Prioritizing Land Conservation to Protect Water Quality in North Carolina's Triangle Region

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Executive Summary

The Triangle is a rapidly urbanizing region in the Piedmont of North Carolina. Excessive run-off of nitrogen, phosphorus, sediment, and other pollutants associated with urban development and poor agricultural practices increasingly threaten the region's water quality. The Triangle Land Conservancy (TLC), a local land trust, works in this region to safeguard the Triangle's surface water quality. TLC reduces threats to regions of high quality water by protecting lands along streams because it is broadly understood that protecting land from development is one of the most cost effective ways to preserve nearby areas of high-quality water.

The primary goal of this study is to help guide TLC in their strategic conservation planning through the development of a computer-driven site prioritization tool. The tool ranks areas of high water quality value in the Triangle using a GIS-based approach to Multi Criteria Decision Analysis. The tool specifically focuses on identifying areas of existing high water quality value in the Triangle region rather than identifying potential areas for high impact restoration projects. In developing the tool, the following criteria were used to assess locations based on their raw water quality value: 1.) various forms of land use and land cover; 2.) effectiveness of vegetated riparian buffers; 3.) amount of aquatic biodiversity; and 4.) adjacency to conserved lands.

The prioritization tool is intended to be user-friendly so that decision makers at TLC can conduct their own prioritization analyses in the future. In response to the reality of scarce funding opportunities available to local land trusts, the tool also permits user flexibility by allowing the user to manipulate the actual prioritization method. Versatility in the prioritization process is incorporated so that TLC can respond to different decision making contexts and funding opportunities while still being strategic in how they protect the Triangle's water resources.

The secondary goal of this study aims to integrate two key components of TLC's mission, which are to protect water quality and protect natural habitat, in order to synthesize opportunities for TLC to leverage greater conservation benefits through land protection. This component builds upon a prior assessment of natural habitat, which focused on prioritizing areas of high natural habitat value in the Triangle. In order to leverage two parts of TLC's work, this study identifies effective riparian buffers that connect important habitat patches of high conservation value.

Table of Contents

Introduction

The Triangle is a geographic region centrally located in the Piedmont of North Carolina and contains some of the most populous areas in the state. The Triangle is characterized by the individual cities and towns, including Durham, Chapel Hill, and Raleigh, which anchor its triangular presence on the map. The region is also home to three major universities, including Duke University, University of North Carolina at Chapel Hill, and North Carolina State University. The "Triangle" nickname was cemented in public consciousness in the 1950s with the creation of Research Triangle Park, which houses many high-tech startups and enterprises in pioneering industries, such as biotechnology, pharmaceuticals, and information technology. The network of cities and towns, cutting edge universities, and pioneering industries make the Triangle a vibrant hub of innovation and creativity.

An abundant supply of clean water is essential to the Triangle's prosperity. The Triangle relies on water from the Upper Neuse River Basin and the Upper Cape Fear River Basin for drinking water. Nearly half of the residents in the Triangle region (including Durham, Raleigh, Hillsborough, and Butner) depend on Falls Lake plus eight additional lakes, and ground water supplies for drinking water in the Upper Neuse River basin (Nicholas Institute for Environmental Policy Solutions). Most of the remainder of the Triangle's residents in the Cape Fear River Basin (including Cary, Apex, Morrisville, and Chatham County) depend on sources of drinking water from Jordan Lake (B. Everett Jordan Reservoir), Cane Creek, and various ground water supplies (Nicholas Institute for Environmental Policy Solutions). Jordan Lake and Falls Lake are the two largest and most critical sources of drinking water for the Triangle region.

Water quality in the region continues to decline and is reaching a critical state of concern for Triangle residents. Many of the Triangle's surface water bodies are listed as Category Five impaired under section 303(d) of the federal Clean Water Act. Under section 303(d) of the CWA, states are required to keep track of impaired water bodies. The CWA specifies that these waters listed as impaired are too polluted or otherwise degraded to meet water quality standards set by the states. In particular, the state of North Carolina has listed large portions of both Falls Lake and Jordan Lake as 303(d) impaired water bodies under the CWA. Since their impoundment in the 1980s by the US Army Corps of Engineers, Jordan Lake and Falls Lake have been consistently characterized as eutrophic or hyper eutrophic, referring to an over-abundance of nutrients in the waters (Tetra Tech, Inc, 2003a; Tetra Tech, Inc, 2003b). Nitrogen and phosphorous are the two most abundant and problematic nutrients responsible for the poor water quality problems and potential algal blooms in the lakes (Tetra Tech, Inc, 2003a; Tetra Tech, Inc, 2003b).

Both point and non-point sources of pollution contribute the region's water quality concerns. Wastewater discharge facilities in the Triangle are the primary point sources of pollution. Nutrients from non-point sources reach the region's water through a variety of mechanisms, including runoff from poor agricultural operations and storm water runoff related to urban development. Additional loads of sediment runoff and other pollutants add to the water quality concerns of the region.

In addition to the current pressures on the region's water quality, the Triangle is one the fastest growing areas in the country. The Triangle has reached nearly 2 million residents and is projected to grow rapidly to over 2.5 million by the year 2035 (Capital Area Friends of Transit; U.S. Census Bureau, 2014). As a result, the condition of water quality is expected to become even more vulnerable. The expected growth in population will significantly increase the demand for clean drinking water while also increasing the amount of wastewater discharge. The quantity of storm water runoff into the region's water bodies will rise as more natural areas are replaced by impervious surface to support the infrastructure of new growth.

It is broadly understood that protecting land from development near water bodies protects the quality of water. Many studies across the United States have shown that forest cover helps to maintain water quality. The findings of a study conducted by the Trust for Public Land, which summarized raw water quality data, forest cover data, and drinking water treatments costs for 60 water treatment plants across the country, found that increased forest cover was significantly related to increased water quality, while low water quality was related to higher treatment costs (Freeman, et al., 2008).   On the other hand, conversion of natural lands into developed areas within a watershed increases the contamination of drinking water and negatively affects its quality. The intensity of urban development is directly linked to the amount of impervious surfaces, like roads, parking lots, and rooftops. As watersheds experience increasing amounts of impervious surface they begin to experience a suite of events that degrade the water quality, starting with alterations in the hydrologic cycle, which affects how water is transported from the land to contributing streams and gives rise to detrimental physical and ecological impacts (Arnold & Gibbons, 1996).

The Triangle Land conservancy (TLC) is a local land trust in the region that works to protect water quality via land conservation. The organization's mission is to protect important open space in the Triangle region to keep the Piedmont of North Carolina a healthy and vibrant place to live and work (Triangle Land Conservancy). TLC advances their mission through the following key outcome areas: 1.) safeguarding clean water; 2.) protecting natural habitat; 3.) sustaining local farms and food in the community; and 4.) providing places for people to connect to nature. The Triangle Land Conservancy reduces threats to clean water by protecting lands along streams, practicing and encouraging land management that keeps soils and pollutants out of streams, and leading the development of more effective collaborative approaches to protecting water (Triangle Land Conservancy). By protecting land from development, TLC is instrumental in creating a buffer between developed land and key streams and waterways in the Triangle.

While there are some regulations in place to try and address the region's water quality issues, there is a need for more integrative and comprehensive approaches to protect the quality of water. To aid the Triangle Land Conservancy in their mission to safeguard clean water, this study aims to determine high priority lands to conserve for the protection of water quality in the Triangle region. In order to prioritize areas of high value to the region's water quality, this study pairs GIS-based techniques with multi-criteria decision analysis (MCDA). MCDA is beneficial to environmental decision making because it provides a systematic framework that takes into account multiple perspectives, attributes, and objectives (Maguire, 2014).

Objectives

The objectives for this study are partitioned into two sections. The first part of this study aims to prioritize locations within the Triangle region that have the highest water quality value through the development of a GIS interface tool. The second part of this study aims to identify opportunities to maximize conservation benefits to the Triangle by leveraging two of TLC's key outcome areas: safeguarding clean water and protecting natural habitat.

Part 1: GIS Interface Tool

The first objective is to develop a GIS-based tool that prioritizes areas of high water quality value using a particular framework of MCDA called Multi-Attribute Utility Theory. The study seeks to build the prioritization tool through completion of the following steps:

1. Identify the tool's fundamental objective.
2. Establish a hierarchy of ecological criteria and measurable indicators within each criterion to assess the water quality value of individual stream reaches in the Triangle region.
3. Develop relative rankings to prioritize catchments of stream reaches in terms of the indicators.
4. Apply weights to criteria and indicators to incorporate unique values of stakeholders in the decision making process.
5. Conduct a weighted linear approach to calculate water quality scores.

The GIS-based tool is intended to be user-friendly so that decision makers at TLC can conduct their own prioritization analyses. In response to the reality of scarce funding opportunities available to local land trusts, the tool also facilitates user flexibility by allowing decision makers at TLC to manipulate the actual prioritization method. Versatility is incorporated into the tool so that TLC can be responsive to different conservation opportunities, particularly ones that provide funding, while being strategic in how they protect the region's water resources.

Part 2: Leveraging Greater Conservation Benefits

The goal of the second part of this study is to synthesize opportunities for TLC to leverage greater conservation benefits through their land protection. The objective is to overlay the results of this study's water quality analysis with an additional prioritization scheme, which identifies areas of high natural habitat value. This part of the analysis aims to integrate two key components of TLC's mission, which are to protect water quality and to protect natural habitat.

Study Area

While there is often a lack of consensus regarding which North Carolina counties define the Triangle region, this study uses six counties in the Piedmont to delineate the Triangle, including Chatham, Durham, Johnston, Lee, Orange, and Wake Counties (Figure 1). Notably, these counties are the same six counties in which the Triangle Land Conservancy focuses their conservation efforts. Chatham and Lee counties lie solely within the Cape Fear River Basin, while portions of Orange, Durham, Wake, and Johnston counties are split by the Cape Fear and Neuse River Basin.   The region primarily draws its drinking water from two major multipurpose reservoirs: Falls Lake and Jordan Lake. Some of the major rivers and streams in this region are Little river, Eno River, Haw River, Rocky River, Neuse River, and Swift Creek.

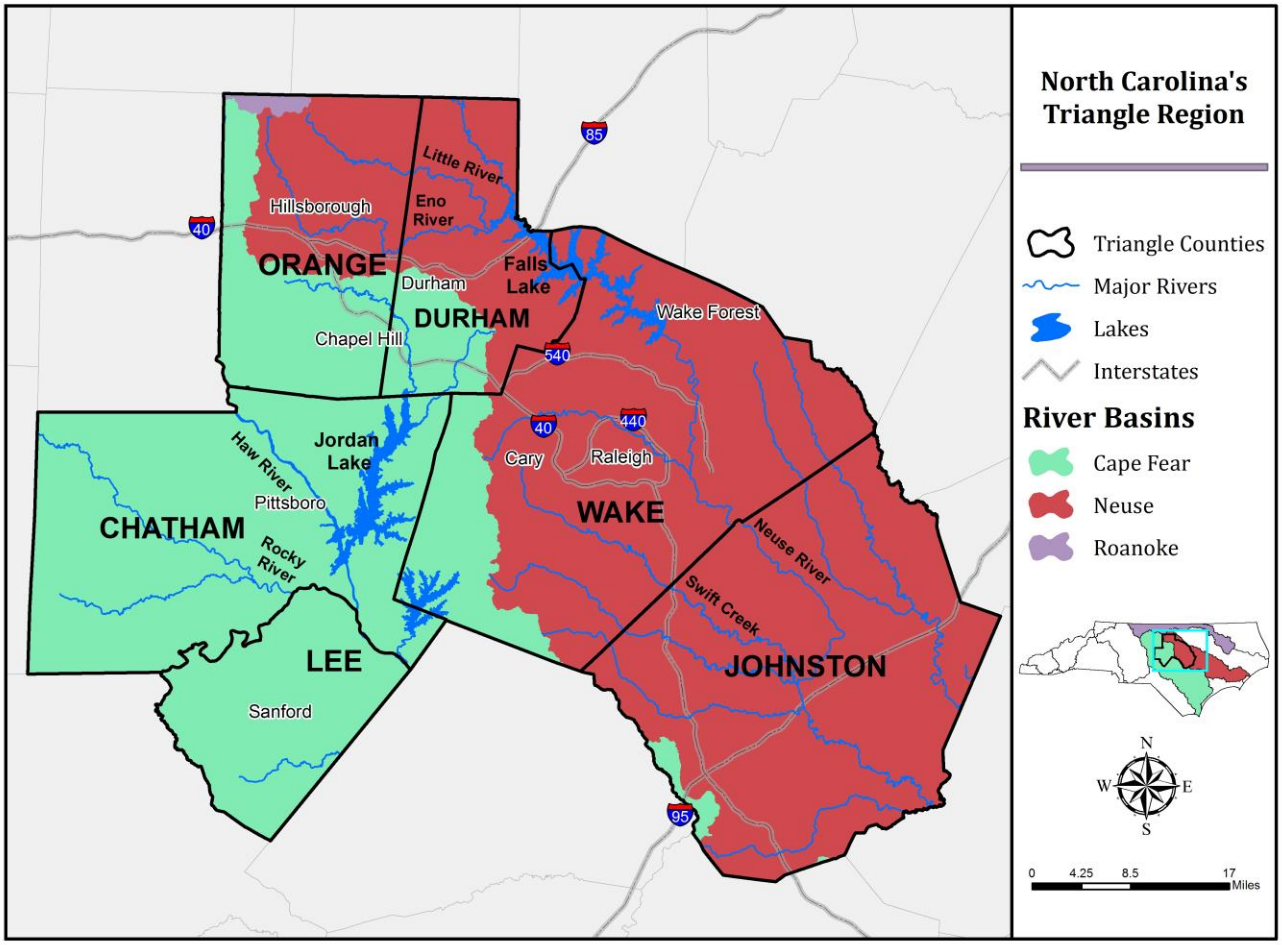

Figure 1. Study Area - Six counties delineating the Triangle region

The six counties that represent the Triangle region in this study consist of approximately 3,319 square miles. The landscape is characterized by a variety of land cover types and uses (Figure 2). Forested vegetation is the predominant land cover type. According to the 2011 National Land Cover Dataset, roughly 40% of the landscape is covered either by deciduous, evergreen, or mixed forests (Multi-Resolution Land Cover Consortium, 2011). The Triangle counties are also among the fastest urbanizing areas in the state of North Carolina. As the Triangle continues to rapidly grow and sprawl outwards, varying intensities of urban development continue to become an ever more distinguishing feature of the landscape. Some of the largest and most prominent municipalities in the region include, Raleigh, Durham, Cary, and Chapel Hill. Raleigh, which is the state's capital, is the biggest and fastest growing city in the region (Capital Area Friends of Transit). The US

Census Bureau estimates that the Raleigh-Durham-Chapel Hill Combined Statistical Area has a total population of 2,075,126 people (U.S. Census Bureau, 2014).

In addition to natural forested areas and varying intensities of urban development scattered across the landscape, agricultural practices are a third distinguishing characteristic of the landscape. Counties in the Triangle region are a large producer of tobacco, sweet potatoes, soybeans, and wheat (North Carolina Department of Agriculture & Consumer Services, 2013). Yet, the Triangle has experienced a shrinking farm economy in the past couple of decades as rates of urban development grow in the region (Hess, 2010).

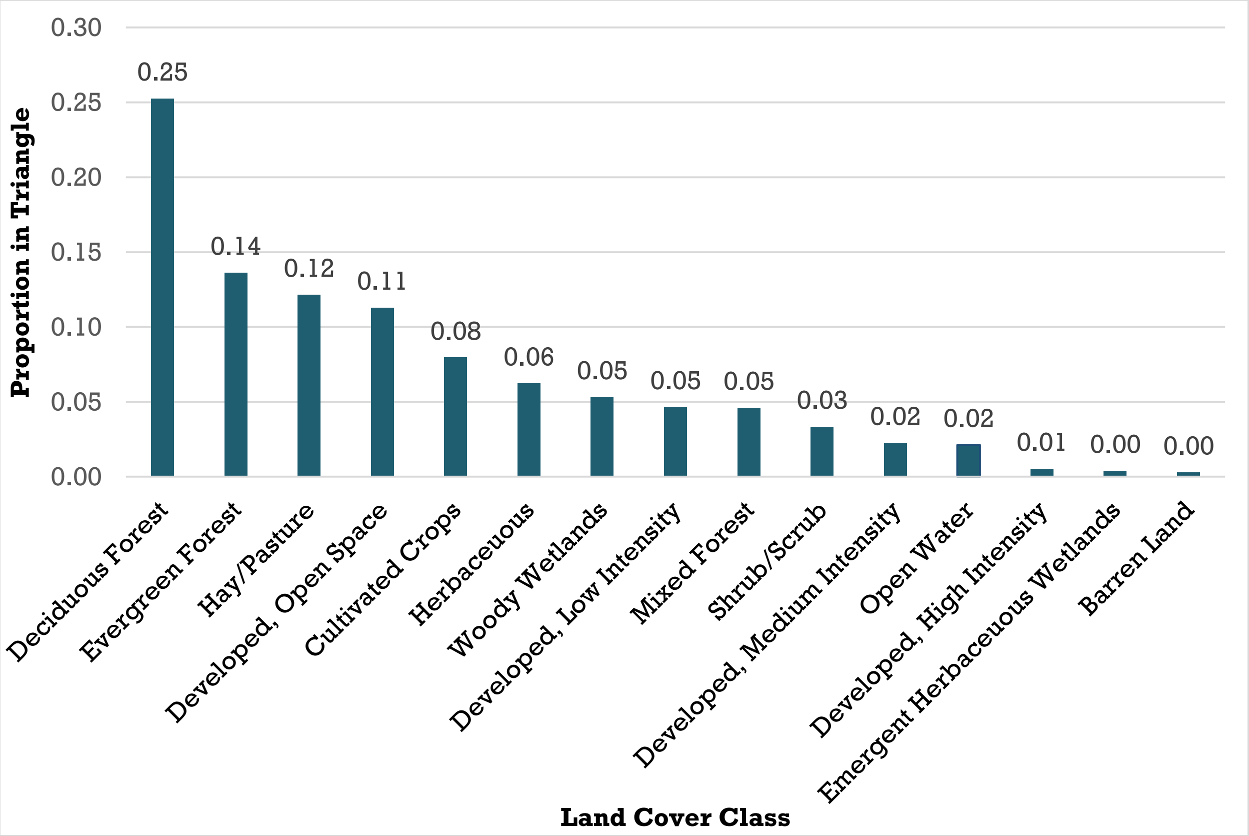

Figure 2. Distribution of Land Cover in the Triangle Region

Methods

Part 1: GIS Interface Tool

This study pairs a multi criteria evaluation framework with GIS-based techniques to prioritize regions of high water quality value in the Triangle region. Geospatial techniques are first used to transform spatial data related to the Triangle's water quality to help guide the decision making process. The spatial data is then paired with Multi Attribute Utility Theory (MAUT), which is a popular methodology in multi-attribute decision making for the environmental sciences (Huang, Keisler, & Linkov, 2011). In general, MAUT is a decision making framework that uses an objectives hierarchy to organize the prioritization (Dyer, 2006). Multi Attribute Utility Theory entails a formal method to address trade-offs among multiple objectives and consider relative satisfaction of individual preferences in the decision making process. Paired with geospatial techniques, MAUT has the capacity to guide land management planning by providing a logical, scientific foundation into which the values of decision makers are incorporated.

The development of the GIS tool that conducts the MAUT prioritization process includes the following steps: 1.) Identify a fundamental objective, 2.) Develop an objectives hierarchy through identification of criteria and measurable indicators, 3.) Develop utility functions; 4.) Apply weighting to indicators and criteria, 5.) Conduct weighted linear combination of indicators and criteria for a final water quality score.

1. Fundamental Objective

The study begins the prioritization process with the identification of a fundamental objective that is aimed to solve a problem. Fueled by significant concerns for the Triangle's water quality, the fundamental objective of this study is to prevent the deterioration of high value water bodies in the Triangle region. The prioritization tool aims to guide the strategic placement of land conservation to protect the Triangle's water quality. The study specifically focuses on identifying areas of existing high water quality value rather than identifying potential areas for high impact restoration projects. The prioritization tool also does not evaluate the capacity brought by the conservation of less pristine sites to protect high quality waters downstream.

2. Objectives Hierarchy

The next step in the prioritization process is to develop an objectives hierarchy with sub-objectives to assess how well the fundamental objective is being met (Figure 3). The first level of the hierarchy identifies the decision maker's main objective. The main objective is shown in the dark grey box at the top of the hierarchy in Figure 3.

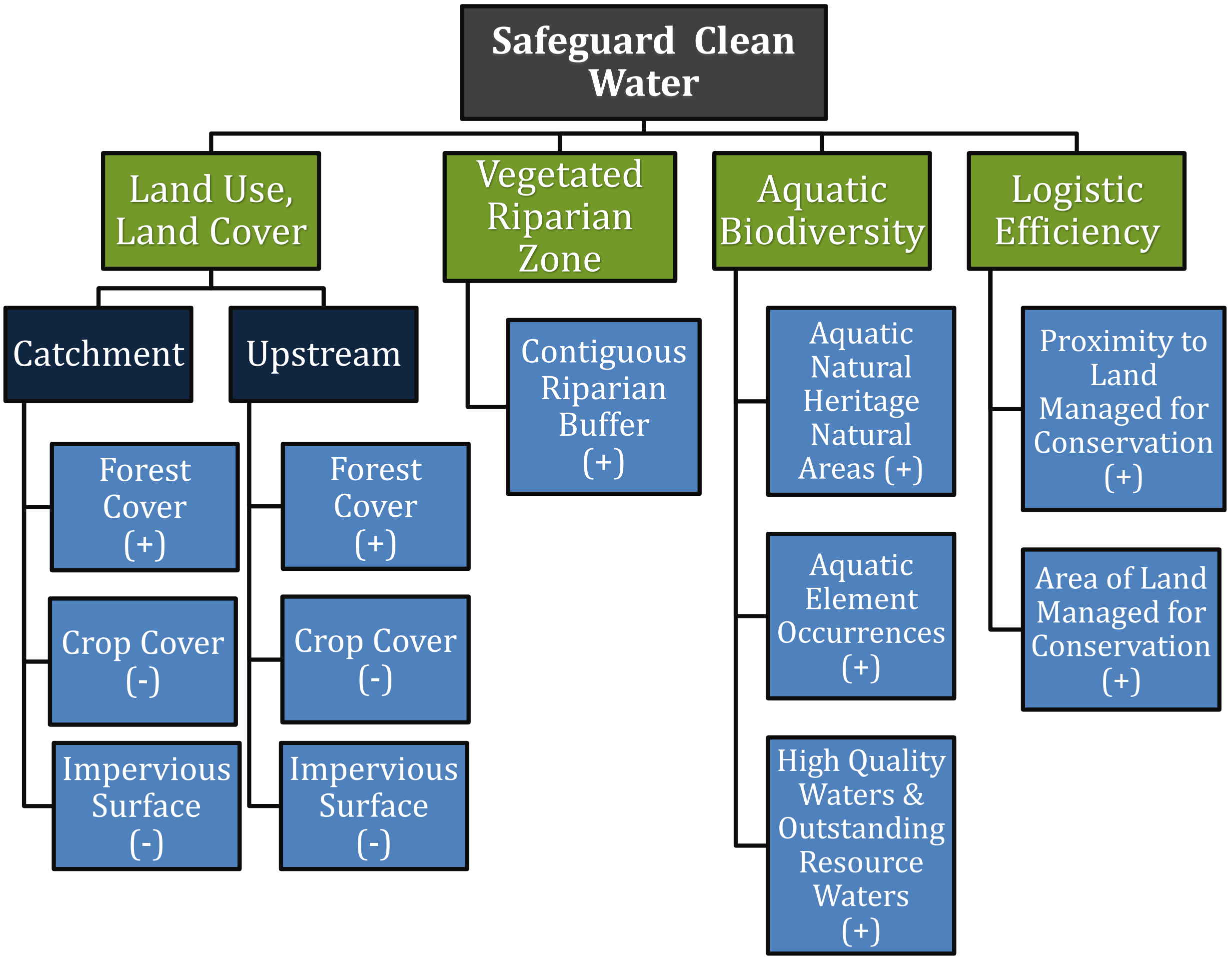

Figure 3. Graphic depicting framework of objectives hierarchy for criteria and indicators. Green boxes indicate ecological criteria and blue boxes display indicators used to assess each criterion. Positive and negative signs indicate whether the indicators contribute positively or negatively to the overall water quality score.

The next step in the prioritization process is to establish criteria that are used to assess how well the primary objective is being met. TLC staff was consulted to identify criteria to include in the analysis. The following criteria were identified: 1.) Land use and land cover; 2.) Vegetated riparian zones; 3.) Aquatic biodiversity; and 4.) Logistic Efficiency. Green boxes in Figure 3 display the water quality criteria selected by TLC staff.

Under each criterion, measurable indicators are identified to evaluate how well each criterion is being met. ArcGIS Desktop was the primary software used to quantify measurable indicators for the prioritization tool (ESRI, 2014). Figure 3 displays the indicators in blue boxes. The plus and minus signs in the blue boxes indicate whether the indicators positively or negatively affect water quality.

The GIS tool is developed to conduct the prioritization of high water quality value for all the catchments of stream reaches in the Triangle study area (Figure 4). Geospatial data for the catchments and the stream reaches was obtained from the National Hydrography Dataset Plus (U.S. EPA & U.S. Geological Survey, 2012). A stream reach is generally defined as a segment of a stream channel that has similar hydrologic features between tributaries (US Geological Survey, 2014). The catchment encompasses the land contributing to the stream segment and is truncated by the catchments of adjacent reaches both upstream and downstream of it. Notably, catchments do not serve the same functional purpose as watersheds because they do not cover the entire amount of land that will eventually contribute to a particular stream reach. The National Hydrologic Dataset delineates catchments for stream reaches across the United States and assigns each catchment a unique 14–digit code (McKay, et al., 2012). The 14-digit code contains two parts: the first 8 digits indicate the hydrologic unit code (HUC) for the sub-basin in which each stream reach exists, and the final 6 digits comprise a code assigned to each individual reach within the basin. The six-county study area includes a total of 6,827 catchments with an average area of 1.77 square kilometers. The prioritization tool is developed to give each catchment an aggregate water quality score based on weightings assigned to the combination of criteria and indicators.

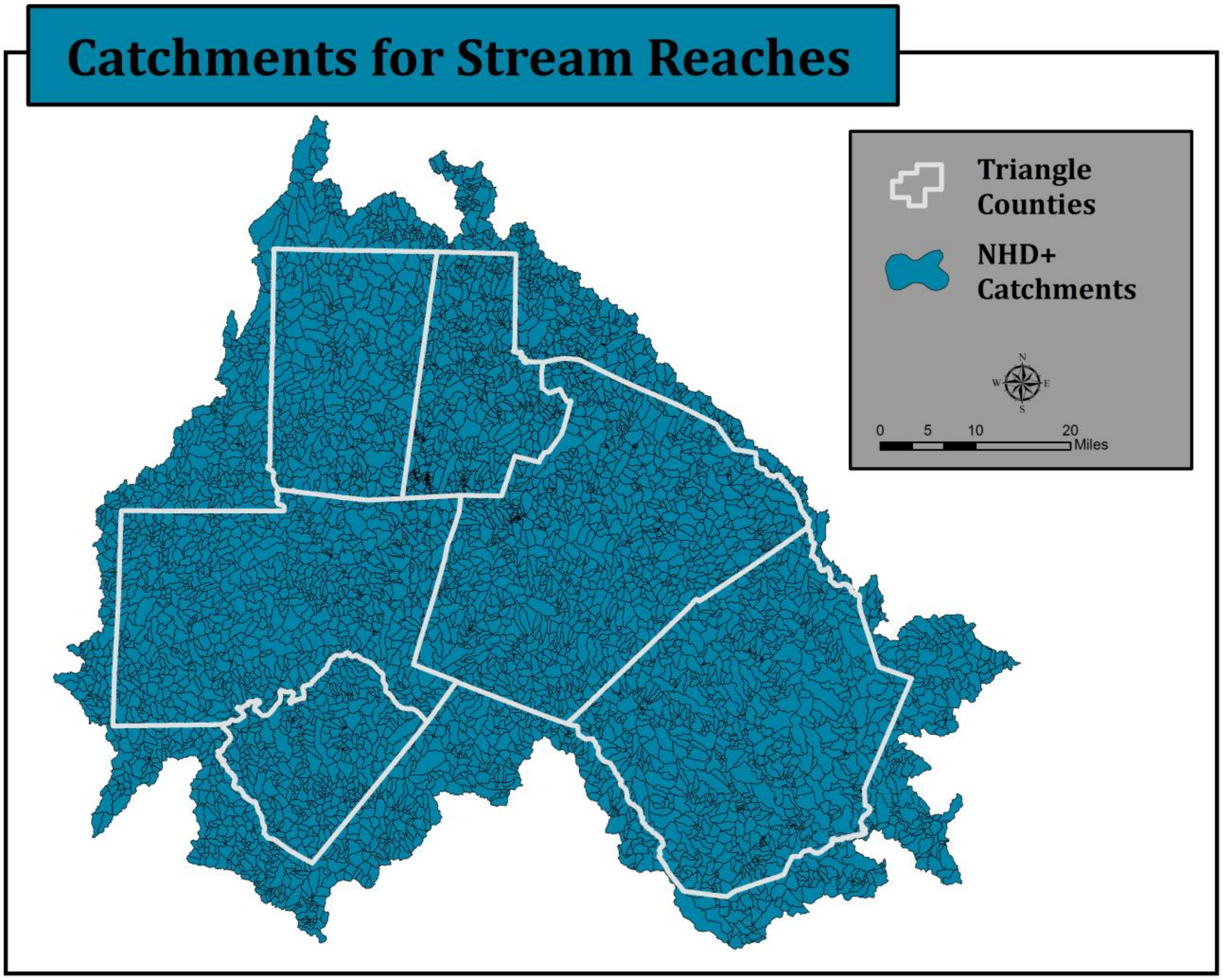

Figure 4. Image displays study's areal unit of analysis, which is the contributing area of land to each stream reach in the Triangle.

2a. Land Use and Land Cover

A land use and land cover criterion was selected for the objectives hierarchy because it provides useful information regarding three major forms of land cover in the Triangle region: 1.) forest cover; 2.) crop cover; and 3.) impervious surface.

Forest cover was chosen because it is an important factor in maintaining water quality. Forests provide natural areas that act as sponges to slow runoff and filter pollutants before it reaches surface water bodies. Perhaps the greatest benefit of forests is that they don't contribute pollution to nearby streams and rivers.

Conversely, the amount of impervious surface and crop cover, which is used as a proxy measurement for the region's agricultural practices, are known to degrade water quality. Many scientific studies have documented the pattern of ecological depredation along streams that drain urban landscapes. Increasing quantities of urban storm water runoff from impervious surfaces primarily drive the ecological changes that urban streams exhibit (Walsh, et al., 2005). Consistent symptoms of ecological deterioration in urban streams include flashier hydrographs, increased concentrations of nutrients and pollutants related to urban development, altered channel morphology and stability, and reduced biodiversity of aquatic organisms (Walsh, et al., 2005; Meyer, Paul, & Taulbee, 2005). Additionally, agricultural activities associated with land classified as crop cover is a major source of nitrogen and phosphorous to surface water bodies, such as rivers and lakes. Excessive inputs of nitrogen and phosphorous cause the eutrophication of streams, which leads to a variety of problems such as toxic algal blooms, loss of oxygen, fish kills, and loss of biodiversity (Carpenter, et al., 1998).

Six different indicators were quantified to assess land use and land cover in the prioritization process (Table 1). The geospatial data used to assess the land use and land cover criterion comes from the 2011 National Land Cover Database (NLCD) (Multi-Resolution Land Cover Consortium, 2011). The first three indicators quantify the percent of each stream reach catchment classified as forest cover, crop cover, and impervious surface. The second three indicators look upstream of each catchment to assess how much of the upstream land contributing to each catchment is classified as forest cover, crop cover, and impervious surface.

2b. Vegetated Riparian Zone

Riparian buffers are known to offer a variety of services that help maintain stream water quality. Notably riparian buffers intercept nutrients and sediment from non-point sources of pollution (Vought, Dahl, Pedersen, & Lacoursiere, 1994; Lowrance, et al., 1984). The roots and other woody debris adjacent to streams are known to slow the speed of incoming water and dampen flashy flows of water. The roots from herbaceous vegetation and trees on the banks of riparian zones also stabilize the stream bank from erosion by regulating the flow of sediment and prevent channelization of streams (Broadmeadow & Nisbet, 2004). In addition to erosion and pollution control, vegetated riparian zones also provide valuable habitat for riparian organisms as well as reducing water temperature by providing shade to streams (Sinokrot & Stefan, 1993).

The vegetated riparian zone is assessed using one indicator (Table 1). The indicator quantifies the proportion of contiguous riparian buffer within a fixed-width buffer of 300-feet on each side of the stream reach. A raster layer was created containing only contiguous forest and wetland cells that are linked all the way to stream channels. The 2011 NLCD is the primary resource for this indicator's geospatial data. This indicator calculates the proportion of contiguous riparian buffer within a fixed width buffer to reduce bias towards catchments that naturally have more riparian buffer because they are larger in size.

2c. Aquatic Biodiversity

Aquatic biodiversity was selected as one of the criteria under the objectives hierarchy to provide a proxy measurement for stream water quality. Water quality is known to be a regional driver of aquatic biodiversity. In particular, an over-abundance of nutrients related to runoff from agricultural practices and urban development, such as nitrogen and phosphorous, is known to threaten aquatic biodiversity (Carpenter, et al., 1998). The prioritization makes the assumption that high biodiversity is positively correlated with high water quality.

There are three indicators quantified using geospatial techniques to assess the aquatic biodiversity of stream reaches in the study area (Table 1). The first indicator assesses the proximity from each catchment to the nearest aquatic Natural Heritage Program's Natural Area (NHNA's - previously named Significant Natural Heritage Area). The North Carolina Natural Heritage Program compiles a list of NHNA's, which represent estimates of the state's best locations for supporting natural biodiversity (NC DENR Natural Heritage Program, 2015a).

The Natural Heritage Program also identifies aquatic element occurrences, which are point locations of rare plant and animal communities in aquatic environments (NC DENR Natural Heritage Program, 2015b). The second indicator under aquatic biodiversity calculates the total number of element occurrences within each catchment.

The third indicator under the criterion for aquatic biodiversity quantifies the distance from each catchment to the nearest waters classified as high quality or outstanding resource waters by the North Carolina Department of Natural Resources. High Quality Waters and Outstanding Resource Waters (HWQORW) are management zones that are classified based on excellent biological and physical characteristics in the state (NC DENR Division of Water Quality, 2007).

2d. Logistic Efficiency

Logistic efficiency refers to the benefit provided by the connectivity of lands managed for conservation. Lands managed for conservation provide greater connectivity of valuable habitat across the landscape, which increases the amount of functional habitat for wildlife. In addition to the ecological benefits, protected lands with greater connectivity are managed more efficiently.

Two indicators were used to quantify logistic efficiency for each catchment (Table 1). The first indicator quantifies the distance between each catchment and the nearest parcel of conserved land. The second indicator quantifies the percentage of each catchment managed for conservation. Geospatial data for these indicators were obtained from the Natural Heritage Program's GIS layer for lands managed for conservation.

Table 1. Summary of criteria and indicators in the objectives hierarchy

Ecological Criteria	Indicators	Raw Indicator Values	Data Source
Land Use and Land Cover (LULC)	1A. % Forest Cover	Area of Forest Cover / Area of Catchment	NLCD (2011)
	1B. % Crop Cover	Area of Crop Cover / Area of Catchment	NLCD (2011)
	1C. % Impervious Surface	Area of Impervious Surface Cover / Area of Catchment	NLCD (2011)
	1D. Upstream Forest Cover	Catchments are assigned a value equal to the cell in the catchment with the largest number of upstream forest cells flowing into it.	NLCD (2011)
	1E. Upstream Crop Cover	Catchments are assigned a value equal to the cell in the catchment with the largest number of upstream crop cells flowing into it.	NLCD (2011)
	1F. Upstream Impervious Surface	Catchments are assigned a value equal to the cell in the catchment with the largest number of upstream impervious cells flowing into it.	NLCD (2011)
Vegetated Riparian Zone	Contiguous Riparian Buffer	Area of contiguous riparian buffer within a 300ft fixed-width buffer / Area of 300ft buffer within catchment [Buffer restricted to NLCD forest and wetland cells]	NLCD (2011)
Aquatic Biodiversity	3A. Aquatic Element Occurrences (EO's)	Number of EO's found within the catchment	NC Natural Heritage Program (2015)
	3B. Natural Heritage Natural Areas (NHNA)	Distance to nearest aquatic NHNA	NC Natural Heritage Program (2015)
	3C. High Quality Water and Outstanding Resource Management Zones (HQWORW)	Distance to nearest HQWORW	NC Natural Heritage Program (2015)
Logistic Efficiency	4A. Distance to managed lands for conservation	Distance to nearest parcel of land managed for conservation	NC Natural Heritage Program (2015)
	4B. Area of managed lands for conservation	Total area of land managed for conservation within the catchment / Area of the catchment	NC Natural Heritage Program (2015)

3. Utility Function

At this point in the prioritization process, the raw geospatial data has been manipulated to quantitatively measure indicators under each criterion. Next, the following steps were taken to develop a utility function for each indicator, which is an essential ingredient to the MUAT formula that takes in account the decision maker's preferences. The utility function is a unit-less scale of measures that describes how relative satisfaction changes over the range of performance values encountered in a decision context and allows direct comparison of diverse measures (Maguire, 2014). One method to develop a utility function is to assume a linear relationship between relative satisfaction and performance level (Maguire, 2014). In order to develop a utility function with a linear relationship, this study standardizes and transforms indicators scores for each catchment so that their values range between 0 and 1.

First, the indicators were converted into a standardized unit of scale because they are measured in different units and are not directly comparable in their raw form. For example, one indicator under aquatic biodiversity measures the distance to the nearest NHNA, while some of the indicators are measured as percentages, such as percent crop cover. The range of observed values for each indicator was normalized to extend between values of zero and one in order to compare indicators with different units. The following equation was used to normalize indicator scores:

$Normalized(x_i) = (x_i - X_{min}) / (X_{max} - X_{min})$

Where:

x_i = *score for the original variable x in the* i^{th} *row*

X_{min} = *minimum value of indicator X*

X_{max} = *maximum value of indicator X*

Next, scores were transformed for each indicator so that they are all positively correlated with increasing water quality value. The scores of indicators that adversely affect water quality were inverted by subtracting each indicator score from one. Scores for the following seven indicators were inverted: 1.) percent crop cover; 2.) percent impervious surface; 3.) upstream crop cover; 4.) upstream impervious surface; 5.) distance to nearest NHNA; 6.) distance to nearest HQWORW management zone; and 7.) distance to nearest parcel managed for conservation. In Figure 3, these indicators are shown in blue boxes with negative signs.

4. Apply Weighting

In addition to the utility function, which expresses relative satisfaction with each alternative in the decision-making context, another important ingredient to MAUT is the expression of priority for each measure (Lyn Maguire). This study incorporates an evaluation of priority by applying a set of fractional weights, which add up to one, to both indicator measures and criteria measures. Within each criterion, a set of fractional weights that sum to one is applied to each indicator score. Additionally, a set of four fractional weights is applied to the four criteria.

5. Weighted Linear Combination for Final Score

The prioritization tool uses a weighted linear combination approach to calculate the final water quality score for each catchment in the study area. First, a weighted sum for indicators in each criterion is obtained by multiplying the indicator score by its respective indicator weight and summed together to produce a score for each criterion. Then each criterion score is multiplied by its corresponding weight and summed together to give a final water quality score to each catchment.

The GIS prioritization tool gives each catchment a water quality score on a scale between 0 and 1. Scores closer to one indicate a higher water quality value, while lower scores closer to zero indicate a lower water quality value.

GIS Prioritization Tool – Functionality and Workflow

The water quality prioritization tool automates the entire prioritization process and runs according to user preferences. The tool was scripted in Python programming language and then put together in ArcGIS's model builder function (Python Software Foundation). The tool enables user flexibility by allowing manual control over both optional and required parameters. For simplicity and ease of use, the user supplies all the required information in one step before running the prioritization tool.

When the user opens the tool, they must first select the input file with the catchment data and specify the name of an output file for the tool to produce. Next, the user has control over three optional parameters. The user can first choose to run the tool in an isolated river basin, either the Cape Fear or Neuse river basin. Second, the user has the option to run the tool in one of the six counties in the study area, including Orange, Durham, Chatham, Lee, Wake, and Johnston counties. Third, the user can run the prioritization tool on catchments that are greater than or equal to a specified area supplied by the user in units of hectares.

After selecting optional parameters, the user must provide input for the required parameters. The user is required to manually specify a combination of weights for indicators in each criterion and the combination of weights applied to the four criteria. The user can provide any combination of weights as long as their sum is equal to one. The tool defaults to an equal weighting scheme when the user opens the tool in the ArcGIS interface. Both the optional and required parameters incorporate versatility into the prioritization process so that TLC can be responsive to different funding opportunities and decision contexts while being strategic in how they protect water resources in the Triangle.

Each time the tool is run, it calculates summary statistics to synthesize the results of each unique prioritization. The tool calculates the average catchment score within a larger watershed boundary, which is defined by a unique 12-digit hydrologic unit code (HUC). The United States Geological Survey identifies 12-digit HUCs as "subwatersheds" and has delineated them to cover 10,000 to 40,000 acres of land (U.S. Geological Survey, U.S. Department of Agriculture, & National Resources Conservation Service, 2009). For each subwatershed, the mean, minimum, maximum, and standard deviation of the catchment water quality scores is calculated and written to a table to aid the user in the decision making process. This step is beneficial because staff at TLC are familiar with the streams associated with the 12-digit subwatershed and can sort subwatersheds based on their average catchment score.

Since the tool is created to respond to various funding opportunities, there is not one optimum way to run the tool. In fact, the context of the decision-making opportunity will guide the parameters used to run the tool. As a result, this study presents nine alternative prioritization scenarios to demonstrate the tool's flexibility. Table 2 summarizes the extent and the weighting schemes for the criteria in the nine different prioritization scenarios.

Table 2. Summary of the nine prioritization schemes. Note that indicators are weighted equally but their weights are not shown in the table.

Scenario Number	Scenario Name	Extent	Land Use/ Land Cover Weight	Vegetated Riparian zone Weight	Aquatic Biodiversity Weight	Logistic Efficiency Weight
1	Pure LULC	Study Area	100%	0%	0%	0%
2	Pure Vegetated Riparian Zone	Study Area	0%	100%	0%	0%
3	Pure Aquatic Biodiversity	Study Area	0%	0%	100%	0%
4	Pure Logistic Efficiency	Study Area	0%	0%	0%	100%
5	Equal Weighting	Study Area	25%	25%	25%	25%
6	TLC Weighting	Study Area	35%	25%	25%	15%
7	Neuse	Neuse River Basin	35%	25%	25%	15%
8	Durham	Durham County	35%	25%	25%	15%
9	Wake	Wake County	35%	25%	25%	15%

Part 2: Leveraging Greater Conservation Benefits

This study's second component builds upon an assessment of natural habitat conducted by Alex Chuman, a 2014 Nicholas School Alumni, which focused on prioritizing natural habitat in the Triangle. The goal of this analysis is to synthesize potential opportunities that would maximize conservation benefits to the Triangle region by leveraging two of TLC's key outcome areas: 1.) safeguarding clean water and 2.) protecting natural habitats.

Chuman completed a series of assessments to prioritize the North Carolina Natural Heritage Program's Natural Areas (NHNA's) as habitat patches in terms of their conservation value. A total of 201 NHNAs in the six counties of the Triangle were included in the analysis. NHNA's that are labeled as "Aquatic Habitat" were excluded from the analysis. A combination of ArcMap modeling and the Geospatial Habitat Assessment tool (GeoHAT) developed by John Fay and Dean Urban at Duke University was used to determine the conservation value of the study area's non-aquatic NHNAs. The criteria used by Chuman to prioritize NHNA's based on their conservation value were 1.) threat to development; 2.) patch geometry; 3.) efficiency (adjacency to conserved land); 4.) biodiversity; and 5.) connectivity. Table 3 provides a summary of each criterion used to determine the conservation value of NHNA's.

Table 3. Description of the five criteria used by Chuman to determine conservation value of the 201 non-aquatic NHNA's.

Criteria for Conservation Value	Description
Threat to Development	NHNAs that are closest to development or highly developed areas are the most threatened and receive the highest score.
Patch Geometry	Patches that have more core area and core area relative to the patch edge rank the highest.
Efficiency	NHNAs that are close to large areas of already managed or protected lands are given the highest score.
Biodiversity/Heterogeneity	NHNAs that have the highest number of habitats and the highest number of plant element occurrences are given the highest score.
Connectivity	Areas that are connected with other NHNAs or connect sub networks of patches receive the highest score relative to isolated patches.

In order to leverage two parts of TLC's work, this part of the study aimed to identify riparian zones that connect NHNAs of high conservation value. More specifically, least cost paths were generated to connect riparian zones with NHNAs. The "Cost Path" tool in ArcGIS generates a least cost path by identifying the most cost effective route between a source and a destination location. The tool identifies the path between the start and end points with the smallest accumulated cost compared to all the potential routes between the two points. Cost is defined in the tool using a cost surface that defines the impedance to move through each cell of the surface. In this analysis, cost is defined as a function of the continuous riparian corridor (Table 4, Figure 5). Raster cells identified as contiguous riparian vegetation were given the lowest cost equal to one. All other types of woody vegetation (deciduous forest, evergreen forest, mixed forest, and woody wetland) were given the next lowest cost of impedance equal to 50. All other types of land use/cover classifications, including varying intensities of urban development, barren land, shrub, herbaceous vegetation, hay, and cultivated crops were given the highest cost of impedance equal to 200. Then a least cost path was generated between all the possible pairs of the total 201 NHNAs.

Table 4. Values of cost used in calculating the least cost paths between NHNA's. Land cover data from the 2011 NLCD is reclassified using these cost values.

Land Use & Land Cover	Cost
Contiguous Riparian Vegetation	**1**
Non Riparian Vegetation	**50**
Non Vegetation	**200**

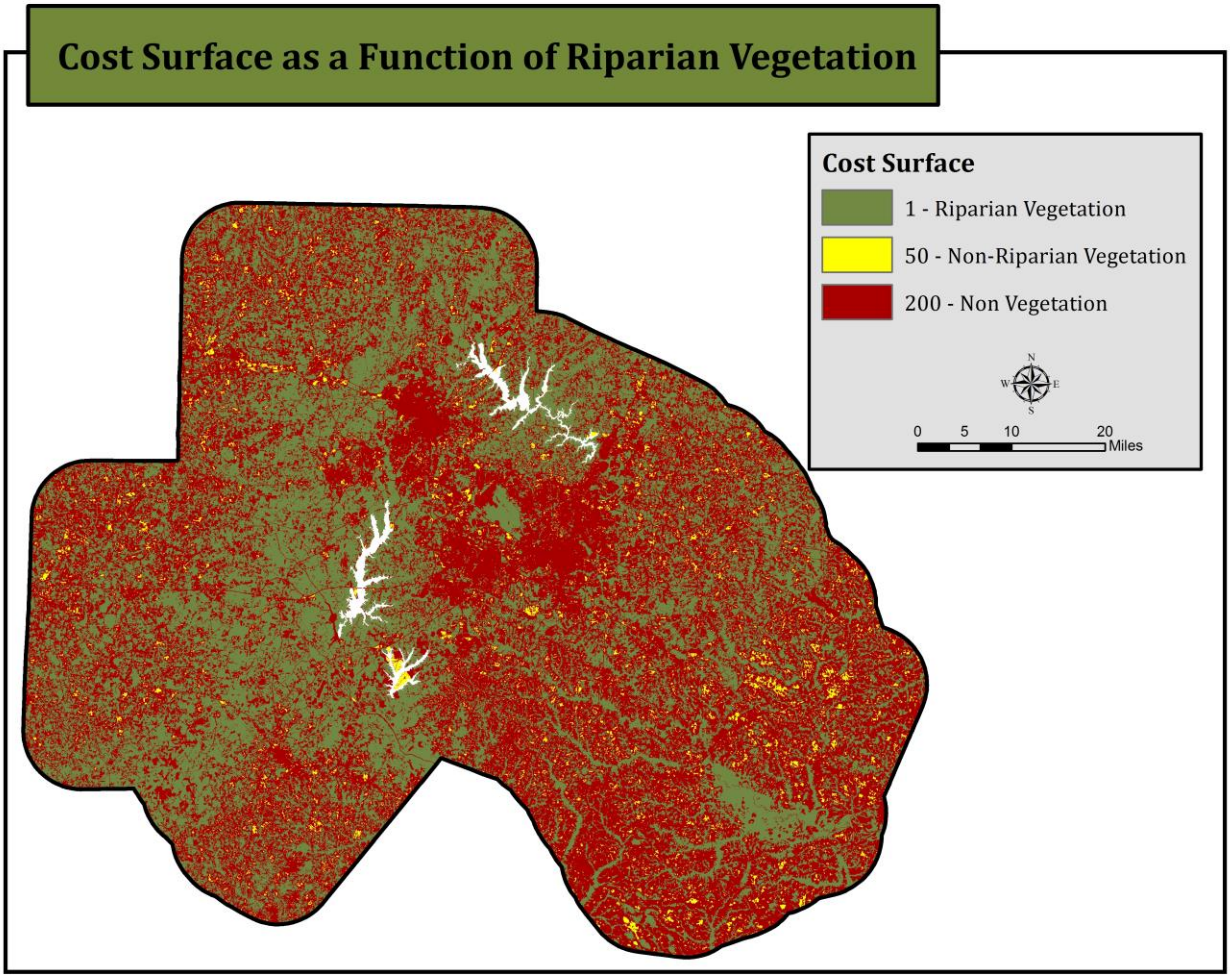

Figure 5. Cost surface created for the Triangle study area

To summarize the results of this analysis, the total number of least cost paths that overlap with each 12-digit HUC was quantified. The results of the natural habitat prioritization assessment and the riparian least cost paths were overlaid to identify potential opportunities for TLC to leverage their conservation work in two of their key outcome areas.

Results

Part 1: Products of GIS Prioritization Tool

The prioritization tool ran successfully for each of the nine different scenarios (Table 2). The first six scenarios use different combinations of criteria weights in the whole study area. A total of 6,827 catchments were scored in each of the first six runs of the tool. The next three prioritization scenarios use the weighting scenario suggested by TLC staff but are processed in clipped regions of the study area using the tool's optional parameters.

The following maps use equal interval breaks to classify water quality scores. Increasing water quality scores are also symbolized using colors that stretch between hues of yellow to hues of green then blue.

Scenario 1

Under scenario 1, the criterion for land use and land cover was weighted 100% in the GIS prioritization tool and no other criteria contributed weight to the prioritization process (Figure 6). This prioritization scheme values catchments that have low amounts of impervious surface and crop cover but have high levels of forest cover. The water quality scores quantified for each catchment range between 0.37 and 0.86. One trend highlighted in this scenario is that Chatham County contains some of the highest scoring stream reach catchments. In fact the majority of the HUCs with the average catchment score in the 90th percentile are located in Chatham County. Another visible trend is that catchments in the lower portion of Johnston County have lower water quality scores, most likely due to the high amounts of crop cover related to the agricultural practices in the county.

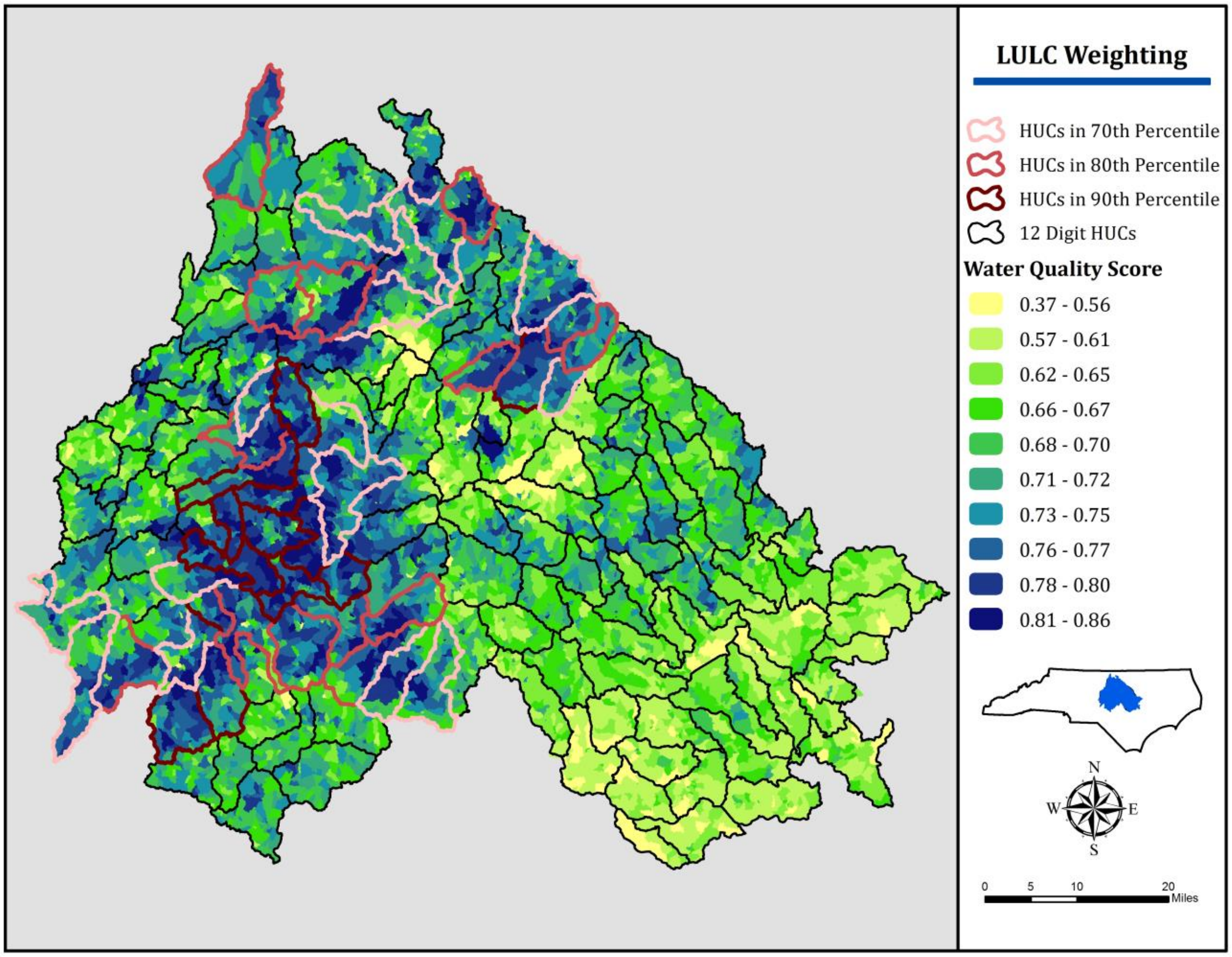

Figure 6. Scenario 1 – 100% of criteria weight going to the Land Use/Land Cover Criterion.

Scenario 2

Under the second scenario, the prioritization process was weighted purely on the vegetated riparian zone (Figure 7). This prioritization scheme aims to rank catchments based on the capacity of their riparian zones to slow down and filter pollutants before reaching the water. Catchments that have a high percentage of the 300 foot buffer on each side of the stream segment covered by woody vegetation were given high water quality scores. The water quality scores cover the full range of values, between 0 and 1. Compared to scenario 1, subwatersheds in the upper 90th percentile for the highest average catchment score are more scattered throughout the study area.

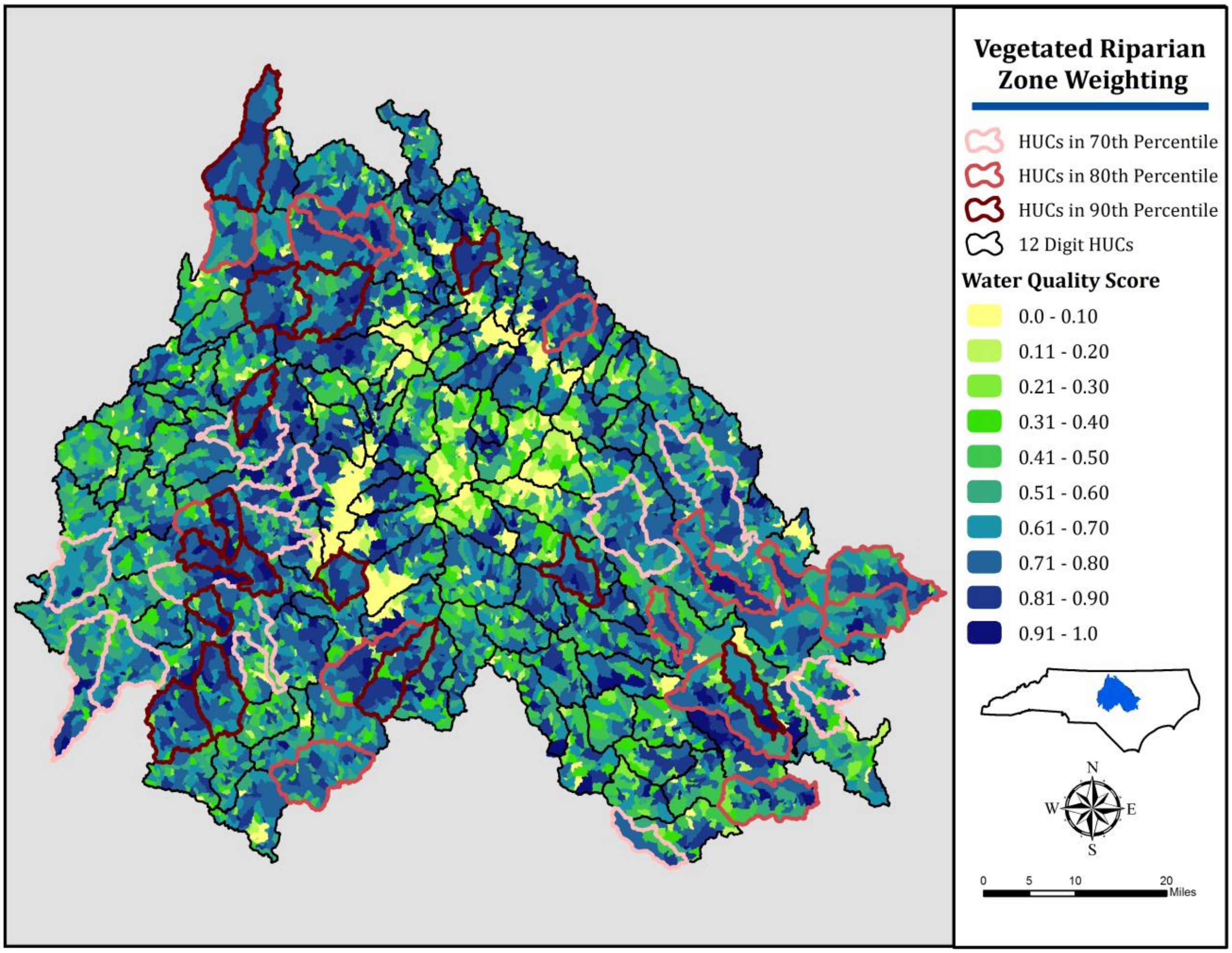

Figure 7. Scenario 2 – 100% of criteria weight going to the vegetated riparian zone criterion

Scenario 3

One hundred percent of the criterion weight goes to aquatic biodiversity in the tool's third prioritization scheme (Figure 8). Each of the three indicators under this criterion contribute one third of the weight applied to indicators. This prioritization scheme values catchments that have high levels of aquatic biodiversity measured in terms of the frequency of rare aquatic plant and animal communities and proximity to high quality waters, outstanding resource waters, and aquatic Natural Heritage Natural Areas. Under this scenario, the catchment scores range between 0.17 and 0.93. The highest density of subwatersheds in the upper 90th percentile appears to be concentrated in Orange County and the northwest portion of Durham County.

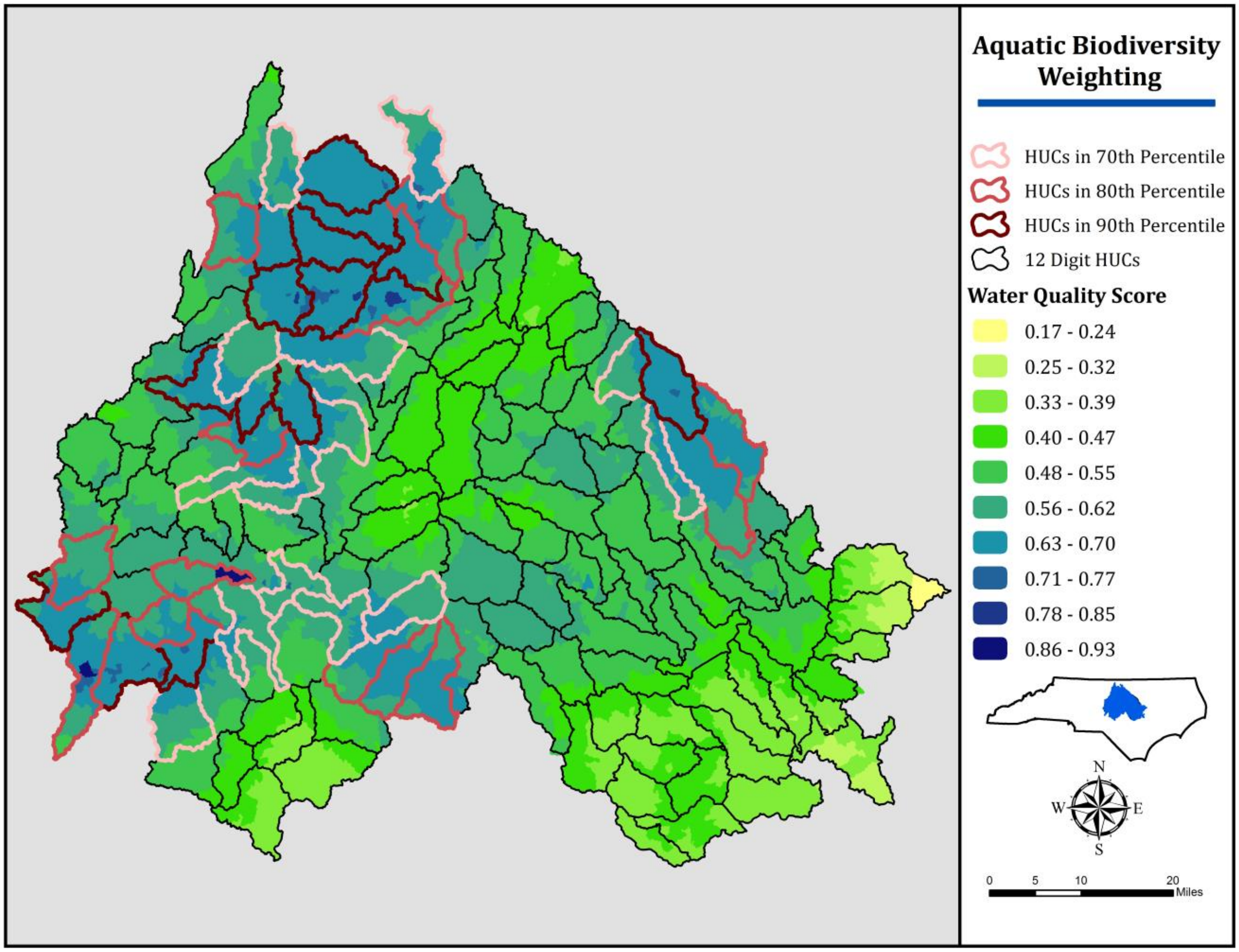

Figure 8. Scenario 3 – 100% of criteria weight going to the aquatic biodiversity criterion

Scenario 4

One hundred percent of the criterion weight goes to logistic efficiency in the tool's fourth prioritization process (Figure 9). Each of the two indicators under logistic efficiency is given 50% of the weight allocated to the indicators. This scenario values catchments that have high acreage of conserved lands and are located in close proximity to conserved lands. The water quality scores quantified for each catchment cover the full range of values between 0 and 1. The highest density of subwatersheds in the upper 90th percentile are concentrated around Falls Lake and Jordan Lake, primarily in Chatham, Durham, and Wake counties.

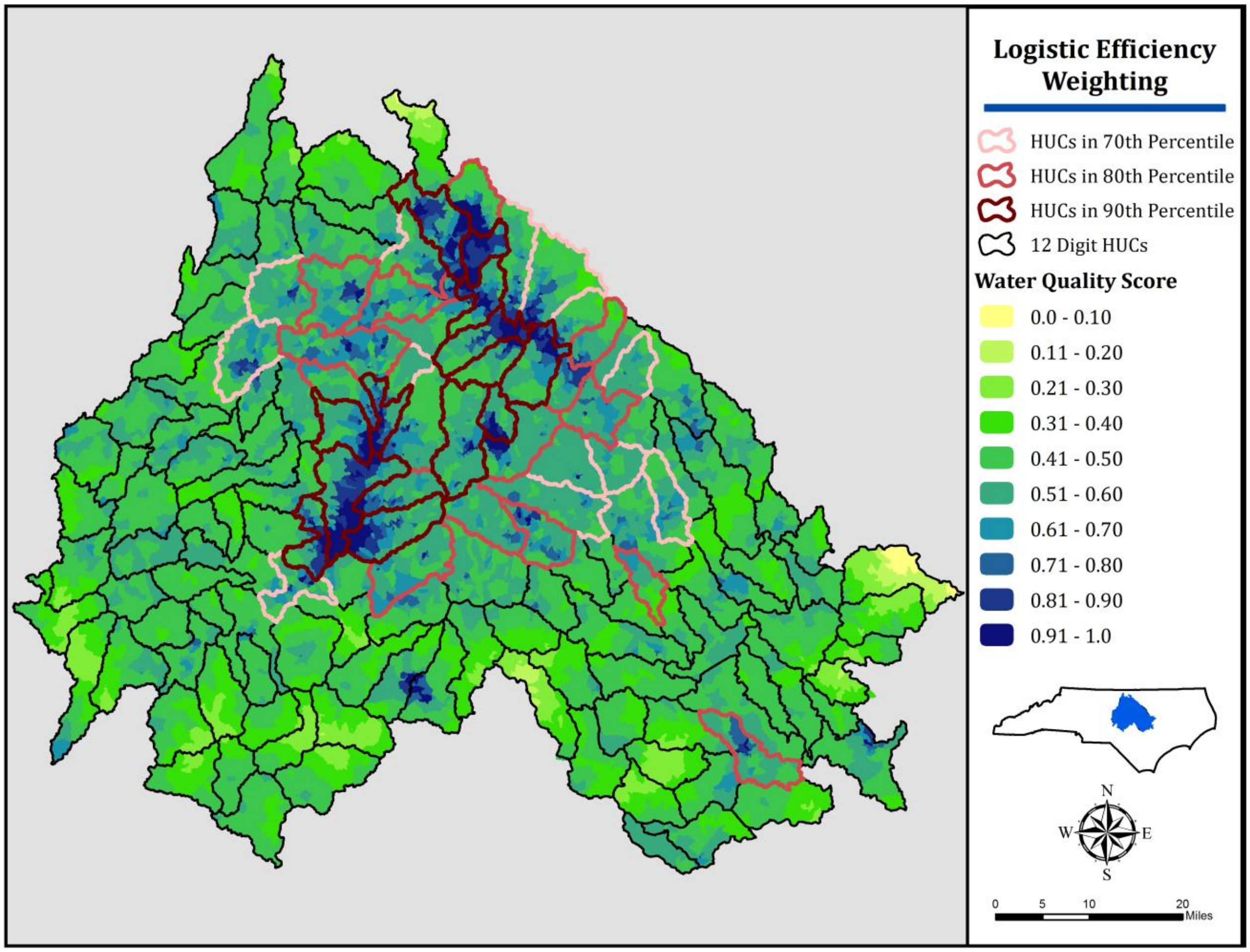

Figure 9. Scenario 4 – 100% of criteria weight going to logistic efficiency criterion

Scenario 5

Under the fifth prioritization scheme, each criterion is given an equal 25% of the weight (Figure 10). Indicators are also weighted equally within each criterion. Thus this scenario values land use & cover, vegetated riparian zones, aquatic biodiversity, and logistic efficiency equally. The range of water quality scores includes values between 0.28 and 0.88. Chatham, Durham, Orange, and Lee counties have high densities of highly ranked catchments. Land around Falls Lake and Jordan Lake are highly ranked. In fact, catchments draining into Lower Knap of Reeds Creek along Upper Falls Lake and streams along Eno River, including Stony Creek and Sevenmile Creek, have the highest average catchment scores.

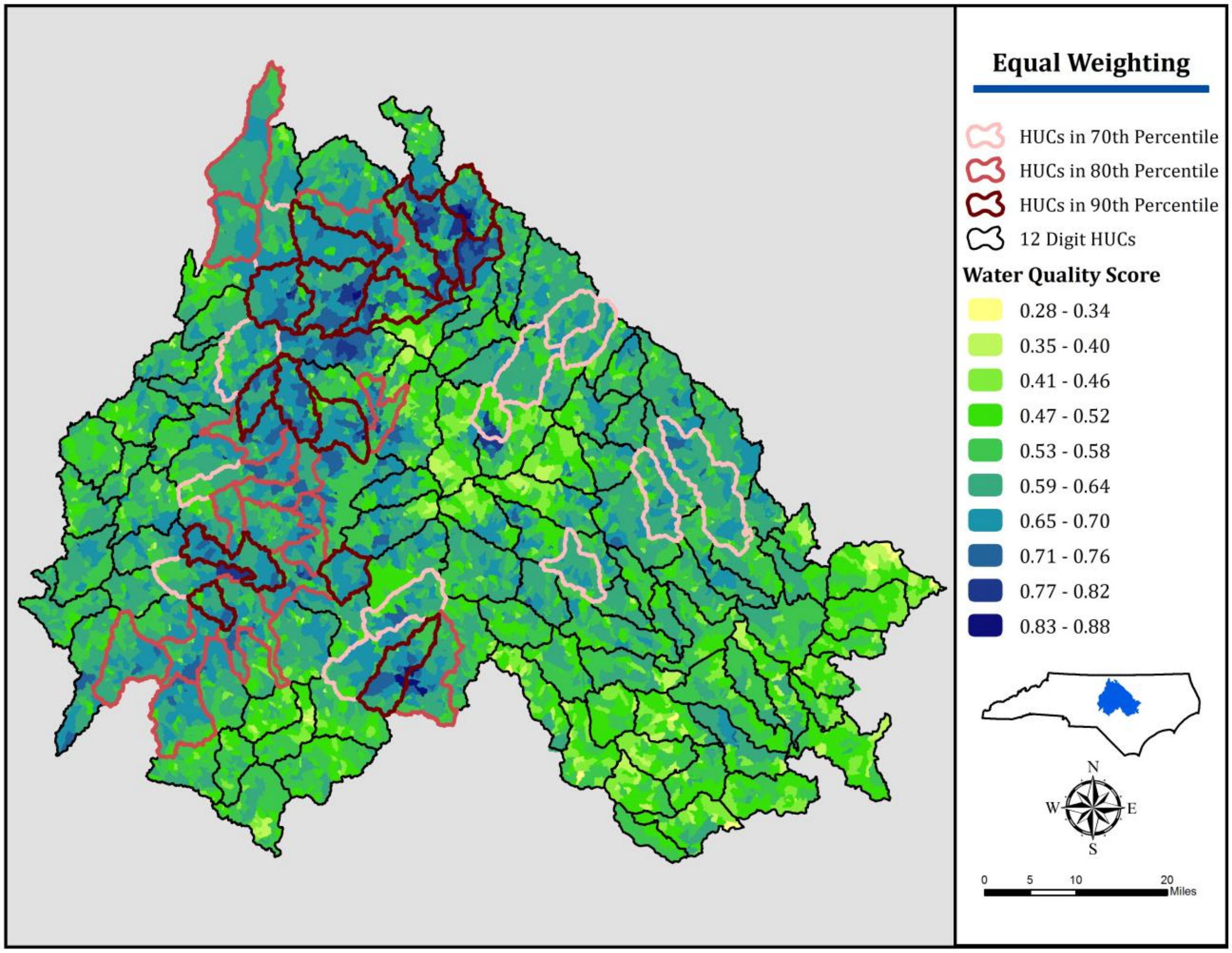

Figure 10. Scenario 5 - Criteria weighted equally.

Scenario 6

The final prioritization scheme in the full study area uses a combination of weights suggested by staff at the Triangle Land Conservancy (Figure 11). Land use and land cover is given the highest weight (35%), aquatic biodiversity and the vegetated riparian zone are weighted equally at 25%, and logistic efficiency is given the lowest weight (15%). The results of this prioritization scheme are very similar to the equal weighting scheme used in scenario 5. Here the catchment scores range between 0.33 and 0.87. Again, Chatham, Durham, and Lee counties have the highest concentration of highly ranked catchments averaged across subwatersheds. Lower Knap of Reeds Creek, Sevenmile Creek, Stony Creek, and Rocky River, and Collins Creek have some of the highest average catchment scores based on the prioritization process using TLC's combination of weights.

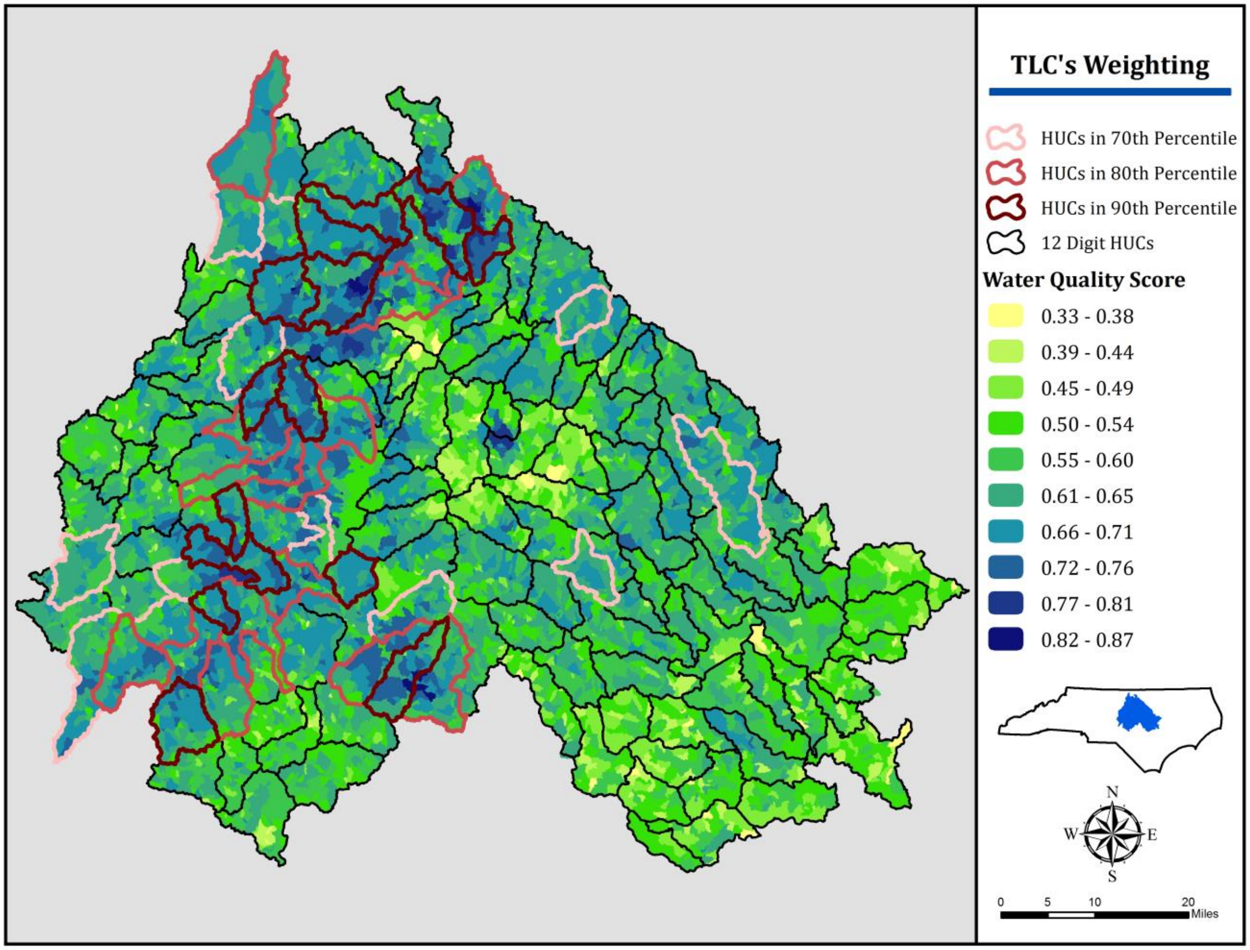

Figure 11. Scenario 6 – TLC suggested weighting

As stated previously in the methods section, the tool writes a table to the user's workspace that quantifies summary statistics for the catchment scores within a larger catchment boundary, which is uniquely identified by a 12-digit hydrologic unit code. An example of this table is shown below and clipped to ten rows showing the ten subwatersheds with the highest average water quality catchment score. This table was produced using the weighting scheme suggested by TLC for the entire study region (Table 5).

Table 5. Example table of summary statistics produced by the GIS prioritization tool. Table is clipped to top ten rows and is sorted in the order of descending mean final catchment scores in the 12-digit HUCs.

HUC 12 Name	Number of Catchments	Mean Final Score	Standard Deviation of Final Score	Minimum Final Score	Maximum Final Score
Lower Knap of Reeds Creek	19	0.71	0.07	0.53	0.78
Sevenmile Creek-Eno River	46	0.69	0.06	0.51	0.85
Rocky River	32	0.69	0.03	0.63	0.75
Stony Creek-Eno River	43	0.69	0.08	0.44	0.87
Collins Creek	19	0.67	0.07	0.49	0.75
Avents Creek-Cape Fear River	31	0.67	0.08	0.44	0.82
Shaddox Creek-Haw River	18	0.66	0.04	0.55	0.72
Cedar Creek	21	0.66	0.06	0.51	0.74
South Fork Little River	34	0.66	0.08	0.46	0.76
University Lake	50	0.66	0.08	0.47	0.78

Scenario 7 - Neuse River Basin

Using TLC's suggested weighting scheme, the prioritization tool was run in the intersection of the Neuse river basin and the study area (Figure 12). The water quality scores range between 0.31 and 0.90. Notably high water quality values tend to concentrate in the upper portion of the Neuse river basin.

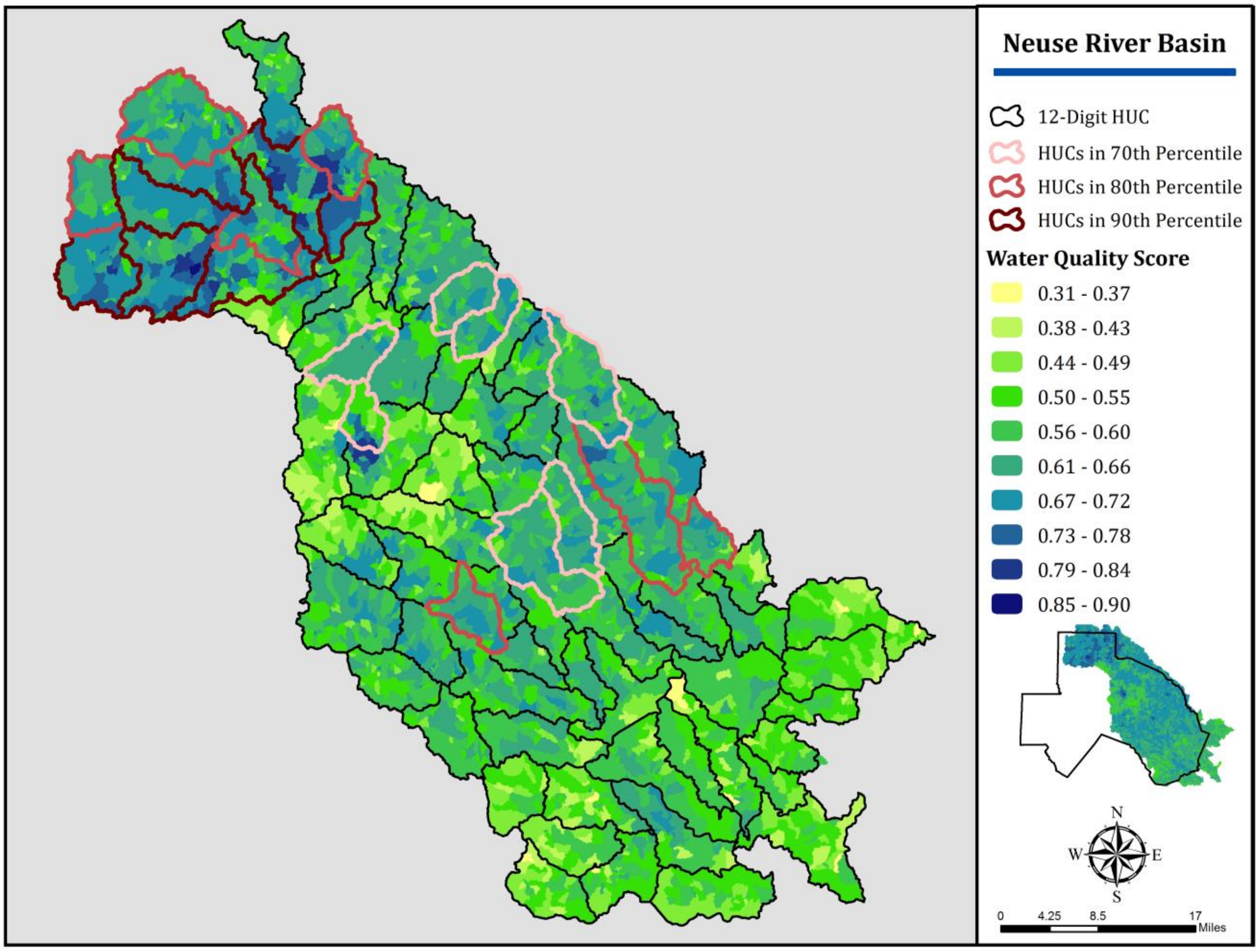

Figure 12. Scenario 7 – Water quality prioritization using the criteria weighting scheme suggested by TLC and the study area is clipped to Neuse River Basin.

Scenario 8 and 9 - Durham & Wake Counties

The prioritization tool was also run for both Durham and Wake counties using TLC's suggested weighting scheme (Figure 13). The highest scoring catchments in Durham are located near its northern border, where the county is less developed. In Wake County, the subwatersheds with a high average catchment score are located at the county's northern and southern perimeter. This is likely because Apex, Cary, and Raleigh are centrally located in the county and the impacts related to urbanization reduce the value of these catchments' water quality scores.

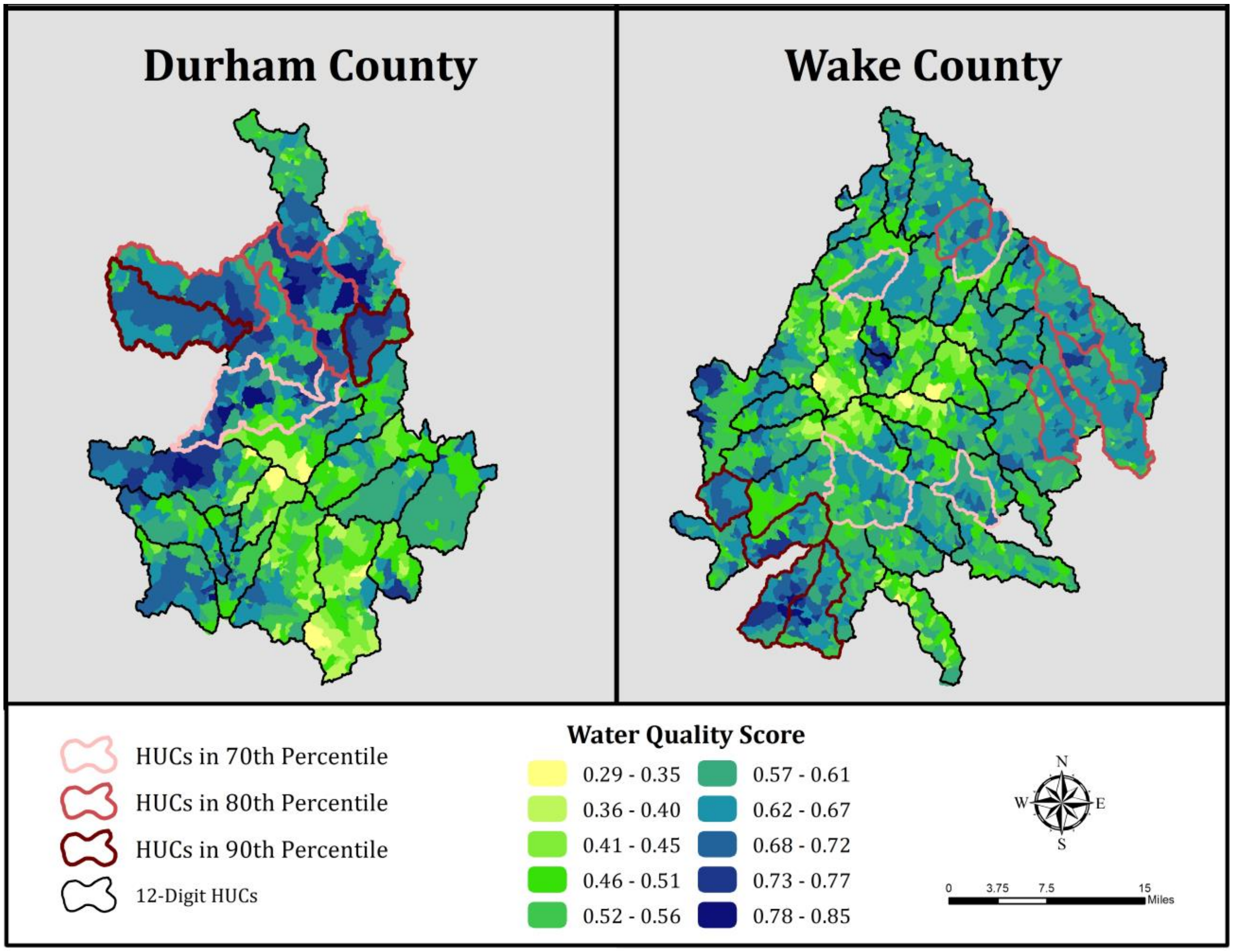

Figure 13. Scenario 8 & 9 – TLC suggested weighting and study area clipped to Durham and Wake County.

Part 2: Least Cost Path Analysis

In ArcGIS, 201,000 least cost paths (LCPs) were generated between habitat patches categorized as NHNAs (Figure 14). Using the cost surface, the corridors between NHNAs are forced to follow contiguous riparian zones of woody vegetation. Notably, the riparian corridors tend to skirt the perimeters of the major municipalities in the study area, including Durham, Chapel Hill, Raleigh, Cary, Apex, Sanford, and Butner.

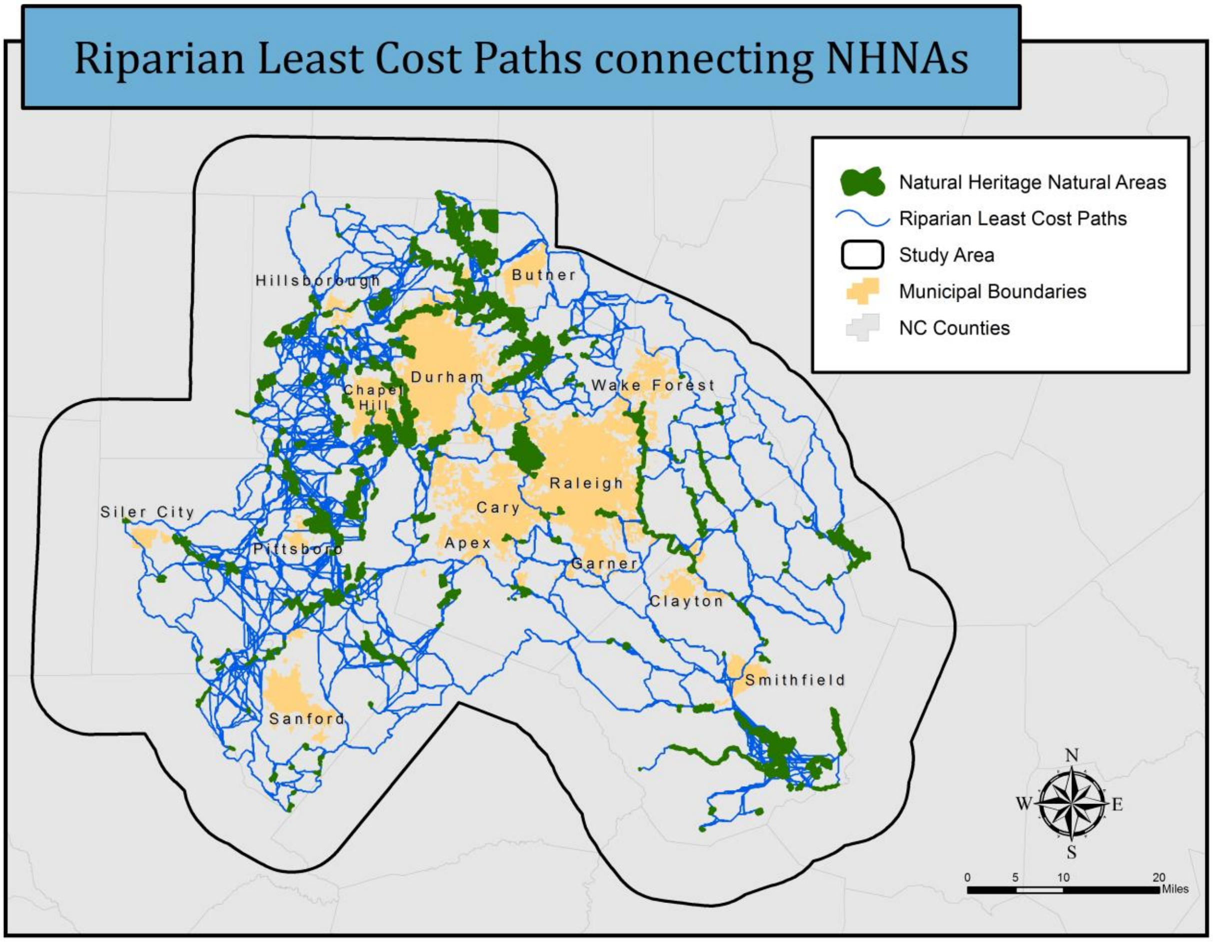

Figure 14. Riparian least cost paths connecting important natural habitat patches called Natural Heritage Natural Areas.

In the following map, subwatersheds (12-digit HUCs) are classified by the number of LCPs intersecting with their boundary (Figure 15). Darker shades of blue indicate that a greater number of LCPs intersect the subwatershed. NHNAs that are privately owned and not managed for conservation are overlaid on top of the subwatersheds that are classified by the frequency of intersecting LCPs. NHNAs are color coded according to their conservation value, which was assessed through the prioritization analysis by Alex Chuman. NHNAs symbolized using red or brown dots are ranked higher according to their habitat conservation value. Notably, subwatersheds that have a higher frequency of intersecting LCPs also tend to contain NHNAs that have high habitat conservation value. Since this map only shows NHNAs that are privately owned and not managed for purposes of conservation, these sites represent opportunities for Triangle Land Conservancy to leverage their mission to protect water quality and habitat in the Triangle region.

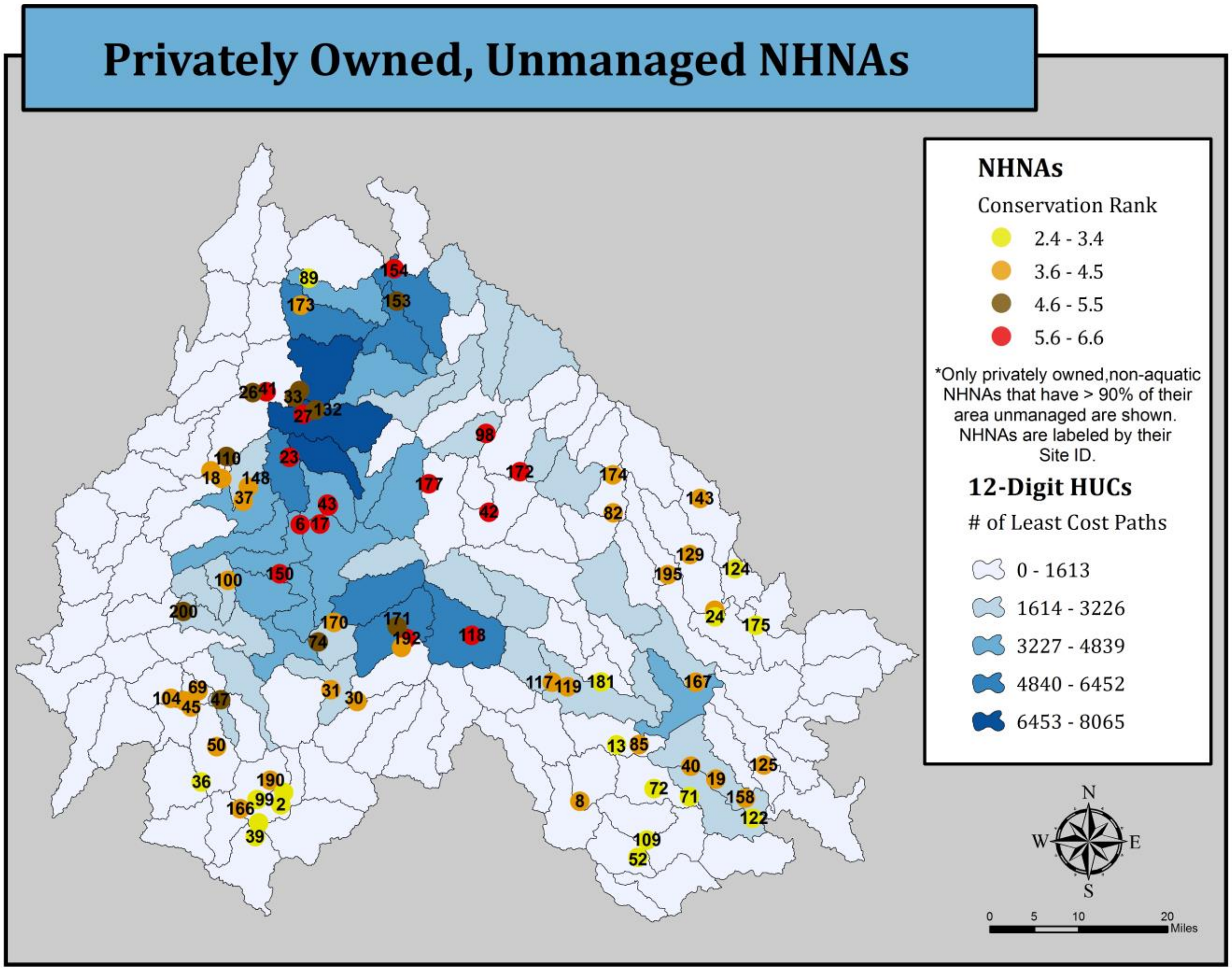

Figure 15. Privately owned, unmanaged NHNAs overlaid on top of 12-digit HUCs symbolized by the number of intersecting LCPs.

The following map overlays TLC projects and nature preserves over the riparian least cost path analysis (Figure 16). The Triangle Land Conservancy can use this map to identify sites were they are already working and are located in watersheds that provide beneficial services by connecting important habitat with vegetated riparian buffers. TLC can leverage continued conservation work in these areas. In particular, Horton Grove and Brumley Nature Preserves, which are both owned and managed by TLC, are located in subwatersheds that are important for connecting NHNAs via riparian buffers. This knowledge should help guide TLC in their management activities and restoration activities so that they are able to protect these high quality areas for their habitat and water quality value.

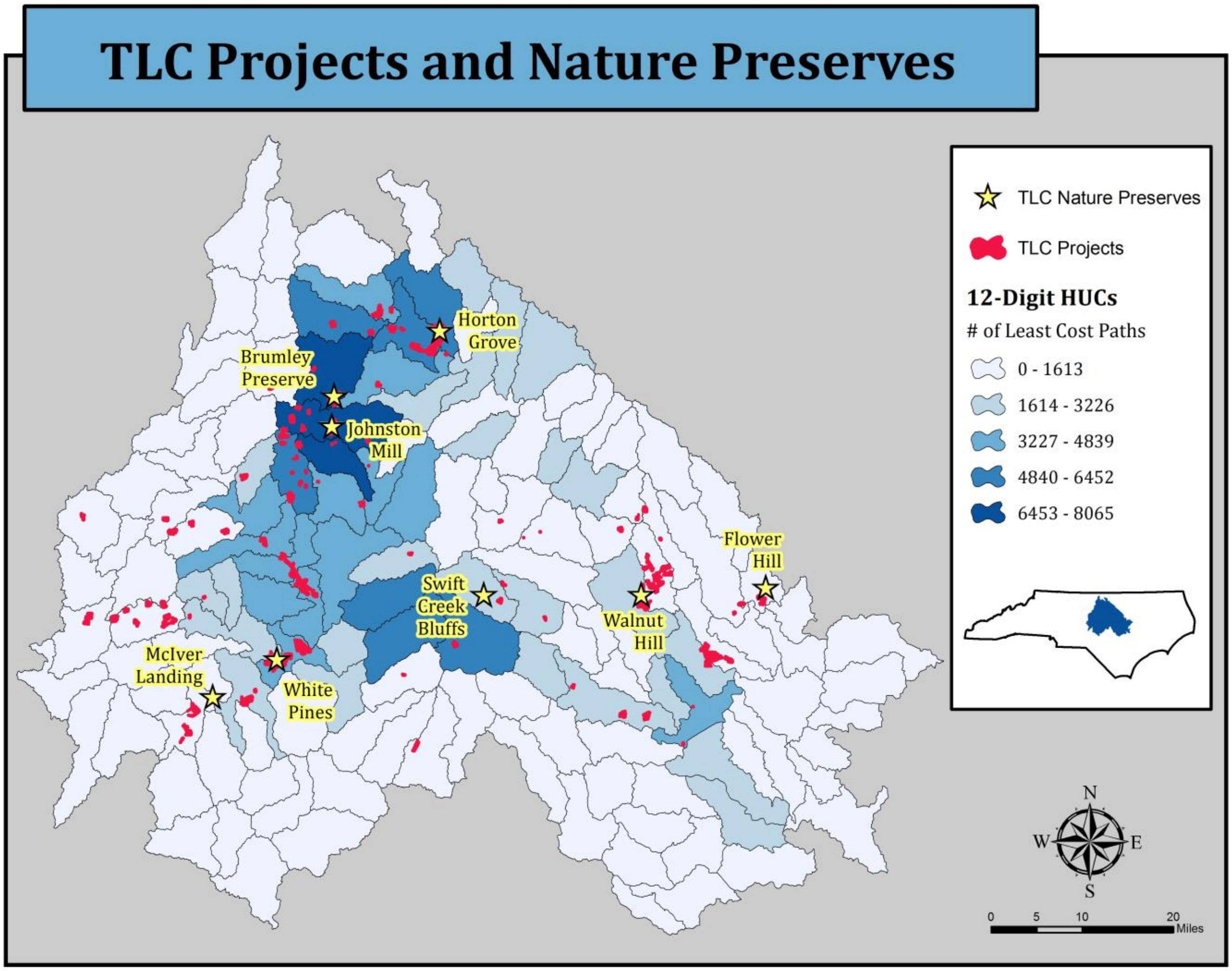

Figure 16. TLCs nature preserves and properties overlaid on top of 12-digit HUCs symbolized by the number of intersecting LCPs.

Discussion

The primary goal of this study was to develop a GIS-based interface tool using methods of MAUT to locate and prioritize areas of high water quality in the Triangle region to protect from the detriments of development. Prioritization through a GIS interface provides a systematic method to maximize conservation benefits by ranking land according to factors associated with its water quality value. The objectives hierarchy required by MAUT provides a more formal basis for evaluating stream reaches in the Triangle based on their water quality. Rather than a reactive approach to land conservation, prioritization encourages strategic evaluation of locations that are not currently managed for conservation but would provide high conservation value to the region.

Geospatial software is uniquely equipped to handle landscape scale prioritizations in a decision-making context. Most conservation-focused organizations, such as local land trusts and conservancies, have limited funds, resources, and time to identify lands to protect. Yet, local land trusts, such as TLC, can leverage the spatial and analytical capabilities of GIS software to help them target their conservation focus at relatively low cost.

The primary benefit of the prioritization tool is that it was designed to be versatile towards various decision-making contexts. The tool facilitates versatility by giving the user control over the weights for criteria and indicators. This function of the tool enables the prioritization process to incorporate the judgements and preferences of stakeholders in the decision-making process. The user is forced to directly compare the criteria against one another by ranking them in terms of their ecological importance to water quality. The variable weighting function also is useful because decision makers can tailor the weighting scheme to particular geographic themes in the landscape. For example, TLC might choose to focus some of their conservation work in areas in the Triangle that are particularly threatened by urban development, in which case they would want to tailor the tool to prioritize areas with low levels of impervious surface. Alternatively, when TLC has funding in a region that has high amounts of agriculture, they may want to give greater priority to areas that have healthy natural riparian zones to act as buffers between animals and water bodies and to filter fertilizers and pesticides before reaching the water.

In addition to the flexibility provided by the variability in weighting schemes, the GIS interface tool also allows the user to run the tool in a specific river basin and/or county in the Triangle. The flexibility offered by these optional parameters is beneficial because it enables TLC to capitalize on different funding opportunities, while being strategic in how they protect water in the Triangle. TLC, along with many other land trusts and nonprofits, receive funds from government sources to acquire, protect, and manage land. This tool can help TLC evaluate opportunities to influence and support local funding initiatives, such as Wake County's Open Space Program. Wake County's Open Space program aims to protect 30% of Wake County's land area as permanent open space and receives funding from voter-approved bonds. As a partner of this program, TLC can run the tool in Wake County to help guide protection of open space and maximize water quality benefits to the region.

The ability to run the tool in a specific river basin also has realistic applications for TLC. For example, TLC works in partnership with the Upper Neuse Clean Water Initiative (UNCWI), which was established in 2005 in response to the growing development pressures on the watershed's water quality. UNCWI is a partnership composed of land trusts, local governments, watershed associations, land owners, and state agencies focused on conserving high priority lands to protect drinking water reservoirs (Conservation Trust for North Carolina, n.d.). TLC also aims to initiate and encourage more collaboration in the Cape Fear River Basin by establishing partnerships and funding mechanisms to protect the basin's water bodies. Both these examples highlight ways in which TLC can use the tool to guide their conservation work.

It is important to bear in mind that GIS-based prioritization tools, such as this one, are only as accurate as the geospatial data and the methodology used to develop the tool. Selection of criteria and indicators that are most appropriate and useful is critical. There is always the potential to add additional indicators and criteria to improve this tool's accuracy and effectiveness. The North Carolina Department of Natural Resources makes it fairly easy to obtain geospatial data on their data portal. In the future, only slight modifications to the tool are required to update it with new and/or more recent data.

It is also important to understand that the prioritization tool is a decision support tool, which means that it should not have the only voice in the decision making process. Rather it is one tool amongst a toolbox of decision making tools that TLC can use to facilitate strategic conservation planning. The tool provides decision maker's a unique framework to consider land conservation projects with the goal of protecting the quality and quantity of water in the Triangle region.

Conclusion

Land trusts play an important role by protecting essential natural areas that provide a variety of scenic, recreational, ecological, and cultural benefits. Strategic conservation planning becomes even more critical as land trusts face challenges, such as sprawling development and degraded water bodies, with limited resources and time. Strategic conservation planning entails the identification of land protection that will most effectively achieve the desired benefits of conservation. The GIS prioritization tool aims to guide strategic conservation planning by ranking sites of high water quality value in the Triangle. The GIS-based approach to multi criteria decision analysis is helpful by reducing time and costs in early planning stages of proactive land conservation. TLC can use the tool to help facilitate deliberative and well thought out decisions, while also considering the overarching goals of their mission.

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