Spring 2022

# A GIS Analysis of Potential Wetland Mitigation Opportunities in the Brandywine Creek Watershed, Chester County, Pennsylvania

Shannon Ryan
sr943566@wcupa.edu

# A GIS Analysis of Potential Wetland Mitigation Opportunities in the Brandywine Creek Watershed, Chester County, Pennsylvania

A Thesis Presented to the Faculty of the

Department of Geography and Planning

West Chester University

West Chester, Pennsylvania

In Partial Fulfillment of the Requirements for the

Degree of Master of Science

By

Shannon J. Ryan

May 2022

Acknowledgements

This thesis would not have been possible without the encouragement and support of Dr. Joy Fritschle. She showed me that there is a niche to be explored for those who are passionate about both the field of Geography and the environment. – now I know what I want to be when I "grow up." Thank you to Dr. Megan Heckert and Dr. Joan Welch for the guidance and insight they provided throughout the thesis process. I am forever thankful for the support from the Geography and Planning Department at West Chester University. Thank you to my husband, Bryan, for his willingness to step up as dog dad during my late thesis nights, to my twin sister, Meghan, for being my best cheerleader, and to my mentor and friend, Teresa, for supporting me along this academic journey. To the rest of my family and friends, thank you for your continuous love and support.

Abstract

Wetlands provide innumerous functions and values that are beneficial to both the natural environment and economic systems. Historically these habitats have suffered significant losses and it is crucial to preserve existing wetlands and plan for future restoration opportunities. This research examines six sub-watersheds within the Brandywine Creek watershed within Chester County, Pennsylvania to determine where potential wetland mitigation opportunities occur. Using a Geographic Information Systems (GIS) analysis, three wetland characteristics including watercourse locations, existing National Wetlands Inventory (NWI) wetlands, and hydric soils were mapped throughout each of the watersheds. Areas of agricultural easements and steep slopes were used to exclude areas from the study. Based on the occurrence of these characteristics, eight sites were selected for ground-truthing investigations. To support findings from these processes, a review of aerial imagery was performed to understand how the site and surrounding landscape have changed over time. Of the eight selected sites, two were deemed suitable for immediate potential wetland mitigation opportunities, four were determined to have the potential for wetland mitigation pending further analysis, and two were determined to be unsuitable for wetland mitigation. The lack of access to private property, presence of agricultural activities, and availability of GIS data provided limitations for a complete and thorough study. This research shows that GIS analysis could be a useful tool in determining where potential wetland mitigation opportunities lie and can serve to benefit future wetland mitigation planning activities, regulating agencies, conservation organizations, as well as the natural and human environments.

Keywords: Wetland Mitigation, Geographic Information Systems, Chester County, Pennsylvania, Ecological Restoration, Wetland Construction, Historical Aerial Imagery

Table of Contents

List of Tables ........................................ vi

List of Figures ........................................ vii

Chapter 1: Introduction ........................................ 7

Chapter 2: Literature Review ........................................ 6

Chapter 3: Study Area ........................................ 20

Chapter 4: Methods ........................................ 26

Chapter 5: Results ........................................ 35

Chapter 6: Discussion ........................................ 59

Chapter 7: Conclusion ........................................ 72

Bibliography ........................................ 76

List of Tables

1. Data source information ........................................................................................ 28

2. Summary of feature measurements within the study area ........................................... 36

3. Summary of methodology results .................................................................................. 41

4. Ground-truthing and aerial imagery interpretation results for the Main Stem Brandywine Creek sub-watershed ........................................................................................ 42

5. Ground-truthing and aerial imagery interpretation results for the East Branch Brandywine Creek sub-watershed ........................................................................................ 46

6. Ground-truthing and aerial imagery interpretation results for the Red Clay Creek sub-watershed ........................................................................................................ 52

7. Ground-truthing and aerial imagery interpretation results for the White Clay Creek sub-watershed ........................................................................................................ 56-57

List of Figures


1. Study area in Chester County, Pennsylvania ............................................................... 21

2. Hydric soils in study area ........................................................................................... 21

3. NWI wetlands in study area ........................................................................................ 21

4. Agricultural easements in study area ........................................................................... 21

5. Methodology flow chart ............................................................................................... 27

6. Results and ground-truthing locations within the study area ........................................ 37

7. Results and ground-truthing locations within the Main Stem Brandywine Creek sub-watershed ................................................................................................................... 39

8. Results and ground-truthing locations within the East Branch Brandywine Creek sub-watershed ................................................................................................................... 44

9. Results within the West Branch Brandywine Creek sub-watershed ............................ 47

10. Results within the Buck Run sub-watershed ............................................................... 49

11. Results and ground-truthing locations within the Red Clay Creek sub-watershed ...... 51

12. Results and ground-truthing locations within the White Clay Creek sub-watershed ... 54

13. Lamb Tavern Wildlife Preserve signage and view of wetlands at EB-1 ...................... 62

14. Signage nearby WC-2 indicating ongoing restoration activities ................................. 64

15. Tree plantings along riparian buffer restoration project at WC-2 ................................ 64

# CHAPTER 1 - INTRODUCTION

Because wetland ecosystems provide many particular functions and values within the environment, the significance of these habitats is profound (Mohan et al. 2022). Wetlands often support a diverse community of plant and animal species that are not found anywhere else in the landscape. Approximately one-third of all plant and animal species that are listed as threatened or endangered in the United States (U.S.) rely on wetland habitats for survival (NPS 2016). These species include bog turtles (*Glyptemys muhlenbergii*), whooping cranes (*Grus Americana*), and lake iris (*Iris lacustris*), among others. Wetlands are tremendously productive, providing a variety of ecosystem services such as water purification, flood regulation, erosion control, and sediment and nutrient transport (Jin et al. 2016). Other habitats across the landscape are able to thrive through the uptake of nutrients provided by wetlands while remaining protected from serious flooding events.

According to the Army Corps of Engineers (ACOE), wetlands are areas throughout the landscape that are regularly inundated or saturated by surface or groundwater at a frequency and duration that supports a population of hydrophytic or partially hydrophytic vegetation (Forsythe et al. 1987). Because of these specific conditions, wetland habitats support a unique number of plant and animal species. The *1987 ACOE Wetlands Delineation Manual and Regional Supplements* outlines three specific criteria an area must meet to be considered a wetland. These include hydrologic, vegetative, and soil characteristics. Areas that meet these three criteria fall under jurisdiction of the ACOE which allows them special protections from several governing bodies.

Even with these protections, wetland habitats are still suffering. As the pressure from increasing human population and development expands, wetlands are being exposed to unpredictable challenges. It is estimated that half of natural wetland areas have been lost in the most developed countries (Gutzwiller and Flather 2011). Agricultural activities have converted these nutrient-rich environments to dry and desolate crop fields. Invasive plant and animal species are now threatening, and often out-competing, the native species that wetland habitats need to survive. Climate change has led to more frequent flooding events, but the unknown future impacts to wetlands could be greater (Mohan et al. 2022). The impact humans have had on wetland habitats are numerous and extensive.

These ecosystems are some of the most important and sensitive within the natural environment. The need to preserve these unique habitats has become widely recognized in recent years as a number of natural and human-influenced threats bear down on them. As the world works through the United Nation's (UN) Decade of Ecosystem Restoration, sensitive ecosystems, including freshwater and wetland types, are being pulled into focus. This rallying cry from the UN aims to halt the degradation of ecosystems and encourage restorative action on a global scale (UN n.d.).

The loss and degradation of wetland ecosystems is not necessarily irreversible (Ainsworth et al. 2013). While the overall goal of the protection and restoration of ecosystems is set at a global scale, these initiatives begin at the local scale. Ecosystem restoration at a local scale has global implications that benefit nature and people (SER n.d.) Preserving and restoring wetland habitats within a small, single watershed has the potential to effect positive changes on the upstream and downstream human and natural communities. Yet, while the need for preservation is great, it is important to plan for possible mitigation opportunities as well. Wetland mitigation is an opportunity to off-set similar habitat loss or degradation by creating new wetland habitats, or restoring and enhancing an existing wetland.

Wetlands within the Brandywine Creek watershed in Chester County, Pennsylvania have an important role to play. The Brandywine Creek watershed is part of the larger Delaware River watershed, which drains into the Delaware Bay (Stroud n.d.). As wetlands are natural tools for water filtration and purification, preserving these habitats throughout the watershed is critical for filtering out contaminants before they reach the bay, and also for maintaining clean drinking water for millions of residents. The Brandywine Creek provides drinking water for many of the urban and suburban areas throughout its coverage area (BRCA 2015). The use of water pulled from the Brandywine Creek will only become more important as the population in Chester County continues to grow. Data collected from the 2020 Census shows that Chester County is the fastest growing county in Pennsylvania (Chesco n.d.).

Higher populations likely mean more stress on sensitive wetland habitats. Although protections and regulations prohibit avoidable impacts to wetlands during construction activities, the stressors from human activities will increase. Along with development comes more stormwater runoff, higher levels of pollution, fragmented wetland habitats – all of which can have a negative impact on wetlands. Urban stormwater runoff is a leading cause of pollution to receiving waters, including streams and wetland habitats (Mallin et al. 2008). Therefore, it is important to understand not only where wetlands currently exist, but also where more could be created throughout the Brandywine Creek watershed so that these potential negative impacts can be offset.

The Brandywine Creek watershed spans the central portion of Chester County Pennsylvania and is made up of seven sub-watersheds (BRCA n.d.; Stroud Research Center. n.d.). Within Chester County, six sub-watersheds including Main Stem Brandywine Creek, East Branch Brandywine Creek, West Branch Brandywine Creek, Buck Run, White Clay Creek, and

Red Clay Creek, make up the majority of the Brandywine Creek watershed. These six sub-watersheds are similar in size, and have mixed land use and land cover (LULC) that makes them appropriate for comparison.

### *Study Purpose*

Because wetlands have specific hydrologic, vegetative, and soil requirements they need to be thoughtfully planned within the landscape. The process of wetland mitigation has to balance these three requirements before shovels break the ground. The purpose of this study is to evaluate suitability of the Brandywine Creek watershed within Chester County, Pennsylvania for potential wetland restoration and mitigation opportunities. The aim of this research is to answer the following questions:

1. Can GIS be a useful tool when planning for potential wetland mitigation opportunities.?
2. Using a GIS analysis, what are potential wetland mitigation opportunities that exist within six sub-watersheds located in the Brandywine Creek watershed in Chester County, Pennsylvania?

To answer these questions, a Geographic Information System (GIS) analysis will be performed with the goal of pinpointing potential locations for wetland mitigation opportunities. Once the desktop analysis is complete, ground-truthing investigations will be performed at the potential sites. These investigations will evaluate the on-site conditions and determine if these locations would be suitable for wetland mitigation activities. Finally, an interpretation of historical aerial imagery will be performed to understand how land use has changed within and around the selected sites. Areas that have previously held wetland environments could indicate that there may be an opportunity to re-establish the necessary hydrology and create a wetland habitat once again. This interpretation could also reveal areas that have historical land use that may not support wetland habitats.

The literature review chapter of this study will further discuss the importance of wetland habitats from both an environmental and economic perspective, historical wetland loss, and a comparison of constructed and natural wetlands. An explanation of current wetland mitigation strategies and the outcomes when creating wetlands will also be presented in the literature review chapter. A comparison of GIS methods that have been used in the determination of where wetland mitigation opportunities may lie will also be included in this chapter. These GIS methods have been used not only to determine the actual location of potential sites, but can also be used to prioritize mitigation and restoration opportunities. Finally, a review of two case studies that have used these methods will end the literature review.

### *Summary*

The goal of this thesis is to evaluate the application of GIS in locating and comparing potential wetland mitigation areas among six sub-watersheds in the Brandywine Creek watershed located in Chester County, Pennsylvania. The thesis includes ideas presented from relevant literature, a description of the study area, an explanation of the methods used, a reporting of the results, and a discussion of findings with recommendations for further research. Chapter 2 includes a review of literature describing the environmental and economic values of wetlands, historical wetland loss, current wetland mitigation regulations, and a review of methodology that has been used in previous research. Chapter 3 describes the study area within the Brandywine Creek watershed in Chester County, Pennsylvania. Chapter 4 details the methodology used to complete this research, including a GIS analysis, ground-truthing reconnaissance, and an interpretation of aerial imagery. Chapter 5 presents the results of this research and Chapter 6 includes a detailed discussion of these results. The final chapter, Chapter 7, details the implications of this study and how this research could support future wetland mitigation studies.

# CHAPTER 2 – LITERATURE REVIEW

This chapter will discuss the importance of wetland habitats from both an environmental and economic perspective. Historical wetland loss throughout the US and Pennsylvania, and a comparison of constructed and natural wetlands throughout the state of Pennsylvania will also be discussed. An explanation of current wetland mitigation strategies provides insight into how regulating agencies determine mitigation amounts and how the process typically works. Because there are a variety of outcomes when creating wetlands, a brief discussion as to why constructed wetlands fail to succeed will also be presented in this chapter. A comparison of GIS methods that have been used in the determination of where wetland mitigation opportunities may lie will also be included in this chapter. These GIS methods have been used not only to determine the actual location of potential sites, but can also be used to prioritize mitigation and restoration opportunities. Finally, a review of two case studies that have used these methods will end this chapter.

## *Environmental Values of Wetlands*

Perhaps the most obvious value of wetland habitats comes from their environmental and natural contributions. Also known as "kidneys of the Earth," wetland ecosystems provide a wide array of natural functions and values that benefit the environment on every scale (Verma and Negandhi 2011). Wetlands serve as multi-function habitats, often performing several ecological functions simultaneously (Mitsch and Goesslink 2000). Any input into a wetland habitat will result in a variety of ecological services. For example, wetlands provide stormwater runoff storage after a heavy rain event. The runoff taken into the wetland is naturally filtered and purified to remove pollutants and sediments. Clean water is deposited back into the landscape and is also held within the wetland to support the growth of hydrophytic vegetation, which is important for sediment runoff and erosion control. This specific vegetation makeup is important for several threatened and endangered species that rely solely on wetlands as habitat and food supply.

Because the environmental values of wetland habitats are increasingly being recognized, the importance of prioritizing wetland mitigation opportunities should be at the forefront of environmental planning and management decisions (Jin et al. 2017). The UN Decade on Ecological Restoration has included wetland ecosystem creation and protection in its global movement. Riparian and wetland ecosystems may be the most critical ecosystem restoration initiative, as these areas are crucial in the persistence of both aquatic and terrestrial habitats (Mohan et al. 2022).

### *Economic Values of Wetlands*

Historically, wetlands have been and continue to be considered a habitat of little to no value (Turner et al. 2000). This perceived lack of value has been a key influencing factor in the destruction of wetland habitats. Yet this is not the case as wetland ecosystems are high-quality habitats that provide environmental and economic values. Sensitive wetland habitats provide immeasurable environmental benefits to the surrounding landscape, plants, and animals. However, wetland ecosystems also provide a variety of natural services that are important for human well-being, and may help to alleviate poverty (Gimenez and Ruiz Mas 2020).

The health of wetland ecosystems has strong implications on the functioning of an economic ecosystem and its population (Verma and Negandhi 2011). Wetland systems in developed areas, specifically in developing countries, are an important natural resource to populations living in that area. They provide many economic resources, such as water availability, fibers, and fish supply (Butchart et al. 2005). For example, wetland-related fisheries make an important contribution to local, national, and global economies. Wild fisheries in coastal wetlands are estimated to contribute $34 billion to the global economy annually (Ibid.). As wetlands near and within developed areas degrade and the productivity of these habitats fail, these important economic services will decrease (Verma and Negandhi 2011). This decrease in economic services may result in greater poverty as incomes obtained from wetland resources fall. It is important to note that the effects of poverty related to wetland degradation are not uniform. Due to traditional gender roles, women are assumed to be closer to nature and have a greater desire to protect it (Joshi et al. 2021). This assumption combined with the notion that women are more likely to be considered marginalized, means that women in poverty are disproportionality affected by wetland degradation.

When considering the economic valuation of wetlands, it is important to understand that a traditional monetary value is difficult to ascertain. Realistically, instilling any type of economic value on a natural resource means that it is more important to consider its value as it pertains to the welfare of society (Gimenez and Ruiz Mas 2020). While wetland functions do not contribute "cash" directly back to their economy, they do offer natural processes that improve the welfare of society for "free." An example of this would be considering a wetland's ability to mitigate climate change through carbon storage versus a constructed process that has the same results. It is estimated that wetlands account for one-third of the world's organic soil carbon pool (Bernal and Mitsch 2012). This storage results from a natural process that does not require human intervention to function. Alternately, manufactured technological and industrial carbon sequestration processes may require a significant time and financial cost. This idea of "free" natural processes extends well beyond climate change, and includes a variety of other process such as flooding storage and control, and water filtration, among others. All of these processes have the potential to make positive contributions to the welfare of society.

It should be noted that the economic value of unconverted wetlands is often greater than converted wetlands (Butchart et al. 2005). For example, intact areas of freshwater marshes and wetlands in Canada have an estimated value of about $5,800 per hectare, compared to an estimated value of $2,400 per hectare for wetlands converted for agricultural uses (Ibid.). Because there has been a significant historical loss of areas of intact, unconverted wetland habitats, considering the economic values of wetland mitigation areas should be a focus of nature conservation programs at all scales (Turner et al. 2000).

### *Historical Wetland Loss*

Wetland habitats are some of the most important ecosystems in the world. Even with these values, wetlands have been destroyed and degraded at an alarming rate throughout time. Of the approximately 89.4 million hectares (ha) of wetland habitat that existed throughout the continental United States in the 1780s, it is estimated that less than 50% of them remain today (Gutzwiller and Flather 2011). By the mid-1970s, approximately 42.8 million ha existed in the continental United States (Mitsch and Hernandez 2012). The majority of wetland loss can be attributed to agricultural activities (Gutzwiller and Flather 2011). In 1972, the Clean Water Act was significantly expanded and paved the way for several wetland protection regulations to follow. The Wetland Conservation Provisions of the Food Security Act (WCP) was enacted in 1985. The WCP withheld United States Department of Agriculture (USDA) benefits from farmers who converted wetlands to cropland (USDA n.d.). This Act deterred farmers from destroying wetlands to use as agricultural fields.

The push for wetland protections gained momentum during the 1960s (Turner et al. 2000). The driving force behind this was the recognized importance of these habitats for migratory bird species. In 1975, the Ramsar Convention provided the framework for wetland conservation at an international-scale (Hettiarachchi et al. 2015). Since then, numerous wetland conservation efforts at every scale have been implemented using the Ramsar Convention standards as a foundation. Yet even with these efforts, wetland habitats are still undervalued and frequently converted to more desirable land uses.

By the early 1990s, the majority of wetland habitat losses were caused by urban and suburban development, specifically in the northeastern U.S. (Turner et al. 2000). The increase in demand for urban and suburban living caused sensitive wetland ecosystems to be destroyed. In many cases, road systems were constructed through wetlands, which would fragment these habitats.

The UN's Decade on Ecosystem Restoration and its global partner, the Society for Ecological Restoration (SER), is a driving force for wetland habitat restoration. The SER initiative begins with specific standards of practice for planning and implementing ecological restoration projects (Gann et al. 2019). These include:

a. Planning and design
b. Implementation
c. Monitoring and evaluation
d. Maintaining ecological restoration projects after completion

These standards are adaptable to project specifics and can be altered to fit any project's size, budget, etc. (Gann et al. 2019). These standards are intended to act as a guide when working through ecological restoration projects to support successful outcomes.

Planning and design highlights the importance of including all project members in all project discussions from beginning to end (Gann et al. 2019). This standard encourages project assessments at all levels, including native ecosystem references, determining a baseline inventory of project characteristics, and establishing a project review procedure, among others. Implementation supports the decisions made during the planning and design process, and also encourages an adaptive management response to any changes that occur throughout the project. Throughout and following the implementation phase, monitoring and evaluation are key to encourage project success. This standard is set to ensure the design is evolving as it should. The final standard, post-implementation, encourages on-going management of the ecological restoration project so that it will continue to succeed and, once again, become a part of the natural environment.

These standards could serve as the framework for successful wetland restoration and creation activities. Today it is estimated that there are approximately 114.6 million ha of wetland habitat in the US, with 43.6 million ha of wetlands occurring in the lower 48 states (Mitsch and Hernandez 2012). Some historical wetland loss has been offset by a push to preserve existing wetlands and mitigate for any disturbances. Efforts set forth by the Ramsar Convention, the UN, SER, and others have resulted in an increase in wetland habitat area. It is estimated that from 1996 to 2005 the continental US gained 10,000 ha of wetlands per year (Mitsch and Hernandez 2012). In the year 1780, it is estimated that Pennsylvania had over 404,685 ha of wetlands (ACB, 1997). After years of historical agricultural and urban development, approximately 163,492 ha of natural wetland habitat persist in the state (Ibid.).

## *Current Wetland Mitigation Regulations*

In Pennsylvania, impacts to wetlands and watercourses are regulated by the Pennsylvania Department of Environmental Protection (DEP) and the ACOE. Impacts include temporary and permanent effects that are considered either direct or indirect. Historically, these agencies were focused on an "acre-to acre" mitigation approach. However, this focus has shifted to replacing the functions and values of the impacted wetland in the newly created wetland.

A physical replica of the original wetland may or may not lead to the mitigation of functions and values lost in the impacted wetland (Campbell et al. 2002). A focus on the introduction of appropriate abiotic materials along with appropriate planning and construction are more likely to lead to a successful mitigation site by allowing for natural ecological processes to begin and persist. However, a significant number of wetland mitigation sites do not lead to a successful end. A study performed on 40 created wetlands in Florida found that 60% of the wetlands were failing or had failed (Ibid.). An analysis of 11 wetland mitigation sites in the San Francisco Bay area found that none of the 11 constructed wetland sites could be considered a success (Ibid.).

A comparison of characteristics of 12 constructed wetland sites in Pennsylvania to the characteristics of 14 naturally occurring wetlands throughout the state detailed the differences between each wetland type. Criteria assessed included the soil and vegetation makeup of each wetland type. These characteristics were then evaluated over the age of constructed wetlands, which ranged from two to 18 years, to determine if the older projects more closely resembled the naturally occurring wetlands. It was determined that soil characteristics within created wetlands differed significantly from those in natural wetlands. Vegetation species and richness in natural wetlands were greater, and more hydrophytic vegetation types were found in natural wetlands rather than in the created wetlands. The soils and vegetative characteristics between the younger and older wetlands differed significantly, however it could not be proven that older constructed wetlands more closely resemble naturally occurring wetlands.

A standard mitigation monitoring schedule for a constructed wetland in Pennsylvania is twice a year during the first three years after construction (DEP n.d). These monitoring events should occur once in the beginning of the growing season, mid-March to mid-October, and once at the end. Then a monitoring event should occur once a year during the fourth and fifth year after construction, for a total of five years. During these five years, it is anticipated that adjustments should be made to the constructed wetland areas if they are considered to be failing. If by the end of the five years the constructed wetland is not considered "successful," regulating agencies can extend the monitoring period until the constructed wetland is considered a success. Much of the success of a constructed wetland comes from the vegetative composition. Regulating agencies often expect at least 85% or more cover of hydrophytic vegetation (Ibid.). If a constructed wetland has a significant amount of hydrophytic species that are invasive, then they will not include this population in their consideration of hydrophytic species coverage.

While five years may seem like a considerable amount of time, many of the issues regarding unsuccessful mitigation sites stem from the lack of long-term monitoring. That, combined with uncooperative developers, often leads to a constructed wetland that has failed. For this reason, regulatory agencies are focusing on an "avoidance and minimization" strategy (Kaza and BenDor 2013). Projects that are not planned to avoid as many aquatic features on the proposed site as possible may not receive the appropriate permits or approval to continue the project. Once a project is approved and mitigation amounts are determined, developers will have to choose a mitigation strategy. If possible, they can plan to restore and expand existing on-site aquatic features, or they can attempt to build a completely new feature.

Determining the success of wetland restoration or mitigation is a challenging and oftentimes contentious notion (Kentula 2000). The idea of success can be considered subjective and is often dependent on the objective of the final outcome. The outcome is almost always focused on the individual project, without considering the implications it will have on the surrounding landscape. Ultimately, decision-makers should be evaluating success of wetland mitigation sites at multiple scales. It is also important that the presence of the three wetland hydrologic indicators, at some level, are being met (Hill et al. 2013). As previously mentioned, hydrophytic vegetative makeup is often the most common measure of wetland mitigation success (Kentula 2000). However, this measurement is also the easiest to attain. If an area is converted with the intention to maintain hydrology, then it will most likely produce a "wetter than normal" environment which will encourage the growth of hydrophytic vegetation that may not have been present before. While this is still important when considering the idea of success, wetland soils and wetland hydrology are arguably harder to achieve and wetland mitigation sites should be monitored for these at some level.

Evidence of success with long-term monitoring has been shown in SER's *Restoration of Leachate-Impacted Wetlands and Associated Mitigation at the University of Connecticut Landfill* (SER N.d.). The planning and design stage of the project began in 1998 and construction was completed in 2008. After project completion, a monitoring period of 10 years was conducted, which included annual monitoring visits. A total wetland area of 1.3 ha was restored and 0.84 ha of new wetland area was created. Over 20 species of native hydrophytic vegetation were planted and persist, appropriate hydrology was established and persisted, and functionality of the ecosystem was restored (Ibid.). The success of this project is attributed to long-term, thorough annual monitoring and adaptive management.

### *GIS Analysis of Wetland Mitigation Sites*

GIS analysis is an important tool in determining site suitability for potential wetland mitigation and restoration areas. The analysis and manipulation capabilities of GIS programs make it a useful tool for preliminary site analysis. The concept of using GIS for selection and ranking analyses has been important step for many different wetland mitigation studies. Oftentimes, this approach is used at a watershed level due to a larger cover of area that could provide more spatially explicit data (e.g., Lin et al. 2006). The majority of research begins with a focus on landcover to determine potential wetland preservation and restoration sites (Lin et al. 2006; Palmeri and Trepel 2002; Russell et al. 1997). Also considered are the presence of United States Fish and Wildlife Service's (USFWS) National Wetlands Inventory (NWI) coverage, elevation and slope, and different land easements (Kauffman-Axelrod and Steinberg 2010). The goal is to use GIS to create a system for planning of potential created or restored wetlands at the watershed level, and to exclude areas that are not considered appropriate. (Kauffman-Axelrod and Steinberg 2010; Lin et al. 2006; Palmeri and Trepel 2002; Russell et al. 1997).

After potential wetland mitigation sites are selected, the next step is to determine the suitability of these sites. As previously mentioned, wetland habitats must consist of appropriate hydrologic, soil, and vegetative characteristics. From the output of potential locations, understanding the hydrology potential is key (Lin et al. 2006; Palmeri and Trepel 2002; Schleupner and Schneider 2012; O'Neil et al. 1997). For this reason, one or more hydrologic variables should be considered when determining site suitability. These could include flood frequency, relative wetness, or locations of watercourses, among others. Vegetative makeup may be derived from a variety of sources, including field surveys, GIS landcover data, or USFWS NWI wetland locations, which are delineated to include appropriate vegetative makeup. Soil types of the selected sites is also an important consideration, as some soil types may not be capable of maintaining hydrology. Combining these three characteristics, possibly with others, and determining where they fall and how they interact across the landscape will yield the suitability of the potential wetland mitigation areas (Palmeri and Trepel 2002). Displaying these features and analyzing how they intersect with each other may provide a relative estimation of potential success (Lin et al. 2006; Palmeri and Trepel 2002; Schleupner and Schneider 2012; O'Neil et al. 1997). It is also beneficial to evaluate the proximity of the hydrologic characteristics. If there are minimal opportunities where the features overlap, there may be the potential to connect the features by expanding hydrology from one feature to another.

Comparing and ranking potential wetland mitigation sites helps in keeping the planning process moving forward. The easiest part of this process is by comparing sites according to spatial and proximal constraints (Palmeri and Trepel 2002; Russel et. al 1997). Ideally, mitigation opportunities should occur in areas where there is enough open or undeveloped land to allow for an extensive and complex wetland area. The presence of hydrologic features that support a wetland should be combined with the overall area coverage to compare and rank potential wetland mitigation sites (Palmeri and Trepel 2002; Russel et al 1997). Determining how the different features are ranked should depend on the final objective of the project.

There are instances of wetland mitigation sites being analyzed and located using the aforementioned methods. For example, a study performed by Russell et al. (1997) used GIS to map relative wetness and landcover within a watershed to determine potential wetland preservation and restoration sites. The initial site selection included areas within the San Luis

Rey River watershed in southern California. This approach relied on two primary data layers, which included an index of “wetness potential” which was derived from United States Geological Survey (USGS) elevation digital elevation models (DEMs). The second layer was comprised of a land use/land cover map derived from a Landsat Thematic Mapper scene. These two layers were combined to determine site suitability, and then sites were prioritized according to spatial and proximal constraints. These constraints included a wetness index, landcover classification, accuracy assessment, and derivation of index parameters (Russel et. al 1997). The resulting data was ranked from low priority restoration to high priority preservation opportunities throughout a total area of 5,471 ha in the San Luis Rey River watershed. This illustrates how a GIS analysis can be used to access and then prioritize wetland restoration and preservation activities.

Another study used a combination of the previously described methods, and a process to evaluate wetland mitigation potential in two different study areas (Palmeri and Trepel 2002). The goal of this analysis was to use GIS to create a scoring system for siting and sizing created or restored wetlands at the watershed level. Using a variety of spatial data layers and GIS procedures, the scoring system was created and applied to two different case studies, the Adige-Bacchiglione Watershed in northeastern Italy and the Neuwuhrener Au River in northern Germany. The data processed through the scoring system resulted in wetlands ranked on a scale from one to five (Palmeri and Trepel 2002). These ranks included evaluation of land use data, elevation, proximity to watercourses, among others. Through this study, it was determined that areas scored three to five were most suitable for wetland construction. A built system, such as the one used in Palmeri and Trepel (2002), could fast-track site determination and provide a quicker system to wetland construction.

To further support the use of GIS analysis to determine potential wetland mitigation opportunities, a combination of field studies, when feasible, and an interpretation of aerial imagery could provide a more complete understanding of a chosen wetland mitigation site. While the GIS analysis is an important first step, understanding the existing in-situ site characteristics is crucial for potential mitigation success. Highly developed areas provide limited space for wetland mitigation activities; therefore, it is important to understand the composition of the areas around the potential wetland mitigation site (Schleupner and Schneider 2012). An interpretation of aerial imagery may provide an understanding of how the selected site and surrounding landscape has changed over time and could indicate how these areas may change in the future.

### *Summary*

Wetland habitats have a major impact on both the natural and human communities. The importance of wetlands extends beyond environmental values as they also influence the economies surrounding them. However, their importance has historically been undervalued and wetlands have been destroyed at an alarming rate A recent push to preserve and restore wetlands is underway as agencies deploy mitigation strategies to encourage an increase in wetland habitat coverage. To assist in this push, GIS analysis can be used to streamline the planning process by determining site suitability for wetland mitigation locations. The results of the GIS analysis are supported through a ground-truthing investigation and aerial imagery interpretation. For this research, a combination of these three methods will be applied to the Brandywine Creek watershed in Chester County, Pennsylvania to uncover where potential wetland mitigation opportunities may lie. This study area will be further discussed in Chapter 3.

# CHAPTER 3 – STUDY AREA

This research includes six specific sub-watersheds within the Brandywine Creek Watershed: Main Stem Brandywine Creek, East Branch Brandywine Creek, West Branch Brandywine Creek, Buck Run, White Clay Creek, and Red Clay Creek (Figure 1). These sub watersheds were chosen because they make up the majority of the Brandywine Creek watershed within Chester County, and are also comparable in size and LULC. Over 90% (approximately 1,000 sq km) of the watershed is in Pennsylvania, and this research will focus on the area that occurs within Chester County (Cruz-Ortiz and Miller 2013). The majority of land cover within the study area consists of agricultural lands and forested areas. The remaining land use includes a mixed use of residential, commercial, industrial development, and undeveloped areas. Undeveloped areas may include grassland fields, forested areas, palustrine wetland habitats, riparian corridors and a variety of other natural environments. This variable LULC has caused an estimated 824 km of watercourse within the Brandywine Creek watershed to be considered impaired for sediments, nutrients, or bacteria (Young 2018). In an effort to improve and protect stream health, restoration efforts including riparian buffers and agricultural best management practices have been implemented throughout the watershed.

The population of Chester County was 524,989 during the 2020 Census, an 8.3% increase from the 2010 Census (Chesco n.d.). The majority of the population within Chester County is white (82.3%), with the remaining population consisting of those who identify as one or more race including Hispanic or Latino (7.6%), Asian (5.9%), Black or African American (5.8%), and American Indian and Alaska Native (0.1%). Almost 6% of the population is considered to be living below the poverty level, which is just half of poverty rate for Pennsylvania. The economic


Figure 1: Study Area in Chester County, Pennsylvania


Figure 2: Hydric Soils in study area

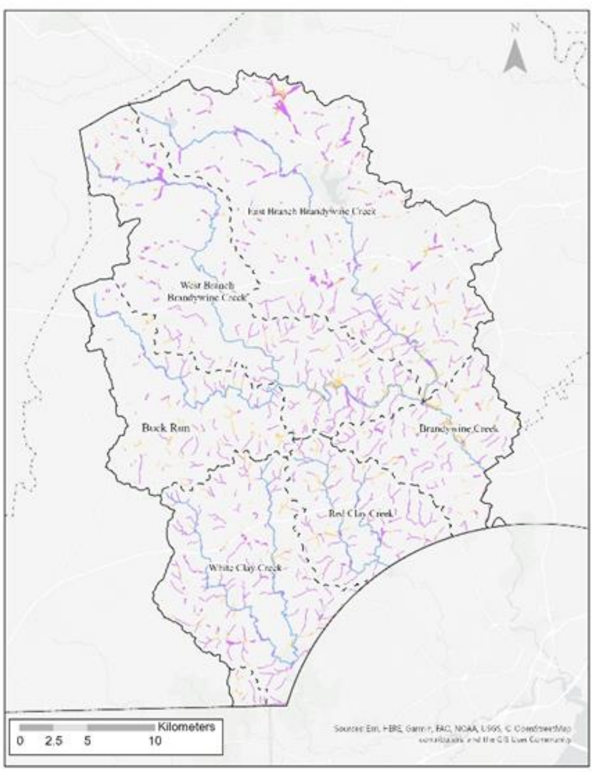



Figure 3: NWI wetlands in study area

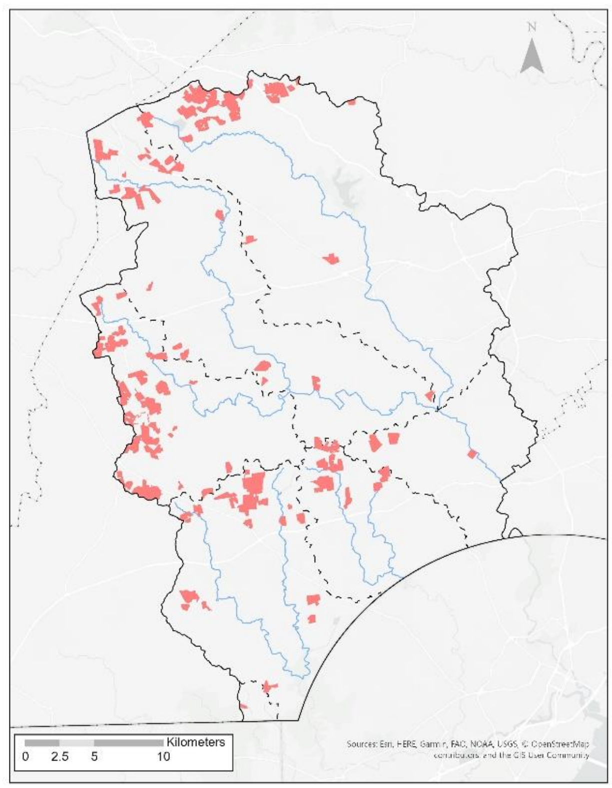
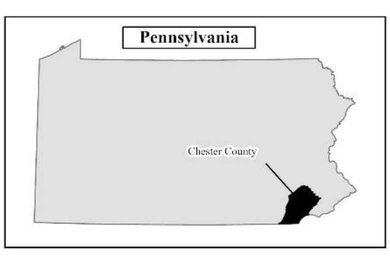



Figure 4: Agricultural Easements in study area




impact of the Brandywine Creek watershed could be a significant contributing factor to this decreased poverty rate. The watershed's water resources and habitats contribute over $890 million in annual economic activity to Pennsylvania and Delaware economies (Cruz-Ortiz and Miller 2013). This contribution comes in the form of water supply, recreational activities, and agriculture use, among others. The Brandywine Creek watershed also accounts for 50,000 jobs, which supports an unemployment rate within Chester County of just 2.3% (Chesco n.d.).

The portion of the Brandywine Creek watershed within the study area consists of six high-flow perennial watercourses and their associated tributaries. The East Branch Brandywine Creek enters the study area from the north-northwest and flows to the southeast. The West Branch Brandywine Creek enters the study area from the northwest and flows to the southeast. The East and West Branches meet in the southeastern portion of the investigation area to form the Main Stem Brandywine Creek. The Main Stem Brandywine Creek flows out of the study area to the southeast. The White Clay Creek begins in the south-southeastern portion of the study area and flows to the south. The Red Clay Creek watersheds begins in the southern portion of the study area and flows toward the south. Buck Run begins in the western portion of the study area and flows to the south, and then to the east into the West Branch Brandywine Creek.

Soils throughout the Brandywine Creek Watershed are variable. Approximately 9% (9,024 ha) of soils within the watershed fall on the USDA's hydric soils list (USDA n.d.) (Figure 2). Hydric soils are an important characteristic of wetland areas as they are needed to support the growth of hydrophytic vegetation. Slopes within the watershed range from 0% to 60%. The highest elevations occur in the western and northwestern portions of the watershed with a gradual decline to the southeast (Chesco n.d.).

According to the USFWS NWI, there are approximately 1,661 ha of wetland habitats within the watershed, which is just 1.6% of the study area (Figure 3). Of this wetland total, 523 ha are described as freshwater palustrine emergent wetlands (PEM). PEM wetland are those that are dominated by low-growing herbaceous vegetation that is typically persistent throughout the entire growing season. Freshwater palustrine scrub-shrub (PSS) and freshwater palustrine forested (PFO) wetland types occupy the remaining 1,138 ha of wetland habitat within the watershed. PSS wetlands are dominated by woody vegetation that is less than six meters (m) in height. PFO wetlands are made up of primarily woody vegetation that is six m in height or taller. All three of these wetland types must have a vegetative makeup that is dominated by hydrophytic or partial hydrophytic vegetation.

The Brandywine Creek watershed is home to a variety of wildlife including fish, birds, reptiles, amphibians, and small mammals. It is considered an Important Bird Area in the mid-Atlantic region by the National Audubon Society, and it is estimated that 200 species of birds are present as either permanent or migrant residents within the watershed (Young 2018). Wetland habitats within the watershed have been found to support populations of the critically endangered bog turtle (*Glyptemys muhlenbergii)* (UDWRC n.d.). Freshwater mussels (*Unionida* s.p.), the most threatened species of organisms within North America, are known to be present within the watershed. The Freshwater Mussel Recovery Program (FMRP) has been active within the Brandywine Creek watershed since its inception in 2007, with the first introduction of mussels occurring in 2011 (Young 2018). Hundreds of native plant species exist within the watershed's boundary, including nine native orchids within the White Clay Creek Watershed. Botanical surveys within the watershed have also found numerous Pennsylvania endangered plant species are present throughout the watershed.

An array of protected land and resource types throughout the study area have aided in preserving natural habitat and stream quality. The Brandywine Conservancy and the Brandywine Valley Association have spearheaded conservations efforts throughout the watershed which has resulted in an estimated 12,950 ha of protected land areas (Cruz-Ortiz and Miller 2013). The Delaware River Watershed Initiative (DRWI) has added an additional 503 ha of protected farmland as well as 36 km of forested riparian buffers (DRWI 2017).

Significant watercourse protections have also improved the functions and values of natural habitats within the study area. The Pennsylvania Scenic River program recognized the lower portion of the Brandywine Creek in 1989 as a Pastoral Designation (DCNR n.d.). The Pastoral Designation refers to the watercourse's capability and productivity for agricultural activities. The Pennsylvania Scenic River program provides protections to designated waterways to preserve their functions and values. In 2000, White Clay Creek was the first National Wild and Scenic River to be protected in its entirety (WCCWA n.d.). The *Wild and Scenic River Act* considers watersheds throughout the nation that provide exceptional values, such as recreational, natural, or cultural, to the landscape and aims to preserve them in their free-flowing condition. This act focuses on a "beyond the riverbank" approach and focuses on preserving a watershed in its entirety (DCNR n.d.). Preserving these watercourses is crucial to maintaining the watershed's integrity and improving the quality of surrounding natural habitats.

The Brandywine Red Clay Alliance (BRCA) has been leading efforts to protect the Red Clay Creek watershed since 1952 (BRCA. n.d.). BRCA has implemented restoration and cleanup projects since its inception, including the *Red Streams Blue* program which focuses on improving the water quality of the impaired sections of Red Clay Creek. The goal of this program is not only to improve water quality, but also to preserve and restore the important wildlife habitats that are present within the watershed.

As of 2020, approximately 16,707 ha throughout Chester County are considered to be areas of preserved farmland (Figure 4) (Chesco n.d.). Preserved land under an agricultural easement will be protected from development and used for agricultural purposes only. These agricultural easements are based upon tax parcel areas. The majority of these easements occur towards the northwestern, western, and southwestern boundaries of the county, however there are a few parcels that fall within the study area. There is a total of 198 parcels within the Brandywine Creek Watershed that are protected under an agricultural easement. This amounts to approximately 4,353 ha. Agricultural easements across these parcels prohibit the land from being used for any purpose other than agricultural activities, therefore they do not qualify as areas for potential wetland mitigation opportunities.

### *Summary*

The Brandywine Creek watershed provides innumerous benefits to Chester County in the form of economic and environmental contributions. It is imperative to maintain and restore the integrity of natural habitats within the watershed so that the county may continue to reap these benefits. Planning the location of future wetland mitigation activities is an important step when considering where environmental improvement opportunities lie within the watershed. A combination of GIS analysis, ground-truthing investigations, and historical aerial imagery interpretation will be used to determine where such opportunities may occur within the Brandywine Creek Watershed, which will be detailed in Chapter 4.

# CHAPTER 4 – METHODS

This chapter will describe the methodology used to identify potential wetland mitigation opportunities in six sub-watersheds within the Brandywine Creek watershed: Main Stem Brandywine Creek, East Branch Brandywine Creek, West Branch Brandywine Creek, Buck Run, White Clay Creek, and Red Clay Creek watersheds. A variety of data collection and GIS analysis was utilized. The methods pertaining to the GIS manipulation and analysis will be presented in this chapter. Using ArcGIS Pro (Esri 2022) data files were manipulated, analyzed, and compared to determine where potential wetland mitigation opportunities are located within the six sub-watersheds. To confirm this analysis, several locations that were considered to have the characteristics of a potential wetland mitigation area were selected for ground-truthing. The potential selected locations were also evaluated against aerial imagery to understand how land use in the area has evolved over time. Through the combination of GIS analysis, field reconnaissance, and aerial imagery interpretation, it was possible to gain information about where potential wetland mitigation opportunities occur within the study area.

## *GIS Data Collection*

All of the GIS data used in this study was collected from the public domain (Figure 5). A variety of databases were used, including: Pennsylvania Spatial Data Access (PASDA), Chester County, WikiWatershed (which is curated by the Stroud Water Research Center), the SFWS NWI, and ArcGIS Living Atlas of the World (Table 1). PASDA is an online spatial database platform that contains a significant amount of GIS data for the state of Pennsylvania, including state and county boundary lines which were used in this study. Polylines showing the approximate locations of watercourses throughout the state were also

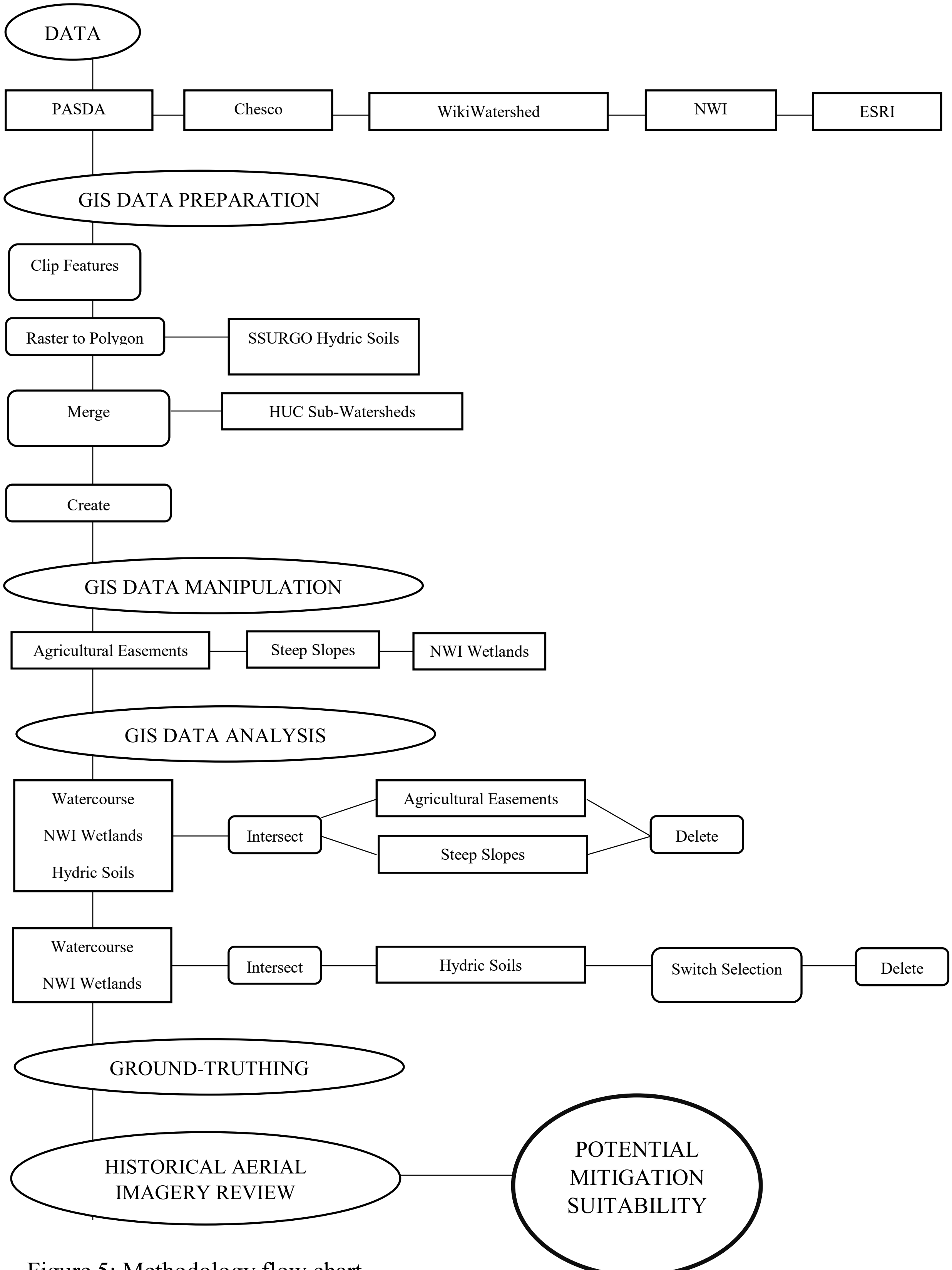



Figure 5: Methodology flow chart

| GIS DATA FILE | YEAR PUBLISHED | COLECTION | DATA SOURCE |
|---|---|---|---|
| Pennsylvania State Boundary Line | 2022 | PASDA | PA Department of Transportation |
| Chester County Boundary Line | 2022 | PASDA | PA Department of Transportation |
| Municipal Boundary Lines | 2021 | -- | Chesco |
| Brandywine Watershed Boundary Line | 2021 | -- | WikiWatershed |
| Sub-Watershed Boundary Lines | 2021 | -- | WikiWatershed |
| Watercourse Lines | 1998 | PASDA | PA Department of Environmental Protection |
| Hydric Soil Polygons | N.D. | Esri | |
| NWI Wetlands Polygons | 2005 | -- | USFWS |
| Steep Slope Polygons | 2021 | -- | Chesco |
| Agricultural Easement Polygons | 2020 | PASDA | PA Department of Agriculture |

Table 1: Data source information

downloaded from PASDA. Chesco has a GIS platform focused solely on Chester County, Pennsylvania. Chesco provided the municipality boundary lines and steep slope areas. WikiWatershed is an online toolkit consisting of hydrographic information used for watershed mapping that can assist in many different scenarios including data analysis, planning purposes, etc. (Stroud, n.d.). The USFWS curates the NWI which is a public access platform providing spatial wetlands data across the US. The NWI provided known wetland boundary lines throughout the Brandywine Creek watershed, which assisted in determining potential wetland mitigation opportunities. The final dataset was downloaded from Living Atlas, ESRI's online collection of spatial data including data layer and maps. A raster file of U.S. Soil Survey Geographic (SSURGO) hydric soils data was download from Living Atlas.

### *GIS Data Preparation*

To maintain consistency, all of the downloaded data was assigned the North American Datum of 1983 (NAD 83) Pennsylvania State Plan South coordinate system in meters in ArcGIS Pro. The data files were clipped to the Brandywine Creek watershed boundary line. Any portions of the data that occurred outside of the study area were excluded from this analysis. The data files, with the exception of the SSURGO data, were in a vector format. The SSURGO raster dataset was converted to vector data using the Raster to Polygon tool in the Conversion toolset.

The watershed area data for the sub-watersheds collected from WikiWatershed was download in three different hydrologic unit codes (HUC). HUCs identify hydrological features throughout North America based on a hierarchical system of drainage area (USGS n.d.). The Brandywine Creek watershed is considered a HUC-8 (HUC #02040205) as it has a larger drainage area than the six sub-watersheds considered for this study. The area of the six- sub-watersheds used for this research can be derived from HUC-10 and HUC-12. The watersheds derived from HUC-10 were the Brandywine Creek, East Branch Brandywine, and West Branch Brandywine, which were represented in their entirety.

The final three sub-watersheds, Buck Run, Red Clay Creek, and White Clay Creek were derived from HUC-12. HUC-12 data was evaluated and joined to create one sub-watershed comparable in size to the HUC-10 areas. This was to maintain a general size consistency between all of the watersheds within the study area. The watershed area for Buck Run was incorporated into one HUC-12. The Red Clay Creek HUC-12 watershed data collected from WikiWatershed consists of watershed data for the Red Clay Creek, the East Branch Red Clay Creek, and the West Branch Red Clay Creek. The drainage area for the White Clay Creek is significantly larger than the drainage area for the Red Clay Creek, so the main stem of the White Clay Creek is considered a HUC-10 watershed. The main stem data was combined with the HUC-12 data for the White Clay Creek, which consists of the East Branch of the White Clay Creek, the Middle Branch of the White Clay Creek, the West Branch of the White Clay Creek, Upper White Clay Creek, Middle White Clay Creek, and Lower White Clay Creek. The HUC data for both the Red Clay Creek and White Clay Creek watersheds were joined together, which will be used in combination with the other sub-watershed boundaries to manipulate the remaining downloaded data files.

Before the data was manipulated, a geodatabase was prepared using the Lambert's conformal conic projection and the Pennsylvania State Plane South the coordinate system to maintain consistency. The created watershed boundaries were uploaded into this geodatabase. Within this geodatabase, five feature datasets were created and named based upon the data that they would contain. The PASDA watercourse lines, NWI wetland polygons, the newly converted

SSURGO hydric soils polygons, Chester County agricultural easement parcel data, and the steep slope polygons were clipped to the study area and uploaded to the appropriate dataset.

### *GIS Data Manipulation*

In order to effectively evaluate the potential mitigation areas within the six sub-watersheds, tax parcels were compared to agricultural easement records and identified as such. Parcels with an existing agricultural easement were extracted as a new feature class and saved in the appropriate geodatabase feature dataset. Any other data that intersected with these easement parcels would be deleted from the analysis, as only agricultural activities are permitted. The resulting data consisted of features that occurred outside the agricultural easement parcels throughout each of the sub-watersheds.

The SSURGO hydric soils data was ranked into five categories by hydric soil percentage- Not hydric (0%); Partially Hydric (1-25%); Partially Hydric (26-50%); Partially Hydric (51-75%); Partially Hydric (76-95%); and All Hydric (96-100%). Because it takes a considerable amount of time for anaerobic conditions to form in the upper part of the soil, areas with a hydric soil percentage of 75% or less were omitted from the analysis (USDA n.d.). Only the soils with 76-95% make up of hydric soils and those considered all-hydric are important considerations when evaluating potential mitigation opportunities and in supporting successful mitigation opportunities.

The Chester County steep slope dataset contained two categories of slopes. These include moderate slopes, those with a slope of 15-24%, and steep slopes, or any slope 25% or greater. Because the steepness of a slope correlates directly with how quickly water moves across it, areas considered steep slopes were not included. When planning wetland mitigation activities, it is important that potential areas can maintain inundation for a significant amount of time to support hydrologic characteristics (Milner 2003). Using the Select by Attributes tool, areas considered moderate slopes were selected and deleted from the dataset, leaving just the areas considered steep slopes. Features that intersected with steep slope areas were not considered when selecting potential wetland mitigation areas.

The final GIS data manipulation consisted of determining the appropriate feature types in the NWI dataset. The ACOE and PA DEP require mitigation for palustrine type wetlands, including PEM, PSS, and, PFO. The NWI dataset contains information about the previously mentioned wetland types, as well as bodies of open water. Open water areas were omitted from this analysis because there are currently no mitigation requirements for these aquatic features.

### *GIS Data Analysis*

Once the data was manipulated for relevance and location, the resulting features were displayed in ArcGIS Pro. In order to determine which areas could have potential for wetland mitigation it was important to exclude any portions of the PASDA watercourse lines, NWI wetlands, and SSURGO hydric soils that intersected areas of agricultural easements or occurred on steep slopes. Using the Select by Location Tool, the hydrologic characteristic features that intersected steep slopes or agricultural easements were selected. The selected features were deleted from analysis, resulting in data that could be appropriate for potential wetland mitigation activities.

Ideally, mitigation areas would include nearby existing wetlands and watercourses that occur in hydric soils. Using the Select by Location Tool, NWI wetlands that intersected with hydric soils were selected. This selection was switched within the Attribute Table resulting in a selection that included NWI wetlands that did not intersect with hydric soils. These selected features were deleted from analysis. The same procedure was followed to exclude segments of watercourses that did not intersect with hydric soils.

This process of data preparation, manipulation, and analysis yielded the locations of portions of the original features that included all three of the wetland characteristics considered in this study. The manipulated features also excluded any portions of the features that occurred within agricultural easements or on slopes greater than 25%.

### *Ground-Truthing and Aerial Imagery Interpretation*

With the manipulated data files displayed over an ESRI 2020 Aerial Image Base Map the watersheds were visually analyzed for potential mitigation opportunities. Areas that consisted of selected hydric soils, existing NWI palustrine wetlands, a nearby watercourse that occurred outside of agricultural easement areas, and off of steep slope areas were evaluated against the aerial imagery basemap. These locations contained the previously mentioned characteristics, and were not overlaying developed areas. These locations were also chosen because the surrounding landscape consisted of open space to allow for wetland mitigation construction.

Characteristics evaluated during the ground-truthing site investigation included hydrological, soil, and vegetative. Wetlands must meet these three criteria to be considered a wetland habitat type (Forsythe et al. 1987). If these criteria are met and the surrounding landscape allows for the development of a wetland mitigation area, the chance of successful mitigation increases (Milner 2003). During the ground-truthing investigation, the in-situ site characteristics were evaluated. Specifically noted were the hydrologic and vegetative conditions. When feasible, a soil evaluation was performed to determine if hydric soils were present at the site. This included a soil pit dug to approximately 18 inches. Soil removed from the pit was analyzed for color, texture, and the presence of redoximorphic features.

To support the findings from the GIS data analysis and the ground-truthing investigation, historical aerial imagery was reviewed. This interpretation consisted of comparing imagery from PASDA and Google Earth over an approximate 90-year time frame (1930s to present). During this interpretation, the potential locations and surrounding areas were examined to determine the historical and current LULC. Significant changes, including increased development, consistent agricultural use, or other noticeable shifts in land use were noted. The goal of the aerial imagery interpretation was to evaluate whether any historical land uses would prohibit successful wetland mitigation. It was also used to determine whether or not there was a sufficient area of undeveloped land for wetland mitigation activities. The information gained was used in conjunction with the ground-truthing results to evaluate wetland mitigation opportunities at the selected locations.

### *Summary*

Using a combination of GIS analysis, ground-truthing investigations, and aerial imagery interpretations, six sub-watersheds within the Brandywine Creek watershed in Chester County, Pennsylvania were analyzed for potential wetland mitigation locations. These locations included areas where watercourses, NWI wetlands, and hydric soils intersected outside of agricultural areas and off of steep slopes. The on-site and surrounding landscapes were then evaluated through ground-truthing investigations and aerial imagery interpretations. This methodology resulted in the identification of locations throughout the study area that could be considered for wetland mitigation activities. The suitability of these locations will be discussed in Chapter 5.

# CHAPTER 5 - RESULTS

The results of the GIS analysis, ground-truthing investigation, and aerial imagery interpretation to determine potential wetland mitigation opportunities within six sub-watersheds located in the Brandywine Creek watershed will be presented in this chapter. Results will be presented over the entire study area as well as within each individual watershed. An explanation of findings during the ground-truthing investigation and aerial imagery interpretation will also be presented. The results of this analysis will identify where potential wetland mitigation opportunities occur within the study area.

## *Total Study Area*

The total study area consisted of the Main Stem Brandywine Creek, East Branch Brandywine Creek, West Branch Brandywine Creek, Buck Run, White Clay Creek, and Red Clay Creek sub-watersheds, which, in total, cover approximately 993 sq. km. (Table 2). Agricultural easement areas consist of approximately 4,353 ha across 209 parcels. Steep slopes cover approximately 6,223 ha across the study area. NWI palustrine wetlands occupy approximately 21 ha throughout the total study area, including approximately 13 ha of PEM wetland habitats and 8 ha of PSS/PFO wetland habitat. USA SSURGO hydric soils occur in approximately 346 ha. The total length of watercourses in both watersheds is approximately 17,570 m (Table 2).

The majority of the agricultural easements occur along the northern boundary and in the southcentral and southwestern portion of the total study area (Figure 6). This indicates that wetland mitigation opportunities in these areas may be more challenging to accomplish as the easements will restrict the potential extent of construction within these areas. Steep

| Watershed | Total Area (sq. km) | Ag. Easements | Steep Slopes (ha) | NWI Wetlands (ha) | Hydric Soils (ha) | Watercourse Length (m) |
|---|---|---|---|---|---|---|
| Brandywine Watershed | 993 | 4,353 | 6,223 | PEM: 13<br>PSS/PFO: 8<br>Total: 20.4 | 346 | 17,570 |
| Main Stem Brandywine Creek | 87 | 144 ha<br>11 parcels | 531 | PEM: 0.9<br>PSS/PFO: 1.4<br>Total: 2.3 | 13 | 1,916 |
| East Branch Brandywine Creek | 319 | 967 ha<br>45 parcels | 2,163 | PEM: 5<br>PSS/PFO: 1<br>Total: 6 | 123 | 3,580 |
| West Branch Brandywine Creek | 216 | 732 ha<br>30 parcels | 1,629 | PEM: 4<br>PSS/PFO: 2<br>Total: 6 | 61 | 1,484 |
| Buck Run | 126 | 1,258 ha<br>68 parcels | 735 | PEM: 0.6<br>PSS/PFO: 0.7<br>Total: 1.3 | 27 | 2,865 |
| Red Clay Creek | 86 | 500 ha<br>18 parcels | 353 | PEM: 0.8<br>PSS/PFO: 0<br>Total: 0.8 | 23 | 1,507 |
| White Clay Creek | 158 | 812 ha<br>37 parcels | 812 | PEM: 1<br>PSS/PFO: 3<br>Total: 4 | 98 | 6,218 |

Table 2: Summary of feature measurements within the study area

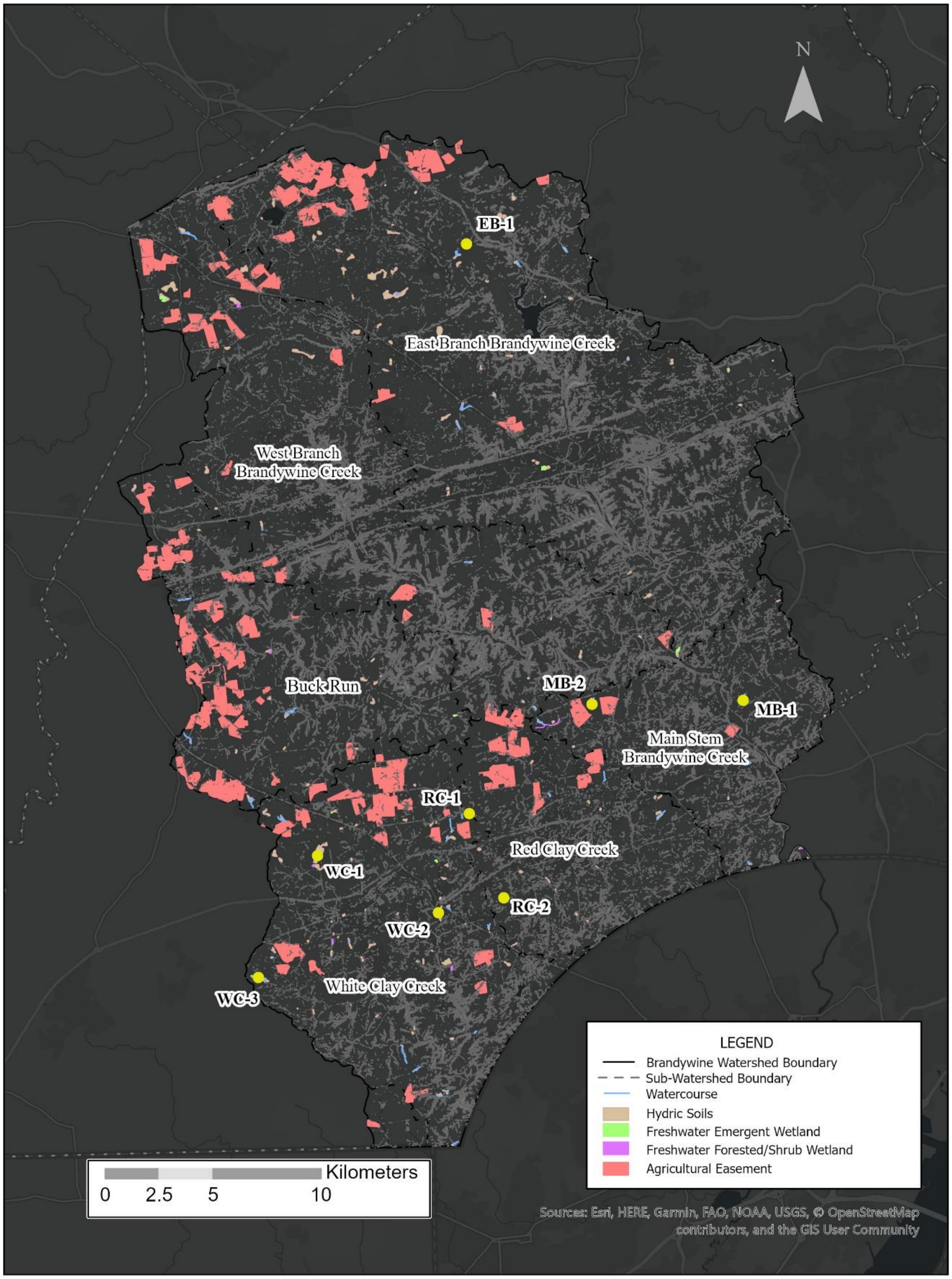



Figure 6: Results and ground-truthing locations within the study area

slopes are present throughout the majority of the study area, but there is a higher concentration of steep slopes in the central portion of the investigation area. Unsurprisingly, the majority of the NWI wetlands appear along the watercourse polylines, which are distributed throughout the entire study area. Hydric soils appear near watercourse polylines, but also occur independently of any other wetland characteristic (Figure 6).

A total of eight sites throughout the study area were selected for ground-truthing investigations. Seven of the eight sites occur in the southern portion of the study area. Coordinates for each of the ground-truthing investigation areas were located in Decimal Degrees using ArcGIS Pro (ESRI 2020). The sites were visited and evaluated for potential wetland mitigation opportunities by determining the existing on-site hydrologic, soil, and vegetative conditions. The surrounding landscape was also examined to determine if there were enough open space areas to support a potential wetland mitigation construction opportunity.

### *Main Stem Brandywine Creek*

The Main Stem Brandywine Creek sub-watershed covers approximately 87 sq. km (see Table 2). Agricultural easement areas consist of approximately 144 ha across 11 parcels. Steep slopes cover an area of approximately 531 ha across the watershed. NWI palustrine wetlands consist of approximately 2.3 ha throughout the watershed, including 0.9 ha of PEM wetland habitat and 1.4 ha of PSS/PFO wetlands. USA SSURGO hydric soils occur in approximately 13 ha. The total length of watercourses in the Main Stem Brandywine Creek watershed is approximately 1,916 m.

Within the Main Stem Brandywine Creek sub-watershed, preserved agricultural areas are clustered primarily within the northwestern corner, with four parcels occurring in the central portion (Figure 7). The same is true for NWI wetlands, hydric soils, and watercourse polylines.

Figure 7: Results and ground-truthing locations within the Main Stem Brandywine Creek sub-watershed

There are a few instances of these features occurring along the southern edge of the watershed boundary. Steep slopes are present throughout the watershed. An evaluation of features that occurred outside of agricultural easement areas and away from steep slopes determined two locations within the watershed that could be suitable for wetland mitigation activities and were identified for ground-truthing investigations (Table 3).

The first area occurs near the central portion of the investigation area within Birmingham Township. This ground-truthing location was selected at “MB-1.” MB-1 occurs on private property and is setback a considerable distance from public roads. A thorough ground-truthing investigation was difficult to perform at this location due to these circumstances. The only noticeable wetland characteristic observed during the ground-truthing investigation was the presence of a watercourse. Much of the surrounding LULC was light residential development, with a forested area to the south. Elevation within this area slopes downwards in the direction of the potential wetland mitigation area. Recent aerial imagery does show probable wetland locations along the riparian corridor in this investigation area, which drains into a pond. An interpretation of historical aerial imagery from PASDA and Google Earth shows heavy agricultural use until the late 1980s to the early 1990s, when the first signs of residential development appear in the area (Table 4). From this point on, the primary land use shifts to residential development.

The second location occurs along the northern boundary of the Main Stem Brandywine Creek sub-watershed in Pocopson Township. This ground-truthing location was selected as “MB-2.” MB-2 occurs on private land that is primarily agricultural, with some residential development to the west. Due to its location on private land, a thorough ground-truthing

| Watershed | GIS Analysis | Ground-Truthing | Current LULC | LULC Historical Aerial Imagery |
|---|---|---|---|---|
| Main Stem Brandywine Creek | 2 sites | MB-1: No<br>MB-2: Potential | MB-1: Residential/Forested<br>MB-2: Agricultural | MB-1: Agricultural/Residential<br>MB-2: Agricultural/Wetland |
| East Branch Brandywine Creek | 1 site | EB-1: Immediate | EB-1: Nature Preserve | EB-1: Agricultural/Forested |
| West Branch Brandywine Creek | 0 Sites | - | - | - |
| Buck Run | 0 sites | - | - | - |
| Red Clay Creek | 2 sites | RC-1: Potential<br>RC-2: No | RC-1: Agricultural/Open Land<br>RC-2: Mixed Use | RC-1: Agricultural<br>RC-2: Mixed Use |
| White Clay Creek | 3 sites | WC-1: Potential<br>WC-2: Immediate<br>WC-3: Potential | WC-1: Agricultural/Forested<br>WC-2: Restoration Efforts<br>WC-3: Mixed Use | WC-1: Agricultural/Forested<br>WC-2: Undeveloped Land<br>WC-3: Agricultural/Undeveloped |

Table 3: Summary of the methodology results. GIS Analysis (Column 1) lists the number of potential sites identified through GIS analysis. Ground-Truthing (Column 2) includes the results of the field investigation. These include not suitable for wetland mitigation (No), potentially suitable for wetland mitigation pending further investigation (Potential), and suitable for wetland mitigation activities (Immediate). The Current LULC (Column 3) and LULC in Historical Aerial Imagery (Column 4) columns describe the LULC at each site historically and currently.

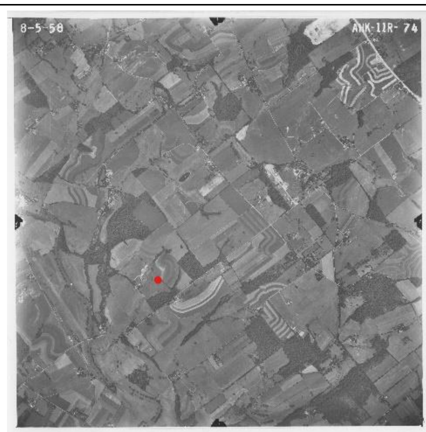
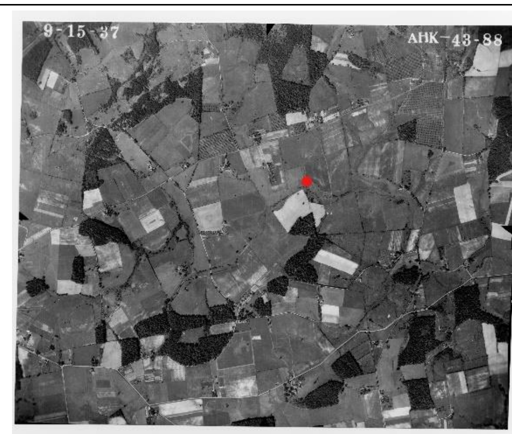
| ID | MB-1 | MB-2 |
|---|---|---|
| **Municipality** | Birmingham Township | Pocopson Township |
| **Ground-Truthing View** |  |  |
| **Current Aerial Imagery** |  Photo Credit: Google Earth (2021) |  Photo Credit: Google Earth (2021) |
| **Historical Aerial Imagery** |  Photo Credit: PASDA (1958) |  Photo Credit: PASDA (1937) |

Table 4: Ground-truthing and aerial imagery interpretation results for the Main Stem Brandywine Creek sub-watershed.

investigation at MB-2 was not possible. Elevation is slightly sloped to the south in the direction of MB-2. An existing PEM wetland area with noticeable drainage patterns is present immediately to the north of MB-2. An interpretation of aerial imagery from PASDA and Google Earth shows the persistence of this potential wetland over time. Land use remains mainly agricultural until the mid-2000s, when the first signs of residential development appear to the west of MB-2.

### *East Branch Brandywine Creek*

The East Branch Brandywine Creek sub-watershed covers an area of approximately 319 sq. km (see Table 2). A total of 45 parcels make up an area of agricultural easements that is approximately 967 ha. Steep slopes cover an area of approximately 2,163 ha within the watershed. NWI palustrine wetlands make up approximately 6 ha across the watershed. This includes approximately 5 ha of PEM wetlands and 1 ha of PSS/PFO wetlands. USA SSURGO hydric soils make up a total area of approximately 123 ha within the East Branch Brandywine Creek sub-watershed. The total length of watercourses in the watershed is approximately 3,580 m.

Agricultural easements within this watershed occur primarily in the northern portion (Figure 8). Steep slopes are present throughout the watershed. NWI wetlands, hydric soils, and watercourse polylines are dispersed throughout the study area. The single occurrence of an intersection of these three features that occurs outside of agricultural easements and off of steep slopes is present toward the northern end of the watershed. This is the only location eligible for ground-truthing within the East Branch Brandywine Creek sub-watershed and was selected for ground-truthing as “EB-1.” (see Table 3)

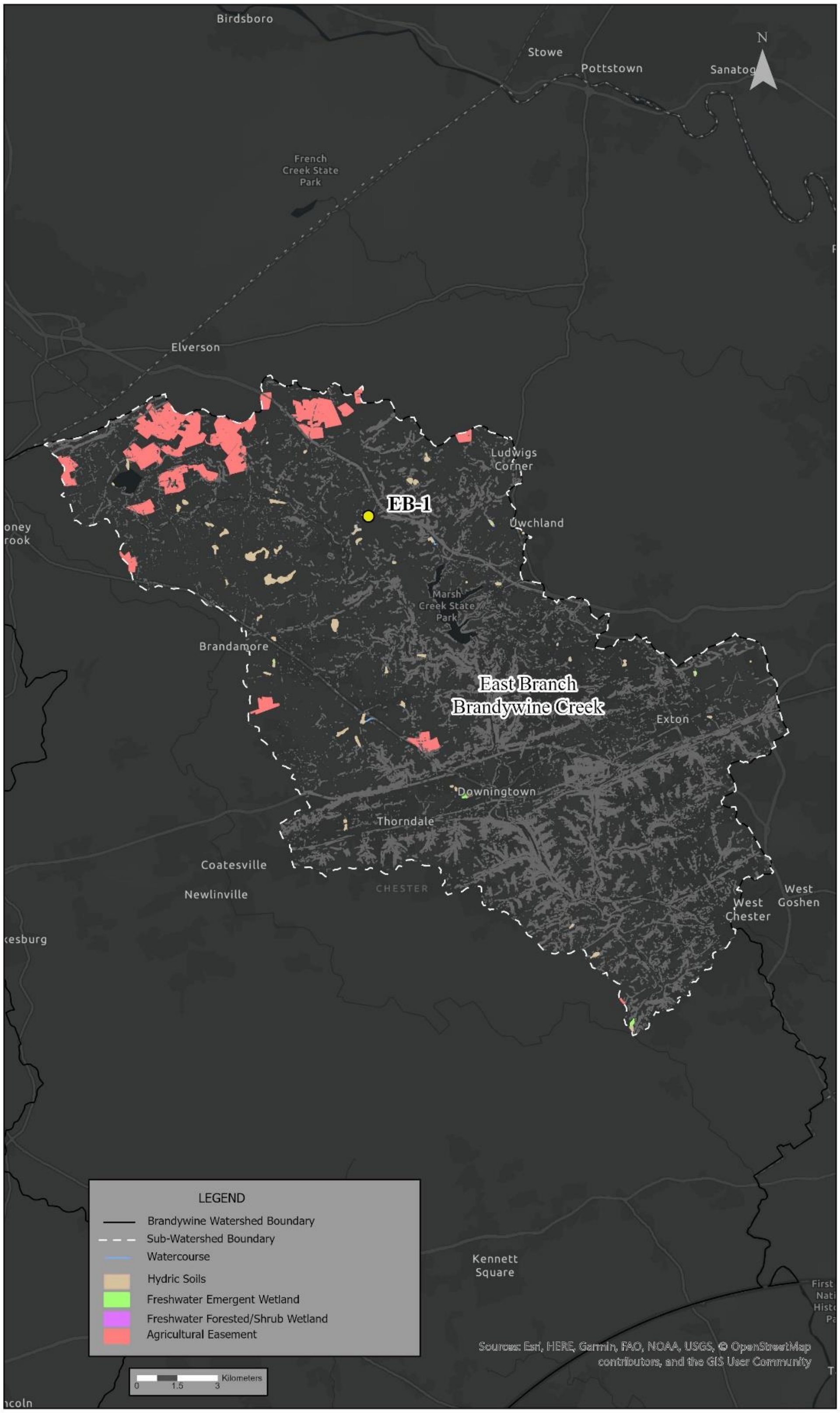



Figure 8: Results and ground-truthing locations within the East Branch Brandywine Creek sub-watershed

EB-1 is located in Wallace Township. This ground-truthing location falls within the Lamb Tavern wildlife preserve and is a mainly forested area. The surrounding land use consists of light residential development and agricultural fields. During the ground-truthing observation, an existing PSS/PFO wetland habitat was observed and appropriate wetland vegetation, hydrology, and soils were noted. Elevation is relatively stable, with little noticeable slope. Recent aerial imagery appears to show a potential PEM wetland present to the southwest of EB-1. An interpretation of aerial imagery from PASDA and Google Earth shows a mix LULC of agricultural activities and forested areas surrounding EB-1, until the late 1980s to early 1990s when residential begins to appear (Table 5). The area immediately surrounding EB-1 remains forested.

### *West Branch Brandywine Creek*

The West Branch Brandywine Creek sub-watershed spans an area that is approximately 216 sq. km. (see Table 2). Agricultural easements cover an area that is 732 ha in size and consists of 30 parcels. Steep slopes cover an area of approximately 1,629 ha. NWI palustrine wetlands account for approximately 6 ha, with 4 ha of PEM wetland habitats and 2 ha of PSS/PFO wetland habitats. USA SSURGO hydric soils cover an area of approximately 61 ha. The total length of watercourses within the watershed is approximately 1,484 m.

Agricultural easements within the West Branch Brandywine Creek sub-watershed are clustered towards the northern and southern portions (Figure 9). Areas of steep slopes are concentrated primarily from the central to the southern portion of the watershed. All areas of NWI wetlands occur only in the northern end of the watershed, while small areas of hydric soils and watercourse are present throughout the study area. No locations within the West Branch

| **ID** | EB-1 |
|---|---|
| **Municipality** | Wallace Township |
| **Ground-Truthing View** |  |
| **Current Aerial Imagery** |  Photo Credit: Google Earth (2021) |
| **Historical Aerial Imagery** |  Photo Credit: PASDA (1971) |

Table 5: Ground-truthing and aerial imagery interpretation results for the East Branch Brandywine Creek sub-watershed.

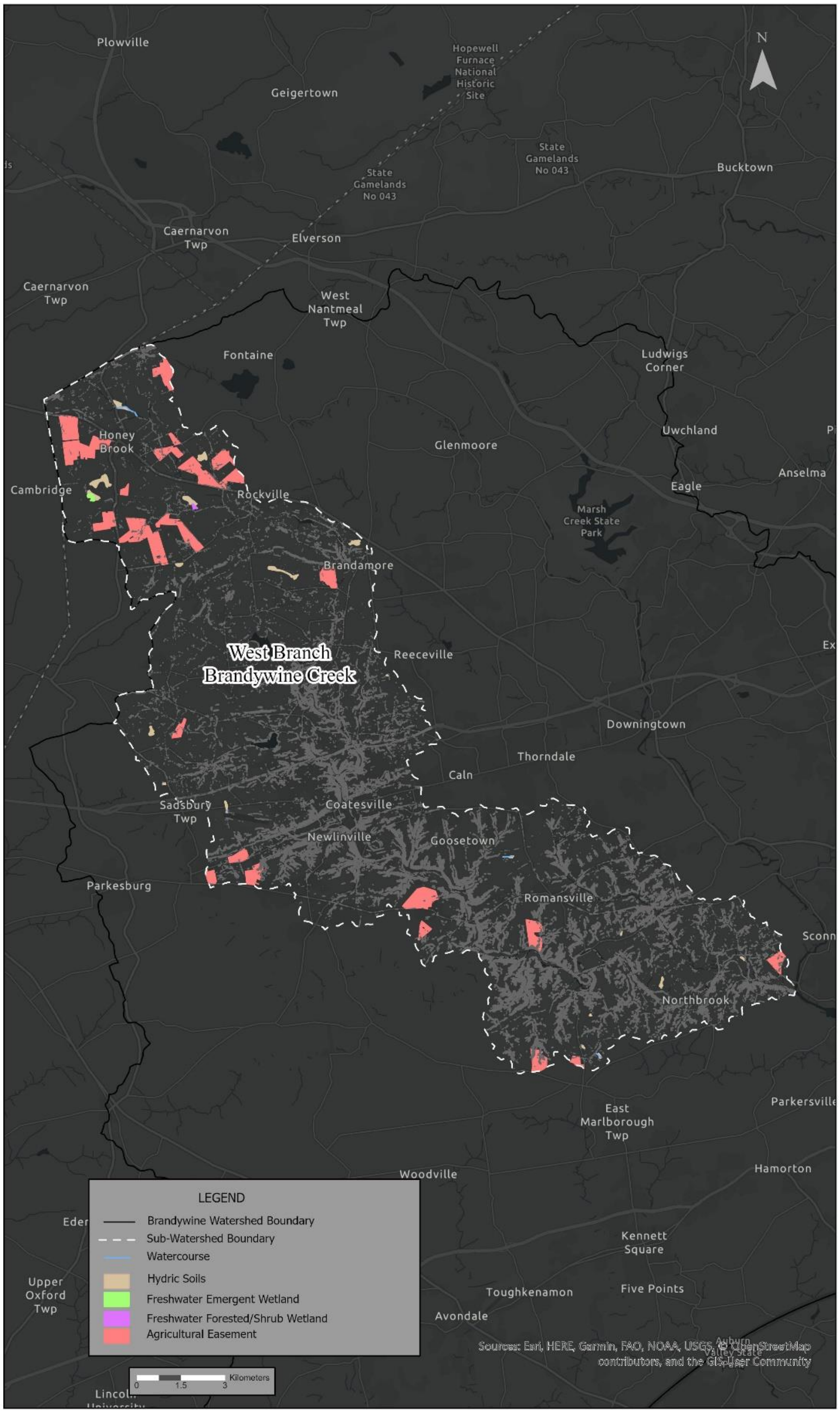



Figure 9: Results within the West Branch Brandywine Creek sub-watershed

of the Brandywine Creek watershed were eligible for a ground investigation; therefore, one was not performed within this watershed.

### *Buck Run*

Buck Run Watershed covers an area of approximately 126 sq. km. (see Table 2). A total of 68 parcels protected for agricultural easements make up an area of 1,258 ha within the watershed. Steep slopes cover an area of approximately 735 ha. Area of NWI wetlands total an area approximately 1.3 ha. This includes 0.6 ha of PEM wetlands and 0.7 ha of PSS/PFO wetlands. USA SSURGO hydric soils cover approximately 27 ha within the watershed. The total length of watercourses within the watershed is approximately 2,865 m. Agricultural easements occur primarily in the northern portion and along the western boundary of the watershed (Figure 10). Areas of steep slopes are concentrated through the central portion and towards the eastern boundary. Only two areas of NWI wetlands are present in the Buck Run Watershed – one in the central portion and on in the southeastern corner. Small areas of hydric soils and watercourse are dispersed throughout the watershed. No locations within the Buck run watershed were eligible for a ground-truthing investigation; therefore, one was not performed within this watershed.

### *Red Clay Creek Watershed*

The Red Clay Creek watershed covers approximately 86 sq. km. (see Table 3). Agricultural easement areas consist of approximately 500 ha and includes 18 parcels. Steep slopes cover an area of approximately 353 ha. NWI palustrine wetlands occupy approximately 0.8 ha throughout the watershed, all of which are considered PEM wetland types. USA SSURGO hydric soils occurred in approximately 23 ha. The total length of watercourses in the Red Clay Creek watershed is approximately 1,507 m.  Within the Red Clay Creek watershed, preserved agricultural areas

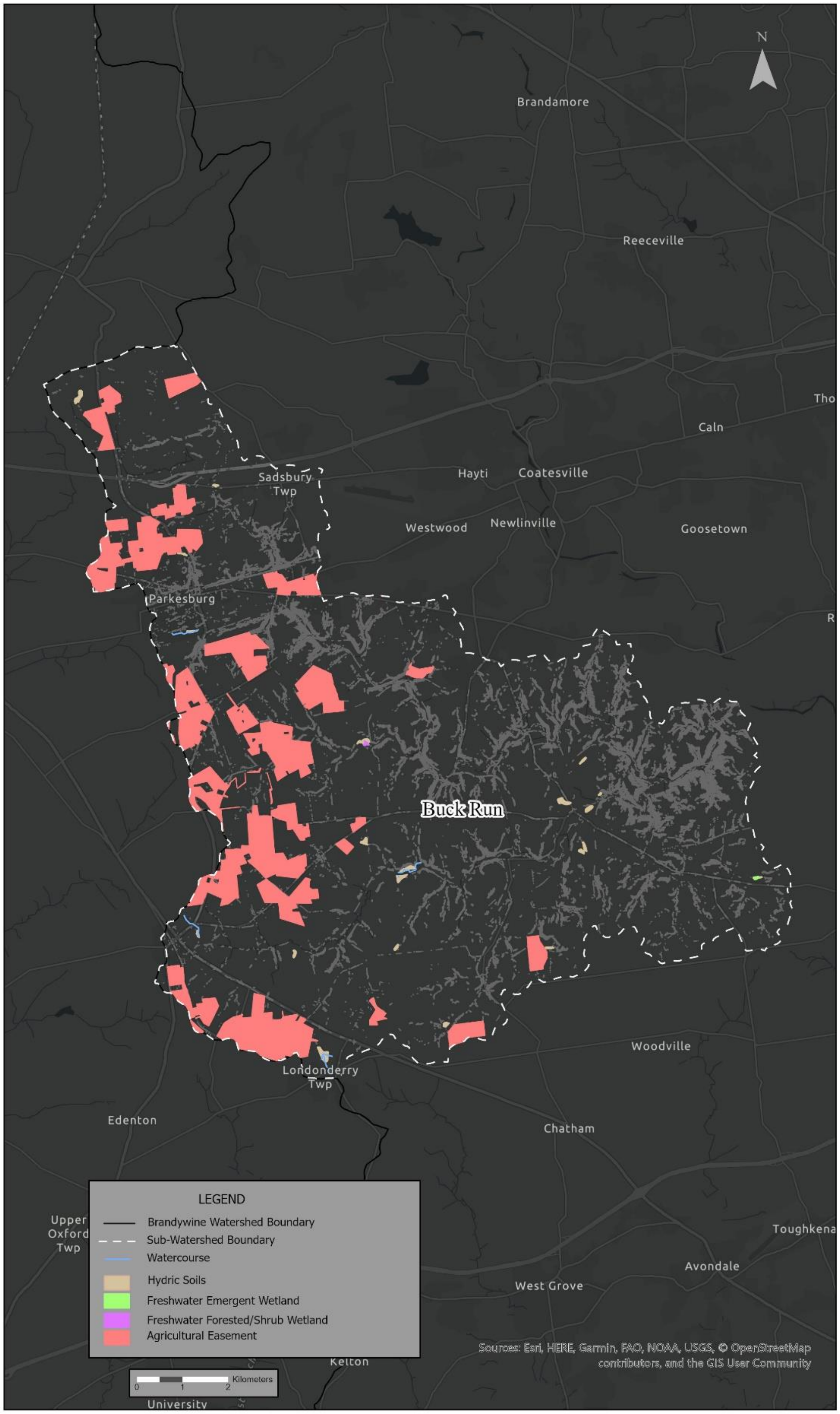



Figure 10: Results within the Buck Run sub-watershed

occur primarily along the northern boundary (Figure 11). Areas of steep slopes occur throughout the study area, with more density towards the southern boundary. Two small areas of NWI PEM wetlands are present along the western boundary of the watershed. Small areas of hydric soils and watercourse are present throughout the watershed. Two of these areas intersect with the NWI wetlands, making these locations eligible for ground-truthing (see Table 2).

The first location occurs towards the northern end of the western boundary. This area was selected for ground-truthing as "RC-1." RC-1 is located in West Marlborough Township. RC-1 occurs on private property and is setback a considerable distance from public roads. A thorough ground-truthing investigation was difficult to perform at this location due to these circumstances. There was a noticeable watercourse with pockets of hydrophytic vegetation present along the banks. The primary LULC surrounding RC-1 consists of heavy agricultural use and open land. Elevation within this area is relatively stable with no noticeable slope. An interpretation of recent aerial imagery shows potential PEM wetlands to the north. A noticeable watercourse emerges from a forested riparian corridor and flows to the south through RC-1. An interpretation of historical aerial imagery from PASDA and Google Earth shows relatively unchanged landcover surrounding RC-1, with agricultural activity remaining the primary land use over time. (Table 6).

The second location occurs along the western boundary of the Red Clay Creek watershed, south of RC-1 in Avondale Borough. This location was selected for ground-truthing as "RC-2." RC-2 occurs on private property and is setback a considerable distance from public roads. A thorough ground-truthing investigation was difficult to perform at this location due to these circumstances. The surrounding land use is variable and includes forested areas, agricultural activities, and residential and commercial development. Elevation slopes from the north to the

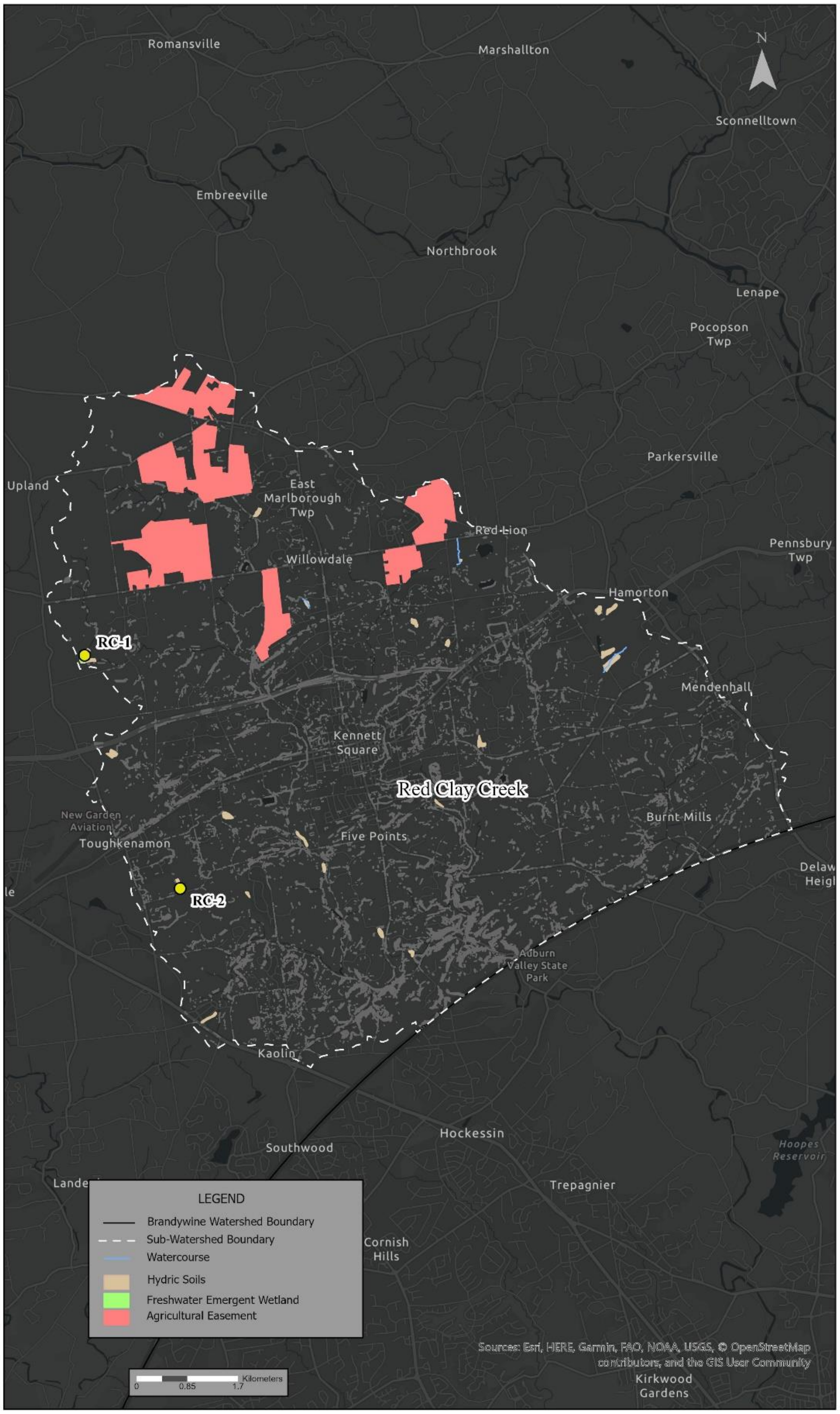



Figure 11: Results and ground-truthing locations within the Red Clay Creek sub-watershed

| **ID** | RC-1 | RC-2 |
|---|---|---|
| **Municipality** | West Marlborough Township | Avondale Borough |
| **Ground-Truthing View** |  |  |
| **Current Aerial Imagery** |  Photo Credit: Google Earth (2021) |  Photo Credit: Google Earth (2021) |
| **Historical Aerial Imagery** |  Photo Credit: PASDA (1971) |  Photo Credit: PASDA (1946) |

Table 6: Ground-truthing and aerial imagery interpretation results for the Red Clay Creek sub-watershed.

south towards RC-2. An interpretation of recent aerial imagery does not show noticeable wetlands or watercourses; however, tree cover may inhibit this review. An interpretation of aerial imagery from PASDA and Google Earth shows relatively unchanged site conditions, as the area consists of a mixed land use in aerial imagery collected during the 1940s (Table 6). Changes in the surrounding landscape include an increase in residential and commercial development.

### *White Clay Creek Watershed*

The White Clay Creek watershed covers approximately 158 sq. km. (see Table 2). Agricultural easement areas consist of approximately 812 ha and includes 37 parcels. Steep slopes cover an area of approximately 812 ha. NWI palustrine wetlands occupy approximately 4 ha throughout the watershed, including 1 ha of PEM wetland habitat and 3 ha of PSS/PFO wetland habitat. USA SSURGO hydric soils occurred in approximately 98 ha. The total length of watercourses in the White Clay Creek watershed is approximately 6,218 m.

Agricultural easements throughout White Clay Creek watershed tend to centralize in the northern portion (Figure 12). Areas of steep slope are present throughout the White Clay Creek watershed, and increase in density towards the southern boundary. NWI wetlands are present in the central and northern portions of the watershed, but are absent in the southern portion. Areas of hydric soils and watercourses are present throughout the watershed. These features intersected at three locations within the watershed, resulting in three ground-truthing locations (see Table 3).

The first location selected for ground-truthing occurs towards the northern end of the watershed in London Grove township. This area was selected for ground-truthing as “WC-1.” WC-1 occurs on private property and is setback a considerable distance from public roads. A thorough ground-truthing investigation was difficult to perform at this location due to these

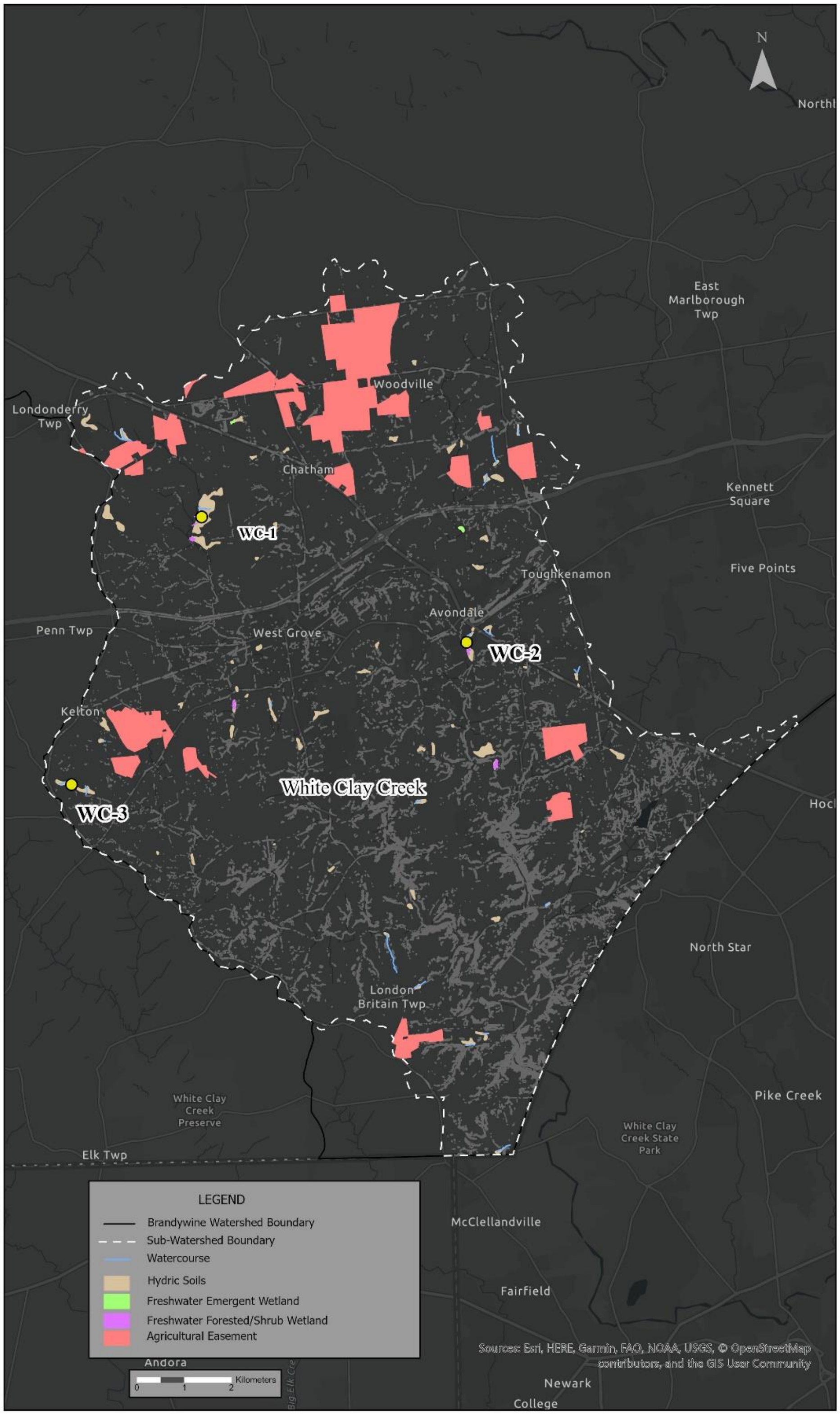



Figure 12: Results and ground-truthing locations within the White Clay Creek sub-watershed

circumstances; however, a watercourse and potential wetland vegetation could be observed from a roadside view. The surrounding land cover consists of a forested area and agricultural fields. Overall, an interpretation of historical aerial imagery from PASDA and Google Earth shows relatively unchanged site conditions and land use that is comparable to present day (Table 7).

The second ground-truthing site occurs to the southeast of WC-1 in Avondale Borough. This area was selected for ground-truthing as “WC-2.” WC-2 occurs on private property and is setback a considerable distance from public roads. A thorough ground-truthing investigation was difficult to perform at this location due to these circumstances. Land use around WC-2 is a mix of open land and light to medium density residential. Signage near WC-2 details recent wetland restoration efforts, and a constructed riparian buffer was noted in this area. An interpretation of recent aerial imagery shows a mix of PEM and PSS/PFO wetland habitats near WC-2 and a noticeable watercourse. Early historical aerial imagery from PASDA indicates that the area immediately surrounding WC-2 was cleared of tree-cover; however, it does not appear to be used for agriculture. Moving forward, this area remains untouched and slowly evolves to become a forested area.  Outward from WC-2, the land cover is a mixed use of agricultural, residential and undeveloped areas. Development appears to the north during the early to mid-2000s.

The final location selected for ground-truthing occurs in New London Township, which is southwest of WC-1 and west of WC-2. This area was selected for ground-truthing as “WC-3.” WC-3 occurs on private property and is setback a considerable distance from public roads. A thorough ground-truthing investigation was difficult to perform at this location due to these circumstances. There was a watercourse and hydrophytic vegetation observed in areas near WC-3 during the ground-truthing investigation. Surrounding land use is mixed and consist of forested areas, agricultural fields, and residential development. An interpretation of recent aerial imagery

<table>
<tr><th>ID</th><th>WC-1</th><th>WC-2</th><th>WC-3</th></tr>
<tr><td>Muni.</td><td>London Grove Township</td><td>Avondale Borough</td><td>New London Township</td></tr>
<tr><td>Ground-Truthing View</td><td></td><td></td><td></td></tr>
<tr><td>Current Aerial Imagery</td><td><br>Photo Credit: Google Earth (2021)</td><td><br>Photo Credit: Google Earth (2021)</td><td><br>Photo Credit: Google Earth (2021)</td></tr>
</table>

Table 7: Ground-truthing and aerial imagery review results for the White Clay Creek sub-watershed.

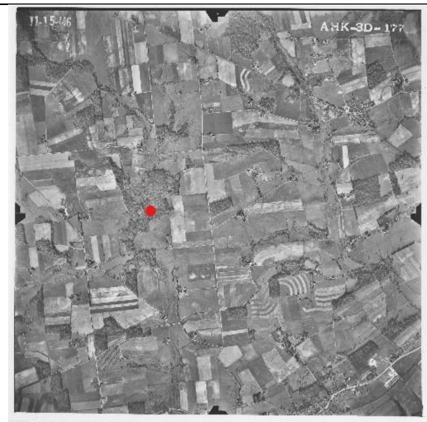
| | | | |
|---|---|---|---|
| **Historical Aerial Imagery** | <br>Photo Credit: PASDA (1946) | <br>Photo Credit: PASDA (1946) | <br>Photo Credit: PASDA (1946) |

Table 7 cont.: Ground-truthing and aerial imagery review results for the White Clay Creek sub-watershed.

shows a potential PEM and PSS/PFO wetland complex to the northeast of WC-3. An interpretation of early historical aerial imagery from PASDA shows that the land use immediately surrounding WC-3. Moving forward, this agricultural activity in this area decreases and this area converts back to undeveloped land, including some forested areas. The land cover further out from WC-3 is relatively similar to the current land use.

### *Summary*

The total study area consisted of the Main Stem Brandywine Creek, East Branch Brandywine Creek, West Branch Brandywine Creek, Buck Run, White Clay Creek, and Red Clay Creek watersheds, that make up the Brandywine Creek watershed in Chester County, Pennsylvania. NWI Wetlands, watercourse lines, and US SSURGO hydric soils were present in areas throughout the watershed (see Table 2). After the GIS analysis, eight sites throughout the study area were selected for a ground-truthing investigation (see Table 3). An aerial imagery interpretation supported the GIS analysis and ground-truthing results, and it was determined that two sites were deemed suitable for immediate wetland mitigation activities, four sites would require further investigations, and two sites are unsuitable for wetland mitigation activities. An in-depth discussion of the results will be provided in Chapter 6.

# CHAPTER 6 - DISCUSSION

This chapter discusses the results from the GIS analysis, ground-truthing investigation, and aerial imagery interpretations performed on areas throughout the Main Stem Brandywine Creek, East Branch Brandywine Creek, West Branch Brandywine Creek, Buck Run, Red Clay Creek, and White Clay Creek sub-watersheds in Chester County, Pennsylvania. An explanation of how this research relates to previous studies, as well as future directions for research will be included in this chapter. The discussion will also include a review of the limitations encountered throughout this study, which may have impacted the results of this analysis, as well as what the future implications of this research may include.

Through an analysis and manipulation of GIS data, locations throughout the six sub-watersheds that could provide potential wetland mitigation opportunities were determined. The data was focused primarily on environmental conditions which consisted of watercourse, hydric soil, and NWI mapped wetland locations. Areas that contain all three of these qualities were deemed more likely to support successful wetland communities. Exclusionary features included agricultural easements and steep slopes. A considerable amount of area throughout the sub-watersheds were found to be under agricultural easements, which prohibits the land to be used for anything other than agricultural activities. Slopes at 25% or greater also covered a significant area throughout each sub-watershed. Because water is more unlikely to inundate across a steep slope, these areas were excluded from the determination of potential wetland mitigation locations. Features that intersected with either one or both of these features to any extent were excluded from the analysis.

To support the results from this GIS analysis, ground-truthing sites within four sub-watersheds were investigated. The East Branch Brandywine Creek sub-watershed had one location that was eligible for a ground-truthing investigation. Two ground-truthing locations were present in the Main Stem Brandywine Creek and Red Clay Creek sub-watersheds. The White Clay Creek sub-watershed had three locations that were eligible for ground-truthing investigations. In total, eight sites were selected for ground truthing within the study area. Two sub-watersheds, Buck Run and West Branch Brandywine Creek did not have any locations where all three of the wetland characteristics intersected outside of the exclusionary features.

### *Wetland Mitigation Suitability*

The ground-truthing investigations yielded a variety of results for wetland mitigation opportunities at the selected sites (see Table 2). Of the eight sites, two were determined to be unsuitable for wetland mitigation activities. Both of these determinations were made based on the lack of open, undeveloped space surrounding the ground-truthing location. The sites include one location within the Main Stem Brandywine Creek sub-watershed (MB-1) and one location within the Red Clay Creek sub-watershed (RC-2). An interpretation of aerial imagery supports this determination as evidence of historical and current development is clear.

Four of the ground-truthing sites were determined to have the potential for wetland mitigation; however, their location among agricultural fields may require further investigation and possible remediation before mitigation activities could take place. These locations include one site in the Main Stem Brandywine Creek sub-watershed (MB-2), one site within the Red Clay Creek sub-watershed (RC-2), and two sites within the White Clay Creek sub-watershed (WC-1 and WC-3). These ground-truthing locations occur among open agricultural fields, which could provide a large area for a mitigated wetland to be created. They also contained an intersection of the three wetland characteristics analyzed in this study. An interpretation of aerial imagery shows possible wetlands near the ground-truthing location, indicating that there is the potential for these habitats to succeed in this area. However, agricultural activities occurring in nearby existing wetlands are likely causing degradation to the naturally occurring hydrologic, vegetative, and soil characteristics within that wetland. Areas of cropland often include soils that area devoid of many nutrients and hydrologic characteristics that a wetland habitat needs to thrive (Rosolen et al. 2015). With this in mind, wetland mitigation activities at these four locations could be possible, but remediation activities may be required before construction activities can begin.

The final two sites were determined to be the most suitable for immediate wetland mitigation activities. These include the ground-truthing site in the East Branch Brandywine Creek sub-watershed (EB-1) and one site within the White Clay Creek sub-watershed (WC-2). Both of these sites were located in areas that included enough undeveloped open space for wetland mitigation activities. These sites occurred approximately 0.25 km away from active agricultural fields, with a forested buffer between the two land types. This would help to limit negative impacts from farming activities. They also consisted of an intersection of analyzed wetland characteristics. Both of these ground-truthing locations were found near existing wetland habitats within or immediately adjacent to the site.

The location within the East Branch Brandywine Creek sub-watershed occurred within the Lamb Tavern Wildlife Preserve (Figure 13). This preserve is supported by the Chester County Department of Parks and Preservation (Chesco n.d.). The goal at the Lamb Tavern Wildlife Preserve is to preserve the significant natural resources that occur within the area. The ground-truthing investigation resulted in the presence of existing wetlands that included the appropriate hydrologic, vegetative and soil characteristics. The protections afforded to this area through the Chester County Department of Parks and Preservation, as well as the presence of

Figure 13: Lamb Tavern Wildlife Preserve signage and view of wetlands at EB-1

wetland habitats and surrounding open space make this location suitable for wetland mitigation activities.

The location occurring within the White Clay Creek sub-watershed fell within an area of active wetland and riparian buffer restoration activity, which was indicated by signage in the area (Figure 14). Noticeable tree plantings could be seen throughout the area surrounding this ground-truthing location (Figure 15). The restoration within this project was funded by the Pennsylvania Watershed Restoration and Protection Program (WRPP) and the Borough of Avondale, in which it occurs. The goal of the WRPP is to support and maintain restored stream reaches throughout the state that have been degraded by nonpoint source pollution runoff (DCED n.d.). Ultimately, these efforts will remove these streams from the DEP Impaired Waters list and restore their natural function and values. The implementation of this program within this ground-truthing location could assist in supporting potential wetland mitigation activities.

### *Research Comparison*

This research indicates that GIS is a useful tool for wetland mitigation planning, and supports the outcome of previous research. Identifying potential wetland mitigation locations throughout a watershed or sub-watershed and then prioritizing these sites based on suitability helps to streamline the planning process (O'Neill et al. 1997). A GIS analysis that includes hydrologic features and current land use conditions will lead to successful wetland mitigation activities, as this includes an evaluation of the physical and biological characteristics early in the site selection process (Russell et al. 1997).

An analysis that begins with these particular features should be suitable in locations with a variety of land uses. Previous studies performed included areas of heavy agricultural use, along

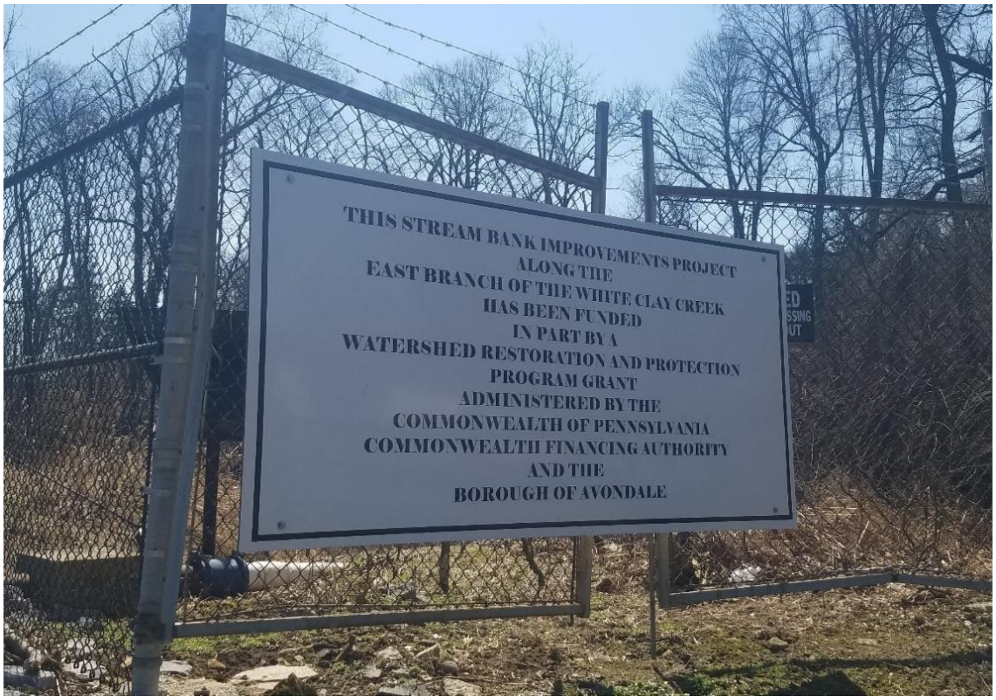


Figure 14: Signage nearby WC-2 indicating ongoing restoration activities


Figure 15: Tree plantings along the riparian buffer restoration project at WC-2

riparian corridors, and undeveloped land, among others (O'Neill et al. 1997; Russell et al. 1997; Schleupner and Schneider 2012). This research consisted of a study area with mixed land use, including agricultural, developed, and undeveloped land. With all land types considered, this analysis resulted in several locations that could support created wetlands. This indicates that this wetland mitigation GIS analysis procedure can be performed on all land types and still yield results.

When considering the locations of existing wetlands, hydrologic features, and hydric soils, it should be noted that the intersection of these is not consistent throughout the landscape (Palemeri and Trepel 2002; Russell et al. 1997). Locations for wetland mitigation activities do not occur regularly throughout a landscape, and, in some cases (e.g. Buck Run and West Branch Brandywine Creek), there may not be an appropriate location at all. Instances with only "low-ranking" suitability may also occur (Palmeri and Trepel 2002). In these cases, a determination should be made as to whether wetland creation activities should even be attempted (Lin et al. 2006; Milner 2003). Unless the inclusion of a wetland habitat is crucial to a particular aspect within the study area, such as endangered species habitat, then focus should be shifted to a different location.

The goal of this analysis and previous studies is not to replace field investigations, but rather to target potential locations (O'Neill et al. 1997). As determined in this research, certain locations that satisfied the GIS analysis for wetland mitigation suitability were deemed unsuitable after a ground-truthing investigation was performed. It is important that GIS and other desktop analysis are used as a support tool for the wetland mitigation planning process, and not as the final determination.

## *Study Limitations*

The main limitation encountered during this analysis was the lack of accessibility to ground-truthing sites. A thorough investigation of on-site conditions could not be performed at several of the locations due to their occurrence on private lands. For this reason, the only investigation that could be performed was a visual inspection from the edge of a public road. Notes and a roadside review on the surrounding land use provided some insight into potential suitability.

Another limitation of this study pertained to the open space areas surrounding the potential mitigation areas. Large open spaces near hydrologic features are desirable for wetland mitigation purposes (Milner 2003). The majority of the open spaces surrounding the ground-truthing sites were being used for agricultural activities. Agricultural activities have a significant impact on the soils on which they occur (Rosolen et al. 2015). Some of the soils throughout the areas could potentially be heavily contaminated or completely stripped of their nutrients. To confirm the suitability of soils in the sites, a soil analysis may need to be performed to determine if they could support wetland type habitats.

While the GIS analysis portion of this thesis revealed several potential wetland mitigation sites, there are some limitations with the publicly-available datasets used. The primary limitation is due to the lack of thorough ground-investigations with NWI wetlands. The USFWS NWI wetlands inventory relies primarily on remote sensing and aerial imagery review (USFWS n.d.). It is estimated that the NWI's accuracy for identifying wetlands is about 90%, but determining the extent and boundaries of the identified wetlands is lacking (Ibid.). Of the identified wetlands, 95% of the well-defined wetland boundary lines are expected to fall within +\- 5.9 m of the true location. This means that, through this analysis, there was the potential for a wetland to extend almost six m outside of the NWI estimated boundary.

### *Future Directions for Research*

Further research on the wetland mitigation opportunities within this study area and beyond should be performed to narrow down potential wetland mitigation opportunities. Because wetlands require specific hydrologic and soil characteristics, the data used in this analysis was intended to serve as a foundation for future research. Additional GIS datasets could provide a deeper insight into suitability for wetland mitigation at selected sites. This additional data should be evaluated on a case-by-case basis and should consider the goals of the project from multiple aspects (Kentula 2000). For example, if one of the goals of the wetland creation is to provide habitat for a specific endangered species, including additional datasets in the study could narrow down appropriate locations.  If the goal of this study was to create more bog turtle (*Glyptemys muhlenbergii*) habitat within Chester County, additional data sets could include vegetative makeup, tree cover, and soil types. Bog turtles are typically found in open-canopy, PEM wetlands with a muck-type substrate, so adding additional datasets identifying potential locations with minimal tree cover and soils that could form into “muck” are important (USFWS, n.d.).

Gaining access to perform thorough ground-truthing investigations at selected locations would show the condition of the on-site characteristics and if they are able to support a wetland habitat (O’Neill et al. 1997). A thorough on-site evaluation of surrounding landcover is important to determine possible negative impacts that could affect constructed wetland. This could include pollution from stormwater run-off from residential or agricultural activities, for example.

Because of the impact they have on the surrounding landscape, this research could be used as a starting point to inform farmers about the importance of sound agricultural practices. In this thesis, the majority of the ground-truthing locations occurred within areas with some level of agricultural use. Because of Chester County's high population, these areas are may be the only ones that remain with the extent and characteristics to support wetland mitigation activities (Chesco n.d.). Agricultural activities in these areas are having a direct impact on the surrounding natural environment. Using this research to inform farmers about the minimal locations throughout the landscape that could support wetlands may encourage them to evaluate their farming practices and make changes that are less detrimental to natural habitats.

To support these discussions, areas under agricultural easements can be included in the GIS analysis. This will show that there are more opportunities for wetland mitigation if these areas are included for consideration. With this information, parties concerned with wetland mitigation can approach farmers and private landowners with the inclusion of this areas and explain the importance of allowing wetland mitigation on their property. Included in this discussion should be potential compensation opportunities through the USDA's Conservation Reserve Enhancement Program (CRP). The CRP allows farmers to convert their agricultural fields back into natural environments, including wetland habitats (USDA n.d.). The CRP provides financial assistance and technical guidance during the conversion process. Participants will receive an annual rental payment on enrolled acres for the term of the contract (Ibid.). Any successfully constructed CRP wetlands will not only support the participant financially, but will also support any remaining privately-owned acres through natural environmental processes.

While the idea of constructed' wetland "success" may remain somewhat subjective, establishing a general standard could ensure their persistence. Creating guidelines and goals that detail what the physical characteristics of a constructed wetland should contain for it to be considered a success would support current and future mitigation efforts. These would include hydrologic conditions, vegetative and soil makeup. These goals might not be achieved within a uniform timeline, so a monitoring timeframe should be determined on a case-by-case basis (SER n.d.). Throughout the monitoring timeframe, adaptive management techniques should be encouraged (Kentula 2000; Milner 2003; SER n.d.). Reacting immediately to issues identified within the mitigated wetland supports a successful outcome.

This success should be defined at three levels – compliance success, functional success, and landscape success (Kentula 2000). Compliance success considers the terms of the agreement for the project, such as a permit. Functional success evaluates whether the proposed ecological functions and values of the habitat have been met, whereas landscape success measures how the mitigated wetland fits into the ecological functions of the landscape or region. The created wetland should be sustainable and fit seamlessly into the landscape, while meeting the needs of any compliance guidelines.

It is important to note that while the methodology used in this research provided information regarding where the most suitable wetland mitigation opportunities lie within the Brandywine Creek watershed, it lacks the consideration as to where wetland habitats may be the most needed. Areas that are lacking some or all of the inclusionary features during the GIS analysis would not be considered for ground-truthing and aerial imagery interpretations. If a specific area (municipality, county, etc.) is inclusionary features, revisions could be made to this methodology to show where wetland mitigation opportunities may lie within their study area. For example, their may be a large, undeveloped area along the banks of a stream. Even though this area may lack hydric soils and existing wetland habitats, certain mitigation strategies could support a constructed wetland in this area.

### *Summary*

Through this analysis, it was determined that there are potential wetland mitigation opportunities throughout the Brandywine Creek watershed in Chester County, Pennsylvania. Yet, the location and extent of these opportunities differ. The West Branch Brandywine Creek sub-watershed and Buck Run sub-watershed were found to have no eligible wetland mitigation opportunities. The East Branch Brandywine Creek sub-watershed had only one location deemed suitable for wetland mitigation activities. This location was determined to have the potential for immediate wetland mitigation activities after an evaluation of the on-site conditions and the surrounding land use. After the GIS analysis, two sites within the Main Stem Brandywine Creek sub-watershed were selected for ground-truthing investigations. The ground-truthing investigation followed by a review of aerial imagery determined that one site was not suitable for wetland mitigation activities due to a lack of available open space. The second location has the potential to be a wetland mitigation area, but further analysis may be required due to agricultural land use.

The same is true for the two sites that were investigated within the Red Clay Creek sub-watershed. A lack of open space excluded one of the selected locations, while the other site requires further analysis. The final sub-watershed, White Clay Creek, had three locations deemed eligible for wetland mitigation. Two of the sites have the potential for future wetland mitigation activities pending further investigation into the conditions of the surrounding landscape. The third location was determined to have the potential for immediate mitigation activities, as on-site conditions and the surrounding land cover could support a constructed wetland's success.

There were some limitations encountered over the course of this study. These include lack of access to private property during the ground-truthing investigation, presence of agricultural fields nearby the selected locations, and the availability and quality of GIS data. Even with these limitations, the future implications of this research were clear. Including more GIS datasets in this process would further narrow down potential wetland mitigation opportunities. Access to ground-truthing sites and the surrounding landscape would reveal the conditions of the on-site characteristics and to what extent they could support a wetland environment.

This research could also serve as a starting point to open conversations surrounding wetland mitigation. Presenting the identified locations to farmers and explaining the importance of the conditions of the surrounding land use may encourage them to implement sound agricultural practices. This research also recognizes the inconsistencies in universal wetland mitigation standards. It is important that agencies regulating wetlands also recognize these inconsistencies so that guidelines could be establish that support the success of wetland mitigation areas.

# CHAPTER 7 – CONCLUSION

Human development activities have led to substantial amounts of wetland habitat loss throughout the world (Gutzwiller and Flather 2011). This habitat loss has had a significant negative impact on the surrounding landscape as wetlands are important for carbon sequestration, flood control, and other natural functions (Jin et al. 2016). The environmental values of wetland habitats are extensive and are often under-valued. The economic values of wetland habitats are just as important as the environmental values (Verma and Negandhi 2011). The health of a wetland ecosystem is often comparable to the health of the surrounding economic ecosystem. Wetlands in developed areas may provide direct and indirect economic resources to the surrounding populations. These habitats also have an effect on the global economy as they provide "free" natural functions important to human life.

There have been efforts historically that focused on the preservation and restoration of existing wetlands, as well as the creation of constructed wetlands to help offset historical loss. Recently, there has been a push that recognizes the importance of wetland habitats and encourages not only preservation and restoration, but also on effective wetland creation practices (Hettiarachci et al. 2015). This push helps to support regulations set forth by the ACOE and DEP and are used to control wetland and watercourse impacts related to human development. The focus has shifted from an acre-to-acre approach to a replacement of functions and values (DEP n.d.). This means that any wetland impacts that occur during development must be replaced in a way that replicates their condition in the constructed wetland.

Past studies have been done to determine if a GIS analysis can assist in determining site suitability for wetland mitigation locations (e.g., Lin et al. 2006; O'Neil et al. 1997; Palmeri and Trepel 2002; Russell et al. 1997; Schleupner and Schneider 2012). These studies include a variety of techniques, but the final goal is generally the same – how to identify and prioritize wetland mitigation locations. To support the findings of the GIS analysis, field evaluations and aerial imagery reviews are often performed.

For this thesis, six sub-watersheds within the Brandywine Creek watershed in Chester County, Pennsylvania used a combination of GIS analysis, field investigations, and aerial imagery interpretations to determine where potential wetland mitigation opportunities may lie. These locations were evaluated over six sub-watersheds, including the Main Stem Brandywine Creek, East Branch Brandywine Creek, West Branch Brandywine Creek, Buck Run, Red Clay Creek, and White Clay Creek. To determine suitability, the focus was placed on three environmental factors that are key in supporting persistent wetland habitats – watercourse locations, USA SSURGO hydric soils, and NWI mapped palustrine wetlands. Any of these features that fell within areas protected under an agricultural easement or on an area of steep slopes (25% or greater) were not considered in this research. Land protected under an agricultural easement can only be used for farming activities, so wetland mitigation would not be permitted in these areas. Because water moves more quickly across areas of steep slopes, it is less likely to remain in these areas long enough to support wetland habitats, so these areas were also excluded.

Through the GIS analysis, it was determined that eight areas within the Brandywine Creek watershed were eligible for a ground-truthing investigation. These included one location within the East Branch Brandywine Creek sub-watershed, two locations within the Main Stem Brandywine Creek and Red Clay sub-watersheds, and three locations within the White Clay Creek sub-watershed. The ground-truthing results were combined with an interpretation of aerial imagery to determine site suitability. After the GIS analysis, ground-truthing investigation, and aerial imagery interpretation, it was determined that two sites, one within the East Branch Brandywine Creek sub-watershed and one within the White Clay Creek sub-watershed, could have the potential for immediate wetland mitigation activities. Four sites, one within the Main Stem Brandywine Creek sub-watershed, one within the Red Clay Creek sub-watershed, and two within the White Clay Creek sub-watershed, were deemed to have the potential for wetland mitigation activities pending further analysis. The remaining two sites, one within the Main Stem Brandywine Creek sub-watershed and one within the Red Clay Creek sub-watershed were determined to have no potential for wetland mitigation activities due to the absence of undeveloped open space.

This research correlated with previous studies that determined a GIS analysis to be a useful tool for wetland mitigation studies. Using GIS as the first tool to identify and then prioritize wetland mitigation activities streamlines the wetland mitigation creation process (O'Neill et al. 1997). This methodology could also be used across a variety of land use types and still yield results. In some cases, the results were that no locations were deemed suitable for wetland mitigation, or could be considered "low-priority" areas (Palmeri and Trepel 2002). In these cases, the project should be reevaluated and possibly moved to a more suitable location unless it is crucial to a particular aspect of the landscape. These decisions should be made with the support of a ground-truthing investigation and aerial imagery interpretation, as the results of a GIS analysis should not be the final determination.

Although there were limitations within this analysis, the future implications of this research could be beneficial to wetland mitigation activities. Incorporating more datasets into the GIS analysis could narrow down potential mitigation locations even further. This additional data would need to be considered on a case-by-case basis based on the final goal of the constructed wetland. Having open access to perform an in-depth evaluation of the existing on-site conditions, and the conditions of the surrounding landscapes would further determine the mitigation potential at identified locations.

This research could also be used to begin discussions about the importance of wetlands and wetland mitigation. Because selected sites often occurred within active agricultural fields, it is important that farmers are informed about the importance of wetland habitats, as well as how they could benefit from wetland mitigation activities through the USDA's CRP program. Including these benefits while explaining why these locations may be the only options for wetland mitigation in Brandywine Creek watershed may encourage them convert some of their land to wetland habitats and to implement sound agricultural practices.

Aside from the land use concerns, there is an issue with defining when a mitigation project can be considered a "success." Standards set forth by both regulating agencies and conservation organizations lack consistency in wetland mitigation planning and monitoring. For example, conservation organizations recommend a more fluid timeline for monitoring than is required by most regulating agencies. It is important that regulating agencies and conservation agencies work to create a standard wetland mitigation procedure, so that an idea of "success" can be identified and strived for.

While this research shows where it is most likely for successful mitigation to occur, it does not consider where wetland mitigation may be the most needed. When evaluating these areas, revisions to this methodology could be made so that areas lacking some or all of the inclusionary features are considered in the analysis.

This thesis has shown that a GIS analysis can be used to evaluate potential wetland mitigation sites. Ground-truthing investigations and aerial imagery interpretations were used to support the GIS analysis and assist in making a final determination. While this study can lead to a more efficient analysis and discussion of wetland habitat creation, it is important to understand that created wetlands are not a true replacement for naturally occurring wetlands. The focus of wetland habitats should be on preserving what the state of Pennsylvania has left, and using created wetlands as a support system for natural wetland environments. Naturally occurring wetlands, throughout Pennsylvania and beyond, have the potential to improve global environmental health with their role in mitigating climate change. This role is a crucial tool in supporting the efforts set forth by ecological preservation organizations and the UN's Decade of Ecosystem Restoration. Wetland mitigation is more than just restoring lost habitats – it is about supporting the health of the modern world.

# BIBLIOGRAPHY


Alliance for the Chesapeake Bay (ACB). 1997. https://www.allianceforthebay.org/ (last accessed 18 March 2022).

Ainsworth, D., N. Azzu, D. Bikaba, D.J. Bisaccio, K.B. Zeynep, B. Bulus, D. Coates, J. Corriero, C.L. de la Rosa, A. Dobson, M.V. Dodson, C. Fowler, C. Gibb, J. Grekin, C. Hattam, T. Hay-Edie, S. Iqbal, L.A. Jose-Castillo, M.Am. Khan, C. Kretsch, P. Lee, C. Lusty, M. Leveille, C. Lewis, U. Nilsson, K.Noonan-Mooney, K. Pintus, N. Pratt, R. Raymond, J. Scott, R. Sessa, J. Shimura, A. Summit, G. Tiddens, T.V. Waut, and J. Webb. 2013. *The Youth Guide to Biodiversity: Freshwater Ecosystems*. United Nations Decade on Biodiversity, Rome, Italy.

Bernal, B. and W. J. Mitsch. 2012. Comparing carbon sequestration in temperate freshwater wetland communities. Global Climate Change Biology. 18: 1636-1647.

Brandywine Red Clay Alliance (BRCA). 2015. *Our Watersheds*. http://www.brandywineredclay.org/ (last accessed 18 March 2022).

Butchart, S., E. Dieme-Amting, H. Gitay, S. Raaymakers, and D. Taylor. 2005. *Millennium ecosystem assessment, ecosystems and human well-being: wetlands and water*. World Resources Institute, Washington. D. C.

Campell, D.A., C.A. Cole, and R.P. Brooks. 2002. A comparison of created and natural wetlands in Pennsylvania, USA. *Wetlands Ecology and Management*. 10: 41-49.

Chester County, PA - Official Website (Chesco). n.d. *Chester County, Pennsylvani*a. www.chesco.org (last accessed 30 March 2022).

Cruz-Ortiz, C. and K. Miller. 2013. *Economic value of the Brandywine Creek watershed.* University of Delaware, Newark, Delaware.

Delaware River Watershed Initiative (DRWI). 2017. *Brandywine-Christina.* https://4states1source.org/ (last accessed (18 March 2022).

Environmental Protection Agency (EPA). n.d. www.epa.gov (last accessed 28 March 2022).

ESRI. 2020. ArcGIS Pro (Version 2.5).

Forsythe, S.W., R.T. Huffman, W.B. Parker, and D.R. Sanders. 1987. *Corps of Engineers wetlands delineation manual*. Y-87-1, Environmental Laboratory, Vicksburg, Mississippi.

Gann G. D., T. McDonald, B. Walder, J. Aronson, C.R. Nelson, J. Jonson, J.G. Hallett, C. Eisenberg, M.R. Guariguata, J. Liu, F. Hua, C. Echeverria, E.K. Gonzales, N. Shaw, K. Decleer, and K.W. Dixon. 2019. International principles and standards for the practice of ecological restoration. *Restoration Ecology*.

Gimenez, F.D. and C. Ruiz Mas. 2020. The valuation of recreational use of wetlands and the impact of the economic crisis. *International Journal of Environmental Research and Public Health.* 17(3228): 1-16.

Google. 2021. Google Earth Pro (Version 7.3).

Gutzwiller, K. J. and C. H. Flather. 2011. Wetland features and landscape context predict the risk of wetland habitat loss. *Ecological Applications*. 21(3): 968-982.

Hettiarachci, M., T.H. Morrison, and C. McAlpine. 2015. Forty-three years of Ramsar and urban wetlands. *Global Environmental Change*. 32: 57-66.

Hill, T., E. Kulz, B. Munoz, and J. R. Dorney. 2013. Compensatory stream and wetland mitigation in North Carolina: an evatluation of regulatory success. *Environmental Management*. 52: 1077-1091.

Hu, S., Z. Niu, Y. Chen, L. Li, and H. Zhang. 2017. Global wetlands: Potential distribution, wetland loss, and status. *Science of the Total Environment*. 586: 319-327.

Jin, H., C. Huang, M. W. Lang, L-Y. Yeo, and S. V. Stehman. 2017. Monitoring of wetland inundation dynamics in the Delmarva Peninsula using Landsat time-series imagery from 1985 to 2011. *Remote Sensing of Environment*. 190: 26-41.

Joshi, D., B. Gallant, A. Hakhu, S. De Silva, C. McDougall, M. Dubois, and I. Arulingam. 2021. Ramsar Convention and the wise use of wetlands: rethinking inclusion. *Ecological Restoration*. 39(1): 36-44.

Kauffman-Axelrod, J.L. and S. J. Steinberg. 2010. Development and application of automated GIS based evaluation to prioritize wetland restoration opportunities. *Wetlands*. 30(3): 437-438.

Kaza, N, and T. K. BenDor. 2013. The land value impacts of wetland restoration. *Journal of Environmental Management*. 127: 289-299.

Kentula, M. 2000. Perspectives on setting success criteria for wetland restoration. *Ecological Engineering*. 15: 199-209.

Lin, J. P., S. G. Bourne, and B. A. Kleiss. 2006. Creating a wetland restoration decisions support system using GIS tools. *Ecosystem Management and Restoration Research Program.*

Mallin, M.A., V.L. Johnson, and S.H. Ensign. 2008. Comparative impacts of stormwater runoff on water quality of an urban, suburban, and rural stream. *Environmental Monitoring and Assessment.* 159:475-491.

Milner, G. 2003. Wetland mitigation strategies for success. *Land and Water*. 47(1).

Mitsch, W.J. and J.G. Gosselink. 2000. The values of wetlands: importance of scale and landscape setting. *Ecological Economics.* 35: 25-33.

Mitsch, W.J. and M. E. Hernandez. 2012. Landscape and climate change threats to wetland of North and Central America. *Aquatic Sciences*. 75(1): 133-149.

Mohan, M., A. Chacko, M. Rameshan, V.G. Goplkrisna, V.M. Kannan, N.G. Vishnu, S.A. Sasi, and K.R. Baiju. 2022. Restoring riparian ecosystems during the UN-Decade on Ecosystem Restoration A global perspective. *Anthropocene Science*. 1: 42-61.

National Park Service (NPS). 2016. https://www.nps.gov/subjects/wetlands/why.htm (last accessed 4 April 2022)

O’Neill, M. P., J. C. Schmidt, J. P. Dobrowloski, C. P. Hawkins, and C. M. U. Neale. 1997. Identifying sites for riparian wetland restoration: application of a model to the Upper Arkansas River Basin. *Restoration Ecology*. 5(4S): 85-102.

Palmeri, L., and M. Trepel. 2002. A GIS-Based score system for siting and sizing of created or restored wetlands: two case studies. *Water Resources Management.* 16: 307–328.

Pennsylvania Department of Community and Economic Development (DCED). n.d. https://dced.pa.gov/ (last accessed 19 March 2022).

Pennsylvania Department of Conservation and Natural Resources (DCNR). n.d. https://www.dcnr.pa.gov/Pages/default.aspx (last accessed 4 April 2022).

Pennsylvania Department of Environmental Protection (DEP). n.d. https://www.dep.pa.gov/Pages/default.aspx (last accessed 30 March 2022).

Pennsylvania State University (Penn State). n.d. Pennsylvania Spatial Data Access: The Pennsylvania Geospatial Database Clearinghouse. www.pasda.psu.edu. (last accessed 18 March 2022).

Pittman, S. E., T.L. King, S. Faurby, and M. E. Dorcas. 2011. Demographic and genetic status of an isolated population of Bog turtles (*Glyptemys muhlenbergii*): implications for managing small populations of long-lived animals. *Conservation Genetics*. 12(6): 1589 1601.

Rosolen, V, A.B. De-Campos, J.S. Govone, and C. Rocha. 2015. Contamination of wetland soils and floodplain sediments from agricultural activities in the Cerrado Biome (State of Minas Gerais, Brazil). *Catena*. 128: 203-210.

Russell, G. D., C. P. Hawkins, and M. P. O'Neill. 1997. The role of GIS in selecting sites for riparian restoration based on hydrology and land use. *Restoration Ecology*. 5 (4S): 56-68.

Schleupner, C. and U. A. Schneider. 2012. GIS-Based estimation of wetland conservation potentials in Europe. *Applied Ecology and Environmental Research*. 10(4):385-403.

Society for Ecological Restoration (SER). n.d. *USA: Restoration of Leachate-Impacted Wetlands and Associated Mitigation at the University of Connecticut Landfill.* https://www.ser.org/ (last accessed 2 April 2022).

Stroud Research Center. n.d. WikiWatershed. https://wikiwatershed.org/ (last accessed 2 April 2022).

Turner, R. K, J.C.J.M., van den Bergh, T. Soderqvist, A. Barendregt, J. van der Straaten, E. Maltby, and E.C. van Ierland. 2000. Ecological-economic analysis of wetlands: scientific integration for management and policy. *Ecological Economics*. 35: 7-23.

United Nations (UN). n.d *United Nations Decade on Ecosystem Restoration 2021–2030.* www.decadeonrestoration.org/about-un-decade. (last accessed 3 April 2022).

United States Department of Agriculture (USDA). n.d. *Natural Resource Conservation Science*. www.nrcs.usda.gov. (last accessed 20 March 2022).

United States Geological Survey (USGS). n.d. https://www.usgs.gov/ (last accessed 18 March 2022).

University of Delaware Water Resources Center (UDWRC). n.d. Piedmont Basin watersheds: White Clay Creek. *Delaware Watersheds*. https://www.delawarewatersheds.org (last accessed 19 March 2022).

Verma, M and D. Negandhi. 2011. Valuing ecosystem services of wetlands – a tool for effective policy formulation and poverty alleviation. Hydrological Sciences Journal. 56(8): 1622-1639.

White Clay Creek Watershed Association (WCCWA). n.d. *White Clay Creek National Wild and Scenic River*. www.whiteclay.org. (last accessed 19 March 2022).

Young. J. 2018. *The 2018 Brandywine-Christiana state of the watershed report: an examination of a watershed that provides great value to Pennsylvania and Delaware.* Coalition for the Delaware River.