Assessing the current and future status of aquatic and hydrologic ecosystem services in the French Broad River Basin

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Executive Summary

Ecosystem services are the benefits that people receive from nature and are an increasingly important component of conservation planning. Ecosystem services are critical for human health and well-being, and include both services with direct value to people, such as forests providing downstream communities with clean drinking water, and services with have indirect value, such as the knowledge that endemic wildlife species like the giant hellbender salamander still exist in the mountain streams of North Carolina.

This project assesses the current state of several water-related ecosystem services in western North Carolina's French Broad River Basin, which includes the city of Asheville, and compares this to a potential future state given predicted changes in development patterns and climate. We used three different geospatial models to estimate how land in the French Broad River Basin contributes to freshwater ecosystem services on the subwatershed level: a riparian buffer model to assess the ability of vegetation to protect water quality by preventing pollutants from reaching waterways, annual water yield and sediment export models to identify the subwatersheds most important to provisioning water quantity and regulating sediment, and species distribution models to identify the subwatersheds that provide the most aquatic species habitat. We initially ran all the models with present-day datasets, and then used projected climate and development data for the middle of the 21st century to evaluate how these ecosystem services will change. The riparian buffer model does not take climate variables into account, so its future projection is only based on development data; future projections for all other models include both development and climate change data.

Our findings show that climate change and development may have significant implications for water quality, water quantity, and habitat to support aquatic biodiversity in western North Carolina around the middle of the 21st century. Expanding urban development into forested areas is expected to decrease the ability of riparian buffers to filter and retain nonpoint source pollution. Decreases in pollution filtration by riparian buffers will affect several drinking water supply watersheds that currently provide water for more than 80,000 people. Development and more intense rainfall patterns are also predicted to contribute to increased soil erosion into rivers and streams, which may result in rising expenses in drinking water filtration and increased stress on hydropower turbines. Water yield is also expected to increase, which is likely to result in greater potential for flooding. Many rare and threatened aquatic species are likely to experience significant reductions in suitable habitat. Several game fish species that are currently widespread across the French Broad River Basin are projected to be divided into several subpopulations, which could have ramifications for their long-term persistence as well as make fishing more difficult in some areas.

We identified thirteen subwatersheds that should be prioritized for conservation action based on their projected changes in water yield, sediment export, and pollution filtration. These are areas where municipalities, government agencies, and nonprofits should consider focusing their efforts to protect drinking water sources and mitigate flood risk through land protection and restoration. We also identified six subwatersheds that are important for aquatic wildlife based on their current and future predicted aquatic species richness and amount of habitat for modeled aquatic species. These priority areas currently provide a large amount of habitat for many aquatic species that are important to people, and they are projected to continue to provide habitat for these species as the climate changes. Conservation efforts in these areas are needed to ensure that these subwatersheds remain suitable climate refuges for aquatic organisms.

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Introduction

Ecosystem Services

People have long recognized that their well-being is related to the health of their environment, and places with healthy environments are often some of the most desirable places to live. The city of Asheville in North Carolina, for example, consistently ranks as one of the best places to live in the United States, and many of the reasons it is so desirable are directly related to its clean water, extensive forestland, and overall scenic beauty (Carmichael, 2016). Asheville has a host of craft breweries that rely on its plentiful clean water, tourists flock to the area to experience the fall foliage along the scenic Blue Ridge Parkway, and residents enjoy hiking, trout fishing, and kayaking. For the more intrepid nature lovers who know where to look, the area is also home to a host of remarkable wildlife species, such as hellbender salamanders, river otters, and bobcats.

All of these things are examples of ecosystem services, which are the direct and indirect benefits people receive from nature (Millennium Ecosystem Assessment, 2005b). The concept of ecosystem services (sometimes called environmental services) grew out of the environmental movement in the second half of the 20th century to describe a very old and simple idea—that nature provides a valuable service by producing the oxygen we breathe, the timber with which we build our homes, and the clean water we drink (Gomez-Baggethun et al., 2010). Most of the time these ecosystem services are things we take for granted, until something happens to diminish or even destroy a service upon which we rely.

The study of ecosystem services elucidates the connection between natural systems and socio-economic systems and provides a coherent means of assessing and valuing ecosystem processes that directly benefit people (Millennium Ecosystem Assessment, 2005a). Over the past few decades it has come to be seen as a powerful tool for encouraging policy makers and the private sector to support the protection and sustainable management of vital natural resources, since it provides a framework for valuing (both in monetary and non-monetary terms) the connection between environmental health and human well-being (Brauman et al., 2007).

The 2005 Millennium Ecosystem Assessment serves as a framework for much of the current research on ecosystem services (Brauman et al., 2007). The Millennium Ecosystem Assessment was commissioned by the United Nations Secretary-General in 2000 and engaged more than 1,360 experts over four years in assessing the conditions and trends of the planet's ecosystem services (Millennium Ecosystem Assessment, 2005b). This assessment divided ecosystem services into four key categories: supporting, provisioning, regulating, and cultural services. All of these services are connected to measures of human well-being such as security, livelihoods, health, social relationships, and freedom (Fig. 1). These classifications help to recognize the myriad and often interconnected ways that people benefit from ecosystem services and provide a means of evaluating the many ways in which these different services are threatened by unsustainable development and land use change. The Millennium Ecosystem Assessment (2005b) concluded that humans have drastically degraded and depleted ecosystem services over the past 50 years and that we can no longer take it for granted that ecosystems will be able to sustain future generations.

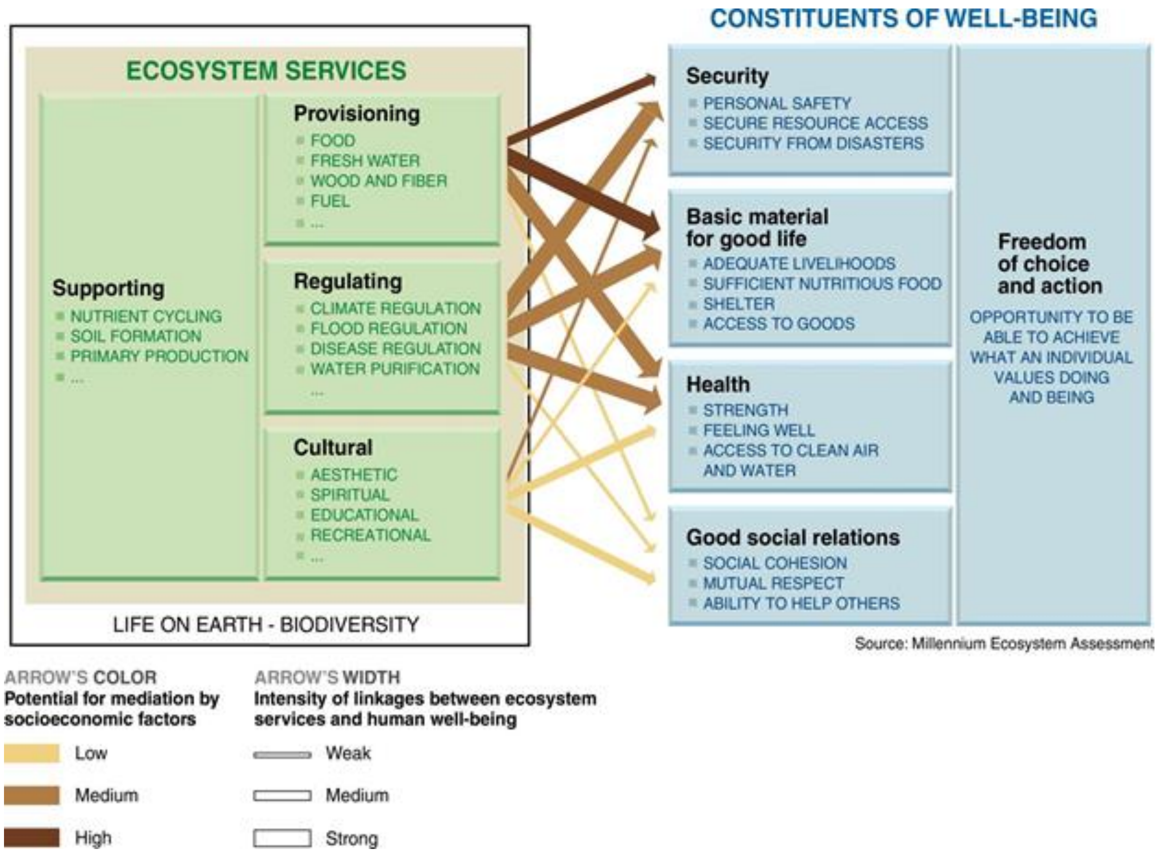

Figure 1: The four categories of ecosystem services and their connection to human well-being. Source: Millennium Ecosystem Assessment, 2005b.

One of the most important ecosystem services studied by the Millennium Ecosystem Assessment is global freshwater provisioning. Only 2.5% of the Earth's water is freshwater, and the vast majority of this is either frozen or is present as soil moisture or groundwater (Millennium Ecosystem Assessment, 2005a). The amount of freshwater available in surface water or shallow aquifers is estimated to make up just tenths of 1% of the Earth's water (Millennium Ecosystem Assessment, 2005a). One of the seminal studies in valuing global ecosystem services placed more value on inland aquatic ecosystems than on all other non-marine ecosystems combined (Costanza et al., 1997).

One of the major threats to the continued provisioning and regulation of water-related ecosystem services is land use change (Millennium Ecosystem Assessment, 2005a). The conversion of forested watersheds to pasture, agriculture, and urban areas can trigger significant changes in the water cycle, particularly in evapotranspiration, infiltration rates, and runoff quantity and timing (Millennium Ecosystem Assessment, 2005a). For this reason, the preservation of a healthy aquatic ecosystem requires management of the land within its watershed (Millennium Ecosystem Assessment, 2005a).

Our project focuses on both in-stream aquatic ecosystem services and hydrologic ecosystem services, which are generally defined as the benefits people receive from the role that terrestrial ecosystems play in preserving the quality of freshwater ecosystems (Brauman et al. 2007). Natural ecosystems such as forests and wetlands provide a variety of valuable hydrologic ecosystem services to people, including provisioning water, regulating water flow and water quality, supporting habitat for aquatic wildlife, and providing cultural services such as recreation areas. A study by Elsin et al. (2010), for example, found that reducing stream turbidity (suspended sediment in water) by 5% across North Carolina's Neuse River Basin (Piedmont/Coastal area) would result in a cost savings of up to $2.7 million over thirty years in reduced water treatment costs. Stream turbidity can be reduced by transitioning cropland and other land uses with high soil erosion potential to forest and pasture (Elsin et al., 2010). A 2002 study by the Trust for Public Land and the American Water Works Association analyzed 27 water suppliers in the United States and found that every 10% increase in forest cover decreased water treatment costs by around 20% (Ernst, 2004). Among these suppliers, the percentage of forest cover in the watershed explained 50-55% of the variation in treatment costs (Ernst, 2004). These cost savings are significant, with treatment costs ranging from $923,450 in watersheds that are 10% forested to $297,110 in watersheds that are 60% forested (Ernst, 2004).

The loss of hydrologic and aquatic ecosystem services affects people in significant ways. The loss of forests, for example, can result in more intense floods as precipitation quickly runs over the ground and into rivers, causing them to exceed their banks and damage homes and other infrastructure (Brauman et al., 2007). Increased surface runoff also means that the precipitation does not sink into the ground, and this decreased groundwater storage and flow can result in more extreme droughts as rivers no longer have the groundwater they need to maintain their base flow during dry spells (Brauman et al., 2007). The loss of forests and other vegetation can also increase the amount of soil that erodes into rivers and reservoirs, which can drive up the costs of sediment removal at water filtration plants and hydropower dams (Brauman et al., 2007). Lastly, more variable stream flow and increased sediment also harm many sensitive aquatic species.

Many government agencies and non-government organizations are seeking to better understand hydrologic and aquatic ecosystem services and potential threats so they can act to mitigate these threats. One of the leading non-governmental organizations working on this issue is The Nature Conservancy. The Nature Conservancy commissioned this analysis to better understand the distribution of these ecosystem services in the French Broad River Basin of western North Carolina and how these services will be affected by future development and climate change. The Nature Conservancy plans to use this information to guide its prioritization of land conservation and restoration activities in the river basin.

The French Broad River Basin (Fig. 2) is part of the larger Southern Blue Ridge Ecoregion, which spans the North Carolina and Tennessee border and stretches up into southern Virginia and down into the northern corners of South Carolina and Georgia. This 9.4 million-acre ecoregion has long been prioritized by The Nature Conservancy and other conservation organizations because it is a hotspot for biodiversity, and contains over 400 rare plant species, 120 endemic terrestrial communities, and 66 at-risk aquatic species (TNC and Southern Appalachian Forest Coalition, 2000). It also contains some of the largest remaining un-fragmented forest blocks in the eastern United States (TNC and Southern Appalachian Forest Coalition, 2000). We chose this river basin for our analysis based on its importance to biodiversity and because it contains a population center that benefits from ecosystem services related to drinking water, water-based recreation, and hydropower. It is also projected to experience changes in population, development, and climate which will likely affect these ecosystem services.

The Nature Conservancy

The Nature Conservancy (TNC) is a large international conservation organization that was founded in 1951, and works in more than 70 countries and all 50 U.S. states (The Nature Conservancy, n.d. a). Its mission is to "conserve the lands and waters on which all life depends," and since its founding TNC has helped to protect 120 million acres of land and thousands of miles of river (The Nature Conservancy, n.d. a). In North Carolina alone, TNC has protected over 700,000 acres, often turning these areas into state parks and public access areas (The Nature Conservancy, n.d. b). Currently, the North Carolina chapter owns and manages approximately 100,000 acres of land (Julie DeMeester, Water Program Director, TNC personal communication, October 2016).

In the Southeastern U.S., TNC and its partners have prioritized land protection in areas that have an important role in supporting clean and abundant freshwater sources for drinking water, recreation opportunities, and aquatic species habitat. Forests in the Southeast cover around 27 percent of the total land area and supply an estimated 34 percent of the total water yield (Lockaby et al., 2011). These forests also supply surface drinking water to nearly 50 million individuals living in an estimated 2,130 communities (Caldwell et al., 2014). These forests and sources of freshwater are threatened, however, by population growth in the Southeast, which is projected to increase by 34-65% by 2060, and a corresponding increase in impervious surface of 17-30% (U.S. Environmental Protection Agency, 2009). Water yield is also threatened by changes in climate and forest structure; in the Southern Appalachian forests of North Carolina annual water yield has decreased by 22% from the 1970s to 2013 due to changes in climate, evapotranspiration, and the shift in forest structure from hickory and oak to tree species that require more water (Caldwell et al., 2016).

TNC is currently working to identify opportunities for land protection and restoration in western North Carolina and the Southern Appalachians, and is interested in understanding the connection between forest management activities and water resources. They have been working with the U.S. Forest Service and other partners on activities such as controlled burns to restore fire-adapted forests, riparian restoration to protect drinking water and aquatic species, and acquisition of habitat that may be more resilient to changes in climate (Julie DeMeester, Water Program Director, TNC, personal communication, February 2017).

Project Objectives

Our objectives are to assess the current state of aquatic and hydrologic ecosystem services in the French Broad River Basin, including where sources of ecosystem services are located within the watershed and how ecosystem services may be affected by future climate and land use changes. This information will give TNC a better understanding of the issues facing aquatic and hydrologic ecosystem services in the French Broad River Basin as they seek to expand their work in that region. It will also identify areas within the watershed that are particularly valuable for the provision of ecosystem services and areas that are vulnerable to degradation, which will help TNC to select projects that will be effective in preserving aquatic and hydrologic ecosystem services.

Our analyses aim to answer the following questions:

- Which subwatersheds in the French Broad River Basin are currently most important for providing aquatic and hydrologic ecosystem services?

- How will climate change and development in the French Broad River Basin affect aquatic and hydrologic ecosystem services through effects on riparian buffers, sediment export, water yield, and important aquatic species habitats?

Methods

Study Area

The French Broad River Basin encompasses more than 5,000 square miles of land in western North Carolina and eastern Tennessee (Fig. 2). It was home to 800,000 people in 2010, and its population is growing rapidly; the estimated population growth for counties in the French Broad River Basin from the year 2000 to 2020 ranges from 10 percent to 30 percent (United States Census Bureau, 2010; French Broad RBRP Overview, 2009). In the city of Asheville, by far the largest metropolitan area in the basin, this growth is entirely due to in-migration from out of the area (Boyle, 2015). The natural setting of the French Broad River Basin is an important factor in its attractiveness to newcomers. According to the 2011 National Land Cover Database, most of the land in the French Broad River Basin is forested, and 29% of land in the basin is protected, much of it as part of national forests and Great Smoky Mountains National Park (PAD-US, 2016) (Fig. 2).

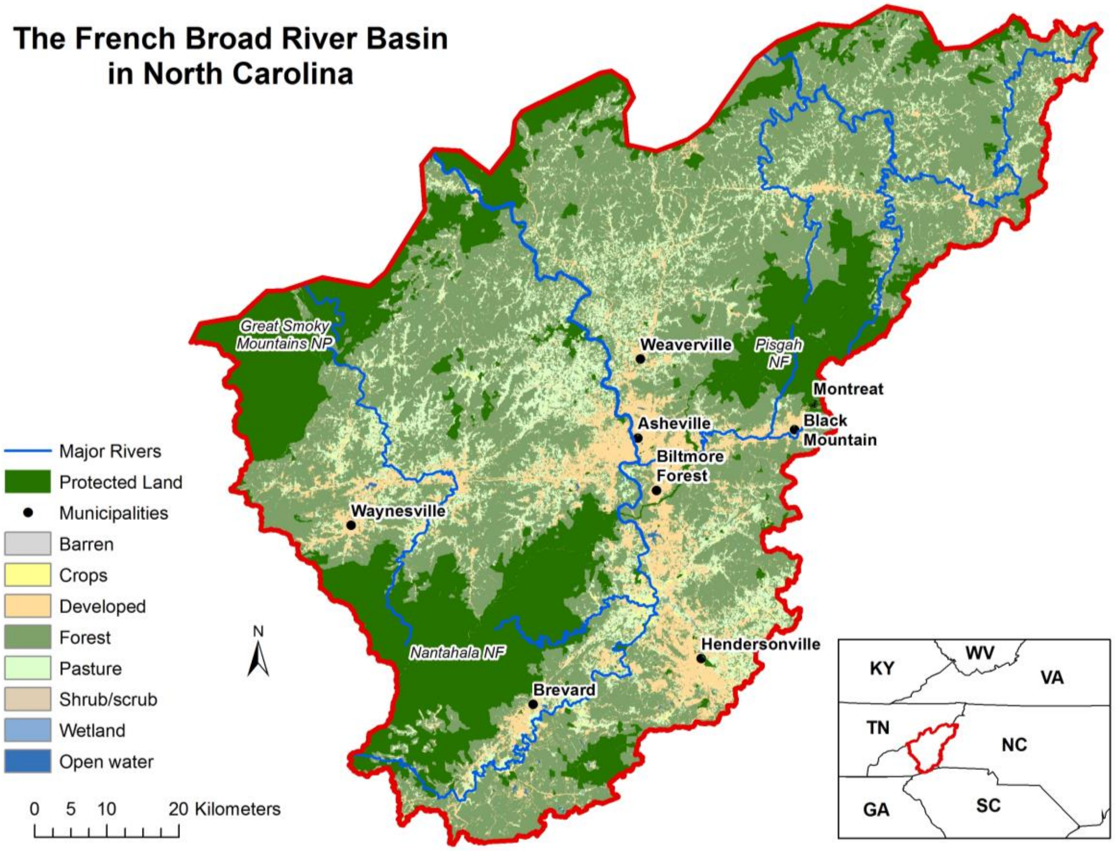

Figure 2: Land cover, protected land, municipalities, and major rivers in the North Carolina French Broad River Basin

Clean water and high-quality aquatic ecosystems play a key role in the quality of life of the French Broad River Basin's residents and in attracting visitors. Surface water originating in the basin provides drinking water to one million people (RiverLink, n.d.). There are 11 towns in North Carolina that withdraw water from rivers and reservoirs in the French Broad; collectively they withdraw 38.95 million gallons per day (Tutwiler and Clark, 2011). The biggest water users are the cities of Asheville and Hendersonville (Tutwiler and Clark, 2011).

Clean drinking water also plays an economic role; at least 20 breweries currently exist in Asheville, with another 20 within 25 miles of the city (BreweryMap, 2017). In 2014, breweries directly employed 263 people in the 10th and 11th congressional districts, which cover western North Carolina and Asheville, with beer wholesalers and retailers adding another 3,939 jobs (Kiss, 2015). These breweries include local companies that were founded in Asheville and several national brands, including New Belgium, Sierra Nevada, and Oskar Blues (Glenn, 2012). New Belgium Brewing invested $140 million in a new Asheville facility in 2015, which is projected to provide 140 full-time jobs (Kiss, 2015; Dahl, 2015). Breweries often cite the high-quality, low-mineral mountain water as an asset to their business (Kiss, 2014).

Tourism and recreation are also key components of the economy for cities in the French Broad River Basin. In Asheville, the leisure and hospitality industry employed more than 25,000 people in 2015, making it the city's second-largest industry by employment (Asheville Area Chamber of Commerce, 2015). Many of the recreational opportunities that attract tourists depend on high-quality aquatic resources. Waterfalls are common destinations for hiking trails, and rivers host whitewater rafting, canoeing, and swimming. Fishing for trout and smallmouth bass is another popular recreational activity (NC Environmental Education, n.d.).

The water quality of a river or stream is dependent to a large degree on the land upstream. Studies have shown that watersheds with a high percentage of forest cover tend to have better water quality than those with more agricultural land or impervious surfaces (Miller et al. 2011). Despite its large amount of forested land and low developed area relative to many other watersheds in North Carolina, the French Broad River Basin still faces challenges to its water quality. Waste from livestock on agricultural lands and problems with septic and sewer systems introduce pathogens into the water, which can make bodies of water unsafe for swimming and consumption. Between 2004 and 2008, 25% of monitoring sites sampled in the French Broad River Basin exceeded the standard for fecal coliform bacteria (North Carolina Department of Environmental Quality, 2011). Pesticides that run off from agricultural lands directly threaten aquatic invertebrates, which are an important part of the food chain that supports game species like trout. Habitat degradation can take many forms, including stream channelization and removal of riparian vegetation. This can cause accelerated erosion and sedimentation and exacerbate other pollution problems, such as an increase in metals and pesticides reaching streams due to decreased filtering capacity when riparian buffers are lost. Development and its associated increase in impervious surface cover increase water runoff after storms, which causes increased erosion and flooding (North Carolina Department of Environmental Quality, 2011).

Threats: Climate Change and Development

Aquatic and hydrologic ecosystem services are threatened by many factors, but two of the biggest threats include climate change and development. Our analysis considered how these ecosystem services might change around the middle of the 21st century given projected urban growth and climate change in the French Broad River Basin (Table 1). This helps to identify the subwatersheds with the greatest and least resilience to the effects of climate change and development.

We obtained data on projected development patterns from the FUTure Urban Regional Environmental Simulation (FUTURES), which predicts where new urban growth will occur based on an integrated model of factors such as slope, distance from protected areas, distance to roads, road density, forests, and distance to attractions such as lakes, rivers, and urban centers (Meentemeyer et al. 2013; Fig. 3). This model was produced by the Center for Geospatial Analytics at NC State, and is based on the SLEUTH urban growth model (Clarke and Gaydos, 1998). SLEUTH predicts urban growth based on spreading from urban areas, development around existing roads, and spontaneous growth, and helps to predict where low and medium-density development will occur (Terando et al., 2014). The FUTURES model uses a similar spreading model, and predicts that the study area will have 27,648 acres of new development by 2050 (about a 1.5% increase relative to the total land area in the FBRB), with most of this change coming from forests, shrubs, and pasture being converted to development (Fig. 3).

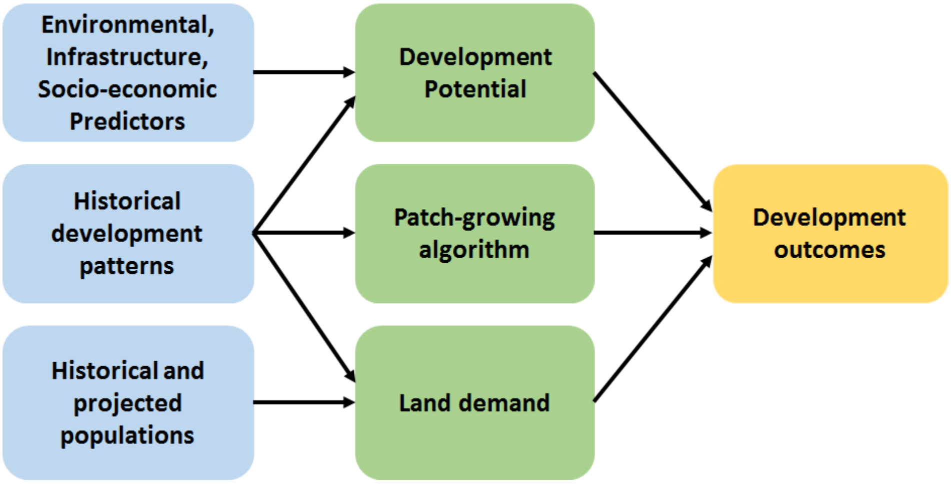

Figure 3: FUTURES model input variables. Adapted from Meentemeyer et al. 2013.

We obtained data on projected climate changes from the Climate Wizard Tool, which was developed through a collaboration between The World Bank, CGIAR-CCAFS, The International Center for Tropical Ecology, Climate Central, The Nature Conservancy, and three U.S. universities (Girvetz et al. 2009). We used several climate datasets in our analyses, including precipitation, temperature, potential evapotranspiration, and erosivity (a measure of the potential ability of soil to be eroded by rain or surface runoff). Each dataset was at a resolution of 0.5 degrees (about 50km pixels) (Girvetz et al. 2009).

We used climate models for a high CO_2 emissions scenario (A2) and a moderate emissions scenario (A1B) for the mid-21st century to see how potential changes to precipitation, evapotranspiration, and temperature might influence aquatic and hydrologic ecosystem services (IPCC, 2000; Fig. 4). Different general circulation models sometimes have very different predictions of how temperature, precipitation, and other climate variables may change, so we took the median values of sixteen general circulation models and averaged them to come up with the values we used in our analysis. These general circulation models were developed by organizations such as the National Oceanic and Atmospheric Association Geophysical Fluid

Dynamics Laboratory, the National Air and Space Association's Goddard Institute for Space Studies, and the National Center for Atmospheric Research, among others (Girvetz et al. 2009).

Both the A2 and A1B emissions scenarios were developed as part of the Special Report on Emissions Scenarios commissioned by the Intergovernmental Panel on Climate Change in 2000. As Figure 4 shows, each scenario incorporates different assumptions about population growth, the rate of socio-economic development, and the adoption of clean and energy efficient technology (IPCC, 2000). The A2 scenario is characterized by a continuously increasing global population that surpasses 10 billion by 2050, slow adoption of renewable energy, and a slow rate of energy efficiency increases (IPCC, 2000). The more moderate A1B emission scenario assumes that the global population will reach around 8.5 billion by the mid-century and then decline to 7 billion by 2100 (IPCC, 2000). It also assumes that economic growth will rapidly increase, but that countries around the world will achieve a balance between clean energy and energy based on fossil fuels (IPCC, 2000).

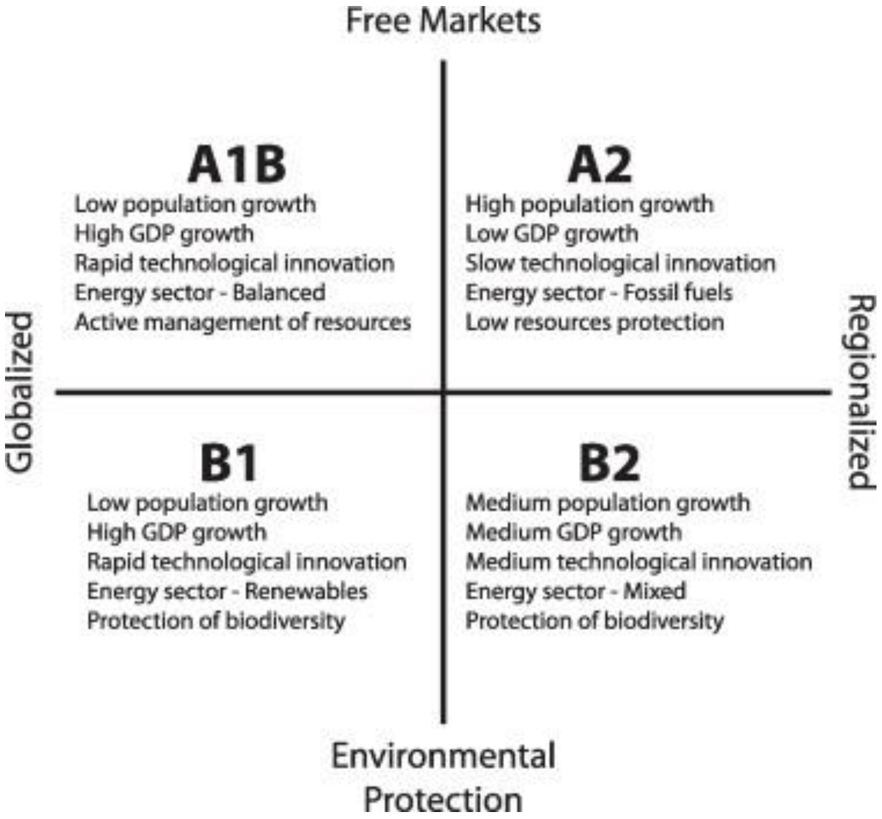

Figure 4: Emissions scenarios developed from the Special Report on Emissions Scenarios by Nakicenovic et al. 2000. Figure source: Sleeter et al. 2012.

We evaluated how ecosystem services may change around the middle of the 21st century by analyzing five different scenarios of development and climate change (Table 1). By comparing the current models of ecosystem services to future ecosystem services we were able to determine which subwatersheds are likely to be the most and least affected by climate change and development, and to offer recommendations for potential conservation action to mitigate these changes.

Table 1: Future development and climate scenarios

Scenarios	Models Run	Data Used
Development	Riparian buffers Sediment export Water yield Aquatic species habitat	Land use/land cover
Development and Climate (A1B)	Sediment export	Erosivity, land use/land cover
	Water yield	Precipitation, potential evapotranspiration, land use/land cover
	Aquatic species habitat	Precipitation, temperature, land use/land cover
Development and Climate (A2)	Sediment export	Erosivity, land use/land cover
	Water yield	Precipitation, potential evapotranspiration, land use/land cover
	Aquatic species habitat	Precipitation, temperature, land use/land cover
Climate (A1B)	Sediment export	Erosivity
	Water yield	Precipitation, potential evapotranspiration
	Aquatic species habitat	Precipitation, temperature
Climate (A2)	Sediment export	Erosivity
	Water yield	Precipitation, potential evapotranspiration
	Aquatic species habitat	Precipitation, temperature

Ecosystem Services in the French Broad River Basin

To determine the subwatersheds in the French Broad River Basin that are most important for providing aquatic and hydrologic ecosystem services, we modeled the effects of terrestrial ecosystems on water quantity, water quality, and aquatic species habitat. Our models considered both current and projected data to determine where changes are likely to occur in the future. Due to the large size of the French Broad River basin, we calculated and displayed our results on the subwatershed level, with each subwatershed identified by a 12-digit Hydrologic Unit Code (HUC).

Riparian Buffers

We evaluated the ability of terrestrial ecosystems in the French Broad River Basin to protect water quality by modeling riparian buffers and their capacity to prevent nonpoint source pollutants from reaching waterways. Nonpoint source pollution, also called diffuse pollution, is rain or snowmelt runoff that carries both natural and manmade pollutants from urban and agricultural land to the water and is considered one of the leading threats to water quality (United States Environmental Protection Agency, 2016). Riparian buffers are areas of vegetated land cover that perform important functions such as stabilizing streambanks, shading aquatic habitats, and filtering pollutants to promote water quality. Most commonly, riparian buffers are quantified as the total amount of vegetated land cover within a fixed distance of a stream, such as 50 meters on either side. This simplistic measure can be problematic, however, because it does not consider other factors that can influence the filtering potential of a riparian buffer (Baker et al., 2006). Although riparian vegetation directly adjacent to the stream provides shading and streambank stability, vegetation further outside the traditional fixed distance can also have an impact on the amount of pollution prevented from reaching the aquatic ecosystem. Additionally, the traditional fixed distance method does not consider elevation, terrain, slope, and other variables that influence the path that pollutants travel from the pollution source to the water.

To overcome these limitations of the fixed distance method, we modeled effective riparian buffers, which include three main concepts: connectivity, retention, and aggregation. Connectivity refers to the riparian vegetation that is contiguous between pollutant source and the water, where gaps in coverage would lead to a lower filtering potential. Additionally, for the contiguous vegetation to filter pollutants out of the ecosystem, it must lie within the flow path between the pollutant source and the water. Retention refers to the rate of pollutant uptake by the riparian buffer and depends on the specific characteristics of the watershed, including soil type and vegetation. Assuming that these characteristics are uniform throughout the watershed, the width of the buffer is considered a proxy for retention, where greater buffer width results in greater pollutant filtration. Aggregation combines all of the effective buffer areas within a watershed to calculate its total buffer area (Baker et al., 2006).

We modeled effective riparian buffers in the French Broad River Basin using geospatial software (ArcGIS 10.5 and the Spatial Analyst extension from the Environmental Systems Research Institute). First, we used land cover datasets to identify forested vegetation and nonpoint sources of pollution from urban and agricultural land. For the current scenario, we used the 2011 National Land Cover Dataset, and for the 2050 scenario we used the FUTURES Land Cover Dataset. The path of water flowing between pollutant sources and waterways was determined using a 30-meter digital elevation model, where the direction of flow is down the steepest path. The effective riparian buffer width between pollutant source and the water was calculated as the total amount of forested vegetation present within the flow path (Fig. 5).

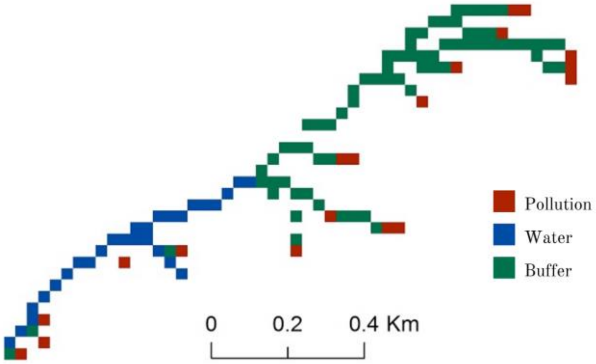

Figure 5: Diagram of effective buffer width along flow path between pollution source and stream.

Different subwatersheds contain different amounts of pollutant sources, so we compared the filtering potential of each subwatershed by calculating a potential pollution reduction for each subwatershed, as described by Baker et al. (2006). Theoretically, the effective riparian buffer method can yield the exact same results for subwatersheds that have different amounts of pollution sources and vegetated land cover. For example, a subwatershed with high amounts of pollution and low vegetated land cover can have the same amount of effective riparian buffers as a subwatershed with low amounts of pollution. The potential pollution reduction calculation allows for a better comparison of the filtering potential of the riparian buffers based on the amount of land contributing nonpoint source pollution within each subwatershed. To determine the potential pollution reduction, the inverse buffer width was calculated as 1/(buffer width+1) for each pollution source. Then all inverse buffer widths were summed within each subwatershed and divided by the total area of the subwatershed. For each subwatershed, this value is an estimate of how much the effective riparian buffers along the flow path potentially reduce the delivery of pollutants to the water.

InVEST

The purpose of this analysis was to evaluate the effect of terrestrial ecosystems on water quantity, and water quality regulation through filtering out sediment. For this we used the Natural Capital Project's Integrated Valuation of Ecosystem Services and Tradeoffs software (InVEST 3.3.1). InVEST is useful for rapid assessments of the general patterns and changes in hydrologic ecosystem services due to land use/land cover or climate change impacts (Vigerstol and Aukema 2011). It uses spatial data that represents the study area as a grid of pixels, and captures biological, geological, meteorological, and physical variables to provide an estimate of the relative contribution of each pixel to the ecosystem services being modeled (Sharp et al. 2016). It is best used to assess the impacts of land cover change on multiple ecosystem services over a large river basin, so it is a good fit for our analysis (Vigerstol and Aukema 2011).

There are many tools available for modeling hydrologic ecosystem services and linking these ecosystem functions to water resources, but the results of these different tools are not always comparable (Vigerstol and Aukema, 2011). We selected InVEST after considering four publicly available, free tools for modeling hydrology and water-related ecosystem services, including the Soil and Water Assessment Tool (Arnold et al., 1998; Arnold and Fohrer, 2005), the Variable Infiltration Capacity model (Liang et al., 1994, 1996; Nijssen et al., 1997), Artificial Intelligence for Ecosystem Services (Villa et al., 2009), and InVEST (Tallis and Polansky, 2009). After reviewing the parameters and applications of each of these tools, we concluded that InVEST was the best option for our purposes. This was based primarily on the fact that we wanted a tool that used a GIS platform, which gave us the flexibility of combining the outputs of this analysis with the other ecosystem services we modeled. The two most commonly used GIS-based tools are InVEST and Soil and Water Assessment Tool. Secondly, we wanted a tool that we could run with publicly available data, and that did not require significant hydrology expertise. InVEST is significantly less data-intensive and technical than Soil and Water Assessment Tool, which is why we ultimately selected InVEST for our analysis (Vigerstol and Aukema, 2011).

We ran two InVEST models on annual water yield and sediment export. The outputs include spatial datasets that allow us to examine which subwatersheds have the greatest positive and negative effect on the current provisioning of hydrologic ecosystem services, including hydropower and drinking water. While the results of these models include the total amount of water yield and sediment exported from each subwatershed, it is important to note that there is a high degree of uncertainty in these values due to the fact that this study did not attempt to calibrate the models to measured data. This analysis is therefore best used to examine the relative differences between subwatersheds in the French Broad River Basin with respect to the modeled hydrologic ecosystem services, and to evaluate how these ecosystem services might change given future development and climate scenarios.

Water Yield

The water yield model is designed to estimate the average annual volume of water that flows out of each subwatershed. It does this through a water balance equation that calculates the difference between precipitation and actual evapotranspiration in each pixel, and assumes that the water that is not lost to evapotranspiration eventually flows out of the subwatershed. Since this model estimates the average water balance over a long period of time, it can ignore water storage.

Evapotranspiration is the water lost either to evaporation into the atmosphere or due to transpiration – the evaporation of water from the leaves and stems of plants. Different plants have different transpiration rates based on their physiology, root depth, and the soils they are growing in (Food and Agriculture Organization of the United Nations, 1998). The water yield model attempts to capture this complexity by requiring several spatial datasets on precipitation, reference evapotranspiration, land use/land cover, soil depth, and plant available water content (Table 2). Plant available water content is the amount of water available in the soil that plants are able to use. We calculated this by dividing the total amount of water each soil type is capable of storing (available water storage) by the depth of the soil available to plants (root restricting layer depth). The model also requires a biophysical table that includes the average rooting depth of each major vegetative land use class (e.g., deciduous trees, shrubs, crops, pasture, etc.), as well as details on the specific rate that each of these plant types transpires.

We used rooting depth data by Schenk and Jackson (2002) and Canadell et al. (1996) to determine the appropriate values for the land classes found in the study area. For the data on the transpiration rates of different plants (evapotranspiration coefficient), we used the values provided in the InVEST User's Guide and sample biophysical table. The model also requires a z parameter, which is an empirical constant that helps to calibrate the model based on local precipitation and hydrogeological characteristics (Sharp et al. 2016). The z parameter can be estimated from the following equation:

Equation 1: Z parameter

$$Z = \frac{(\omega - 1.25)P}{AWC}$$

In the above equation, P is average annual precipitation, AWC is the average plant available water capacity, and ω is a constant that predicts water-energy partitioning (Sharp et al. 2016). Xu et al. (2013) developed a model for estimating the ω parameter based on the study area basin's latitude, drainage area, elevation, and other variables. Their global model estimated a ω parameter of 3.8-4.5 for the southeastern U.S.; we used the value of 3.8 for this analysis. Average annual precipitation in the French Broad is 1,258 mm/year and the average plant available water capacity is 169.2 mm. This results in a Z parameter of 19, which is within the typical range of 1-30 for this parameter.

Water Yield Sensitivity Analysis

We ran a sensitivity analysis to determine how uncertainty in the climate change projections may influence the model results for water yield. We conducted a one-at-a-time sensitivity analysis to evaluate how the water yield model outputs changed when the input parameters increased or decreased by up to 20%. We based this sensitivity analysis on a study by Redhead et al. (2016) on the InVEST water yield model in the United Kingdom, which found that the input variables with the greatest impact on model outputs included precipitation, potential evapotranspiration, and the Z parameter. The other variables that Redhead et al. (2016) evaluated (i.e., plant available water content, rooting depth, and evapotranspiration coefficients) had very little impact on the model outputs, and so were not included in the sensitivity analysis for this study. To determine the sensitivity of these parameters, we took the original values of the three datasets, increased/decreased them at intervals of 10%, and then reran the water yield model at each interval with all other parameters the same except for the parameter being evaluated.

Table 2: Inputs to water yield model

Input	Type	Value (range)	Source
Precipitation	Raster (30m)	[925-2234] mm	PRISM Climate Group (2004) – 800m averaged for 1981-2010
Reference evapotranspiration	Raster (30m)	[820-1264] mm	Trabucco and Zomer (2009) – 30 arc sec. averaged for 1950-2000
Root depth	Integer	Forest: [3270-4000] mm Shrub: 2140 mm Grass/herbs: 370 mm Pasture/hay: 1000 mm Crops: 370 mm	Schenk and Jackson (2002) – geometric mean rooting depth data; Canadell et al. (1996)
Kc coefficient	Decimal	Development: 0.3-0.5 Forest/wetlands: 1-1.2 Shrub: 0.398 Grass/herbs: 0.65 Pasture/hay: 0.85 Crops: 0.65	Sharp et al. (2016)
Plant available water content	Raster	[0-0.4667]	Soil Survey Staff (2016)
Depth to root restricting layer	Raster	[0-1500] mm	Soil Survey Staff (2016)
Z parameter	Integer	19	Sharp et al. (2016)
Land use land cover	Raster (30m)		Homer et al. 2015

Sediment Export

The second model we ran in InVEST was the sediment model, which quantifies sediment export across the watershed. It calculates the total amount of soil loss or soil retention per pixel based on the revised universal soil loss equation (Fig. 6), and outputs estimates of how much sediment is exported from each subwatershed each year.

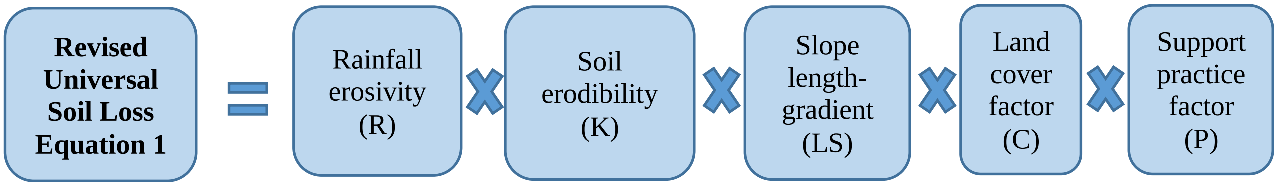

Figure 6: Revised universal soil loss equation (Renard et al., 1997)

In the revised universal soil loss equation, soil loss is increased by the first three factors including rainfall erosivity (R), soil erodibility (K), and the slope length-gradient factor (LS). The slope length-gradient factor captures the combined effect of slope steepness and slope length on erosion, with slope length referring to the distance between the point where overland water flow first occurs and the point where the slope decreases enough for sediment deposition to occur. This potential for soil loss is then reduced by the final two variables in the equation, including the land cover factor as a proportion of erosion relative to a fallow state (C), and the support practice factor (P), which takes into consideration soil conservation practices like terracing. The algorithm then uses a sediment delivery ratio to determine how much of the potential soil that erodes from each pixel will later be trapped by downstream vegetation before entering a stream. If there is a forested riparian buffer, for example, this will help to trap sediment that eroded from higher elevations before it enters the stream.

We obtained the mean rainfall erosivity index averaged over the period of 1971-2000 from the USGS (Wieczorek and LaMotte 2010). Some of the soils erodibility data were included in the USGS gSSURGO files, and we filled in the remaining gaps with less detailed USGS STATSGO data from Schwarz and Alexander (1995). Details on the other variables are included in Table 3.

Table 2: inputs to sediment retention model

Input	**Type**	**Value (range)**	**Source**
Erosivity	Raster (30m)	[2350-9216] MJ·mm/(ha·hr·yr)	USGS/Wieczorek and LaMotte 2010
Erodibility	Raster (30m)	[0.00263-0.0645] ton·ha·hr/(ha·MJ·mm)	USGS/Soil Survey Staff 2016; Schwarz and Alexander 1995
DEM	Raster (30m)	[248-2032] m	USGS
USLE C factor	Decimal	Ag.: 0.13 Forest: 0.001 Grass/Shrub: 0.011 Managed timber: 0.03 Pasture: 0.003 Urban: 0.1	Wischmeier and Smith 1978
USLE P factor	Decimal	Ag./pasture: 1 Forest/timber: 1 Grass/Shrub: 1 Urban: 0.5	Hamel et al. 2015
Threshold flow accumulation	Integer	1000	
Borselli k parameter	Decimal	2	Sharp et al. 2016
Borselli IC0 parameter	Decimal	0.5	Sharp et al. 2016
Max SDR value	Decimal	0.8	Sharp et al. 2016

InVEST Future Scenarios

After running the water yield and sediment export models with the current land use/land cover data and climate data, we then ran them again five times with projected development and climate data under two CO_2 emissions scenarios for the mid-21st century (Table 1). We then compared the results of the current and future models to determine which subwatersheds are likely to experience the greatest changes in water yield and sediment export around 2050.

The future climate data we used from the Climate Wizard Tool showed that precipitation, potential evapotranspiration, and erosivity are all expected to increase by 2050 under both climate scenarios we evaluated (Fig. 7). As mentioned previously, these values were calculated from the median predictions of 16 general circulation models, which were then averaged together to produce average annual values for the French Broad River Basin.

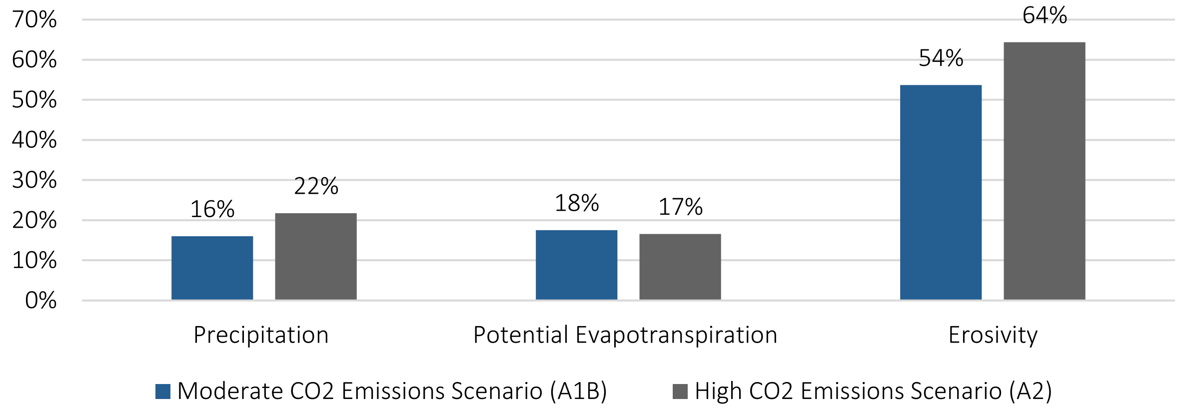

Figure 7: 2050 climate variable increases over current levels for the water yield and sediment export models

Important Aquatic Species

Several of the aquatic ecosystem services in the French Broad River Basin, including freshwater fishing opportunities and the existence value of rare species, directly depend on the presence of suitable habitat for relevant species within the watershed. The purpose of this analysis was to assess the current distribution of habitat for important aquatic species within the French Broad River Basin, and to examine what effects climate change and development might have on the amount of habitat available to these species through 2050.

There are many statistical techniques that can be used to predict where habitat for a particular species is located, based on a set of variables that include information about elements of habitat thought to be important to that species. For example, a land cover dataset that includes forest types would be useful for predicting habitat for a bird species that requires certain kinds of trees for nesting. In general, these techniques examine a set of locations where individuals of a species have been found and compare the values of environmental variables at those locations with the values of environmental variables at other locations where individuals of the species have not been found. The statistical models differ in the type of input data required, the information provided about how well the model fits the data, and whether the model can be used to predict if a new location is habitat or nonhabitat (Urban, 2016). We chose to use the Maxent model for this analysis because it accepts both continuous and categorical input variables, provides information about the model fit and the importance of individual environmental variables, and can be used to classify new samples as habitat or nonhabitat (Phillips, Dudik, & Schapire, 2017). Studies have shown that Maxent has excellent predictive power relative to other habitat distribution models, especially when fewer than 30 presence points are available for a modeled species (Wisz et al., 2008).

Maxent requires two datasets to create a habitat model for a species: a set of presence points, which contain the environmental variables for locations where an individual of that species has been found; and a set of background points, which contain the environmental variables for locations where an individual of that species has not been found. For this analysis, we used a set of presence points originally compiled for a statewide habitat analysis of aquatic species in North Carolina (Endries, 2011). These data were collected from the North Carolina Natural Heritage Program Element Occurrence Dataset, the North Carolina Museum of Natural Sciences Research and Collections Section Dataset, the North Carolina Wildlife Resources Commission Priority Species Monitoring Dataset, and the North Carolina Wildlife Resources Commission Trout Distribution Dataset. The geographic location of each species presence point is the stream segment in which that species was found.

We selected 12 aquatic species for habitat modeling: 8 listed as species of special concern, threatened, or endangered by North Carolina or federally; and 4 game fish species that are target species for anglers in the FBRB (Table 4). Each of these species had at least 18 presence points within the FBRB. In total, the selected species include one amphibian species, eight fish species, and three mussel species.

Table 4: Aquatic species included in Maxent habitat models

Scientific Name	Common Name	Type	State Status	Federal Status	Game Species?
Cryptobranchus alleganiensis	Eastern hellbender	Amphibian	Special Concern	None	No
Erimystax insignis	Blotched Chub	Fish	None	Species of Concern	No
Etheostoma acuticeps	Sharphead darter	Fish	Threatened	None	No
Luxilus chrysocephalus	Striped shiner	Fish	Special Concern	None	No
Percina squamata	Olive darter	Fish	Special Concern	Species of Concern	No
Micropterus dolomieu	Smallmouth bass	Fish	None	None	Yes
Oncorhynchus mykiss	Rainbow trout	Fish	None	None	Yes
Salmo trutta	Brown trout	Fish	None	None	Yes
Salvelinus fontinalis	Brook trout	Fish	None	None	Yes
Alasmidonta raveneliana	Appalachian elktoe	Mussel	Endangered	Endangered	No
Lampsilis fasciola	Wavy-rayed lampmussel	Mussel	Special Concern	None	No
Strophitus undulatus	Creeper, Squawfoot	Mussel	Threatened	None	No

The selection of background points is an important factor determining how well the model fits the data and the usefulness of its predictions. Providing background points from too wide a geographic area, especially including areas where the species cannot occur, will result in a model that fits the data extremely well, but does not provide useful predictions. For example, a Maxent model of penguin habitat that included points from around the world for background data would likely show that penguins live in cold areas with ice cover at extreme north and south latitudes. While this is correct, none of this is new information, and it does not help to determine what areas within those geographic bounds are suitable for penguin habitat. A better penguin habitat model would include only background points from locations within the penguins' known range where penguins have not been found. On the other hand, providing background points from too narrow a geographic area can limit the model's ability to predict whether new sample points are habitat or nonhabitat. This is especially important when using the model to predict habitat in new geographic locations or under different future scenarios, where the values of environmental variables for those new locations may be outside the range of values in the training data (the background and presence points originally used to create the model). When Maxent encounters a value outside the range of the training data, it is forced to extrapolate the relationship between that variable and habitat probability, which may not reflect the true species response to that variable. Therefore, it is best to include training data from as wide a range of geographic locations as possible, while excluding data from locations outside of the species' geographic range.

To include as many background points as possible from across North Carolina without using any points from areas outside the species' geographic range (e.g. coastal streams for mountain species), we created a custom set of background points for each modeled species. Each set of background points consisted of all stream segment catchments in any HUC-8 catchment where that species had been found. In other words, we looked at all of the stream segment catchments where the species had been found, identified all of the HUC-8 catchments in which those stream segment catchments were located, and extracted the rest of the stream segment catchments in those HUC-8 catchments as background points (Figure 8).

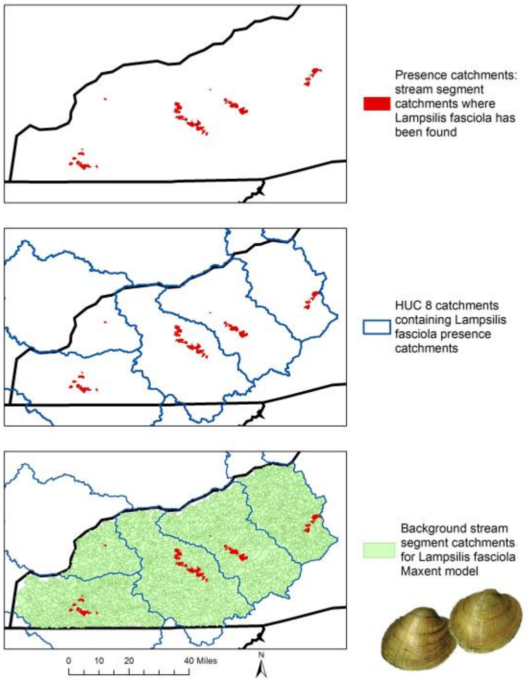

Figure 8: Example background points selection process for Lampsilis fasciola Maxent model.

Next, we selected the environmental variables that would be used to create each species model. We started with 15 environmental variables, based on those used in the Endries 2011 analysis, that were available for the entire state (Table 5). In addition, all variables that would be affected by either climate change or development needed to have a corresponding future projected dataset for 2050. These variables relate to the environmental conditions within a stream but do not account for the species' ability to reach a stream section. Some streams that appear to be suitable habitat for a given species in these models may not be accessible to individuals of that species due to an obstruction (e.g. dam or culvert) or an area of unsuitable habitat between an existing population of that species and the modeled stream.

Table 5: Environmental variables and data sources used for Maxent habitat models

Variable name	Variable type	Data source - present	Data source - future
Drainage area (square kilometers)	Upstream	NHDPlus V2 - Catchment Attributes	NHDPlus V2 - Catchment Attributes
Strahler stream order	Stream segment	NHDPlus V2 - Flowline	NHDPlus V2 - Flowline
Gradient	Stream segment	NHDPlus V2 - Flowline	NHDPlus V2 - Flowline
Sinuosity	Stream segment	NHDPlus V2 - Flowline	NHDPlus V2 - Flowline
Mean annual temperature (degrees Fahrenheit)	Catchment	WorldClim - Present	WorldClim - 2050
Mean annual precipitation (millimeters)	Catchment	WorldClim - Present	WorldClim - 2050
% forest	Catchment	NLCD 2011	FUTURES 2050
% developed	Catchment	NLCD 2011	FUTURES 2050
% cropland	Catchment	NLCD 2011	FUTURES 2050
% pasture	Catchment	NLCD 2011	FUTURES 2050
% barren	Catchment	NLCD 2011	FUTURES 2050
% shrubland	Catchment	NLCD 2011	FUTURES 2050
% wetland	Catchment	NLCD 2011	FUTURES 2050
Geology type	Stream segment	USGS - NC Geology	USGS - NC Geology
% riparian disturbance	Stream segment	NLCD 2011	FUTURES 2050

To create the simplest possible species models without variables that did not contribute significantly to the outcome or variables that did not contribute additional information, we selected a subset of these variables for each species model (Appendix I, Tables 11 and 12). While most of the environmental variables were continuous, two were categorical and therefore required different statistical techniques. Elimination of extraneous continuous variables that did not contribute significantly to the outcome was done by testing the correlation between each variable and the presence or absence of each species with a Pearson's product-moment correlation. Variables that were not significantly ($p<0.05$) correlated with the species presence or absence were excluded from that species' model. Extraneous categorical variables were identified through an analysis of variance (ANOVA) test that compared the mean and variance of presence/absence for each species within each level of the categorical variable (for example, each geology type) with the variance between different levels of the variable. Again, variables for which the ANOVA was insignificant at $p=0.05$, indicating that different levels of the variable did not have different presence/absence rates, were excluded from the analysis for that species.

After this first variable screening step, we checked the remaining variables in each species model for strong correlations with each other. For continuous variables, this was done with a correlation matrix that shows the strength of correlation between each pair of variables. The correlation between two variables represents the amount of variability in one variable that can be explained based on the other variable. High correlation indicates that the two variables provide very similar information, and one of them can be excluded from the model without losing a large amount of data. We removed one variable from any pair that was correlated at 0.8 or greater. To determine which of the pair of variables to remove, we first removed any variables that were correlated with multiple other variables, to minimize the total number of excluded variables. We prioritized keeping climate variables over other types, since they were necessary to see any effect in our future climate projections. Finally, we retained variables that we thought contained more information (for example, the stream disturbance variable has more information than the individual land cover variables since it is based on multiple land cover variables).

Once variable selection was complete, we ran a separate Maxent analysis for each species, using all of the species' presence points in North Carolina and background points for stream segment catchments in relevant HUC-8 catchments as described above. The environmental variables selected for each species in the variable screening process were summarized on a stream segment and stream segment catchment scale from present-day datasets for each presence and background point. We used the resulting Maxent model for each species to predict the species' present-day habitat distribution in the FBRB by projecting the models onto a new set of present-day environmental variables containing all of the stream segment catchments within the FBRB.

The output of each Maxent projection is a value from 0 to 1 for each stream segment catchment, representing the probability of the species occurring in that stream segment. To classify stream segments as habitat or nonhabitat for a species, the user must select a threshold probability; all segments with a probability above the threshold are classified as habitat, and all segments with a probability below the threshold are classified as nonhabitat. To assist with our selection of a threshold value for each species' habitat model, we used 70% of the presence points for each species to create the habitat model for that species and the remaining 30% of the presence points to test the model (after Poulos and Chernoff, 2014). Keeping some presence points for model testing allows Maxent to calculate the test sensitivity (proportion of testing points that are designated as habitat) and selectivity (1 - proportion of the background points that are designated as habitat) resulting from various threshold values. We used Maxent's "balance" threshold, which minimizes the training omission rate, the threshold value, and the fractional predicted habitat area.

We summarized the resulting Maxent projection in two ways: by species and by HUC-12 catchments in the FBRB. To summarize by species, we calculated the total amount of habitat (measured in kilometers of stream length) projected to be available to each species in the FBRB. To summarize by HUC-12 catchment, we calculated the total number of species and total amount of habitat (measured in kilometers of stream length) for those species projected to exist in each HUC-12 catchment in the FBRB.

Future Scenarios

We predicted the species' 2050 habitat distribution in the FBRB under five different climate change and development scenarios by projecting the models onto five new sets of environmental variables derived from future climate and development projections (Table 1). The temperature and precipitation variables were updated for the climate change scenarios, and the land cover variables were updated for the development scenario. Again, we classified each stream segment catchment as habitat or nonhabitat for each species under the five future scenarios with the "balance" threshold. We summarized the five resulting Maxent projections in two ways: by species and by subwatersheds in the FBRB. To summarize by species, we calculated the total amount of habitat (measured in kilometers of stream length) projected to be available to each species under each scenario. To summarize by HUC-12 catchment, we calculated the total number of species and amount of habitat (measured in kilometers of stream length) projected to exist in each HUC-12 catchment under each scenario.

Sensitivity Analysis

Our results for changes in species habitat distributions in the future depend on predicted future climate variables; as discussed above, the predicted values for these variables are uncertain. To assess the sensitivity of our results to changes in the predicted variable values, we conducted a one-at-a-time sensitivity analysis similar to the one described in the InVEST water yield section above. Starting with the predicted temperature and precipitation values for the moderate-emissions climate change scenario, we changed each of these by -20%, -10%, 10%, and 20% and re-ran the species models with these updated climate variables, holding all other variables in the model (including the other climate variable) constant. We recalculated the projected species richness and amount of aquatic species habitat per subwatershed, as well as the amount of habitat per species, for each of these model projections. Comparing these results to our original results for the moderate-emissions climate scenario (A1B) allowed us to see how much the results change if the moderate-emissions climate projection over or under-estimates temperature or precipitation in the FBRB.

Results

Riparian Buffers

To consider how water quality in the French Broad River Basin may be impacted by future development and land use change, we quantified riparian buffers using current and projected land use data. For each subwatershed, we calculated the effective riparian buffers along the flow paths between nonpoint source pollution (including both urban and agricultural land) and waterways to determine where vegetated land cover is providing the greatest benefit to aquatic ecosystem services. Intuitively, a larger amount of riparian buffer would suggest greater vegetated land cover and fewer pollution sources. However, because effective riparian buffers are a measure of only the vegetated land cover that connects pollution source to the water, a greater amount of riparian buffer in this analysis indicates more pollution sources. Any vegetated land outside of the flow path would not be counted as effective riparian buffers. Figure 9 shows two similar land cover scenarios, where scenario B contains more urban land cover than scenario

A. Despite the decrease in vegetated land cover, scenario B would likely contain a larger amount of effective riparian buffers because there is more vegetated land cover between the pollution sources (urban land) and the water. Although vegetated land slightly decreases in scenario B, more vegetation is counted as effective buffer because it falls within the flow path between pollution source and the water.

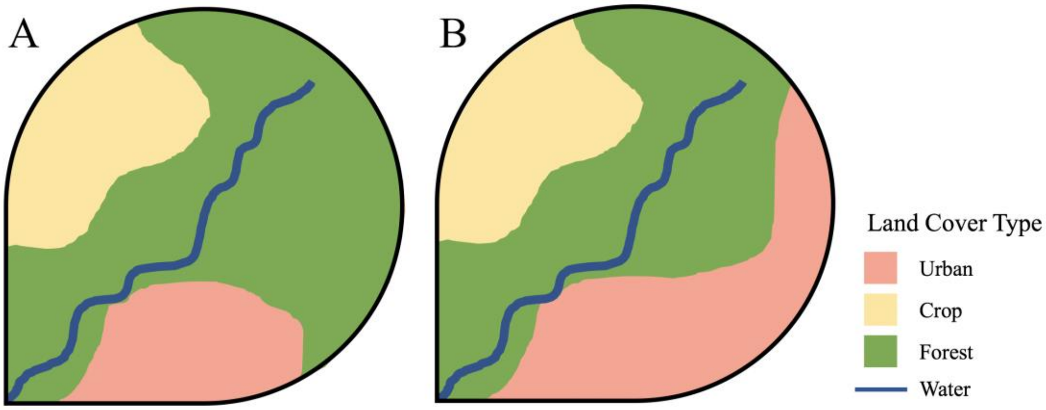

Figure 9: Scenarios A & B, showing that greater urban & crop land cover results in a greater amount of effective riparian buffers.

For the current scenario, the mean effective riparian buffer per subwatershed was 31,455 square meters (Fig. 10). In general, the southern and eastern portions of the FBRB contain a greater amount of effective riparian buffers because they have large amounts of nonpoint source pollution and less protected land and vegetated land cover than other parts of the FBRB. The Cataloochee Creek subwatershed, which is located within the Great Smoky Mountains National Park, provides the least amount of buffer (about 15,000 square meters); the North Fork Swannanoa River subwatershed, which is protected by the Conservation Trust for North Carolina, provides the greatest amount (over 80,000 square meters).

Considering the 2050 future scenario of development only, the mean effective riparian buffer per subwatershed increases to about 43,129 square meters. Per subwatershed, the changes in effective riparian buffers from the current scenario to the 2050 scenario range from a decrease of 21% to an increase of just over 200%. This overall large increase is a result of the projected increases in pollution sources and the corresponding increases in flow paths through vegetated land between pollution source and the water. Again, the southern and eastern portions of the FBRB provide greater amounts of effective riparian buffers. Similar to the current scenario, the Cataloochee Creek subwatershed provides the least amount of riparian buffers with just over 15,000 square meters. The East Fork French Broad River subwatershed, located at the southernmost portion of the FBRB, provides the greatest amount of riparian buffers (104,000 square meters) due to large increases in pollution sources. In general, areas that are currently protected are predicted to have a lower change in effective riparian buffers than in other regions of the FBRB.

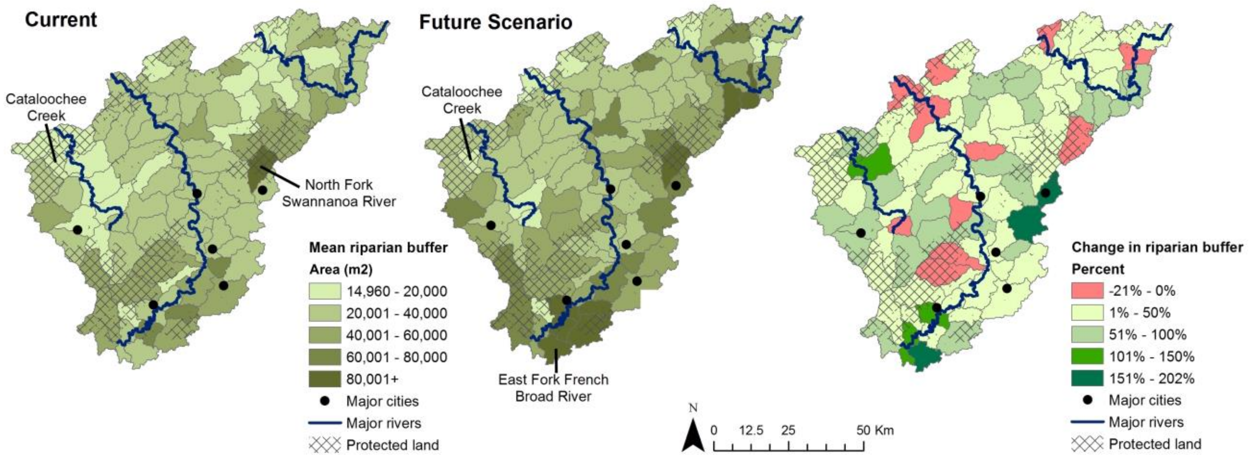

Figure 10: Effective riparian buffers by subwatershed for current and future scenarios with percent change.

The potential pollution reduction was calculated for each subwatershed in the FBRB to show where the effective riparian buffers are potentially preventing higher or lower amounts of nonpoint source pollution from entering the water. Because the effective riparian buffers were calculated as the length of flow between pollution source and the water, this calculation assumes that the greater the width of the effective buffer, the greater the filtering potential of that buffer. The potential pollution reduction would be smaller in subwatersheds where the pollution source is closer to the water than in subwatersheds where the pollution is further from the water and the flow path contains vegetated land cover (i.e. effective riparian buffer). It is important to note that the potential pollution reduction by effective riparian buffers in not a comprehensive indication of water quality currently or how it may change in the future. There are other characteristics of the watershed that also impact water quality, including other sources of pollution and the specific filtering potential of each riparian buffer. However, this analysis provides insight to the land cover characteristics of each subwatershed and their potential impact on water quality.

Overall, the potential pollution reduction is greater in the northern and western portion of the FBRB where more land is currently protected (Fig. 11). In the current scenario, the effective riparian buffers in six subwatersheds provide low potential pollution reduction. In the 2050 development only scenario, that number of subwatersheds in which the effective riparian buffers provide low potential pollution reduction increases to 13. The potential pollution reduction by effective riparian buffers in the 2050 development only scenario is expected to decrease by up to 12% from the current scenario. The East Fork French Broad River subwatershed is projected to experience a 12% decrease in potential pollution reduction, and 16 other subwatersheds are anticipated to experience a decrease of between 5% and 10% in potential pollution reduction in the 2050 future scenario. These results indicate that the projected increases in nonpoint source pollution are not buffered as well as the current scenario, either because pollution sources fall closer to the waterway or because less vegetated land cover is present in the flow path.

To consider how the projected future changes in potential pollution reduction will impact people living within the FBRB, the public surface drinking water supply sources from the NC Department of Environmental Quality were overlaid on the percent change in potential pollution reduction (Fig. 11). There are two drinking water supply intakes in the Upper Jonathans Creek subwatershed currently serve nearly 10,000 individuals, and that subwatershed is expected to experience a 6% decrease in potential pollution reduction by 2050. The Grassy Creek-North Toe

River subwatershed is expected to experience a 6% decrease in potential pollution reduction; it contains two drinking water supply intakes that currently serve 2,200 individuals. Additionally, there are 4 other drinking water supply intakes, including the city of Asheville, that together currently serve over 71,000 individuals and are located within subwatersheds that are expected to experience a decrease in potential pollution reduction by effective riparian buffers of 2.5% to 5%. For these subwatersheds that provide drinking water supply to the FBRB, the predicted decreases in filtering potential by riparian buffers are moderate, but should be considered in planning for management activities aimed at preserving water quality.

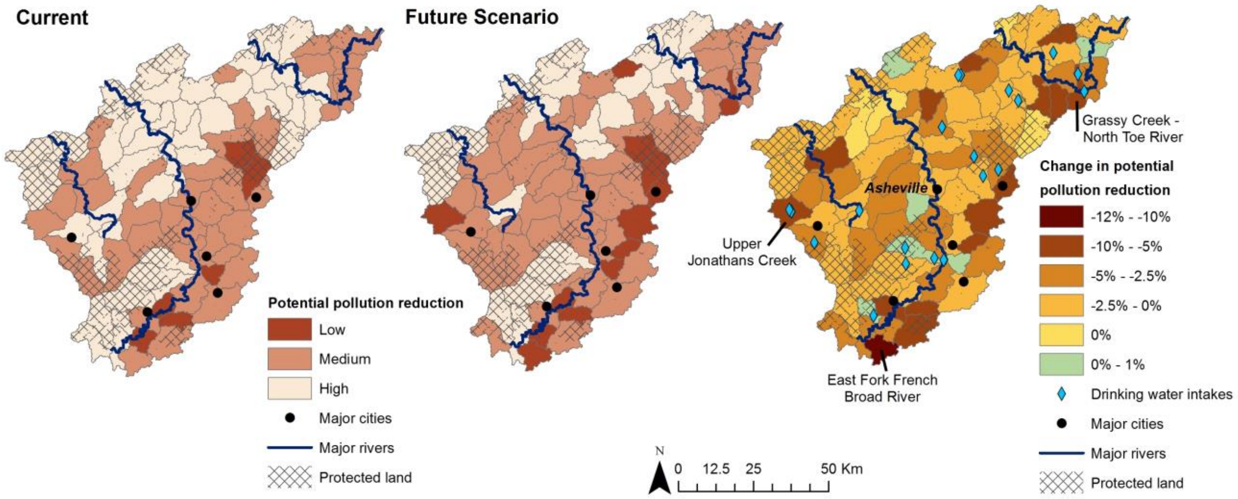

Figure 11: Potential pollution reduction by subwatershed for current and future scenarios with percent change.

InVEST

The results of the InVEST models show that the total amount of both annual water yield and sediment export in the French Broad River Basin can be expected to increase by 2050 under all five climate and development scenarios (Table 6). At the subwatershed level, however, there is a high degree of variability, with some subwatersheds showing substantial decreases in water yield (Fig. 12) and even some small decreases in sediment export (Fig. 13). Climate change is predicted to have the greatest impact on water yield, resulting in an average watershed-wide increase in water yield of 24% under the moderate A1B climate scenario and a 40% increase in water yield under the high A2 climate scenario. At the subwatershed level, predicted changes in water yield range from decreases of 40% to increases of up to 224% (Fig. 12). The subwatersheds predicted to experience the greatest increases in water yield are largely concentrated in the greater Asheville area, while the subwatersheds with the greatest decreases are mostly in subwatersheds with large portions of protected land. The future scenario that just considers development shows the smallest increases in water yield, which is the result of the fact that the FUTURES urban growth model does not predict significant increases in development in the French Broad River Basin by 2050.

For the sediment model, development and climate change seem to have nearly equal effects on increasing sediment export. The model predicts an average watershed-wide increase in sediment export of 40% with predicted future development, a 40% to 50% increase for both the A1B and A2 climate scenarios, and a 106% to 126% increase if development and climate change co-occur (Table 6). Development and climate change have an additive effect for the water yield model, but for the sediment model there are clearly some nonlinear effects that cause the total amount of sediment exported under the climate change and development models to be greater than the sum of the climate only and development only models.

The values of water yield and sediment export reported in Table 6 represent the average annual volumes that are yielded/exported from each subwatershed, and are summed for the French Broad River Basin as a whole. Water yield is the total volume of water that flows from the landscape in an average year, and can be compared to measured stream gage flow data at the outflow point of each subwatershed. It is important to note that the volumes included in Table 6 and Figures 12 and 13 should be considered as rough estimates of long term trends, and may vary considerably from measured data in any given year based on precipitation, temperature, and other variables. As mentioned previously, this analysis is best used to evaluate changes between current and future scenarios, and did not attempt to calibrate the model to measured data on water yield or sediment export.

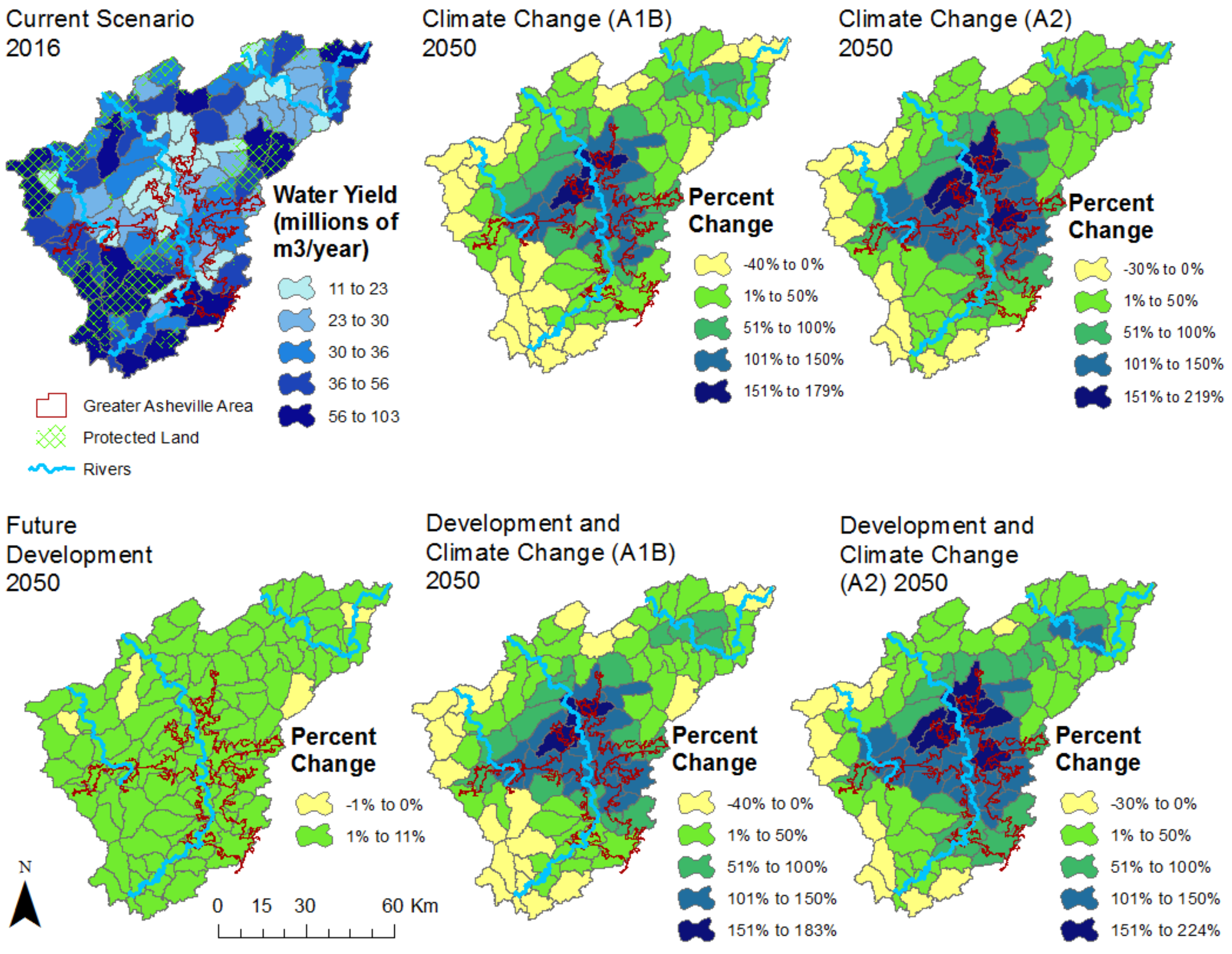

Figure 12: Current water yield in the French Broad River Basin, and predicted percent changes under five climate and development scenarios in 2050.

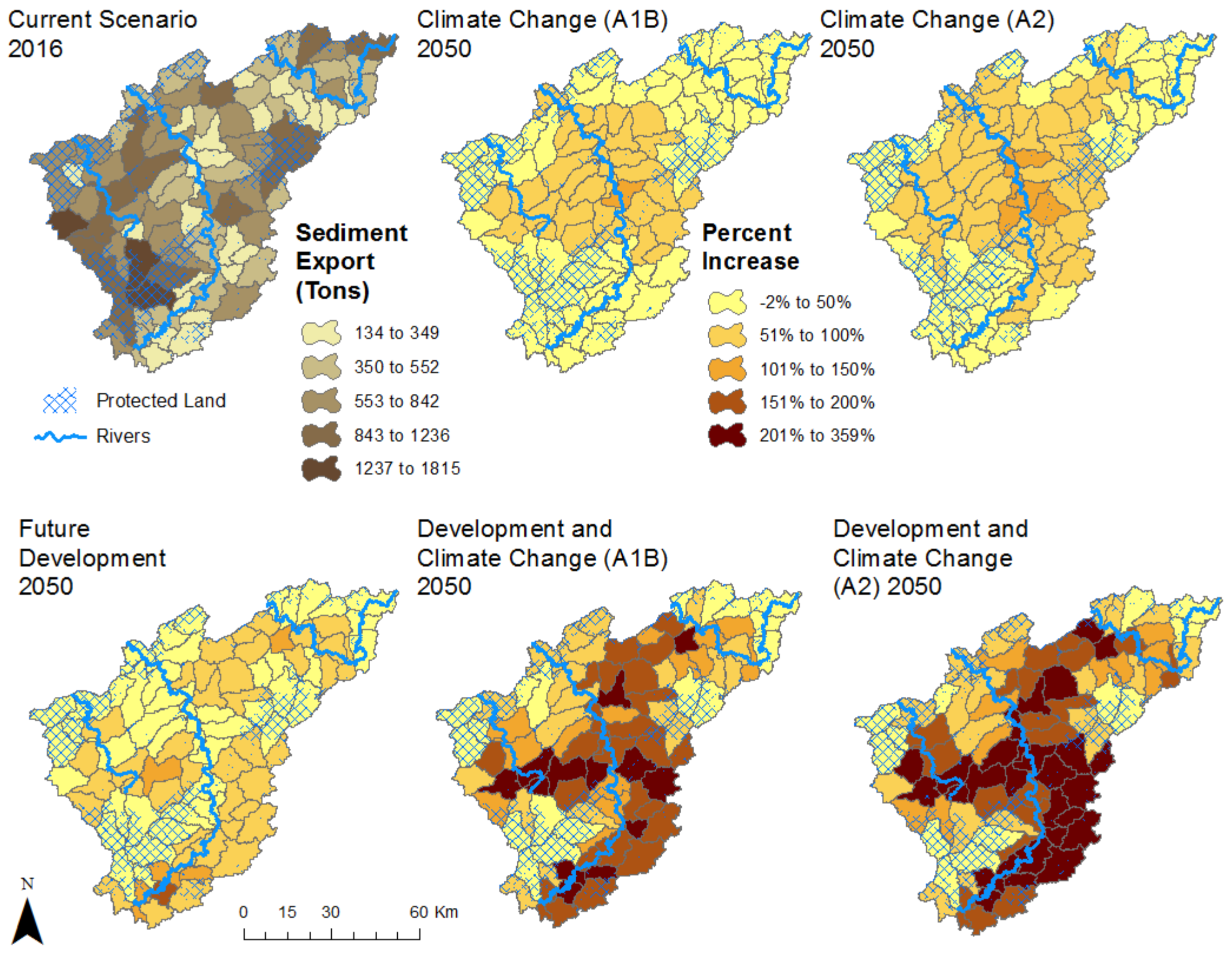

Figure 13: Current sediment export in the French Broad River Basin, and predicted percent changes under five climate and development scenarios.

Table 6: Predicted increase in hydrologic ecosystem services in 2050

Scenario	Ecosystem Services	Subwatershed average	Total FBRB	Total FBRB % Increase
Current Scenario	Annual Water Yield (millions of m3)/year)	39.9	3,552	NA
	Sediment Export (tons/year)	602	53,597	NA
Future Development	Annual Water Yield (millions of m3)/year)	40.8	3,635	2%
	Sediment Export (tons/year)	845	75,280	40%
A1B Climate Scenario	Annual Water Yield (millions of m3)/year)	49.4	4,397	24%
	Sediment Export (tons/year)	840	74,834	40%
A2 Climate Scenario	Annual Water Yield (millions of m3)/year)	55.8	4,962	40%
	Sediment Export (tons/year)	900	80,168	50%
Future Development and A1B Climate Scenario	Annual Water Yield (millions of m3)/year)	50.4	4,487	26%
	Sediment Export (tons/year)	1,240	110,446	106%
Future Development and A2 Climate Scenario	Annual Water Yield (m3)/year)	56.8	5,052	42%
	Sediment Export (tons)	1,359	121,024	126%

InVEST Sensitivity Analysis

As figures 12 and 13 demonstrate, the different subwatersheds showed widely varying degrees of change in water yield and sediment based on their different features (e.g., land cover, slope, soils, etc.). We therefore tested the sensitivity of the model to changes in precipitation, potential evapotranspiration, and the Z parameter by evaluating the ten largest subwatersheds (Fig. 14). The sensitivity analysis revealed that the model was most sensitive to changes in precipitation, with a 20% increase in precipitation resulting in an average increase in water yield of over 50% among the ten largest subwatersheds. Water yield was less sensitive to changes in potential evapotranspiration, with a 20% increase in evapotranspiration resulting in an average decrease in total water yield of 16%. Of the three modeled parameters, water yield was the least sensitive to the Z parameter, with a 20% increase in the Z parameter resulting in an average decrease in water yield of 5% among the ten largest subwatersheds.

The results of the sensitivity analysis show that if the climate models are overestimating precipitation by even a relatively small amount it could cause InVEST to greatly overestimate future water yield. Similarly, if the climate models are overestimating potential evapotranspiration it could cause InVEST to underestimate future water yield. The climate data for the moderate A1B climate change scenario predicts that the average precipitation in the study area will increase by 16% by 2050, and potential evapotranspiration will increase by 18%. The fact that precipitation has a stronger effect on the model than evapotranspiration results in the model's prediction that water yield will substantially increase under this scenario. Under the A2 scenario precipitation is predicted to increase by 22%, while potential evapotranspiration is predicted to increase by only 17%, which results in this scenario having even more extreme predictions of water yield increases. The Z parameter influences the total amount of water predicted in the current and future scenarios, but would not have an effect on the percent change between the current and future scenarios since it is the same for both.

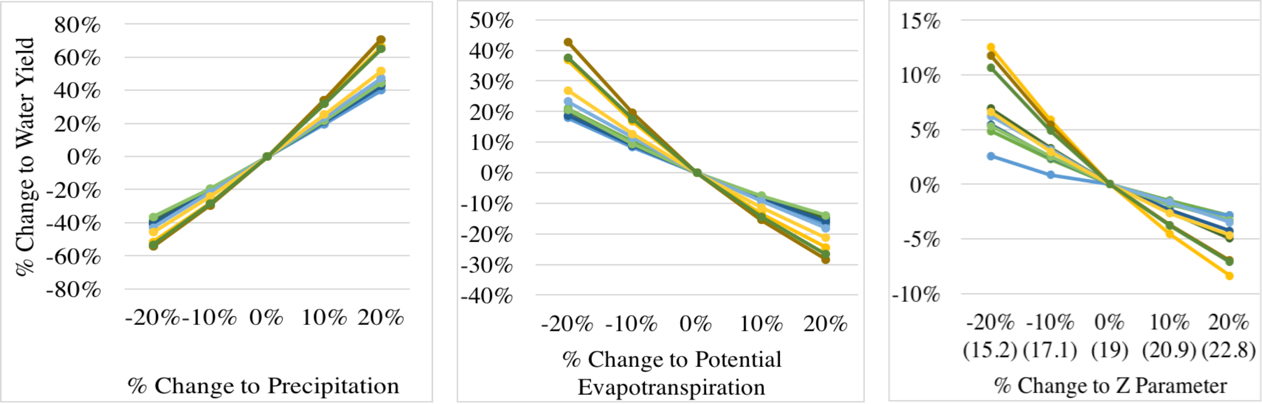

Figure 14: Water yield model sensitivity analysis in the 10 largest subwatersheds of the French Broad River Basin. The percent changes are shown relative to a baseline run using data from PRISM Climate Group (2004) and Trabucco and Zomer (2009).

Important Aquatic Species

Aquatic habitat by subwatershed

Each of the 89 subwatersheds in the FBRB is projected to contain habitat for at least seven of the twelve modeled species; 21 of the subwatersheds are projected to contain habitat for all twelve species. Subwatersheds with higher numbers of species tend to be located in the central and northeastern portions of the FBRB, specifically in the central and southern portions of the Upper French Broad River basin, the eastern portion of the Pigeon River basin, and the north-central portion of the Nolichucky River basin (Fig. 15). Subwatersheds with lower numbers of species are located in the northeastern part of the Upper French Broad River basin and along the western boundaries of the Pigeon and Upper French Broad River basins. These species distribution results may be partially due to bias in the underlying presence points dataset; since there are more people in the developed areas in the central portions of the FBRB, species are more likely to be seen there than in more remote areas, and the model predicts more species to exist in these areas.

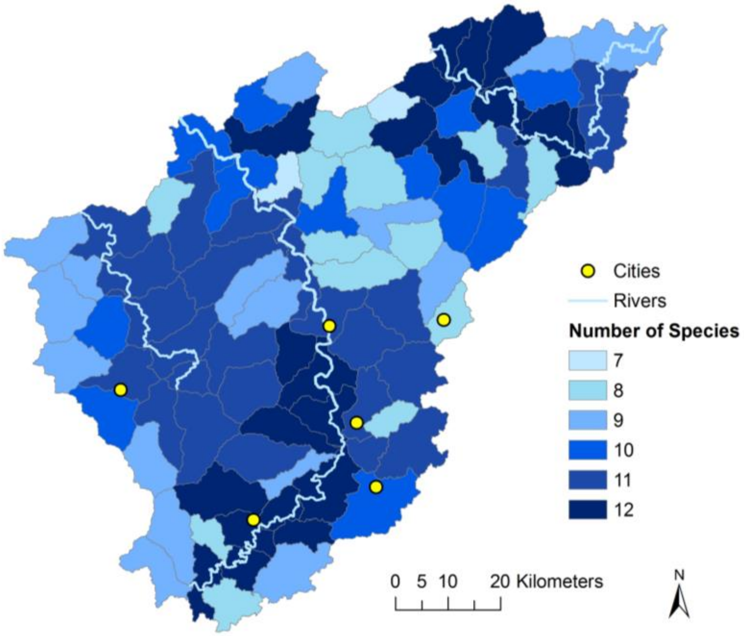

Figure 15: Projected number of aquatic species per subwatershed, present-day

The amount of species habitat by subwatershed, as measured by stream kilometers, shows a slightly different pattern (Fig. 16). Many of the subwatersheds projected to contain 11 or 12 species contain relatively little species habitat, especially those in the central-south portion of the Upper French Broad River basin and the northern portion of the Nolichucky River basin. This may be partially due to development; while these areas are highly sampled and therefore predicted to contain many species, the large amount of developed land means that there is less suitable aquatic habitat available overall for these species. In addition, some of the modeled species have very different habitat requirements, so subwatersheds that are projected to contain 11 or 12 of the modeled species include some species with little to no overlap in suitable habitat. In contrast, the subwatersheds with the highest amount of habitat, such as those in the northeastern and western FBRB, tend to contain large amounts of habitat for more widespread species such as trout (which overlap in their habitat preferences) resulting in a greater total amount of habitat.

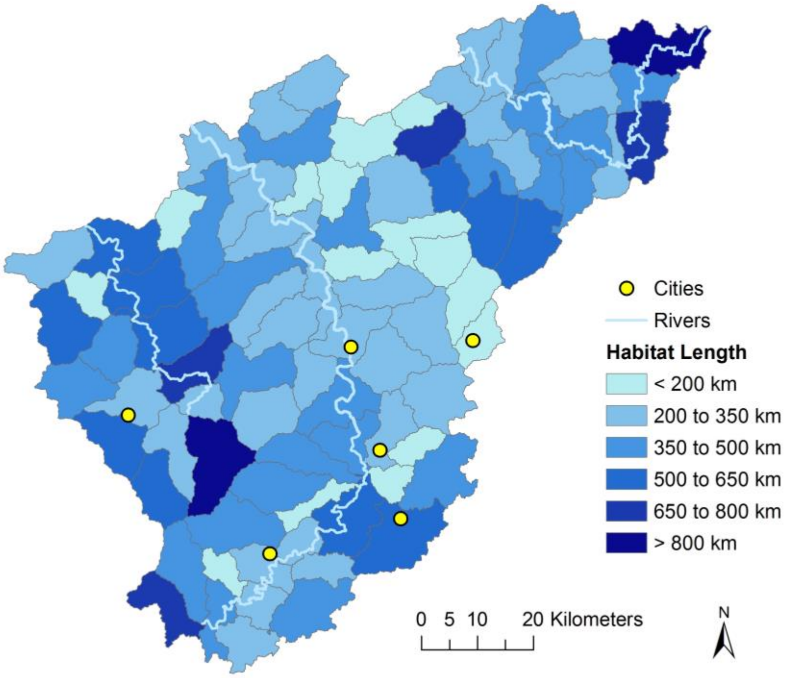

Figure 16: Projected amount of aquatic species habitat by subwatershed, present-day

Overall, climate change is projected to have a much greater effect than development on aquatic species distributions in the FBRB; this is likely due to the relatively small amount of development projected in the area through 2050. The average number of species per subwatershed is projected to remain the same as present (10 species) for the development-only, high-emissions climate change, and development plus high-emissions climate change scenarios, while decreasing slightly to 9 species for the moderate emissions climate change scenario and 8.8 species for the development plus moderate-emissions climate change scenario. The slightly larger effect of the moderate-emissions climate change scenario on species richness compared to the high-emissions scenario is due to differences in the two scenarios' precipitation projections. While the high-emissions scenario projects greater precipitation overall than the moderate-emissions scenario, some of the subwatersheds in the southern part of the FBRB are predicted to experience more precipitation under the moderate-emissions scenario than the high-emissions scenario. This resulted in slightly lower overall species richness in the moderate-emissions scenario than the high-emissions scenario. From a habitat amount perspective, the average stream length per subwatershed was about the same as the present-day projection for the development only scenario and somewhat lower for the other four scenarios, especially the development plus moderate-emissions climate change scenario (Table 7).

Table 7: Change in average HUC-12 habitat amount for future scenarios.

Scenario	Habitat amount, stream kilometers	% change from present
Present	366	n/a
Development Only	364	-1%
Climate Change Only, A1B	306	-16%
Climate Change Only, A2	310	-15%
Development + Climate Change, A1B	287	-22%
Development + Climate Change, A2	308	-16%

As Figure 17 shows, many subwatersheds are projected to lose at least 20% of their present-day modeled aquatic species richness in the moderate-emissions climate change scenario (A1B). The results for the high-emissions climate change scenario (A2) and both development plus climate change scenarios look very similar to Figure 16, so they are not shown here (Appendix III). Catchments in the southern part of the FBRB are the most affected; this appears to be driven by the predicted increase in precipitation in those areas. Many of the species models show a decline in habitat suitability when the precipitation exceeds a certain value, which varies by species (see Appendix III for full habitat distribution model results, including responses to individual variables).

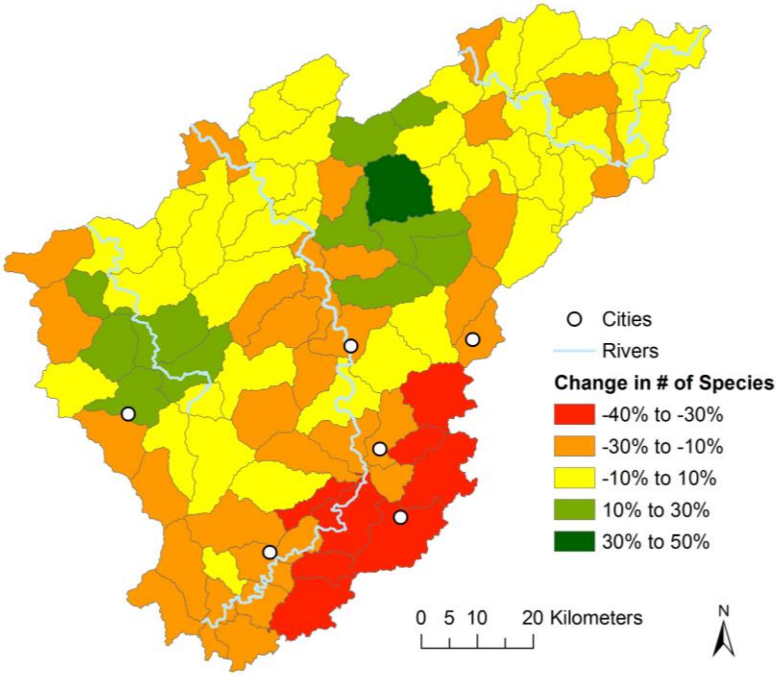

Figure 17: Projected change in number of species per subwatershed from the present-day scenario to the 2050 moderate-emissions climate change scenario.

The map showing the change in habitat amount per subwatershed from the present-day scenario to the 2050 moderate-emissions climate change scenario looks similar, but changes in habitat amount tend to be more severe than changes in species richness (Fig. 18). This is because the projected changes to temperature and precipitation will limit the amount of habitat that remains suitable for a given species, but as long as some amount of habitat for that species remains in a subwatershed, it has not lost that species. Therefore, we expect more dramatic changes to habitat amount than to species richness.

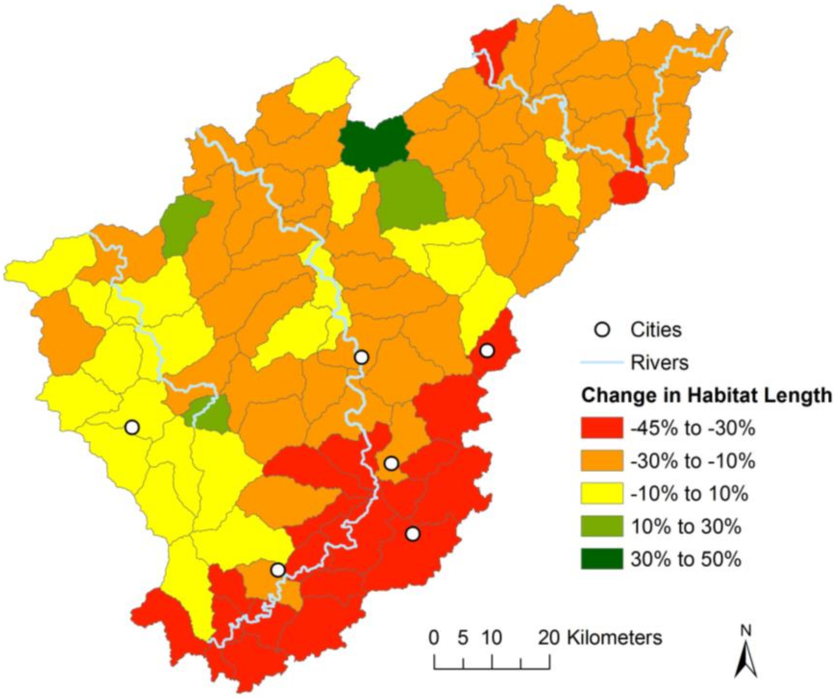

Figure 18: Projected change in amount of aquatic habitat per subwatershed from the present-day scenario to the 2050 moderate-emissions climate change scenario.

Aquatic habitat by species

The 12 aquatic species that we modeled with Maxent are all projected to occur in the FBRB under the present-day scenario. The amount of projected habitat for each species ranges from 548 stream kilometers (*Etheostoma acuticeps*, the sharphead darter) to 7800 stream kilometers (*Oncorhynchus mykiss*, the rainbow trout). The four top species in terms of projected available habitat are all game fish species, and the bottom four species are two mussels and two fish, all of which are listed as special concern, threatened, or endangered at either the state or federal level (Table 8).

Table 8: Projected present-day FBRB habitat for modeled species, with listing and game species status

Species	Projected FBRB habitat (km)	State Status	Federal Status	Game species?
Oncorhynchus mykiss	7802	None	None	Yes
Salmo trutta	7144	None	None	Yes
Salvelinus fontinalis	5651	None	None	Yes
Micropterus dolomieu	3138	None	None	Yes
Cryptobranchus alleganiensis	2136	Special Concern	None	No
Luxilus chrysocephalus	2111	Special Concern	None	No
Erimystax insignis	1617	None	Federal Species of Concern	No
Strophitus undulatus	1482	Threatened	None	No
Percina squamata	1105	Special Concern	Federal Species of Concern	No
Alasmidonta raveneliana	721	Endangered	Endangered	No
Lampsilis fasciola	621	Special Concern	None	No
Ethestoma acuticeps	548	Threatened	None	No

The three trout species are widely distributed throughout the FBRB, especially concentrated in the higher-elevation areas in the northeastern and western parts of the basin. The native brook trout, *Salvelinus fontinalis*, is shown as an example in Figure 19. The brown and rainbow trout distributions look similar, but are projected to occur in virtually all of the higher-elevation catchments as well as more of the lower-elevation catchments than the brook trout (Appendix III). The projected distribution for *Etheostoma acuticeps*, the sharphead darter, looks very different; this species is confined to the larger, lower-elevation rivers in the FBRB (Fig. 20). *Percina squamata*, *Lampsilis fasciola*, and *Alasmidonta raveneliana* also have similar projected distributions (Appendix III).

Half of the modeled aquatic species are projected to experience negative effects on the amount of habitat available to them in the FBRB through 2050 due to climate change, and half are projected to experience little or positive change (Table 9). Again, the projected changes to climate will have a much greater effect on the amount of habitat available to these species than the small amount of projected development. None of the modeled species is projected to experience a greater than 6% loss or gain of habitat due to development, and the development plus climate change scenario results are very similar to their corresponding climate change-only results. While only the climate change results are included in Table 9, the full results table is in Appendix II, Table 13.

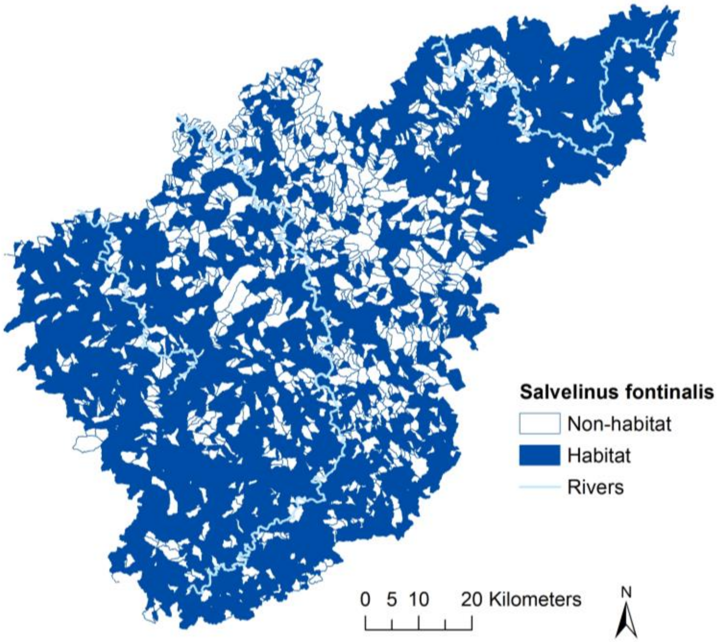

Figure 19: Projected habitat distribution for Salvelinus fontinalis in the FBRB, present-day

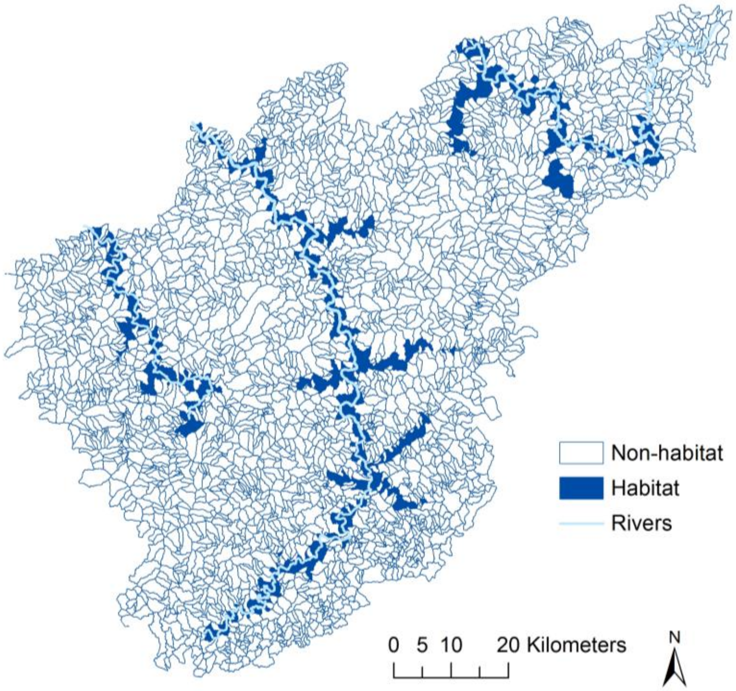

Figure 20: Projected habitat distribution for Etheostoma acuticeps in the FBRB, present-day

Table 9: Projected % change from present habitat amount in the FBRB for each modeled species and 2050 climate change scenario

Species	**Moderate Climate Change**	**High Climate Change**
Salmo trutta	-58%	-52%
Luxilus chrysocephalus	-61%	-60%
Cryptobranchus alleganiensis	-43%	-43%
Oncorhynchus mykiss	-37%	-34%
Micropterus dolomieu	-24%	-13%
Lampsilis fasciola	-18%	-18%
Ethestoma acuticeps	0.0%	0.0%
Strophitus undulatus	5.1%	27%
Alasmidonta raveneliana	7.1%	7.4%
Salvelinus fontinalis	33%	22%
Percina squamata	55%	49%
Erimystax insignis	98%	87%

Overall, the species likely to be most affected by climate change in the FBRB in terms of the amount of suitable habitat are *Salmo trutta*, *Luxilus chrysocephalus*, *Cryptobranchus alleganiensis*, and *Oncorhynchus mykiss*. Species including *Erimystax insignis, Percina squamata,* and *Salvelinus fontinalis* are projected to see an increase in suitable habitat in the FBRB by 2050, and the suitable habitat area for the remaining species is projected to remain about the same as present or has multiple possible outcomes depending on the climate scenario. However, the overall change in the amount of habitat in the FBRB does not take into account whether the location of that habitat changes, and therefore whether the species will be able to reach future habitat areas. For example, *Cryptobranchus alleganiensis* is projected to lose about 40% of its current habitat in the FBRB under all of the climate change and development plus climate change scenarios. In the present-day scenario, this species appears to be in the rivers and large tributary streams throughout the FBRB. In all of the climate change and climate change + development scenarios, it loses a large part of the habitat in the central FBRB, splitting one large, interconnected habitat area into several smaller, isolated areas (Fig. 21). Again, these models only assess whether a particular stream segment is likely to provide suitable habitat for a species. They do not evaluate whether a species will be able to reach suitable stream segments from its current distribution, or if individuals will be blocked by an area of unsuitable habitat or a physical obstruction.

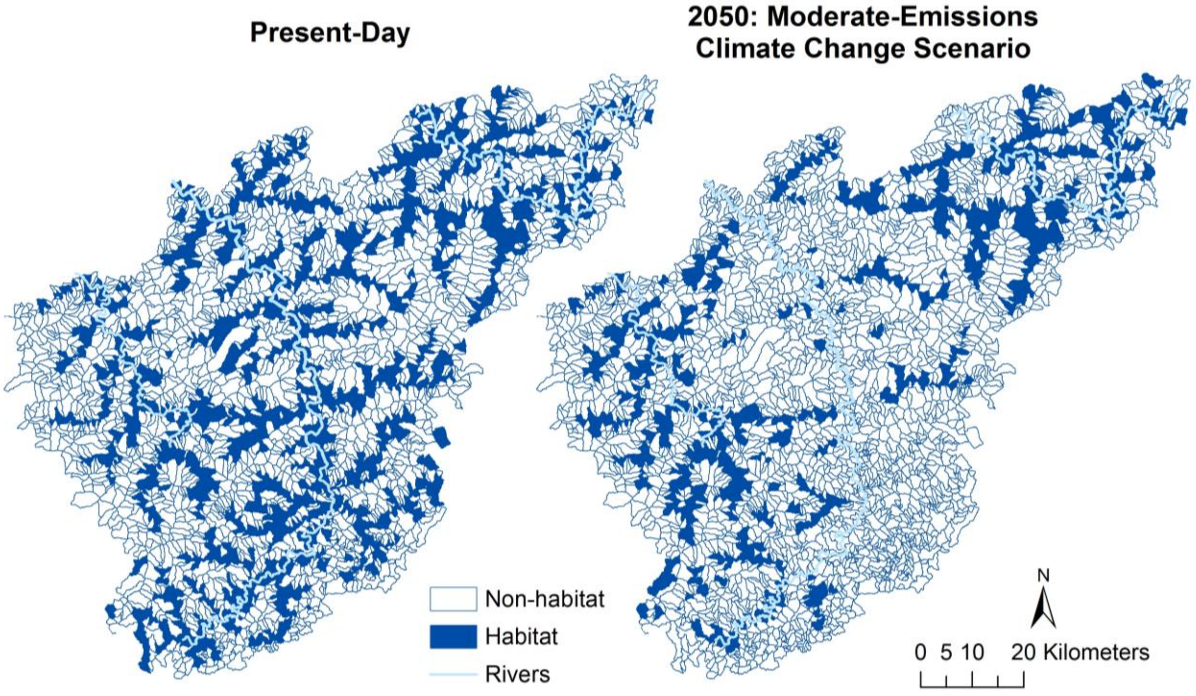

Figure 21: Comparison of projected Cryptobranchus alleganiensis habitat area in the present-day and development plus climate change A2 scenarios.

Model performance

The AUC is a statistic derived from a Maxent model that gives a measure of how well the model fits the input data; an AUC of 1 is a perfect fit, and an AUC of 0.5 indicates that the model is no better than a random prediction. AUCs are calculated separately for the data used to train the model and for test data. Our Maxent habitat models performed well overall, with training AUCs ranging from 0.854 to 0.980 and test AUCs from 0.814 to 0.963 (Table 21, Appendix I, “Results Tables”). The majority of both test and training AUCs were above 0.9, and all test AUCs were above 0.8 except for *Erimystax insignis*. (See Appendix II, Table 14 for AUC values for all Maxent models.)

Variable importance

The Maxent program tests the importance of each environmental variable to the habitat model by creating a model based on each variable by itself and comparing how well it fits the data relative to the final model, containing all of the environmental variables. In these tests, the cumulative drainage area was the most important variable for six out of the twelve habitat models, temperature and precipitation were each the most important variable for two of the twelve models, and stream order and geology were each the most important variable for one habitat model (Appendix II, Table 15). Slope was one of the top three variables for four of the twelve models, and maximum elevation was one of the top three variables for five of the twelve models. The riparian disturbance variable was the only other variable among the top three for any of the species models.

Sensitivity analysis

The species distribution model results were much more sensitive to changes in temperature than to changes in precipitation. None of the tested changes to the precipitation variable resulted in a mean change of more than 5% in the number of species per subwatershed, while a 10% decrease in temperature resulted in a 13% increase in the mean number of species per subwatershed, and both tested increases to temperature resulted in a greater than 17% drop in the mean number of species per subwatershed (Fig. 22).

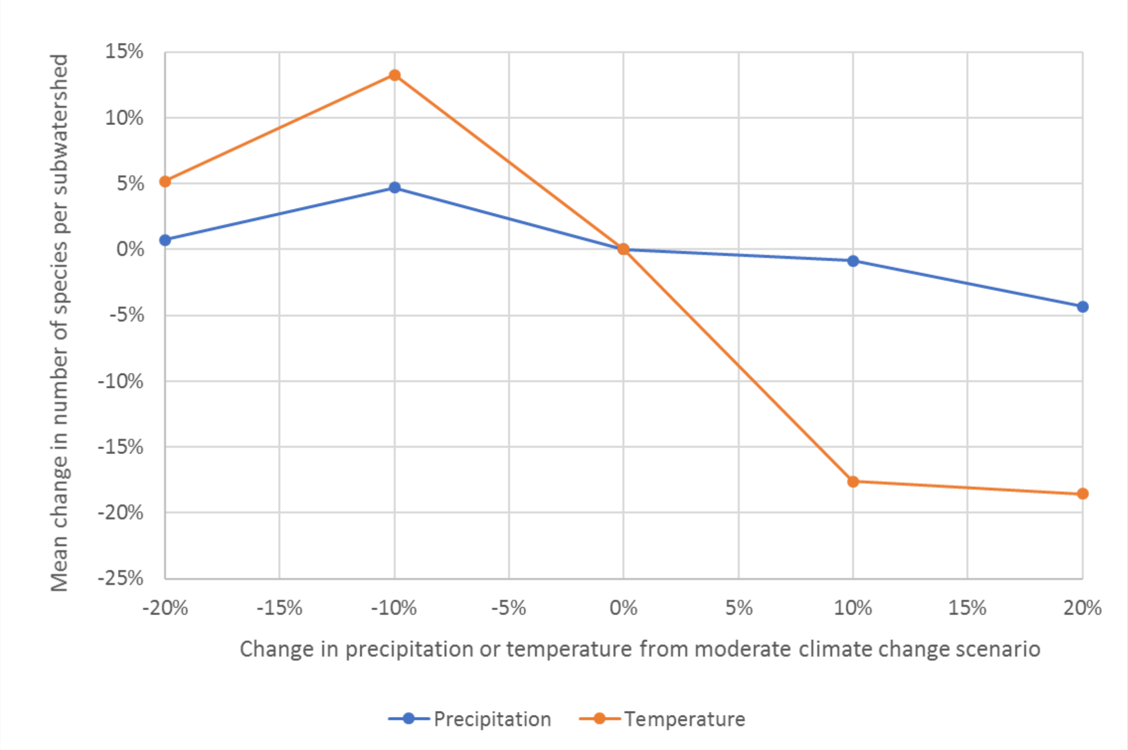

Figure 22: Analysis of sensitivity of mean change in number of species per subwatershed to changes in precipitation or temperature

Similarly, none of the tested precipitation changes except for the 20% decrease resulted in a greater than 4% change in habitat amount per subwatershed, while all of the tested temperature changes resulted in at least a 20% change in habitat amount per subwatershed (Fig. 23).

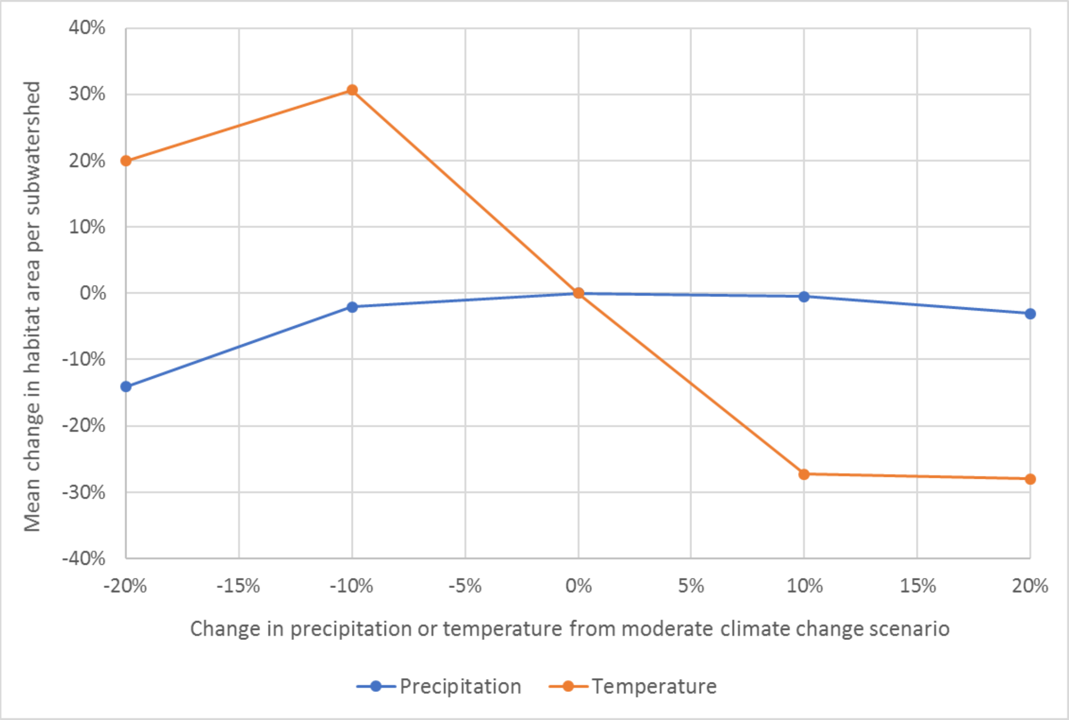

Figure 23: Analysis of sensitivity of mean change in habitat area per subwatershed to changes in precipitation or temperature

On an individual species basis, we compared the projected change in habitat amount from present for the moderate climate change scenario to the projected changes from present for each of the sensitivity analysis models (with either temperature or precipitation changed by -20% to 20% from the original moderate climate change projection). We assessed whether each species showed a stable direction of change from present as temperature and precipitation were varied (i.e. the projected changes in the amount of habitat for the sensitivity analysis models matched the direction of change predicted by the original moderate climate change scenario). We also evaluated whether each species showed a stable magnitude of change from present as temperature and precipitation were varied (i.e. the projected changes in the amount of habitat for the sensitivity analysis models were all within 20 percentage points of the predicted change for the moderate climate change scenario). Based on these evaluations, we divided the modeled species into three groups: those with stable direction and magnitude of change, those with stable direction but unstable magnitude of change, and those with unstable direction of change. We are most certain of our predictions about the response to climate change of the species in the “stable direction and magnitude” groups and least certain of our predictions about the responses of species in the “unstable direction” groups. For the precipitation sensitivity analysis, seven of the twelve modeled species showed stable direction and magnitude of change, two showed stable direction and unstable magnitude of change, and three showed unstable direction of change (Table 10). For the temperature sensitivity analysis, three species showed stable direction and magnitude of change, two species showed stable direction and unstable magnitude, and seven showed unstable direction (Table 10). Full results of the sensitivity analysis by species are in Appendix 16.

Table 10: Results of sensitivity analysis by species response

PRECIPITATION

Stable direction and magnitude	Stable direction, unstable magnitude	Unstable direction
Cryptobranchus alleganiensis	*Lampsilis fasciola*	*Alasmidonta raveneliana*
Erimystax insignis	*Percina squamata*	*Luxilus chrysocephalus*
Ethestoma acuticeps		*Salvelinus fontinalis*
Micropterus dolomieu		
Oncorhynchus mykiss		
Salmo trutta		
Strophitus undulatus		

TEMPERATURE

Stable direction and magnitude	Stable direction, unstable magnitude	Unstable direction
Ethestoma acuticeps	*Cryptobranchus alleganiensis*	*Alasmidonta raveneliana*
Luxilus chrysocephalus	*Micropterus dolomieu*	*Erimystax insignis*
Salvelinus fontinalis		*Lampsilis fasciola*
		Oncorhynchus mykiss
		Percina squamata
		Salmo trutta
		Strophitus undulatus

The results of the sensitivity analysis show that our projections of aquatic species distributions in the FBRB through 2050 are subject to change if the moderate climate change scenario over or under-estimates either temperature or precipitation, but our results are much more sensitive to changes in temperature than in precipitation. Since precipitation projections for the FBRB are much more uncertain than temperature projections, this is actually a good thing. While a 20% increase or decrease in temperature would have a greater impact on our species distribution results than a 20% increase or decrease in precipitation, climate models differ more in their precipitation projections than their temperature projections, so the probability of the climate projections being off in their temperature predictions by that amount is much smaller than for precipitation (Sun et al., 2008). Based on the sensitivity analysis results for individual species, we are least certain in our predictions of the effects of climate change on *Alasmidonta raveneliana*, *Luxilus chrysocephalus*, and *Salvelinus fontinalis*. Depending on the actual precipitation levels in 2050 compared to those predicted by the moderate climate change scenario, these species could either gain or lose habitat in the FBRB.

Discussion

By studying the FBRB at the subwatershed level, we provided results on water quantity and quality and important aquatic species habitat that can be used to guide management aimed at preserving and restoring these important services. Of course, there are many other ways to consider the ecosystem services and threats that were not included in our analysis; data limitations greatly constrained how we analyzed the FBRB. It is also important to note that part of the FBRB is located in Tennessee, but data limitations also constrained our analysis to North Carolina. If data becomes available for Tennessee, these analyses can be completed to provide results for the entire French Broad River Basin.

Riparian Buffers

High water quality in the FBRB is important for many reasons, including drinking water supply, aquatic species habitat, recreational opportunities, and a growing brewery industry. Especially in urban areas, pollution runoff into aquatic ecosystems is prevalent due to the high proportion of impervious surfaces and poses a major threat to water quality and aquatic species habitat suitability. This analysis suggests that the projected increases in development within the watershed by 2050 will likely result in increases in effective riparian buffers and decreases in the potential pollution filtration by these buffers. These findings reveal the need to consider the anticipated changes to and the impact of nonpoint source pollution when prioritizing areas and planning for management and conservation activities. Subwatersheds that are expected to experience the greatest increase in pollution contribution should be prioritized for protection or management, especially if those increases are located within subwatersheds that provide other important aquatic and hydrologic ecosystem services.

There are, of course, many other factors that impact water quality in the FBRB currently and in the future; the results of this analysis should be considered an exploratory assessment of how land cover characteristics may lead to a decrease in water quality on the subwatershed scale. The results provided by this analysis should be considered in conservation and management planning in addition to data on water quality and other types of pollution sources within the watershed, particularly in subwatersheds that provide drinking water supply and other important ecosystem services. Although nonpoint source pollution is considered one of the biggest threats to water quality, point source pollutants also contribute to reduced water quality. In the FBRB, there are numerous point source pollutants, including permitted National Pollutant Discharge Elimination Systems and concentrated animal feeding operations. Sewage system overflows and leaks have also been identified by the Department of Environmental Quality as a major water quality issue in the watershed (North Carolina Environmental Education, n.d.).

Additionally, there are some limitations to this analysis that are important to note. As with many geospatial analyses, we were limited by the availability of data. Our digital elevation model had a cell size of 30 meters by 30 meters, so the flow path based on the terrain may not be completely accurate. The future development data are also only projections of how urban growth may expand throughout the watershed, and any increases in agricultural land were not identified. Although the Baker et al. (2006) method is intended to overcome the conceptual limitations of a traditional riparian buffer analysis, this method may not be a completely accurate representation of the landscape characteristics in the FBRB. For example, the filtering potential of forested land is not, in reality, constant throughout the watershed, and the flow path that connects the pollution source to the water may not always follow the steepest path, as assumed by the model, due to physical impediments to flow.

InVEST

The InVEST analysis predicts that future development and climate change will result in potentially significant increases in water yield and sediment export. Increased sediment in waterbodies may be of concern to the operational hydroelectric dams in the FBRB, since higher levels of sediment may cause abrasion on the hydropower turbines and other components, and may also reduce water storage capacity. There are also numerous other dams in the watershed that do not generate hydropower, but which may still need to take measures to manage this increased sediment. Some of the surface water filtration plants in the FBRB may also find they need new filtration equipment to handle these increases in both sediment and water yield.

The InVEST model predicts that the FBRB could experience significant increases in water yield by the middle of the 21st century, and this result is generally supported by other studies on water yield under climate change. A master's thesis by Suttles (2017) analyzed how development and climate change may impact streamflow around the mid-21st century in the upper Yadkin-Pee Dee watershed of western North Carolina (near the French Broad River Basin), and found that average annual daily streamflow increased across all future scenarios that combined development and climate change, with increases in streamflow ranging from 3.5% to 63% (Suttles, 2017). Additionally, a study by Tao et al. (2014) modeled the effects of a high greenhouse gas emissions (A2) and low emissions (B1) scenario on water discharge in the Mississippi River, and found that annual water discharge would increase by 10.7% to 59.8% by the 2090s. Our results showing increased average annual water yield in the French Broad River Basin of 2% to 42% by the mid-21st century are generally consistent with these other studies.

These results can vary considerably, however, based on the timeframe and greenhouse gas emissions scenarios being evaluated. A study by Duan et al. (2016), for example, used a water supply stress index model to evaluate how water yield may change in national forests under moderate and high greenhouse gas emissions scenarios modeled for the 2030s and 2080s, and found that some national forests around the North Carolina-Tennessee border were predicted to experience up to a 10% increase in water yield while others showed up to a 20% decrease in water yield. Of the three national forests they evaluated in this region, all three showed an increase in water yield under the high emissions scenario modeled for the 2030s, two showed an increase and one decreased under the moderate emissions scenario modeled for the 2080s, one showed an increase and two decreased under the moderate emission scenario in the 2030s, and all three decreased under the high emission scenario modeled for the 2080s (Duan et al. 2016). Our study used different emissions scenarios and focused on a different timeframe (2050s), but this study by Duan et al. (2016) underscores the fact that it is hard to predict how water yield will change in the mountains of North Carolina.

There remains a high degree of uncertainty on how precipitation may change in the southeastern U.S. in the future. Precipitation is the single greatest driver of the InVEST model results showing increased water yield, so this is a major source of uncertainty. A study by Sun et al. (2008) evaluated the effects of two climate scenarios on the water supply stress index in the Southeast in 2020, and found that under the hot and dry climate scenario the water supply stress index in the French Broad River Basin is predicted to increase by 25% to 50%, while under the warm and wet climate scenario it is predicted to decrease by up to 20%. These opposite results are driven by the fact that the hot and dry climate model predicts precipitation will decrease by 10% to 20% by 2020, while the warm and wet climate model predicts it will increase by 10% to 20% (Sun et al., 2008). The Climate Wizard data used for the InVEST analysis was based on the median values of sixteen different general circulation models (not including the two used in the Sun et al. 2008 study), which were then averaged together. The intent is that this method produces a balanced estimate that does not fall to either extreme when it comes to predicting precipitation.

As with any GIS analysis, one of the major limitations in InVEST is the quality of the available data. The majority of current data used in the InVEST analysis was available at a high spatial resolution, with the one major exception being the erodibility data (k factor). This is unfortunately one of the three most influential parameters for the sensitivity of the sediment retention model (Hamel et al., 2015), and thus may have introduced some error into the model. Finally, the data used for the future climate scenarios was of a very low spatial resolution

(50km), which significantly limits the ability of the models to accurately predict how water yield and sediment export might change at a subwatershed level around the middle of this century.

Another potential source of error is the InVEST model itself. While some studies have found InVEST to have a reasonably high level of accuracy in predicting water yield volumes (Redhead et al., 2016), other studies have found that its hydrologic results significantly diverge from the results of the more robust Soil and Water Assessment Tool (Dennedy-Frank et al., 2016). Dennedy-Frank et al. compared the results from the InVEST water yield model to the results of the Soil and Water Assessment Tool in two watersheds in Indiana and Georgia, and found that in one of the watersheds the results were very similar, while in the other watershed the results varied by as much as 20%. A 2016 study by Redhead et al. in the United Kingdom conducted an empirical validation of the InVEST water yield model by comparing the modeled results to measured river flow data in 22 catchments. They found that when using United Kingdom-scale input data the median values of the InVEST model outputs had a percentage difference of less than 10% from the measured stream gage data (Redhead et al. 2016). When using global data from WorldClim and CGIAR, the InVEST outputs varied by up to 20% from measured data (Redhead et al., 2016). Despite these limitations, InVEST is still able to provide a reasonable estimate of water yield volume and sediment export, and predict how these ecosystem services and disservices may change in the future.

Aquatic Species Habitat

Overall, the amount of aquatic habitat currently available to a certain species in the FBRB corresponds quite well to the modeled species' status, in terms of state and federal protection. The four game fish species projected to have the most FBRB habitat in the present scenario are not listed by North Carolina or federally; their large amounts of FBRB habitat make sense given that their populations are not thought to be threatened. On the other end of the spectrum, the three species that listed as threatened or endangered either by North Carolina or the federal government all rank in the bottom four species in terms of the amount of habitat presently available in the FBRB.

The response of aquatic species in the FBRB to climate change and development depends on the particular species; some are projected to see increases in habitat area under future scenarios, while others will likely experience a steep decrease in habitat area. The two non-native trout species (*Salmo trutta* and *Oncorhynchus mykiss*) are both projected to lose large amounts of FBRB habitat under the future climate change and development + climate change scenarios, while the native trout *Salvelinus fontinalis* is projected to gain habitat in the FBRB under the same scenarios. Part of this difference is likely due to these species' different responses to precipitation: the probability of *Salmo trutta* presence peaks at 56 centimeters of precipitation/year and declines rapidly at precipitation levels between that peak and 67 centimeters/year, while the probability of *Salvelinus fontinalis* presence peaks at 61 centimeters/year (the precipitation response of *Oncorhynchus mykiss* is less well defined and has a broader peak between 52 and 70 centimeters/year) (Appendix III). It appears that the areas of the FBRB where *Salvelinus fontinalis* is projected to expand through 2050 under the climate change scenarios are places where the mean annual precipitation is projected to change from less than 47 centimeters/year to greater than 47 centimeters/year. The loss of *Salmo trutta* and *Oncorhynchus mykiss* habitat corresponds to areas where the mean annual temperature is projected to increase above 57°F. However, the *Salvelinus fontinalis* Maxent model does not include mean temperature because it was not significantly correlated with presence/absence during variable screening. It is unclear why; the presence points for *Salvelinus fontinalis* span about the same geographic area of western North Carolina as *Salmo trutta* and *Oncorhynchus mykiss*, so all three species had similar ranges of temperatures in the points used to model the data. The exclusion of temperature from the distribution model for *Salvelinus fontinalis* means that any response of this species to future temperature changes is not captured in this model, and makes it more difficult to accurately compare the responses of the three trout species to climate changes. However, if *Salvelinus fontinalis* is truly less sensitive to air temperature than the other trout species, it may be able to take advantage of the projected higher levels of precipitation in the FBRB over the next 30-40 years.

Cryptobranchus alleganiensis is one non-fish species that appears especially vulnerable to habitat loss in the FBRB due to climate change and development plus climate change. *Cryptobranchus alleganiensis* is projected to lose habitat in areas projected to have mean annual air temperatures greater than 56°F in the future scenarios; in its response curve, the presence probability drops off sharply after that temperature. Since these amphibians also require clean water with little siltation, land protection efforts in the FBRB may be crucial to ensuring that they can persist in those areas where the climate will remain suitable.

Several characteristics of these species models make them less than ideal for predicting where species habitat is currently located and how it will change in the future. As with any geospatial analysis, data availability and resolution were major constraints. Because our species models included presence points from throughout North Carolina, we could only use datasets that included the entire state; land cover and climate-related variables also needed to have equivalent projected datasets for 2050. There were many relevant habitat variables, such as stream temperature and in-stream flow rate and volume, that we were unable to use because no equivalent datasets exist for future scenarios. Instead, we used climate variables (mean air temperature and precipitation on a stream segment catchment scale) that hopefully capture some of the same information. In addition, the limited number of presence points for several of the modeled species likely prevented the model from including the full range of habitats where those species occur. *Luxilus chrysocephalus* was particularly affected by this problem; it had only 21 total presence points, all located in six subwatersheds in the Nolichucky River basin. The resulting species distribution is highly concentrated in that river basin, with only some scattered habitat patches throughout the rest of the FBRB. Other modeled species with few presence points were *Erimystax insignis* (18 presence points) and *Ethestoma acuticeps* (21); all other species had at least 50 presence points. However, even species with many presence points may have bias in the location of those points due to sampling effort and convenience. Remote and rural areas are less likely to be surveyed for aquatic species and may appear less often in sets of presence points than more populated and easily-accessible areas, even though the remote areas might contain better-quality habitat. In some cases, bias toward sampling in convenient streams under road crossings can result in species distribution models showing a positive response to development. For these reasons, projected species habitat distributions should be treated with caution and used to assess general trends and as a first step toward identifying likely locations for a given species.

Recommendations

To guide TNC's plans for conservation work in the FBRB, we identified several groups of priority subwatersheds. Two of these priority groups are based on predicted changes to subwatersheds' water quantity and quality due to development and climate change, and the third is based on predicted changes to subwatersheds' aquatic species richness and aquatic habitat due to climate change.

To protect the subwatersheds most threatened by climate change and development in terms of water yield, sediment export, and potential pollution reduction by effective riparian buffers, we prioritized 13 subwatersheds for conservation action (Fig. 24). This includes two priority categories, Priority A and Priority B, which are expected to experience opposing changes in water yield.

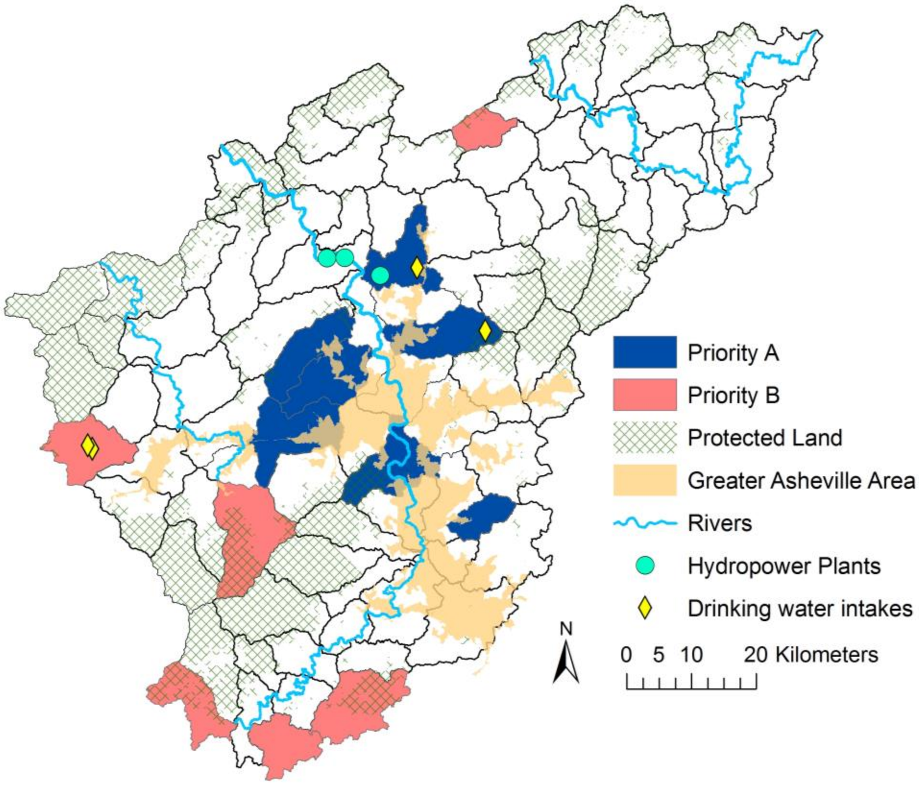

Figure 24: Subwatersheds likely to impact drinking water and hydropower based on water yield, sediment export, and potential pollution reduction.

The Priority A subwatersheds are predicted to experience greater than 100% increase in water yield, greater than 50% increase in sediment export, and greater than 2.5% decrease in potential pollution reduction. These subwatersheds are largely unprotected, and are concentrated in the greater Asheville metropolitan area. Within Priority A subwatersheds, there are two drinking water intakes that currently serve nearly 15,000 people. These subwatersheds also include the Ivy River Hydropower Plant, and likely flow directly into the nearby Marshall Dam and Capitola Plant. These subwatersheds should be prioritized for conservation efforts including partnerships with municipal agencies and nonprofits such as RiverLink to work on stormwater improvement projects, use porous concrete and greenways to increase water infiltration in the soils, and reduce runoff potential.

The Priority B subwatersheds are predicted to experience decreasing water yield of greater than 5% and a decrease in potential pollution reduction of greater than 2.5%. The majority of these subwatersheds are far from urban centers. There are two drinking water intakes located in these subwatersheds, which serve nearly 10,000 people. These subwatersheds may be good areas to focus on forest management strategies with the organizations that currently own these protected lands to increase water yield through prescribed burning, which promotes the persistence of fire adapted, low-water using species such as oak and hickory. In portions of these subwatersheds that are not currently protected, TNC and its partners may consider land acquisition opportunities to begin efforts to promote increased water yield and water quality.

To identify priority subwatersheds for aquatic species protection in the FBRB, we first identified the subwatersheds currently projected to contain at least 11 of the 12 modeled species and to provide at least 500 kilometers of total stream habitat for those species. Eight subwatersheds meet those criteria under the present-day scenario (Fig. 25).

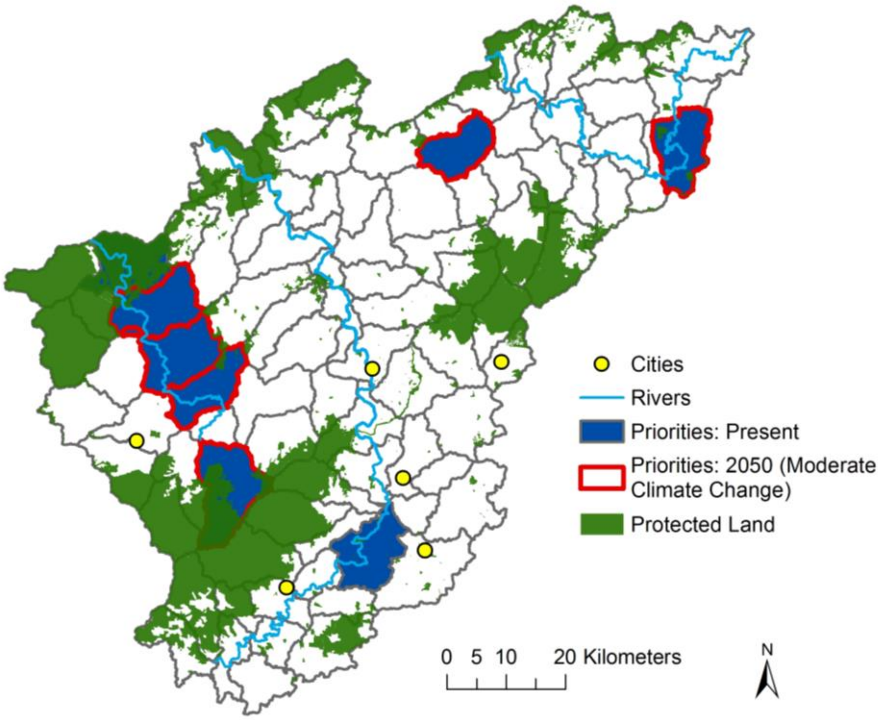

Figure 25: Priority subwatersheds for species protection in the FBRB.

Next, we applied the same criteria to the 2050 moderate climate change scenario. Only six subwatersheds meet the criteria in that 2050 scenario, and they are a subset of the eight present-day subwatersheds. These six subwatersheds are places that currently provide a large amount of habitat for aquatic species that are important to people in the FBRB, and they are projected to continue to provide large amounts of habitat for these species as the climate changes over the next 30 years. Therefore, these are high priorities for protection to ensure that they remain suitable climate refuges for these species into the future. The need for protection is evident when the currently protected land in the FBRB is overlaid on the priority subwatersheds (Fig. 24). With the exception of the East Fork Pigeon River subwatershed, which contains a lot of national forest land, very little of the land within the priority subwatersheds is protected. Concentrating conservation efforts in these areas will maximize the impacts of these efforts on protecting aquatic species that matter to people.

In addition to guiding land conservation and restoration projects, our results can be used for strategic communication efforts. As our analyses show, climate change is projected to have a large impact on many aspects of aquatic and hydrologic ecosystem services in the FBRB.

Combating climate change cannot be accomplished by an organization's land conservation effort, but requires a conscious and consistent effort by the general population. In order to effectively communicate the consequences of climate change and inspire people to act, it is essential to frame the issue by placing it in a context that aligns with individuals' priorities and beliefs. One obstacle for climate change communication is that people tend to think of it as spatially and temporally removed (Shome & Marx, 2009). This can be overcome by identifying local impacts of climate change; in the FBRB, those could include increased flood risk, higher drinking water treatment costs, and the loss of rare species. Describing climate change impacts as future losses that should be avoided, rather than future improvements on the present situation, can also be helpful, as most people are more loss-averse than gain-seeking (Hammond, Keeney, & Raiffa, 2006). Of course, people who live in and visit the FBRB have diverse interests and priorities, so the specific climate change impacts that will resonate vary from person to person. Effective communication about threats to aquatic and hydrologic ecosystem services in the FBRB, targeted to specific groups of people and framed to overcome cognitive biases, can be a valuable tool for conservation.

Conclusion

The future is never easy to predict, but our analysis offers an indication of how the French Broad River Basin is functioning currently and how ecosystem services will be affected by changing climate and land use patterns. Our study analyzed how land use change and two climate change scenarios would impact water quality, water quantity, and aquatic species around the middle of the 21st century. The two climate change scenarios were developed by the IPCC (2000) in their Special Report on Emissions Scenarios, and included a moderate emissions scenario (A1B) and a high emissions scenario (A2).

Our analysis showed that potential pollution reduction by the effective riparian buffers will likely decrease by 2050 as a result of projected increases in urban development and decreases in forest cover. These anticipated changes are particularly important in subwatersheds that contain public drinking water supply intakes, since riparian buffers play an important role in filtering out nutrients and other pollutants before they enter rivers and streams. Our study also revealed that both climate change scenarios are predicted to result in significant increases in both water yield and sediment export. Under the moderate A1B emissions scenario water yield is predicted to increase by over 24% from current levels, while the high A2 emissions scenario is predicted to result in increases in water yield upwards of 40%. When combined with urban growth, the A1B climate scenario could result in a doubling of sediment export, while the A2 climate scenario combined with development showed an increase in sediment export of up to 126%. These substantial increases in water yield and sediment export could result in increased potential for damaging floods, more abrasion on hydropower turbines, and rising expenses in drinking water filtration. Many rare and threatened aquatic species, as well as some game fish species, are also likely to experience significant reductions in suitable habitat in the FBRB, but strategic conservation efforts can help to mitigate some of these effects.

We have identified priority subwatersheds for conservation efforts in the FBRB based on their importance to the provision of ecosystem services including drinking water, hydropower, and aquatic species habitat and their predicted vulnerability due to climate change and development. Land conservation and restoration efforts undertaken by TNC and their partners will help to ensure that these areas continue to provide valuable ecosystem services despite these changes. In addition, localized information about ecosystem services and potential threats to these services in the FBRB can be used to communicate more effectively with specific groups of people, increasing the likelihood that they will take action to protect the ecosystem services they value.

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Appendices

Appendix I: Species Distribution Model Methods

Table 11: Preliminary variable screening for Maxent models. P-values for correlations between each variable and species presence. Variables with insignificant correlations with species presence (p-values greater than 0.05) were not included in that species model (italicized values). (Continued on next page.)

Species	Drainage area	Max elevation	Min elevation	Slope	Stream Order	Precipitation	Temperature
Alasmidonta raveneliana	< 2.2e-16	< 2.2e-16	3.67E-09	< 2.2e-16	*0.9031*	4.69E-07	0.0487
Cryptobranchus alleganiensis	*0.1816*	0.0007	*0.3652*	*0.7756*	< 2.2e-16	0.0288	0.0031
Erimystax insignis	*0.0549*	0.0004	0.0017	*0.9490*	4.24E-06	0.1006	0.0169
Etheostoma acuticeps	< 2.2e-16	4.37E-09	1.91E-07	0.0002	< 2.2e-16	0.0002	3.06E-06
Lampsilis fasciola	< 2.2e-16	< 2.2e-16	8.53E-10	< 2.2e-16	< 2.2e-16	4.33E-16	1.11E-06
Luxilus chrysocephalus	0.0423	0.0002	0.0191	0.0013	3.04E-06	9.29E-08	1.47E-05
Micropterus dolomieu	4.33E-13	2.05E-05	7.55E-15	*0.3392*	< 2.2e-16	*0.6039*	< 2.2e-16
Oncorhynchus mykiss	4.95E-07	< 2.2e-16	< 2.2e-16	*0.3650*	*0.1223*	< 2.2e-16	< 2.2e-16
Percina squamata	< 2.2e-16	2.39E-16	5.96E-13	0.9261	< 2.2e-16	0.0001	1.05E-05
Salmo trutta	0.0003	< 2.2e-16	< 2.2e-16	*0.4680*	*0.0642*	4.19E-13	< 2.2e-16
Salvelinus fontinalis	0.0125	< 2.2e-16	< 2.2e-16	0.0025	0.0003	0.0012	*0.1630*
Strophitus undulatus	7.55E-13	5.67E-09	5.92E-08	*0.2497*	< 2.2e-16	*0.6646*	0.0022

Species	**Geology**	**% Barren**	**% Crop**	**% Developed**	**% Forest**	**% Pasture**	**% Shrub**	**% Wetland**	**% Riparian Disturbance**
Alasmidonta raveneliana	0.0245	*0.7837*	4.94E-07	*0.1264*	0.0002	0.0007	*0.5347*	*0.1248*	1.42E-05
Cryptobranchus alleganiensis	0.0016	*0.6632*	7.09E-06	0.1085	0.0908	0.6317	0.4357	0.3313	4.05E-11
Erimystax insignis	0.0066	*0.0741*	6.00E-05	0.0327	0.0005	0.0373	*0.3381*	0.0829	0.0002
Etheostoma acuticeps	0.0042	*0.5329*	0.0443	*0.8378*	*0.9822*	*0.4230*	*0.9086*	*0.6999*	*0.1029*
Lampsilis fasciola	6.63E-06	*0.8198*	8.48E-11	0.0024	1.73E-06	0.0002	*0.3721*	0.0321	1.98E-08
Luxilus chrysocephalus	*0.0702*	*0.7147*	0.0004	0.0041	0.0002	0.0011	*0.7218*	*0.9036*	2.14E-08
Micropterus dolomieu	<2e-16	*0.2298*	*0.1773*	*0.5540*	3.30E-07	2.18E-05	*0.2170*	0.0168	3.99E-11
Oncorhynchus mykiss	<2e-16	*0.4634*	*0.0844*	2.59E-10	< 2.2e-16	< 2.2e-16	1.08E-06	0.0003	*0.7534*
Percina squamata	6.80E-10	*0.1902*	*0.3908*	*0.1479*	0.0106	*0.0542*	*0.1692*	*0.0607*	0.0173
Salmo trutta	<2e-16	*0.5264*	*0.6317*	0.0153	8.57E-13	2.85E-06	*0.1309*	0.0029	7.34E-10
Salvelinus fontinalis	<2e-16	1.17E-05	*0.0947*	*0.1983*	4.19E-07	1.25E-10	0.0419	0.0398	0.0118
Strophitus undulatus	<2e-16	*0.1191*	0.0142	0.0005	3.76E-05	*0.8166*	*0.4910*	*0.4932*	9.75E-15

Table 12: Secondary variable screening for Maxent models. For each species, pairs of variables are shown that were correlated with each other at 0.8 or higher. The variables in the second column (variable 1) were removed from the relevant species model, and the variables in the third column (variable 2) were retained.

Species	Variable 1 (removed)	Variable 2 (retained)	Correlation coefficient
Alas rave	Min elevation	Max elevation	0.824
Cryp alle	Max elevation	Temperature	-0.824
Erim insi	Min elevation	Max elevation	0.836
Ethe acut	*none*		
Lamp fasc	Min elevation	Max elevation	0.831
Luxi chry	*none*		
Micr dolo	Min elevation	Max elevation	0.964
	Min elevation	Temperature	-0.927
	Max elevation	Temperature	-0.907
	Geology	Temperature	0.856
Onco myki	Min elevation	Max elevation	0.948
	Min elevation	Temperature	-0.898
	Max elevation	Temperature	-0.872
Perc squa	Min elevation	Max elevation	0.830
Salm trut	Min elevation	Max elevation	0.947
	Min elevation	Temperature	-0.896
	Max elevation	Temperature	-0.870
Salv font	Min elevation	Max elevation	0.986
	Min elevation	Precipitation	0.836
	Max elevation	Precipitation	0.828
	% Forest	Precipitation	0.850
Stro undu	Min elevation	Max elevation	0.979
	Min elevation	Temperature	-0.881
	Max elevation	Temperature	-0.877

Appendix II: Species Distribution Model Results Tables

Table 13: Changes in amount of habitat per species from present for each of the five 2050 scenarios

Species	Dev Only	CC Only A1B	CC Only A2	Dev + CC A1B	Dev + CC A2
Salmo trutta	-2.4%	-58.2%	-51.9%	-58.1%	-53.9%
Luxilus chrysocephalus	1.6%	-60.7%	-60.0%	-57.3%	-63.6%
Cryptobranchus alleganiensis	-3.2%	-42.9%	-42.5%	-44.4%	-42.6%
Oncorhynchus mykiss	0.0%	-36.9%	-33.5%	-37.5%	-36.1%
Micropterus dolomieu	-0.8%	-24.2%	-13.4%	-23.6%	-14.0%
Lampsilis fasciola	0.3%	-18.4%	-18.0%	-19.3%	-20.3%
Ethestoma acuticeps	-0.1%	0.0%	0.0%	-0.1%	-0.1%
Strophitus undulatus	-3.8%	5.1%	27.3%	4.4%	25.8%
Alasmidonta raveneliana	-1.2%	7.1%	7.4%	6.2%	7.3%
Salvelinus fontinalis	-0.1%	33.0%	21.9%	33.3%	22.5%
Percina squamata	-2.1%	54.7%	48.6%	46.6%	44.6%
Erimystax insignis	5.7%	97.6%	87.3%	101.6%	88.5%

Table 14: AUC values for Maxent models

Species	Training AUC	Test AUC
Oncorhynchus mykiss	0.854	0.814
Salmo trutta	0.901	0.847
Cryptobranchus alleganiensis	0.928	0.892
Micropterus dolomieu	0.943	0.915
Salvelinus fontinalis	0.954	0.918
Erimystax insignis	0.954	0.724
Strophitus undulatus	0.958	0.947
Luxilus chrysocephalus	0.968	0.921
Alasmidonta raveneliana	0.968	0.974
Percina squamata	0.972	0.923
Ethestoma acuticeps	0.977	0.933
Lampsilis fasciola	0.98	0.963

Table 15: Variable importance to Maxent model by species

Species	**Most important variable**	**2nd-most important variable**	**3rd-most important variable**
Alasmidonta raveneliana	Drainage area	Stream order	Slope
Cryptobranchus alleganiensis	Drainage area	Stream order	Slope
Erimystax insignis	Slope	Stream order	Temperature
Etheostoma acuticeps	Drainage area	Slope	Stream order
Lampsilis fasciola	Drainage area	Slope	Stream order
Luxilus chrysocephalus	Drainage area	Temperature	Stream order
Micropterus dolomieu	Drainage area	Stream order	Slope
Oncorhynchus mykiss	Drainage area	% Riparian Disturbance	Geology
Percina squamata	Drainage area	Stream order	Slope
Salmo trutta	Drainage area	Stream order	Temperature
Salvelinus fontinalis	% Riparian Disturbance	Temperature	Precipitation
Strophitus undulatus	Slope	Stream order	% Forest

Table 16: Sensitivity analysis results by species: percent change in habitat amount from present. Bolded values represent the same direction of change from present as the moderate climate change projection. Values shaded in green are fewer than 10 percentage points different from the moderate climate change projection; values shaded in yellow are 10 to 20 percentage points different, and values shaded in orange are more than 20 percentage points different.

Species	Moderate Climate Change	Precipitation				Temperature			
		-20%	-10%	10%	20%	-20%	-10%	10%	20%
Alasmidonta raveneliana	7.10%	-27.9%	-5.2%	**3.1%**	-2.3%	**14.5%**	**20.8%**	-0.1%	-0.1%
Cryptobranchus alleganiensis	-42.90%	**-58.3%**	**-48.1%**	**-40.3%**	**-37.9%**	**-48.2%**	**-4.1%**	**-82.8%**	**-84.3%**
Erimystax insignis	97.60%	**98.4%**	**98.4%**	**98.4%**	**98.4%**	-91.4%	-46.0%	**125.0%**	**125.0%**
Etheostoma acuticeps	0.00%	**0.6%**	**0.6%**	**0.6%**	**0.6%**	**0.6%**	**0.6%**	**0.6%**	**0.6%**
Lampsilis fasciola	-18.40%	**-23.3%**	**-18.6%**	**-30.0%**	**-46.3%**	3.4%	4.9%	**-28.6%**	**-28.6%**
Luxilus chrysocephalus	-60.70%	60.6%	3.1%	**-88.7%**	**-100.0%**	**-59.9%**	**-59.9%**	**-59.9%**	**-59.9%**
Micropterus dolomieu	-24.20%	**-23.7%**	**-23.7%**	**-23.7%**	**-23.7%**	**-31.0%**	**-13.8%**	**-47.6%**	**-48.8%**
Oncorhynchus mykiss	-36.90%	**-46.3%**	**-38.5%**	**-36.8%**	**-37.6%**	3.2%	3.3%	**-98.2%**	**-100.0%**
Percina squamata	54.70%	**32.2%**	**51.8%**	**41.9%**	**21.2%**	-4.2%	-4.2%	**76.3%**	**76.3%**
Salmo trutta	-58.20%	**-67.1%**	**-59.9%**	**-57.6%**	**-59.1%**	9.0%	9.5%	**-100.0%**	**-100.0%**
Salvelinus fontinalis	33.00%	-38.0%	**7.5%**	**40.5%**	**42.1%**	**33.0%**	**33.0%**	**33.0%**	**33.0%**
Strophitus undulatus	5.10%	**6.4%**	**6.4%**	**6.4%**	**6.4%**	-34.8%	-26.5%	-11.6%	-26.3%

Appendix III: Supporting Documents

Supporting documents are available through DukeSpace (http://dukespace.lib.duke.edu/dspace/) and can be downloaded from the DukeSpace page for this report, which can be found by searching DukeSpace by title (Assessing the current and future status of aquatic and hydrologic ecosystem services in the French Broad River Basin).

Effective riparian buffers, potential pollution reduction, water yield, sediment export, and species distribution results by subwatershed and for individual species are included as ArcMap shapefiles.

Full Maxent model results, including species responses to individual variables, are included in a pdf file.