and steep slopes. Meanwhile, catchments with highest export of nitrogen and phosphorus coincide with the densest residential and urban areas, with highest probability of pollution due to excessive application of fertilizers. In all subwatersheds, except in Christina River, the rate of change of sediment and nutrients export stabilizes in the year 10 or 20 (even in year 5, in some cases). For Christina River, on the other hand, it appears that investing additional funds in conservation activities might offer additional benefit for nutrients retention, as no stabilization of the rate of change is detected. In every case, the sediment export TMDL goal was reached by far. For nitrogen and phosphorus, the goals were reached in some cases, but they were almost always close to the goal, except in the cases were the goal is near 70%.

Introduction

The Brandywine-Christina, located in the northeast U.S and an integral part of the Delaware River Basin, is a valuable watershed that provides multiple services for people and nature. According to a report by The Nature Conservancy and the University of Delaware Water Resources Agency (2015), it is a major source of drinking water (60% of the drinking water to Delaware residents), recreation, biological diversity, and agricultural production. It is also an “economic engine” worth $1.6 billion in annual economic activity, $900 million in annual ecosystem goods and services, and $4.9 billion in annual wages.

Water quality has been significantly degraded in the watershed. In fact, “under the federal Clean Water Act, the 60 local governments in the Brandywine-Christina watershed are required to restore streams to fishable and swimmable goals through watershed-based Total Maximum Daily Loads (TMDLs) set by the United States Environmental Protection Agency (USEPA), Delaware Department of Natura Resources and Environmental Control (DNREC), Pennsylvania Department of Environmental Protection (DEP), and municipal-based National Pollutant Discharge Elimination (NPDES) Municipal Separate Storm Sewer System (MS4) permits” (The Nature Conservancy and University of Delaware, 2015). The Brandywine-Christina watershed is divided into four sub-watersheds: Brandywine Creek, Red Clay Creek, Christina River and White Clay Creek.

During the last two years, University of Delaware Water Resources Agency and The Nature Conservancy in Delaware, funded by a grant from the William Penn Foundation, worked with organizations in the watershed to assess the feasibility of a new business model to restore the health of the watershed: The Brandywine-Christina Healthy Water Fund. The goal of the Water Fund is to “leverage and maximize financial resources to improve the health of the Brandywine-Christina watershed for the benefit of people and nature”. Based on the growing knowledge of the benefits from natural infrastructure in contrast to grey infrastructure, the goals of the Water Fund “will be achieved through a funding mechanism and science-based investment protocol that creates a dependable funding stream for strategic investments in conservation-based restoration projects to meet the watershed’s water quality goals by 2025” (The Nature Conservancy and University of Delaware, 2015).

The broad purpose of this study is to model the most suitable areas for the establishment of Best Management Practices (BMPs), in order to create hypothetical scenarios of future land use as a result of the implementation of such practices. Through the scenarios, we characterize the provision of hydrological ecosystem services (sediment and nutrients regulation), and assess the efficiency of the return of investing on BMPs, on the four subwatersheds of the Brandywine-Christina.

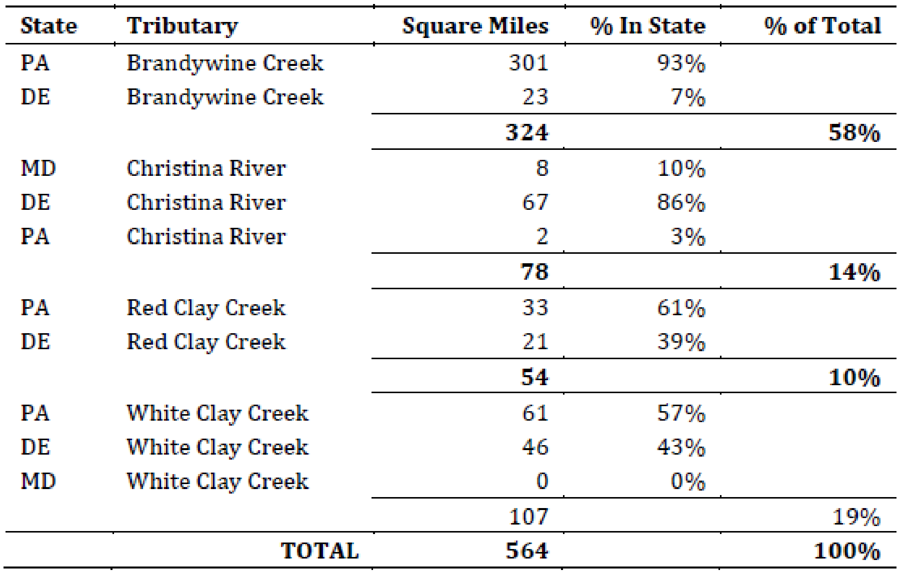
Methods

Study site

The Brandywine-Christina watershed, located between 76°2' W 40°9' N and 75°26' W 39°33' N, has 565 square miles, split between the states of Delaware, Pennsylvania and Maryland (***Figure 9***). According to data from 2005, its land use is distributed as following: 33% of forests and wetlands, 36% of agriculture and 28% of urban/suburban. By 2010, the watershed population density was 1,047 people by square mile (The Nature Conservancy and University of Delaware, 2015).

Table 3 describes the area distribution of the Brandywine-Christina subwatersheds.

Table 3 Area distribution of the Brandywine-Christina subwatersheds. Source: Preliminary Feasibility Study for The Brandywine-Christina Healthy Water Fund (The Nature Conservancy and University of Delaware, 2015).



State	Tributary	Square Miles	% In State	% of Total
PA	Brandywine Creek	301	93%	
DE	Brandywine Creek	23	7%	
		324		**58%**
MD	Christina River	8	10%	
DE	Christina River	67	86%	
PA	Christina River	2	3%	
		78		**14%**
PA	Red Clay Creek	33	61%	
DE	Red Clay Creek	21	39%	
		54		**10%**
PA	White Clay Creek	61	57%	
DE	White Clay Creek	46	43%	
MD	White Clay Creek	0	0%	
		107		19%
	TOTAL	**564**		**100%**

The largest subwatershed is Brandywine Creek, with 58% of the total area, followed by White Clay Creek, with 19%. All subwatersheds area located within the states of Pennsylvania and Delaware, plus Christina River and White Clay Creek are also in Maryland.

Content may not reflect National Geographic's current map policy. Sources: National Geographic, Esri, DeLorme, HERE, UNEP-WCMC, USGS, NASA, ESA, METI, NRCAN, GEBCO, NOAA, increment P Corp.

Content may not reflect National Geographic's current map policy. Sources: National Geographic, Esri, DeLorme, HERE, UNEP-WCMC, USGS, NASA, ESA, METI, NRCAN.

Figure 9 The Brandywine-Christina watershed and its four subwatersheds: Brandywine Creek, Red Clay Creek, White Clay Creek and Christina River.

Table 4 shows the distribution of general land uses in the subwatersheds.

Table 4 Distribution of general land uses in the subwatersheds. Source: Preliminary Feasibility Study for The Brandywine- Christina Healthy Water Fund (The Nature Conservancy and University of Delaware, 2015).

Watershed	Urban/ Suburb. (mi²)	Agric. (mi²)	Forest/ Wetland (mi²)	Total	Urban/ Suburb. (%)	Agric. (%)	Forest/ Wetland (%)
Brandywine	60.1	147.7	117.5	325.4	18%	45%	37%
Red Clay	14.7	20.9	18.4	54.1	27%	39%	34%
White Clay	36.8	38.1	32.3	107.3	34%	36%	30%
Christina	45.2	11.2	20.7	77.1	59%	15%	26%
Brandywine-Christina	156.8	218.0	189.0	563.8	28%	39%	33%

The dominant land use in the watershed is agriculture (39%), which is also the dominant in every subwatershed, except in Christina River, where urban is (59%). In all subwatersheds, forests and wetlands occupy around one third of the area.

Table 5 show the total population and the population growth in the subwatersheds.

Table 5 Population and population growth in the subwatersheds. Source: Preliminary Feasibility Study for The Brandywine -Christina Healthy Water Fund (The Nature Conservancy and University of Delaware, 2015).

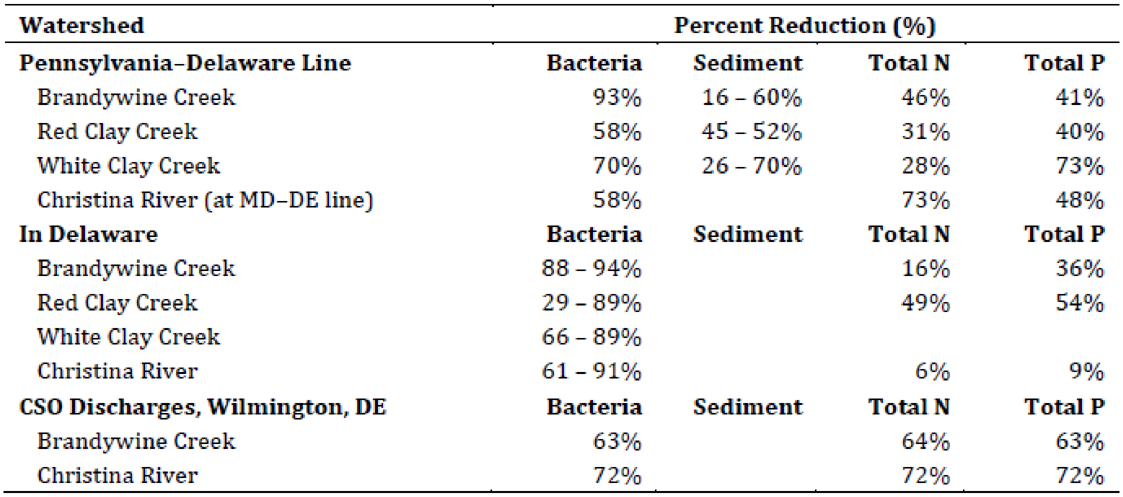
Watershed	Area (mi2)	2000 pop.	2010 pop.	Change	2000 (p/mi2)	2010 (p/mi2)
Brandywine Creek	326	221,413	246,702	25,289	679	757
Red Clay Creek	54	42,630	46,893	4,263	789	868
White Clay Creek	107	118,579	123,506	4,927	1,109	1,155
Christina River	78	166,435	174,196	7,761	2,134	2,233
Brandywine-Christina	564	549,057	591,297	42,240	972	1,047

Given its ‘urbanized’ condition, Christina River subwatershed is the densest populated, followed by White Clay Creek. Brandywine Creek and Red Clay Creek population density is low, nearly half of White Clay Creek’s.

Water quality of the streams in the Brandywine-Christina watershed has been affected by pollutants, including nutrients (such as nitrogen and phosphorus), bacteria, and sediment. Section 303 of the Clean Water Act requires the adoption of watershed-based Total Maximum Daily Loads (TMDLs) to remedy these impairments. For the watershed, the 2006 Brandywine-Christina high flow TMDL mandates reductions in bacteria ranging from 29% to 93%, sediment by over 50%, and nitrogen and phosphorus up to 73% (The Nature Conservancy and University of Delaware, 2015).

Table 6 shows the High flow nonpoint source TMDL reductions in the Brandywine-Christina subwatersheds.

Table 6 High flow nonpoint source TMDL reductions in the Christina Basin. Source: Preliminary Feasibility Study for The Brandywine-Christina Healthy Water Fund (The Nature Conservancy and University of Delaware, 2015).



Watershed	Percent Reduction (%)			
Pennsylvania–Delaware Line	**Bacteria**	**Sediment**	**Total N**	**Total P**
Brandywine Creek	93%	16 – 60%	46%	41%
Red Clay Creek	58%	45 – 52%	31%	40%
White Clay Creek	70%	26 – 70%	28%	73%
Christina River (at MD–DE line)	58%		73%	48%
In Delaware	**Bacteria**	**Sediment**	**Total N**	**Total P**
Brandywine Creek	88 – 94%		16%	36%
Red Clay Creek	29 – 89%		49%	54%
White Clay Creek	66 – 89%			
Christina River	61 – 91%		6%	9%
CSO Discharges, Wilmington, DE	**Bacteria**	**Sediment**	**Total N**	**Total P**
Brandywine Creek	63%		64%	63%
Christina River	72%		72%	72%

Tools

We utilized the Resource Investment Optimization System (RIOS) model by Vogl *et al*. (2015) as well as the Sediment Retention and Nutrient Retention modules of the Integrated Valuation of Environmental Services and Trade-offs (InVEST) model by Sharp *et al.* (2014). Through the RIOS model, we simulated the most suitable areas in the subwatersheds to establish BMPs, under specific budgets, and produced land use scenarios based on these areas. Through InVEST, on the other hand, we assessed the change in sediment and nitrogen export under those scenarios. In the next paragraphs, we briefly describe the science behind the models and the necessary inputs to run them.

RIOS

RIOS is a science-based tool to "prioritizing watershed investments by identifying where protection or restoration activities are likely to yield the greatest benefits for both people and nature at the lowest cost" (Vogl *et al.*, 2015). It helps designing investments for one or several goals, including erosion control, water quality improvement (for nitrogen and phosphorus), flood regulation, groundwater recharge, dry season water supply, and terrestrial and freshwater biodiversity. RIOS can also incorporate other goals into the portfolio design such as avoiding high opportunity cost areas such as production agriculture, or directing investments in a way that benefits poor populations (Vogl *et al.*, 2015).

In its first step, called 'Investment Portfolio Advisor' module, RIOS uses biophysical and social data, budget information, and implementation costs to produce 'investment portfolios' for a given area. These portfolios show what is likely to be the most efficient and effective set of investments that can be made, given a specific budget. The portfolio is a map of activities, or BMPs (e.g. protection, restoration, reforestation, improved agricultural practices), indicating where investments in each activity will give the best returns across all the objectives. RIOS is designed to address multiple ecosystem service objectives (e.g. erosion control, water quality regulation, seasonal flow & flood regulation), and can also be used to address biodiversity or other conservation or social objectives (e.g. poverty alleviation, alternative livelihoods) through user-defined inputs (Vogl *et al.*, 2015).

Once the investment portfolio is created, the 'Portfolio Translator' module guides the user through a set of options to generate scenarios that reflect the future condition of the watershed if the portfolio is implemented. The scenarios generated by the Portfolio Translator module are designed to be used as inputs to InVEST for estimating the ecosystem service return on investment from each portfolio. RIOS creates all required input files for the InVEST sediment retention and water yield/water purification models (Vogl *et al.*, 2015). Further details on the model can be found in Vogl *et al.* (2015)[3]

InVEST

Sediment retention

Erosion and overall sediment retention are mainly determined by climate, soil properties, topography, and vegetation. Some human-driven factors such as agriculture or hydropower production activities (dam construction and operation) also modify sediment dynamics at a catchment scale. Main sediment sources include overland erosion, gullies, bank erosion and

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[3] http://data.naturalcapitalproject.org/rios_releases/RIOSGuide_Combined_07May2015.pdf

mass erosion (Sharp *et al.*, 2014). Although sediment provide benefits to humans such as the fertilization of farmlands in flood plains, they also have negative impacts, such as the shortening of the lifespan in dams and reservoirs, due to their deposition on the bottom of these systems, which affects turbines and increases\ treatment costs of drinking water (Ongley, 1996; U.S Geological Survey, 2014 a). They also increase turbidity in natural aquatic systems, affecting biological dynamics such as reproduction, in fish communities (Ellison *et al.*, 2010).

The biophysical part of the sediment retention InVEST model is split in two modules: 1) sediment delivery and 2) sediment retention. As described by Sharp *et al.* (2014), "the sediment delivery module is a spatially-explicit model working at the spatial resolution of the input DEM raster. For each cell, the model first computes the amount of eroded sediment, then the sediment delivery ratio (SDR), which is the proportion of soil loss actually reaching the catchment outlet". The amount of eroded sediment is calculated based on the revised universal soil loss equation (RUSLE), and the sediment delivery ratio is a function of the upslope area and downslope flow path. Finally, in the sediment retention module, the model estimates the effect of the vegetation in retaining the eroded soil. ***Figure 10*****Error! Reference source not found.** shows the conceptual approach used in the model.

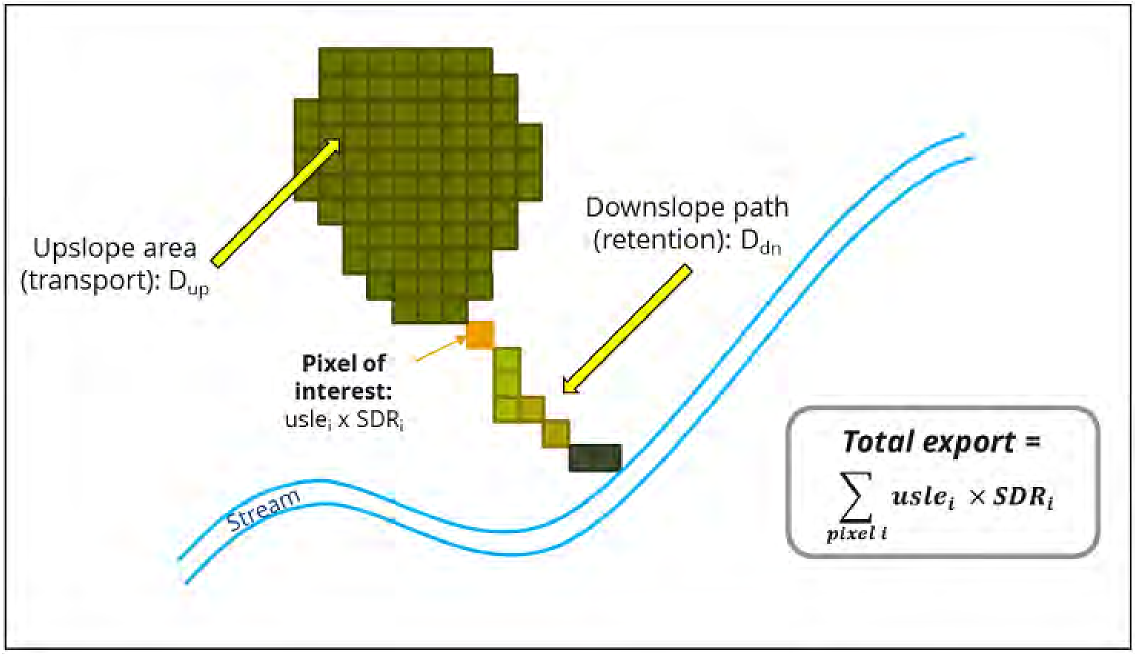

Figure 10 Conceptual approach used in the InVEST sediment model

Nutrients retention

Clean water from healthy aquatic systems is key for preventing waterborne illnesses, and to provide habitat for biodiversity in streams, rivers, lakes, and marine ecosystems. For this to happen, adequate nutrients balance is needed, otherwise, the accumulation of nutrients and toxins in water and fish could be harmful for people consuming them (Vymazal, 2007).

Sources of pollution may be point or non-point. Point sources, such as sewage outlets, are relatively easy to manage because the source is well known, although the mitigation could be expensive because it would require the construction of a water treatment plant. Non-point sources, such as fertilizer from agriculture and oil leaks from cars onto roads, are much more problematic because the source is not easily identifiable. These pollutants are carried by runoff to streams, rivers, lakes and the ocean (Sharp *et al.*, 2014).

Ecosystems provide the service of retaining some non-point pollutants, preventing them to flow into aquatic systems. Vegetation can remove pollutants by storing them in tissue or releasing them back to the environment in another form. Soils can also store and trap some soluble pollutants. Wetlands can slow flow long enough for pollutants to be taken up by vegetation. Riparian vegetation is particularly important in this regard, often serving as a last defense against pollutants entering a stream (Sharp *et al.*, 2014).

The biophysical InVEST nutrients retention model operates in three phases. As described by Sharp *et al.* (2014): 1) calculates annual average runoff from each parcel using the InVEST Hydropower Water Yield model, 2) determines the quantity of pollutant retained by each parcel on the landscape, by estimating how much pollutant is exported from each parcel based on export coefficients from the user inputs, and 3) the amount of downstream pixel retention can be calculated as surface runoff moves the pollutant toward the stream. The model routes water down flow paths determined by slope, and allows each pixel downstream from a polluting pixel to retain pollutant based on that land cover type's ability to retain the modelled pollutant. More details on the models can be found in Sharp *et al.* (2014)[4].

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[4] http://data.naturalcapitalproject.org/nightly-build/invest-users-guide/html/sdr.html#introduction

Data

For this study in the White Clay Creek subwatershed, we used the following input data:

Digital elevation model (DEM): GIS raster dataset with an elevation value in meters for each cell. The DEM used for this work has a spatial resolution of 10 meters (1/3 arc second) and comes from the USGS National Elevation Dataset (NED), mosaicked and filled by the University of Delaware Water Resources Center[5]

Land use/land cover (LULC): GIS raster dataset, with an integer LULC code for each cell. The dataset comes from the Delaware Valley Regional Planning Commission (2012), processed by the Chester County Water Resources Authority (2015).

Precipitation: GIS raster dataset with a non-zero value for average annual precipitation for each cell. The precipitation values should be in millimeters. The dataset is product of an interpolation from data by the NOAA National Centers for Environmental Information, 1981–2010 U.S. Climate Normals.

Rainfall erosivity index (R): GIS raster dataset, with an erosivity index value for each cell. This variable depends on the intensity and duration of rainfall in the area of interest. The greater the intensity and duration of the rain storm, the higher the erosion potential. The units on the index values are $MJ \cdot mm \cdot (ha \cdot h \cdot yr)^{-1}$. For this work, we derived the erosivity from the annual precipitation (provided by the University of Delaware Water Resources Center) using the approach by Cooper (2011).

Root restricting layer depth: GIS raster dataset with an average root restricting layer depth value for each cell. Root restricting layer depth is the soil depth at which root penetration is strongly inhibited because of physical or chemical characteristics. The root restricting layer depth values should be in millimeters. The dataset source is the Soil Survey Staff, Natural Resources Conservation Service, United States Department of Agriculture. U.S. General Soil Map (STATSGO2).

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[5] All data compilation and processing (except as otherwise noted) by the University of Delaware Water Resources Center, 261 Academy St., Newark, DE 19716.

Soil erodibility (K): GIS raster dataset with a soil erodibility value for each cell. Soil erodibility is a measure of the susceptibility of soil particles to detachment and transport by rainfall and runoff. The units on the index values are ton·ha·h·(ha·MJ·mm)$^{-1}$. The dataset source is the Soil Survey Staff, Natural Resources Conservation Service, United States Department of Agriculture. U.S. General Soil Map (STATSGO2) (field: mu_kf).

Riparian continuity: The effectiveness of restoration or protection activities in riparian areas is highly correlated with their continuity. While the retention downslope from an area is a key factor in determining the relative effectiveness of an activity on riparian pixels, the linear retention along the stream channel is most critical for determining relative impacts. Continuous riparian buffers are the most effective at maintaining or restoring sediment and nutrient retention. Therefore, an activity will be most effective at controlling sediment load to a river if it results in a formerly discontinuous buffer being made continuous. This dataset is calculated from retention factors in a linear buffer along streams. We derived the dataset used in this work from data provided by the University of Delaware Water Resources Center, using a preprocessing tool provided by the Natural Capital Project.

Downslope retention index: The downslope retention index describes the relative retention ability of the area downslope of a given pixel. Because activities will have the most impact on areas with little downslope retention, we want to minimize this factor. The downslope retention index is calculated as a weighted flow length, using slope and sediment retention factors as weights. We derived the dataset used in this work from data provided by the University of Delaware Water Resources Center, using a preprocessing tool provided by the Natural Capital Project.

Upslope source index: The upslope source index describes the source area and magnitude of the source reaching a pixel, a factor that is cited frequently as an indicator of the effectiveness of an activity for influencing erosion control. Because activities will be most effective if performed in an area with a large upslope sediment source, we want to maximize this factor. The upslope source index is calculated as a weighted flow accumulation, using an average of all the on-pixel source factors, retention factors, and slope. We derived the dataset used in this work from data provided by the University of Delaware Water Resources Center, using a preprocessing tool provided by the Natural Capital Project.

Figure 11 shows the data inputs to RIOS and InVEST.

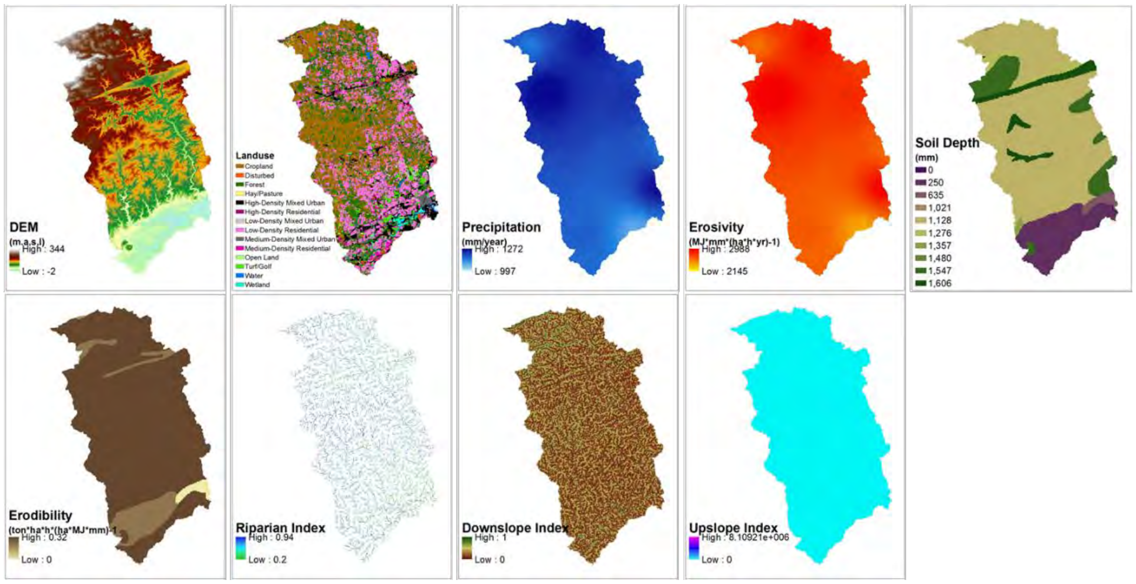

Figure 11 Biophysical inputs to RIOS and InVEST

Additionally, the model requires a biophysical table as input with the following information:

lucode (Land use code): Unique integer for each LULC class (e.g., 1 for forest, 3 for grassland, etc.), must match the LULC raster input.

LULC_desc: Descriptive name of land use/land cover class (optional).

usle_c: Cover-management factor for the USLE, a floating point value between 0 and 1.

usle_p: Support practice factor for the USLE, a floating point value between 0 and 1.

root_depth: The maximum root depth for vegetated land use classes, given in integer millimeters. Non-vegetated LULCs should were given a value of 1.

Kc: The plant evapotranspiration coefficient for each LULC class, used to obtain potential evapotranspiration by using plant physiological characteristics to modify the reference evapotranspiration, which is based on alfalfa.

load_n / load_p: The nutrient loading for each land use. For nitrogen evaluation, supply values in load_n, for phosphorus, supply values in load_p. The potential for terrestrial loading of water quality impairing constituents is based on nutrient export coefficients. The nutrient loading values are given as decimal values and have units of kg. Ha^{-1} yr $^{-1}$.

eff_n / eff_p: The vegetation filtering value per pixel size for each LULC class, as an integer percent between zero and 1. For nitrogen evaluation, supply values in eff_n, for phosphorus, supply values in eff_p. This field identifies the capacity of vegetation to retain nutrient, as a percentage of the amount of nutrient flowing into a cell from upslope. All LULC classes that have no filtering capacity, such as pavement, are assigned a value of zero.

crit_len_n / crit_len_p: The distance (meters) after which it is assumed that a patch of LULC retains nutrient at its maximum capacity. If nutrients travel a distance smaller than the retention length, the retention efficiency will be less than the maximum value eff_x, following an exponential decay.

Table 7 shows the biophysical table used in this study. The data were extracted from are previous studies using InVEST and RIOS, as well as from sample data from both models[6].

Table 7 Biophysical data used in RIOS and InVEST

LULC_desc	lucode	LULC_veg	Kc	root_depth	usle_c	usle_p	sedret_eff	load_n	eff_n	load_p	eff_p	crit_len_n	crit_len_p
Water	1	0	1	1000	0.001	0.001	0.8	0.001	0.05	0.001	0.05	10	10
Low-Density Mixed Urban	2	0	0.1	10	0.001	0.001	0.05	4	0.05	0.5	0.05	10	10
High-Density Mixed Urban	3	0	0.1	10	0.001	0.001	0.05	4	0.05	0.5	0.05	10	10
Hay/Pasture	4	1	0.85	1000	0.02	0.25	0.4	3.1	0.25	0.1	0.25	60	60
Cropland	5	1	0.6	700	0.5	0.4	0.25	11	0.25	3	0.25	60	60
Forest	6	1	1	7000	0.003	0.2	0.6	1.8	0.8	0.011	0.8	100	100
Wetland	7	0	1	7000	0.01	0.2	0.6	2	0.8	0.05	0.8	100	100
Disturbed	8	0	0.2	500	0.01	0.2	0.05	4	0.05	0.05	0.05	10	10
Turf/Golf	9	1	0.85	1000	0.008	0.2	0.4	11	0.4	1.5	0.4	10	10
Low-Density Residential	10	0	0.2	500	0.01	0.001	0.1	7.25	0.05	1.1	0.05	10	10
Medium-Density Residential	11	0	0.3	500	0.001	0.001	0.05	7.5	0.05	1.2	0.05	10	10
High-Density Residential	12	0	0.1	300	0.001	0.001	0.05	7.75	0.05	1.3	0.05	10	10
Medium-Density Mixed Urban	13	0	0.1	10	0.001	0.001	0.05	4	0.05	0.5	0.05	10	10
Open Land	14	0	0.5	2000	0.01	0.2	0.5	2	0.5	0.011	0.5	10	10

Portfolios creation

The conservation portfolios for this study were designed based on two goals: erosion control and water quality improvement (for nitrogen and phosphorus). As a first step, we identified

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[6] http://www.naturalcapitalproject.org/software/#rios for RIOS and http://www.naturalcapitalproject.org/invest/ for InVEST.

the BMPs (activities, from now on) more likely to be implemented on the field using the budget assigned to the portfolio, and the transitions that these activities would produce on the field (a fixed list set by the model) (Table 8). Each activity is linked to one or more transitions, as these represent the actual change on the landscape.

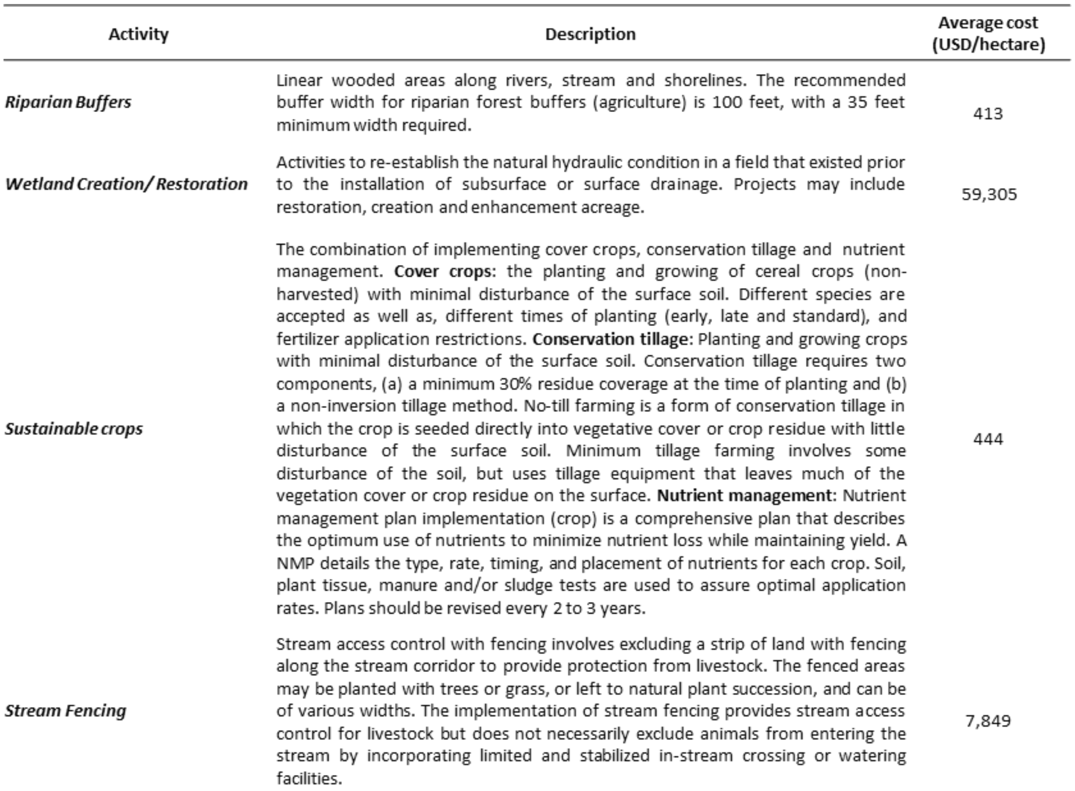
Table 8 Activities and transitions that they produce. The '1s' in the table represent the transitions produced by each activity.

		Activities			
		Riparian Buffers	Stream Fencing	Sustainable crops	Wetland Creation/ Restoration
Transitions	Keep native vegetation	-	1	-	-
	Revegetation (unassisted)	-	1	-	-
	Revegetation (assisted)	1	-	-	1
	Agricultural vegetation management	-	-	1	-
	Ditching	-	-	-	-
	Fertilizer management	-	-	1	-
	Pasture management	-	-	-	-

The University of Delaware Water Resources Agency provided the description of each activity (**Error! Reference source not found.**).

Additionally, we set the model to constrain the "stream fencing" and "riparian buffers" activities to a buffer of 20 meters to every stream in the subwatershed, in order to prevent the model to allocate any of these activities anywhere else. We also constrained the "wetland restoration" to be established only on land uses identified as "wetlands" in the land use map. Finally, we constrained every activity to occur upstream the lowest intake of each subwatershed, in order for the activities to impact the hydrological dynamics that determine the water quality for the beneficiaries using water from the intakes.

Table 9 Description of the activities implemented in the portfolio and average costs. Source: Abt Associates/USEPA 2012).



Activity	Description	Average cost (USD/hectare)
Riparian Buffers	Linear wooded areas along rivers, stream and shorelines. The recommended buffer width for riparian forest buffers (agriculture) is 100 feet, with a 35 feet minimum width required.	413
Wetland Creation/ Restoration	Activities to re-establish the natural hydraulic condition in a field that existed prior to the installation of subsurface or surface drainage. Projects may include restoration, creation and enhancement acreage.	59,305
Sustainable crops	The combination of implementing cover crops, conservation tillage and nutrient management. **Cover crops:** the planting and growing of cereal crops (non-harvested) with minimal disturbance of the surface soil. Different species are accepted as well as, different times of planting (early, late and standard), and fertilizer application restrictions. **Conservation tillage:** Planting and growing crops with minimal disturbance of the surface soil. Conservation tillage requires two components, (a) a minimum 30% residue coverage at the time of planting and (b) a non-inversion tillage method. No-till farming is a form of conservation tillage in which the crop is seeded directly into vegetative cover or crop residue with little disturbance of the surface soil. Minimum tillage farming involves some disturbance of the soil, but uses tillage equipment that leaves much of the vegetation cover or crop residue on the surface. **Nutrient management:** Nutrient management plan implementation (crop) is a comprehensive plan that describes the optimum use of nutrients to minimize nutrient loss while maintaining yield. A NMP details the type, rate, timing, and placement of nutrients for each crop. Soil, plant tissue, manure and/or sludge tests are used to assure optimal application rates. Plans should be revised every 2 to 3 years.	444
Stream Fencing	Stream access control with fencing involves excluding a strip of land with fencing along the stream corridor to provide protection from livestock. The fenced areas may be planted with trees or grass, or left to natural plant succession, and can be of various widths. The implementation of stream fencing provides stream access control for livestock but does not necessarily exclude animals from entering the stream by incorporating limited and stabilized in-stream crossing or watering facilities.	7,849

Finally, we set the budget scenarios for the portfolio's creation. Through discussions with the partners at The Nature Conservancy and the University of Delaware Water Resources Agency, we decided that the portfolio would reflect the following investments in each subwatershed, over a 30-year timeline.

Brandywine Creek:	USD $10,000,000
Red Clay Creek:	USD $10,000,000
White Clay Creek:	USD $15,000,000
Christina River:	UDS $10,000,000

Thus, we created 30 portfolios of investment (one per year), per subwatershed. As the landscape and climate are dynamic, the selection of the areas for the future years should be reassessed adaptively, however, we created these long term portfolios as an attempt to estimate the return of the investment on the provision of ecosystem services.

Although RIOS allows the total budget to be set as ‘floating’, so the model “decides” how much to assign to each activity, this could lead to a portfolio with only the one or two least cost activities, as it works exclusively on cost/benefit basis (Vogl *et al.*, 2015). As no agreement has been reached inside the Water Fund regarding how much of the budget to spend in each activity, we distributed it as a weighted average based on the activity costs, so the most expensive activities would be assigned a higher budget. As a result, every activity in the portfolio would be expected to have the same area. Nevertheless, the model was also set up to proportionally reallocate remaining budget, in case an activity exhausted all potential sites where it could be established. In those cases, the area distribution of the activities would not be equal.

Table 10 presents the annual and total budget distribution for each activity.

Table 10 Annual and total budget distribution among activities.

		Brandywine Creek		Red Clay Creek		White Clay Creek		Christina River	
Activities	**Cost (USD/hectare)**	**Annual investment**	**Total investment**	**Annual investment**	**Total investment**	**Annual investment**	**Total investment**	**Annual investment**	**Total investment**
Riparian Buffers	413	2,022	60,652	2,022	60,652	3,033	90,977	2,022	60,652
Wetland Creation/Restoration	59,305	290,664	8,719,913	290,664	8,719,913	435,996	13,079,869	290,664	8,719,913
Stream Fencing	7,849	38,470	1,154,091	38,470	1,154,091	57,705	1,731,136	38,470	1,154,091
Sustainable crops	444	2,178	65,345	2,178	65,345	3,267	98,017	2,178	65,345
TOTAL	68,011	333,333	10,000,000	333,333	10,000,000	500,000	15,000,000	333,333	10,000,000

Ecosystem services returns

Once we performed the RIOS runs and created the set of conservation portfolios, we selected 5 representative portfolios in order to convert them into land use scenarios to run InVEST: years 1, 5, 10, 20 and 30. We made this decision based on the fact that the InVEST runs are time consuming and, for the purposes of this study, having 5 estimations of change in ecosystem services is enough for a proper assessment. We created the biophysical table used as an InVEST input for each activity, using data from the actual land uses as a reference (Table 11).

Table 11 Biophysical table for the conservation portfolio activities

LULC_desc	lucode	Kc	root_depth	usle_c	usle_p	sedret_eff	load_n	eff_n	load_p	eff_p
Cover crops	101	0.6	700	0.01	0.2	0.25	5.5	0.25	1.5	0.25
Nutrient management	102	0.6	700	0.5	0.4	0.25	5.5	0.25	1.5	0.25
Riparian buffers	103	1	7000	0.003	0.2	0.6	1.8	0.8	0.011	0.8
Stream fencing	104	1	7000	0.003	0.2	0.6	1.8	0.8	0.011	0.8
Wetland restoration	105	1	7000	0.01	0.2	0.8	2	0.9	0.05	0.9

We performed InVEST runs of the described modules (sediment and nutrients) for the baseline land use and for each selected scenario. We graphed the sediment and nutrients export results of each scenario with their respective investment, as shown in Figure 12.

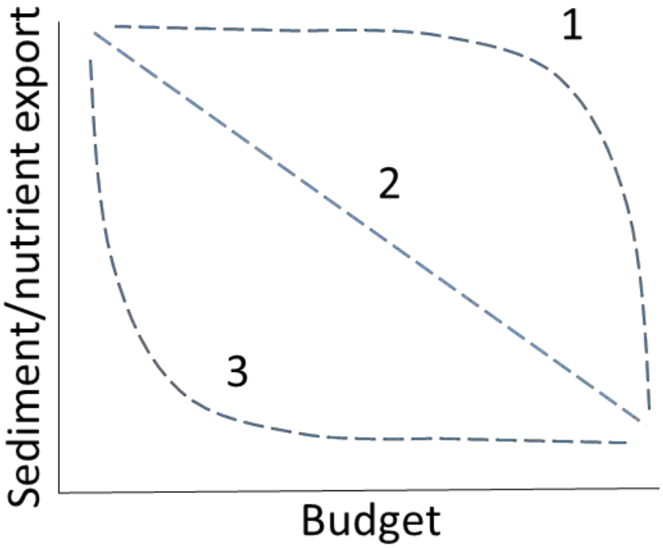


Figure 12 Hypothetical curves of the graph sediment/nutrient export vs budget. Number 1 represents a slow return on invest under low budgets, that becomes quick after certain point (associated to large watersheds), 2 represents an equal level of return across the budget invested, and 3 represents a quick return under a low budget, that stabilizes soon; this break-point should be an indication of when to stop investing, since it is not efficient any more.

We expect that higher investments in natural capital would return higher reductions in sediment and nutrients. What we aim to answer is at what rate these reductions occur, and what is the behavior of such reduction in the graph. These results may serve as a first approach of the investment necessary to reach the reductions required to comply with the standards of the Clean Water Act.

Results

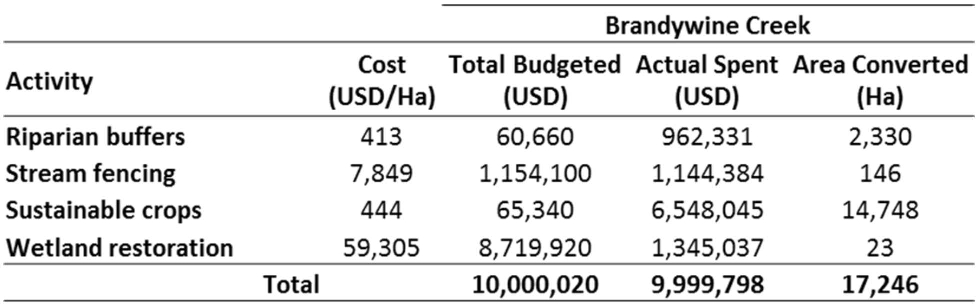
Portfolio of activities

Through RIOS, we produced 30 conservation portfolios for each subwatershed, 1 per year for the 30-year timeline. Each portfolio reflects an accumulated annual investment, showing the areas with activities implemented that year, plus the ones from all past years. In this section, we present a summary of the implementation of the total portfolio (year 30), as well of the maps, for each subwatershed.

Brandywine Creek

Table 12 summarizes the total portfolio results for Brandywine Creek.

Table 12 Summary of total portfolio results in Brandywine Creek



		Brandywine Creek		
Activity	**Cost (USD/Ha)**	**Total Budgeted (USD)**	**Actual Spent (USD)**	**Area Converted (Ha)**
Riparian buffers	413	60,660	962,331	2,330
Stream fencing	7,849	1,154,100	1,144,384	146
Sustainable crops	444	65,340	6,548,045	14,748
Wetland restoration	59,305	8,719,920	1,345,037	23
Total		**10,000,020**	**9,999,798**	**17,246**

Of the USD $10,000,000 budgeted in Brandywine Creek, RIOS reported to spend USD $9,999,798, which represents, virtually, a full use of the budget. This means that there might still be potential areas for activities' implementation under further investment. Largest area is converted to 'Sustainable crops', followed by 'Riparian buffers', 'Stream fencing' and, finally, 'Wetland restoration'. The differences found between total budgeted and actual spent, correspond to the cost-benefit logic of RIOS, which assumes that cheaper activities with higher impact potential would be assigned higher budget. Such is the case of sustainable crops that cause more transitions on the landscape under lower investment.

Figure 13 shows the map of the total portfolio in Brandywine Creek.

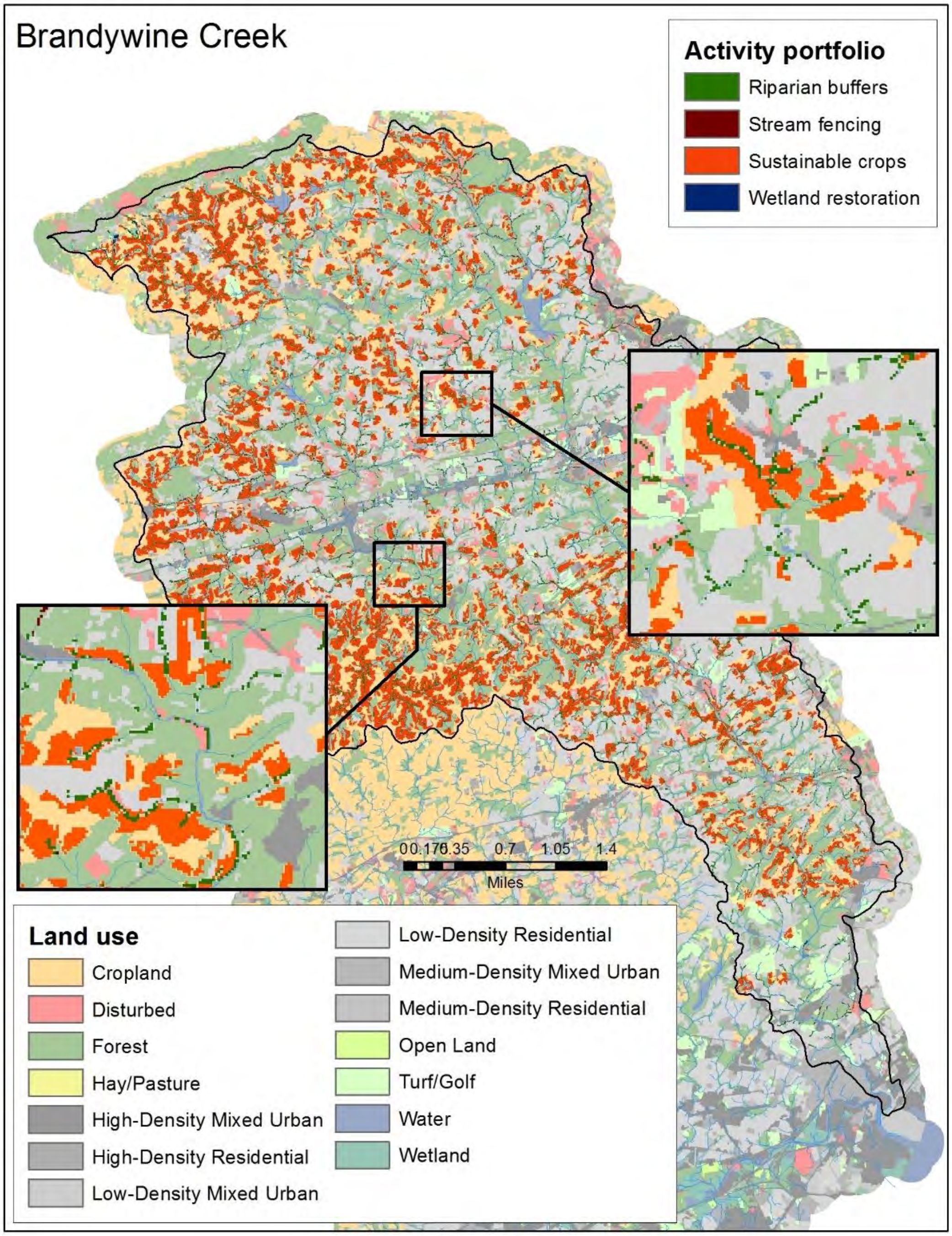


Figure 13 Map of the total portfolio in Brandywine Creek.

The map evidences the dominance of the 'sustainable crops' in the subwatershed, while 'wetland restoration' is not easy to detect given their little area of implementation. The zoom windows show 'stream fencing' and 'riparian buffers' occurring in a 20-meter buffer from all the streams in the subwatershed, as defined in the model's constraints.

Red Clay Creek

Table 13 summarizes the total portfolio results for Red Clay Creek.

Table 13 Summary of total portfolio results in Red Clay Creek

		Red Clay Creek		
Activity	**Cost (USD/Ha)**	**Total Budgeted (USD)**	**Actual Spent (USD)**	**Area Converted (Ha)**
Riparian buffers	413	60,660	173,026	419
Stream fencing	7,849	1,154,100	3,411,254	435
Sustainable crops	444	65,340	1,578,780	3,556
Wetland restoration	59,305	8,719,920	491,045	8
Total		**10,000,020**	**5,654,105**	**4,418**

Of the total USD $10,000,000 budget, a bit more than half was spent by RIOS (USD $5,654,105), due to the exhaust of the potential areas for activity implementation because of the small size of the subwatershed, compared to Brandywine Creek, for example. Here, the 'sustainable crops' was also the widest implemented activity, followed by 'stream fencing' and 'riparian buffers'.

Figure 14 shows the map of the total portfolio in Red Clay Creek.

White Clay Creek

Table 14 summarizes the total portfolio results for White Clay Creek.

Table 14 Summary of total portfolio results in White Clay Creek

		White Clay Creek		
Activity	**Cost (USD/Ha)**	**Total Budgeted (USD)**	**Actual Spent (USD)**	**Area Converted (Ha)**
Riparian buffers	413	90,990	274,909	666
Stream fencing	7,849	1,731,150	7,445,561	949
Sustainable crops	444	98,010	3,291,225	7,413
Wetland restoration	59,305	13,079,880	3,335,906	56
Total		**15,000,030**	**14,347,602**	**9,083**

In White Clay Creek, USD $14,347,602 were invested out of a total of USD $15,000,000. Again, the widest implemented activity was, by far, 'sustainable crops', followed by 'stream fencing' and 'riparian buffers'. The implementation of 'wetland restoration' is considerably higher here than in Brandywine Creek and Red Clay Creek, most probably due to the larger wetland areas in this subwatershed.

Figure 15 shows the map of the total portfolio in White Clay Creek.

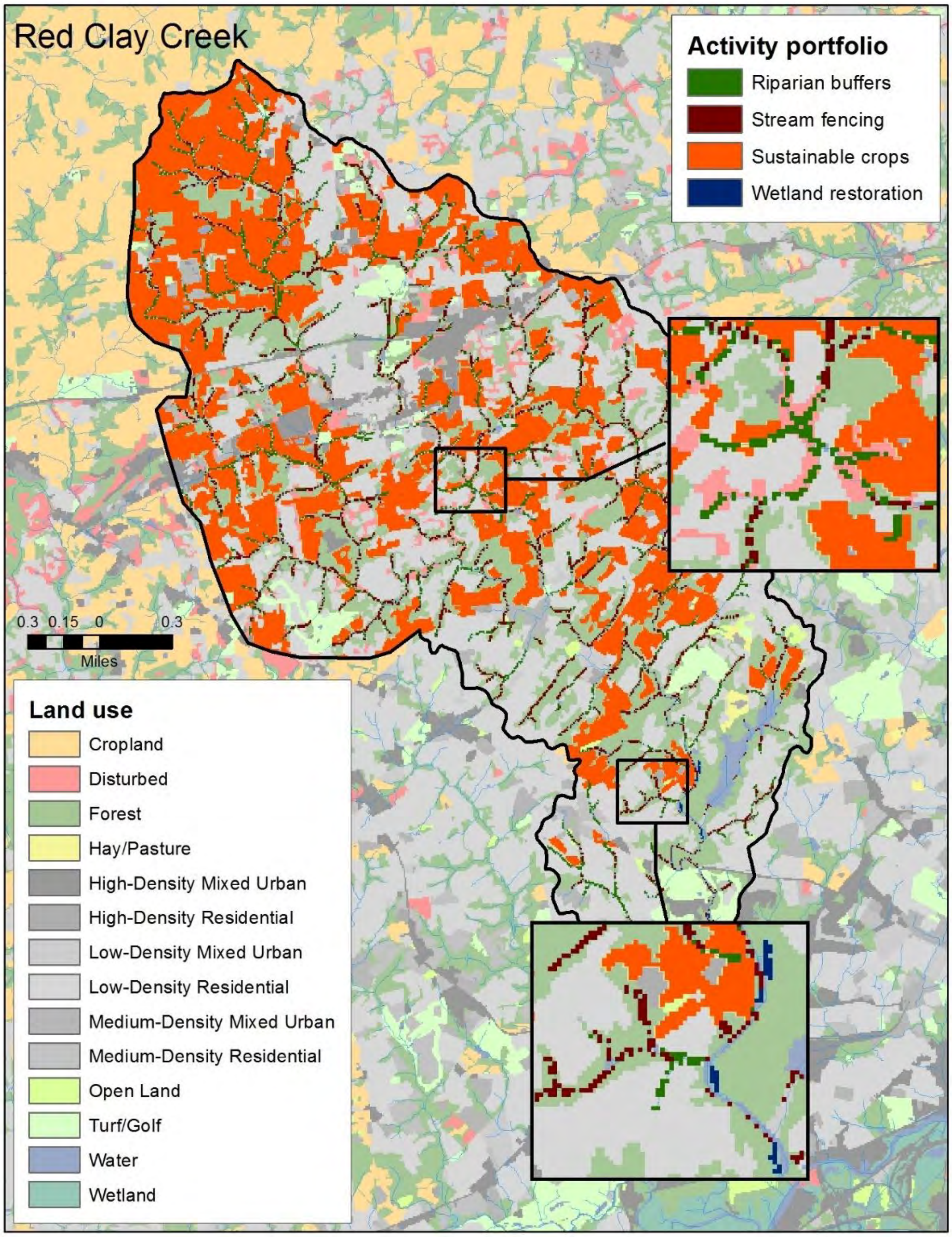


Figure 14 Map of the total portfolio in Red Clay Creek

Again, the map shows the widest distribution of ‘sustainable crops’, with more dominance in the upper zone of the subwatershed. ‘Stream fencing’ and ‘riparian buffers’ occur adjacent to the streams, finding zones with dense implementation in the middle part of the subwatershed. One of the zoom windows shows some areas under ‘wetland restoration’ near forested areas.

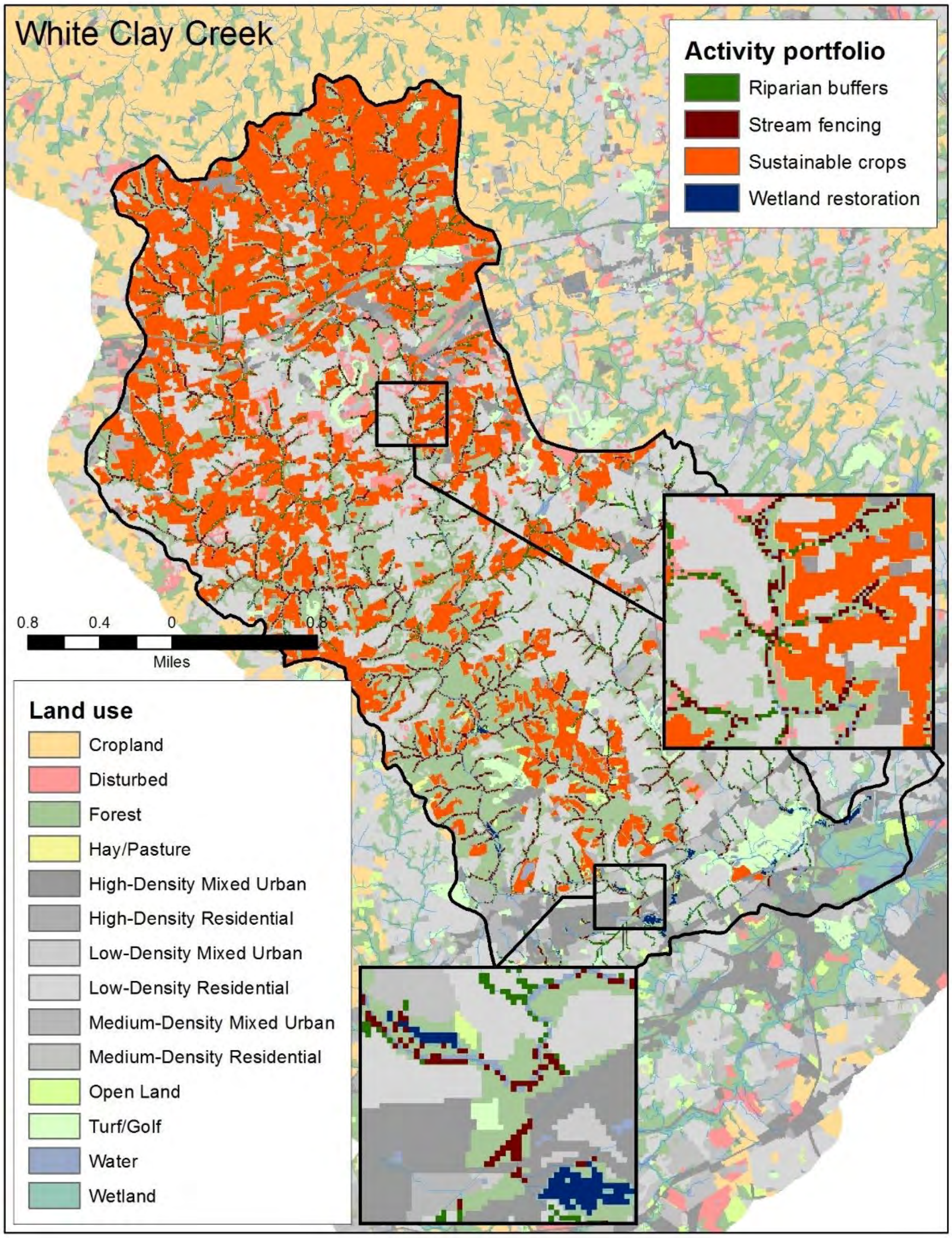


Figure 15 Map of the total portfolio in White Clay Creek

The map shows a larger dominance of ‘sustainable crops’ in the upper part of the subwatershed, probably due to the presence of more agricultural lands. Again, ‘riparian buffers’ and ‘stream fencing’ are found adjacent to streams, while the areas where ‘wetland restoration’ is implemented are found mostly in the lower part of the subwatershed.

Christina River

Table 15 summarizes the total portfolio results for Christina River.

Table 15 Summary of total portfolio results in Christina River

		Christina River		
Activity	**Cost (USD/Ha)**	**Total Budgeted (USD)**	**Actual Spent (USD)**	**Area Converted (Ha)**
Riparian buffers	413	60,660	102,701	249
Stream fencing	7,849	1,154,100	1,144,384	146
Sustainable crops	444	65,340	105,894	239
Wetland restoration	59,305	8,719,920	8,646,669	146
Total		**10,000,020**	**9,999,648**	**779**

The portfolio spent USD $9,999,648, close to the USD $10,000,000 budgeted. Here, 'riparian buffers' was the widest implemented activity, followed by 'sustainable crops'. In this case, the area difference in regard with the other activities, does not seem to be as large. In fact, 'wetland restoration' and 'stream fencing' have the same area of implementation. Given the large wetland cover due to the closeness to the complex of tidal wetlands in the outlet of the watershed, 'wetland restoration' has the highest area of implementation of all the subwatersheds.

Figure 16 shows the map of the total portfolio in Christina River.

The map shows the 'sustainable crops' implementation mostly in the upper areas of the subwatershed. 'Stream fencing' and 'riparian buffers' are, as in every case, adjacent to streams and well distributed across the subwatershed. Most of the 'wetland restoration' implementation areas are found in the middle part of the subwatershed, where the intake is found, which is why there are no activities downstream this point.

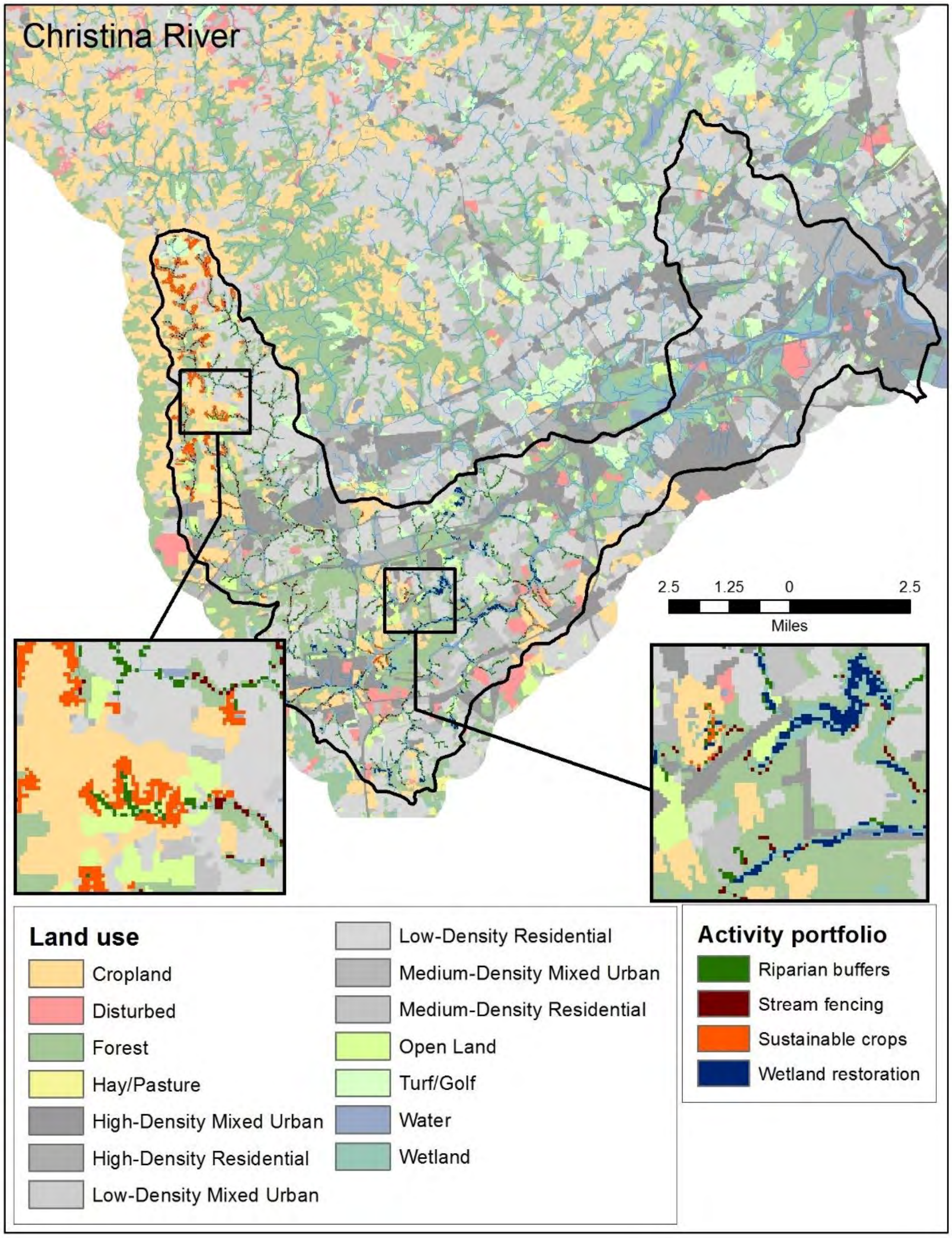


Figure 16 Map of the total portfolio in Christina River.

Baseline, spatial distribution and rates of change

We performed runs of the sediment and nutrients InVEST models for the baseline land use and for the scenarios generated through the total portfolio in each subwatershed, in order to assess the spatial distribution of the potential change in the provision of ecosystem services.

We also assessed the rate of change in the export of sediment and nutrients across the baseline and the 5 scenarios of analysis. This was made as an initial attempt to identify how much investment is needed in the water fund to obtain certain return in ecosystem services provision. We compared the results obtained with the TMDL goals reported in ***Table 6***, in order to verify their compliance of the goals.

Next, we present the maps of the baseline export of sediment and nutrients, as well as the maps showing the spatial distribution of the change in export and the curves with the rate of change.

Brandywine Creek

Figure 17 shows the baseline sediment, nitrogen and phosphorus export of the Brandywine Creek subwatershed.

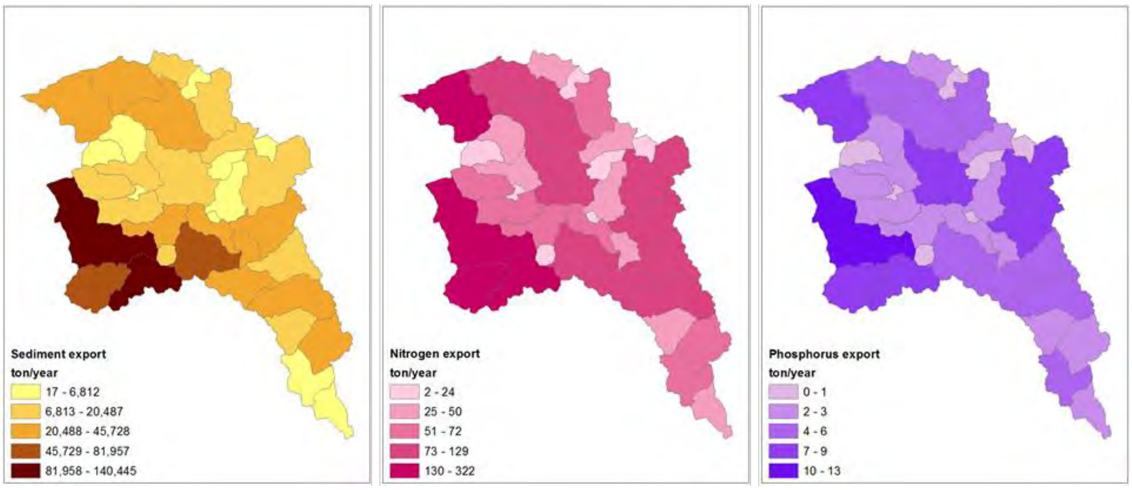


Figure 17 Baseline sediment, nitrogen and phosphorus export by each catchment of the Brandywine Creek subwatershed.

The total baseline annual sediment export in the Brandywine Creek subwatershed is around 895,000 ton. The catchments that contribute the most with this export are on the west of the subwatershed, reaching values in a range between 82,000 and 140,000 ton/year. These catchments are dominated by croplands and the erosivity index is considerably high, in regard to the rest of the subwatershed. On the other hand, some scattered catchments have the lowest export values, with values between 17 and 6,800 ton/year. These catchments are dominated by forests in the upper subwatershed, and urban in the lower subwatershed.

It is important to mention at this point that all the baseline sediment and nutrients results presented here, are the catchment totals, meaning that the area size also determines these values (larger areas are expected to export more sediment and nutrients).

The total baseline annual export of nitrogen and phosphorus is 2,750 ton and 134 ton, respectively. The annual export of both nutrients have a similar spatial distribution, although their magnitudes are different. The highest export areas are located to the west of the subwatershed, some of them coinciding with the highest sediment export catchments, which means that the dominance of croplands also influences the nutrients export. Highest nitrogen export range between 130 and 322 ton/year, and highest phosphorus export between 10 and 13 ton/year.

Figure 18 shows the percentages of change in sediment, nitrogen and phosphorus export between the baseline and the implementation of the total portfolio in Brandywine Creek.

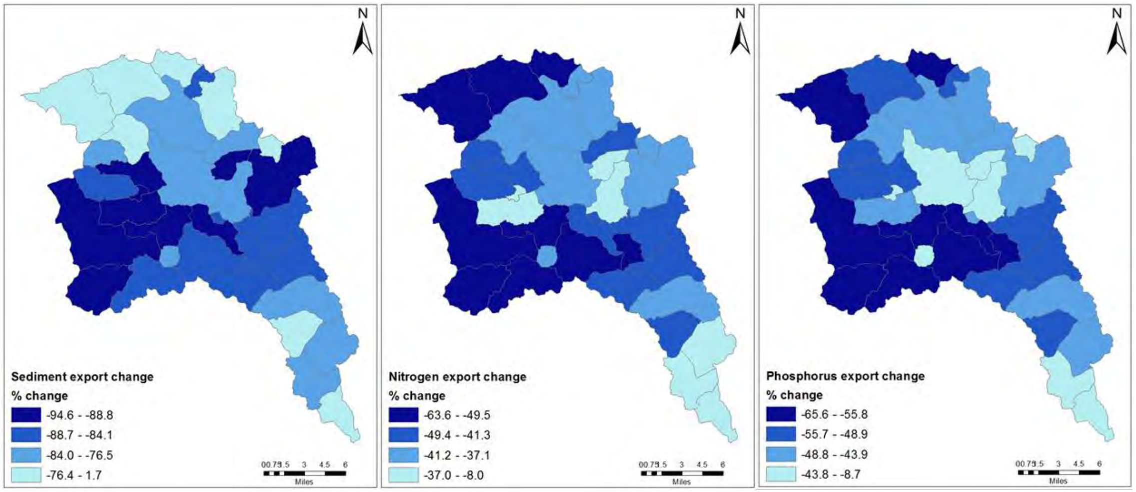


Figure 18 Percentages of change in sediment, nitrogen and phosphorus export for the total portfolio (year 30). Darker blue represents higher change caused by the implementation of the portfolio.

The overall change in sediment export between the baseline and the total portfolio implementation is -84.9%. In other words, 30 years from now, if implemented the proposed conservation portfolio, a reduction in the sediment export of 84.9% is expected. Catchments with the highest change are among the ones with the highest annual exports, with values between -94.6% and -88.8%.

The overall change in nutrients is -53.5% for nitrogen and -46.6% for phosphorus. For both nutrients, the catchments with highest change are located to the west and northwest of the subwatershed, with values ranging between -63.6% and -49.5% for nitrogen, and between -65.6% and -55.8% for phosphorus. The lowest values range between -37.0% and -8.0% for nitrogen, and between -43.8% and -8.7% for phosphorus.

Figure 19 shows the graphs for sediment, nitrogen and phosphorus change across the scenarios, in Brandywine Creek.

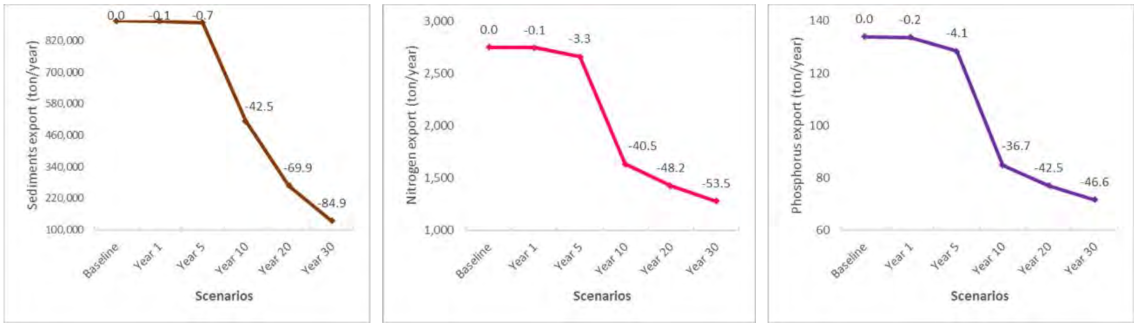


Figure 19 Sediment, nitrogen and phosphorus change across the scenarios of analysis in Brandywine Creek.

In terms of the sediment export TMDL goals, the result of 84.9% reduction in the Brandywine Creek subwatershed exceeds the goal by far, specifically in the Pennsylvania-Delaware line, as the sediment percent reduction here is expected to be between 16% and 60%. Taking a look at the rate of sediment export change in ***Figure 19***, it can be observed that the export change in year 10 is -42.5%, meaning that even investments below the 10-year line would comply with the sediment goal.

Nitrogen reduction of 53.5% exceeds the TMDL goal in both the Pennsylvania-Delaware line (46%), and Delaware (16%). As shown in the rate of change in ***Figure 19***, reaching the goals could be accomplished between years 10 and 20 of implementation.

In the case of phosphorus, the 46.6% reduction in export also exceeds the TMDL goal in both the Pennsylvania-Delaware line (41%), and Delaware (36%). As with nitrogen, reaching the goals could be accomplished between years 10 and 20 of implementation.

Red Clay Creek

Figure 20 shows the baseline sediment, nitrogen and phosphorus export of the Red Clay Creek subwatershed.

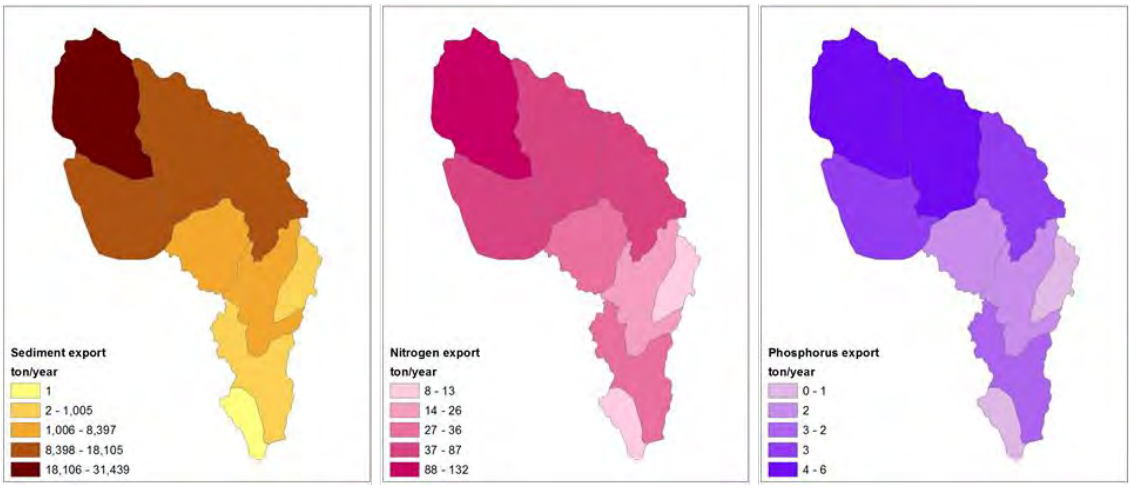


Figure 20 Baseline sediment, nitrogen and phosphorus export by each catchment of the Red Clay Creek subwatershed.

The total baseline annual sediment export in the Red Clay Creek subwatershed is around 93,000 ton. The catchments that contribute the most with this export are on the upper part of the subwatershed, reaching values in a range between 18,000 and 31,000 ton/year, which is highly dominated by croplands, while the other catchments have diverse land uses including urban, that export little sediment due to the impervious soils. The lowest export values are found in the lower subwatershed, with values ranging between 1 and 1,005 ton/year.

The total baseline annual export of nitrogen and phosphorus is 460 ton and 24 ton, respectively. The annual export of both nutrients have a similar spatial distribution, although their magnitudes are different. The highest export areas are located to the upper part of the subwatershed, some of them coinciding with the highest sediment export catchments, which makes sense because of the dominance of croplands. Highest nitrogen export range between 88 and 132 ton/year, and highest phosphorus export between 4 and 6 ton/year.

Figure 21 shows the percentages of change in sediment, nitrogen and phosphorus export between the baseline and the implementation of the total portfolio in Red Clay Creek.

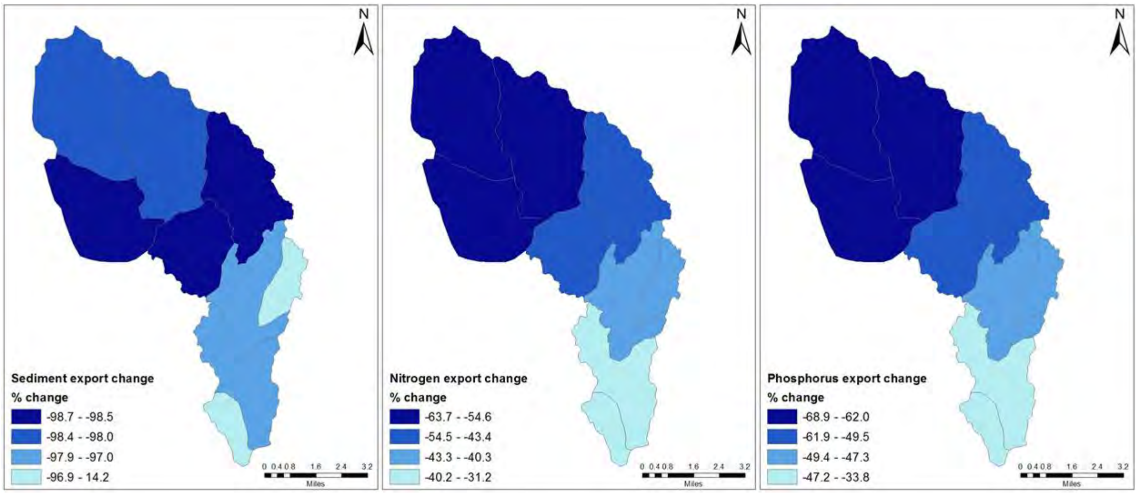


Figure 21 Percentages of change in sediment, nitrogen and phosphorus export for the total portfolio (year 30). Darker blue represents higher change caused by the implementation of the portfolio.

The overall change in sediment export between the baseline and the total portfolio implementation is -98.2%. The catchment with the highest change is located in the upper-mid part of the subwatershed, with a value of -98.7%.

The overall change in nutrients export is -58.9% for nitrogen and -51.4% for phosphorus. For both nutrients, the catchments with highest change are located to the upper part of the subwatershed, coinciding with the highest export catchments, with values ranging between -63.7% and -54.6% for nitrogen, and between -68.9% and -62% for phosphorus. The lowest values range between -40.2% and -31.2% for nitrogen, and between -47.2% and -33.8% for phosphorus.

Figure 22 shows the graphs for sediment, nitrogen and phosphorus change across the scenarios, in Red Clay Creek.

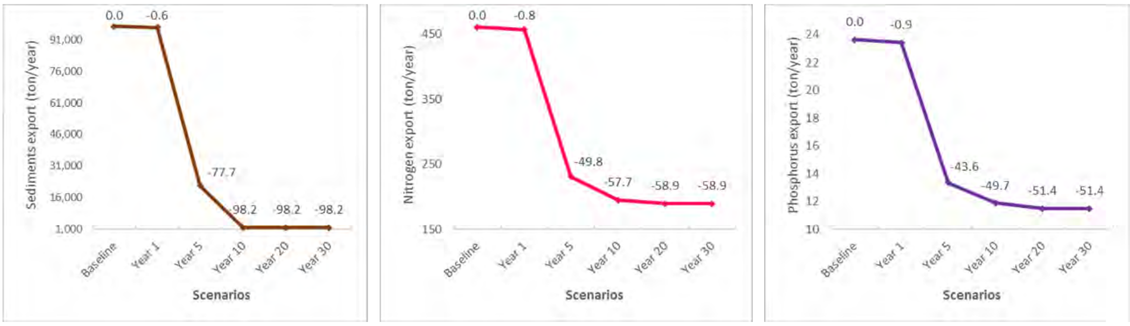


Figure 22 Sediment, nitrogen and phosphorus change across the scenarios of analysis in Red Clay Creek.

In terms of the sediment export TMDL goals, the result of 98.2% reduction in the Red Clay Creek subwatershed exceeds the goal by far, specifically in the Pennsylvania-Delaware line, as the sediment percent reduction here is expected to be between 45% and 52%. Taking a look at the rate of sediment export change in ***Figure 22***, it can be observed that the export change in year 5 is -77.7%, meaning that even investments below the 5-year line would comply with the sediment goal.

Nitrogen reduction of 58.9% exceeds the TMDL goal in both the Pennsylvania-Delaware line (31%), and Delaware (49%). As shown in the rate of change in ***Figure 22***, reaching the goals could be accomplished before the year 5 of implementation.

In the case of phosphorus, the 51.4% reduction in export also exceeds the TMDL goal in the Pennsylvania-Delaware line (40%), but still needs about 3% to accomplish the goal in Delaware (54%). According to the curve, reaching the goal in the Pennsylvania-Delaware line could have been accomplished before year 5 of implementation. In Delaware, on the other hand, the goal might not be accomplished under the current portfolio designed, since the curve shows a stabilization of the change between years 20 and 30 of investment.

White Clay Creek

Figure 23 shows the baseline sediment, nitrogen and phosphorus export of the White Clay Creek subwatershed.

The total baseline annual sediment export in the White Clay Creek subwatershed is around 192.000 ton. The catchments that contribute the most with this export are on the west and north of the subwatershed, reaching values in a range between 19,000 and 40,000 ton/year. There are some scattered catchments in the lower subwatershed with the lowest export values, with values between 2 and 1,605 ton/year.

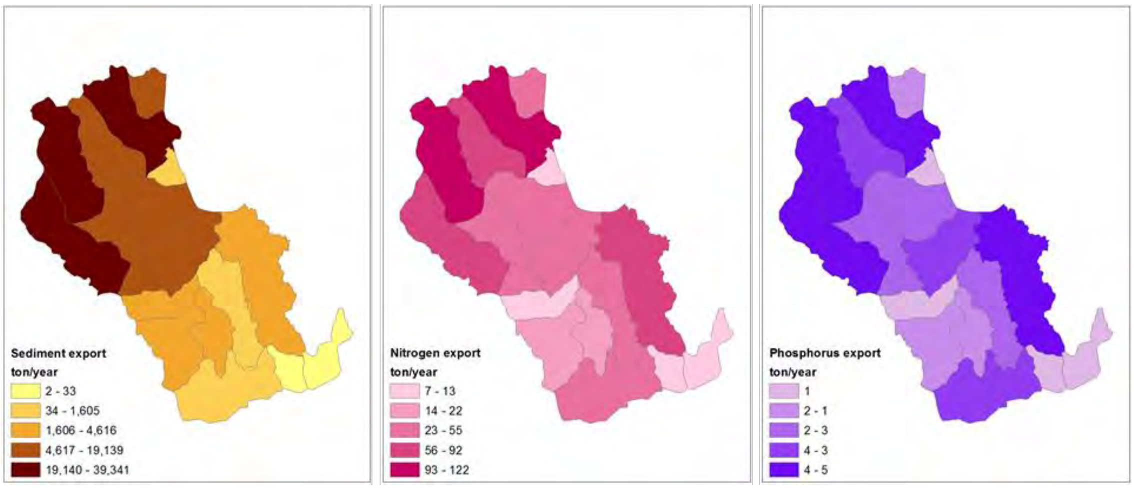


Figure 23 Baseline sediment, nitrogen and phosphorus export by each catchment of the White Clay Creek subwatershed.

The total baseline annual export of nitrogen and phosphorus is 833 ton and 42 ton, respectively. The annual export of both nutrients have a similar spatial distribution, although their magnitudes are different. The highest export areas for nitrogen are located to the upper subwatershed, some of them coinciding with the highest sediment export catchments, while for phosphorus, the highest export catchments are also to the middle and lower subwatershed. Highest nitrogen export range between 93 and 122 ton/year, and highest phosphorus export between 4 and 5 ton/year.

Figure 24 shows the percentages of change in sediment, nitrogen and phosphorus export between the baseline and the implementation of the total portfolio in White Clay Creek.

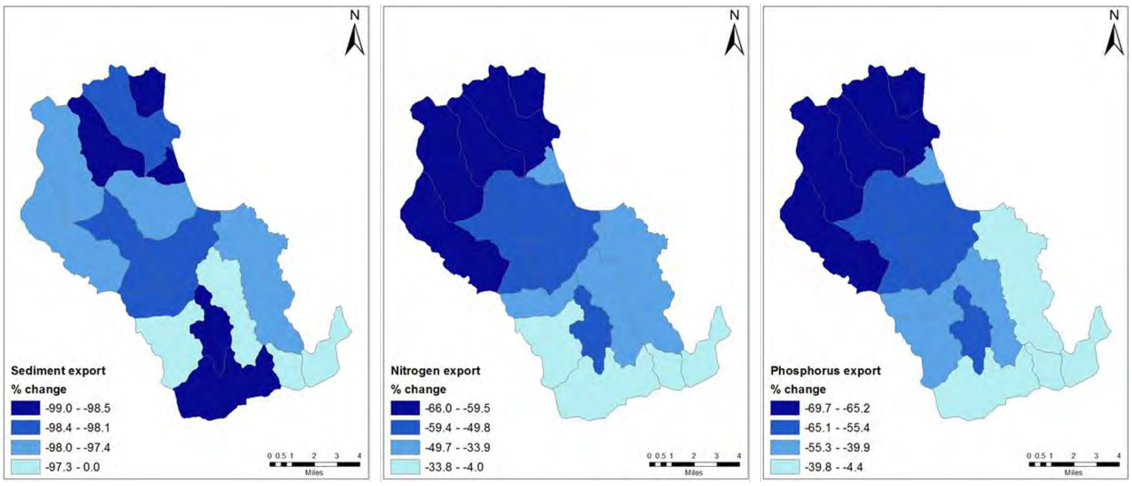


Figure 24 Percentages of change in sediment, nitrogen and phosphorus export for the total portfolio (year 30). Darker blue represents higher change caused by the implementation of the portfolio.

The overall change in sediment export between the baseline and the total portfolio implementation is -98.1%. The catchments with the highest change are located in the upper part of the subwatershed, with values ranging between -99% and -98.5%

The overall change in nutrients is -57-3% for nitrogen and -49.8% for phosphorus. For both nutrients, the catchments with highest change are located to the upper part of the subwatershed, coinciding with some of the highest export catchments, and one in the mid-lower part, with values ranging between -66% and -59.5% for nitrogen, and between -69.7% and -65.2% for phosphorus. The lowest values range between -33.8% and -4% for nitrogen, and between -39.8% and -4.4% for phosphorus.

Figure 25 shows the graphs for sediment, nitrogen and phosphorus change across the scenarios, in White Clay Creek.

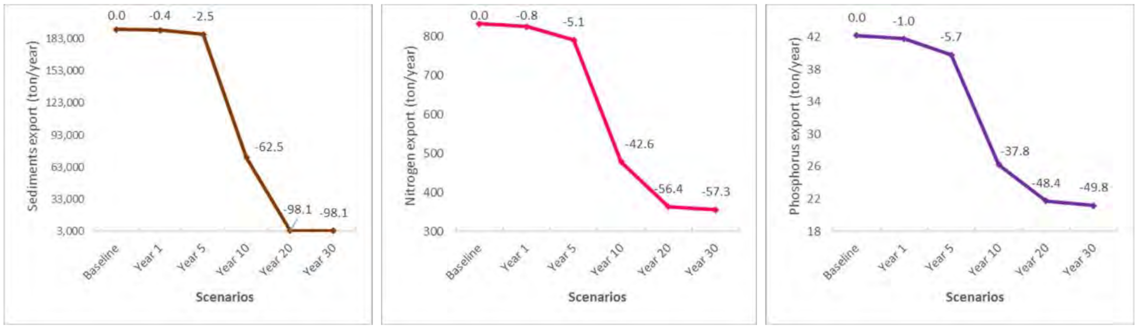


Figure 25 Sediment, nitrogen and phosphorus change across the scenarios of analysis in White Clay Creek.

In terms of the sediment export TMDL goals, the result of 98.1% reduction in the Red Clay Creek subwatershed exceeds the goal by far, specifically in the Pennsylvania-Delaware line, as the sediment percent reduction here is expected to be between 26% and 70%. Taking a look at the rate of sediment export change in ***Figure 25***, it can be observed that the export change in year 10 is -62.5%, meaning that even investments below the 10-year line would comply with the sediment goal.

Nitrogen reduction of 57.3% exceeds the TMDL goal in the Pennsylvania-Delaware line (28%). There is not a TMDL goal for Delaware in the White Clay Creek watershed. As shown in the rate of change in ***Figure 25***, reaching the goal could be accomplished before the year 10 of implementation.

In the case of phosphorus, the 49.8% reduction in export also exceeds the TMDL goal in the Pennsylvania-Delaware line (40%). According to the curve, reaching the goal in the could have been accomplished before year 20 of implementation.

Christina River

Figure 26 shows the baseline sediment, nitrogen and phosphorus export of the Christina River subwatershed.

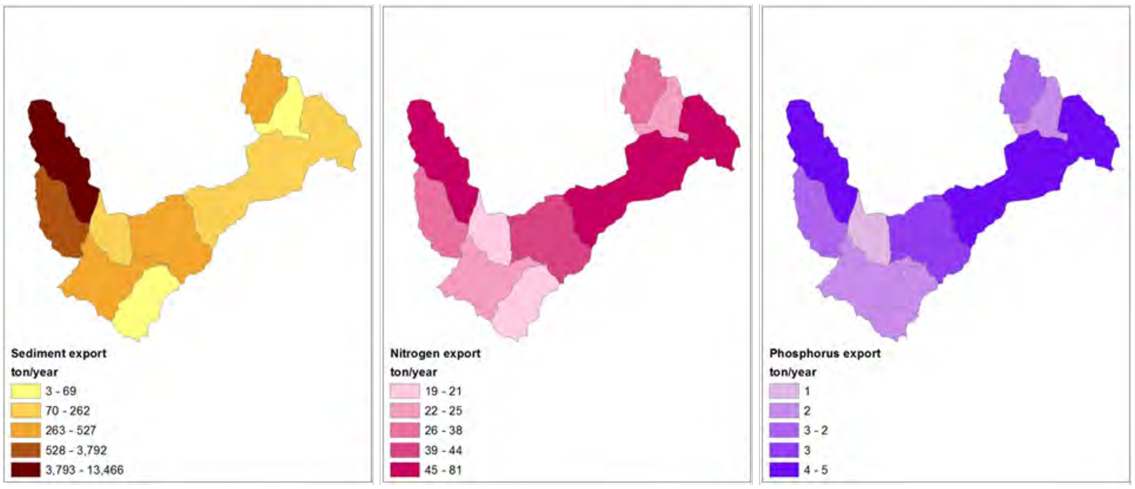


Figure 26 Baseline sediment, nitrogen and phosphorus export by each catchment of the Christina River subwatershed.

The total baseline annual sediment export in the Christina River subwatershed is around 19.000 ton. The catchments that contribute the most with this export are upper part of the subwatershed, reaching values in a range between 3,793 and 13,466 ton/year. There are some scattered catchments in the lower and mid subwatershed with the lowest export values, with values between 3 and 69 ton/year.

The total baseline annual export of nitrogen and phosphorus is 354 ton and 23 ton, respectively. The annual export of both nutrients have a similar spatial distribution, although their magnitudes are different. The highest export areas are located to the upper and lower part of the subwatershed, some of them coinciding with the highest sediment export catchments. The catchment with high export values in the lower part also coincides with the most densely urbanized zone in all the subwatersheds. Highest nitrogen export range between 45 and 81 ton/year, and highest phosphorus export between 4 and 5 ton/year.

Figure 27 shows the percentages of change in sediment, nitrogen and phosphorus export between the baseline and the implementation of the total portfolio in Christina River.

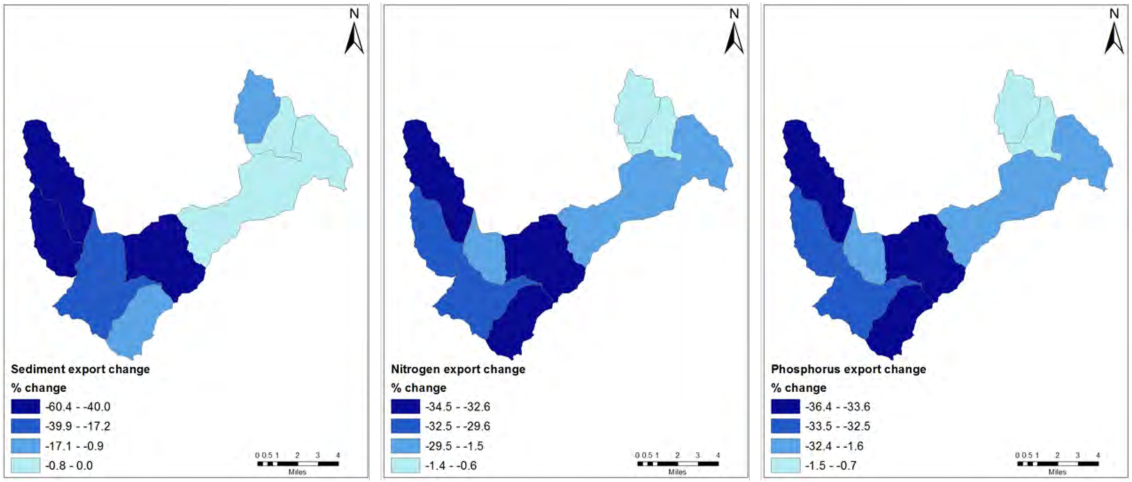


Figure 27 Percentages of change in sediment, nitrogen and phosphorus export for the total portfolio (year 30). Darker blue represents higher change caused by the implementation of the portfolio.

The overall change in sediment export between the baseline and the total portfolio implementation is -54.4%. The catchments with the highest change are located in the upper part of the subwatershed, with values ranging between -60.4% and -40%

The overall change in nutrients is -22.3% for nitrogen and -19.5% for phosphorus. For both nutrients, the catchments with highest change are located to the upper part of the subwatershed, coinciding with some of the highest export catchments, with values ranging between -34.5% and -32.6% for nitrogen, and between -36.4% and -33.6% for phosphorus. The lowest values range between -1.4% and -0.6% for nitrogen, and between -1.5% and -0.7% for phosphorus.

Figure 28 shows the graphs for sediment, nitrogen and phosphorus change across the scenarios, in Christina River.

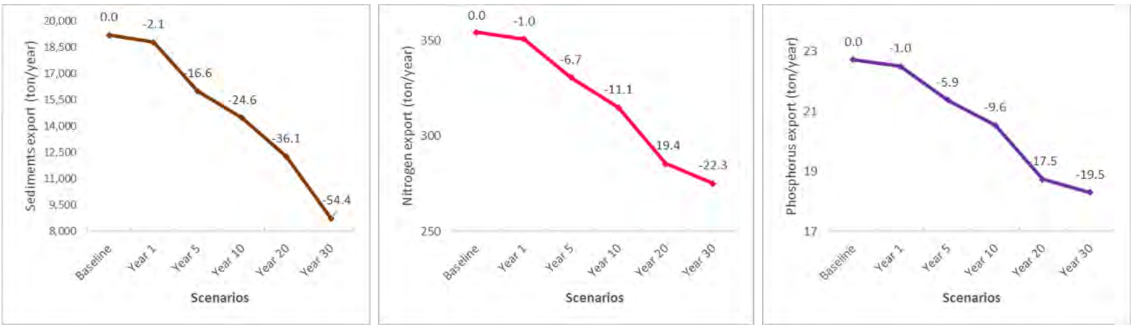


Figure 28 Sediment, nitrogen and phosphorus change across the scenarios of analysis in Christina River.

No sediment TMDL goals have been reported for the Christina River subwatershed. However, it can be observed that the change in sediment export does not seem to stabilize, meaning that further investments may offer additional benefits in sediment reduction.

Nitrogen reduction of 22.3% does not accomplish the goal proposed for the subwatershed in the Pennsylvania-Delaware line (73%), but exceeds, by far, the goal in Delaware (6%). Different from the other subwatersheds, the change in nitrogen does not tend to stabilize, but maintains a continuous decrease. Therefore, based on the rate of change between the years 20 and 30 (2.9%), the continuous implementation of the portfolio in the Pennsylvania-Delaware line of the subwatershed could accomplish the goal in approximately 170 more years if implementation. Given this long time, it might be more adequate to set new strategies to cause a more rapid change. The results also show that reaching the goal in Delaware, could be done around the year 5 of implementation of the portfolio.

In the case of phosphorus, the 19.5% reduction in export does not accomplish the goal proposed for the subwatershed in the Pennsylvania-Delaware line (48%), but exceeds, by far, the goal in Delaware (9%). As with nitrogen, the change in phosphorus does not tend to stabilize, but maintains a continuous decrease. Therefore, based on the rate of change between the years 20 and 30 (2%), the continuous implementation of the portfolio in the

Pennsylvania-Delaware line of the subwatershed could accomplish the goal in approximately 140 more years if implementation. Given this long time, it might be more adequate to set new strategies to cause a more rapid change. The results also show that reaching the goal in Delaware, could be done around the year 10 of implementation of the portfolio.

Error! Reference source not found. shows a summary of the TMDL goals and results from the modelling in the four subwatersheds.

Table 16 Summary of the TMDL goals and results from the modelling in the four subwatersheds. Cells in green show results that accomplish the TMDL goals, and in red, the ones that did not. Source of the TMDL goals: Preliminary Feasibility Study for The Brandywine

Subwatershed	**TMDL goal (%)**			**Modelling results (all subwatershed)**		
Pennsylvania-Delaware Line	**Sediment**	**Total N**	**Total P**	**Sediment**	**Total N**	**Total P**
Brandywine Creek	16 - 60%	46%	41%	84.93%	53.52%	46.56%
Red Clay Creek	45 - 52%	31%	40%	98.17%	58.87%	51.44%
White Clay Creek	26 - 70%	28%	74%	98.13%	57.33%	49.77%
Christina River (at MD - DE line)		73%	48%	54.41%	22.34%	19.47%
In Delaware						
Brandywine Creek		16%	36%	84.93%	53.52%	46.56%
Red Clay Creek		49%	54%	98.17%	58.87%	51.44%
White Clay Creek				98.13%	57.33%	49.77%
Christina River		6%	9%	54.41%	22.34%	19.47%

Cells highlighted in green in the table show the results that accomplish the TMDL goals in the subwatersheds and, in red, the results that did not. The cells that are not highlighted correspond to the ones without a TMDL goal.

Limitations and further steps

A constant limitation in studies related to modelling is the access to good quality data. Although in this case it was relatively easy to obtain it thanks to the help of the University of Delaware Water Resources Agency and to the availability of many national and global datasets, there is always room for improvement: layers with better spatial and temporal resolution and biophysical data from local studies, among others. Also, there is a need to validate and potentially calibrate the model based on field measurements of water quality and turbidity. As this study is a first approach, results on the relative sediment and nutrients change can be trusted with some level of confidence, but absolute values should be dealt with care at least until they can be validated.

Further studies should incorporate the use of climate change projections in the modelling, especially for the long-term future scenarios, considering that the land use, as well as the climate, are dynamic. Also, these first results could be used as an input for reassessing the budget assigned to each activity, in order to efficiently allocate the money that will be used to pay for such activities on the field. For instance, reconsidering the high investment on wetland restoration which, as the results showed, did not cause important changes in sediment or nutrients export.

For this study we used the average activity costs for simplicity purposes. However, given that the costs for some activities are highly dispersed (e.g. USD $2,400 to $116,000 for wetland restoration), we recommend that the future runs specify the conditions under which the costs vary, in order to improve accuracy in the process.

Conclusions

In all subwatersheds, 'sustainable crops' was the widest implemented activity, mainly because it is cheap and implements more transitions than the other activities and, since RIOS operates on a cost/benefit basis, prioritizes it above the others, even overspending its assigned budget. One of the most evident implications of this result is that large areas are impacted with relatively low budgets, and this could change by simply reassigning budget use. For example, by replacing one hectare of 'wetland restoration', 133 new hectares of 'sustainable crops' could be implemented. This has important implications on the decision of where and how to invest, as it might largely change the provision of ecosystem services.

In Brandywine Creek and Christina River the 10 million budget was fully spent, which is interesting since the first is considerably larger than the latter. The answer to this lays on the fact that the investment on 'wetland restoration' in Christina River was near 7 times higher than in Brandywine Creek and, since this activity is the most expensive, the budget was fully spent. Conversely, in Red Clay Creek the actual spent was less than half of the total budget, as the potential suitable areas were exhausted. Finally, the 15 million budgeted for White Clay Creek (assigned in the first phase of this project), was not fully spent either, meaning that perhaps assigning 10 million, as to the other subwatersheds, could have been enough for a good estimation.

Highest sediment exports are found in areas that coincide with high erosivity and steep slopes. On the other hand, catchments with highest export of nitrogen and phosphorus coincide with the areas with croplands and densest residential and urban areas, therefore, with highest probability of pollution by fertilizers and sewage.

TMDL goals for nitrogen and phosphorus were reached in some cases, but they were almost always close to the goal, except in the cases were the goal is near 70%.

In all subwatersheds, except in Christina River, the rate of change of sediment and nutrients export stabilizes in the year 10 or 20 (even in year 5, in some cases). This means that lower budgets than the 10 million proposed (and 15 million for White Clay Creek), should be considered in order to optimize the investments, especially since not all subwatersheds reached the TMDL goals. In other words, the Water Fund should consider investing in conservation activities up to the point where no extra significant benefit is being accomplished, and use the remaining funds to seek for additional strategies to reach the goals.

For Christina River, on the other hand, it appears that investing additional funds in conservation activities might offer additional benefit for nutrients retention, as no stabilization of the rate of change is detected.

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APPENDIX D – Processing steps to produce farm crop and wooded parcel layer

Creation of Chester County Farms and Farm Woodlands layers

1. Select all Chesco parcels>=4 acres (small farm size and up). This can contain other land cover types too. ChescoPar_4AcresUp (18149 polys)
2. Intersect those parcels with the DVRPC land use LU_Type='Agriculture' (use the Definition Query to consider only appropriate polygons). **ChescoPar_4AcresUp_X_Farmland** (11900 polys)
3. Also intersect those parcels from step 1 with the DVRPC woodlands (LU_Type='Wooded'). **ChescoPar_4AcresUp_X_Woodland** (10931 polys)
4. Delete or select only (using Definition Query) polygons from layer from step 2 less than 1 acre. This gets rid of larger parcels adjacent to farmland that is probably of a different type, but that was intersected with DVRPC Agricultural land use type. (9003 polys)
5. Link from **ChescoPar_4AcresUp_X_Woodland** to **ChescoPar_4AcresUp_X_Farmland** layer on field PIN-MAP to determine which woodlands are actually on true farm parcels. Keep only matching records, and create and index if prompted. (8432 polys)

Delaware County, New Castle County, Lancaster County, see below

New Castle

Repeat steps 1 – 5 using the NCC Tax parcels and the State's 2012 layer of landuse

AG= Confined Feeding Operations/Feedlots/Holding, Cropland, Farmsteads and Farm Related Buildings, Herbaceous Rangeland, Idle Fields, Orchards/Nurseries/Horticulture, Other Agriculture, Pasture

Woods= Deciduous Forest, Evergreen Forest, Mixed Forest, Non-tidal Forested Wetland, Shrub/Brush Rangeland, Tidal Forested Wetland