ABSTRACT

GAY, ELLY TAHMASEB. Effects of Riparian Buffer on Streamflow Response to Land Use and Climate Change. (Under the direction of Dr. Katherine Martin).

Rapid land conversion and global environmental change are stressing freshwater resources. Namely, the conversion of land into impervious surfaces hinders the ability of watersheds to provide clean water, slow run-off, and maintain regular base flow. Population growth, and subsequent development, in the Piedmont region of the southeastern United States between Atlanta, GA and Raleigh, NC is among the highest in the country. Uncontrolled growth in the Piedmont will exacerbate the effects of climate change and cause stormwater challenges that threaten human and aquatic ecosystem health. Riparian buffers represent a best management practice for maintaining the hydrologic balance and mitigating against the effects of land conversion. However, our ability to anticipate the effectiveness of current and alternative riparian buffers in mitigating the continued effects of urbanization and climate change remains very limited. To address this information gap, we projected hydrologic response to different levels of buffer protection under a coupled land use/climate scenario for 2060. We used the SWAT hydrologic model to project future streamflow in the Upper Neuse (HUC-8 watershed) under three levels of buffer protection: no additional buffers (currently applied in most NC watersheds), 50-ft (currently applied throughout the Neuse and Tar-Pamlico Basins), and 100-ft (applied in parts of the Chesapeake Bay watershed). Climate trends from the CSIRO GCM RCP 8.5 show an overall warmer future in the Piedmont, punctuated by more extreme precipitation events. Land use projections from the FUTURES urban growth model indicate a doubling low-intensity development across the state from 2.92% in 2016 to 4.62% in 2060. We found that buffer preservation and retention could conserve forestland while also allowing for development to still occur at high levels in the Upper Neuse. The buffer effects on streamflow during the most

extreme flow events were variable and dependent on specific factors within each subbasin. Therefore, further research is needed into the placement of strategic buffers with variable widths throughout watersheds. Understanding the effectiveness of riparian buffers is crucial during a period of global change, where we are pressed to develop innovative strategies that promote the conservation of invaluable ecosystem services.

Effects of Riparian Buffer on Streamflow Response to Land Use and Climate Change

by
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DEDICATION

This thesis is dedicated to my family.

Large, loud, loving – I would not be where I am without your support. Specifically to Afsaneh Regimand, Bahram Regimand, Macey Gay, Jim Gay, and Adam Johnson.

BIOGRAPHY

I was born and raised in Birmingham, Alabama. While I have had fortunate opportunities to travel and explore parts of the world, the Southeast has always been my home. My mother, originally from Iran, was the most influential person in my upbringing and taught me how to think openly and deeply about the world. This influence, coupled with my passion for nature, sparked an intense desire to better understand the interface between environment and society. My interdisciplinary interests first found a home at Furman University, where I graduated with a dual degree in Sustainability Science and Politics and International Affairs. At Furman, I capitalized on a comprehensive curriculum, coupled with fellowship and research opportunities, to better understand the dynamics of both natural and built environments, while also incorporating a more holistic understanding of societal behavior. After graduating from Furman, I wanted to gain industry experience and therefore interned for a year at the U.S. Endowment for Forestry and Communities, whose mission is to collaborate with partners in the private and public sector to advance sustainable and transformative change for the nation's working forests and forest-reliant communities. At the Endowment, I learned the power of partnerships in the management of forests and watersheds and the vast opportunities available at the intersection between academia and industry. My undergraduate education and internship experience drove my desire to further understand how hydrologic processes perform under changing conditions. I decided to pursue a Master of Science in Natural Resources at NC State University to further my technical and analytical skillset, to pair ways of knowing from natural and social sciences, and to explore the power of science in driving our decisions. I care deeply for the Southeast, its resources, and its people. I hope my graduate research can help foster a positive future for all.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

INTRODUCTION

Climate change and development impacts on ecosystem services

Rapid urban development, coupled with the effects of climate change, is taxing the ability of natural systems to provide ecosystem services. By 2050, the global population is projected to reach 9.5 billion people, with 66% of that population living in urban areas (United Nations, 2014). The United States (US), with around 82% of its current population residing in urban areas, is expected to contribute 50 million people to this new, urban population (United Nations, 2014). Urban expansion often results in increased urban sprawl, low-density development surrounding urban regions (Terando et al., 2014) and puts added pressure on ex-urban areas, the semi-rural regions just outside of suburban corridors (Martin et al., 2017). As urbanizing cores expand and become connected, natural systems become increasingly fragmented (Terando et al., 2014). Consequently, the conversion of land to impervious surfaces in the furtherance of urban development disrupts ecosystem services, such as the ability of watersheds to provide stable water resources (Ford, Laseter, Swank, & Vose, 2011; Martin et al., 2017).

Population is rapidly growing in the SE at a rate 40% higher than any other region in the US (Huggett, Wear, Li, Coulston, & Liu, 2013; Terando et al., 2014) and is expected to continue increasing (G. Sun, McNulty, Myers, & Cohen, 2008). With its explosive population growth and subsequent development, the region is experiencing increased water demand juxtaposed against decreasing and less stable water supply. By 2060, continued development at the current rate would result in 30 to 43 million acres of additional urban land cover and consequently, a loss of 11 to 23 million acres (7-13%) of forestland (Wear, 2013). The SE represents a microcosm of growing trends, where population growth and forest conversion are pressuring water demand. The imbalance between growing demand and forest conversion make the region an important location for water resource studies (Huggett et al., 2013; Nagy, Lockaby, Helms, Kalin, & Stoeckel, 2011; G. Sun et al., 2008).

Population growth and urbanization in the SE Piedmont (a region extending between the Appalachian Mountains and the Atlantic Coastal Plain) is predicted to rapidly outpace other areas in the region. The Piedmont attracts uninhibited development owing to its proximity to natural areas, lack of geographic constraints, and pre-existing urban areas (Terando et al., 2014). It is estimated that by 2060, urban areas in the Piedmont are expected to expand 165% (17,800 km^2 in 2009 to 47,500 km^2 in 2060) (Terando et al., 2014). Further, under a highest-loss scenario, the Piedmont will lose 21% of its forest area (Wear, 2013). Development along this corridor is forming a new megalopolis and has already been correlated with regional declines in stream condition (Suttles et al., 2018; Terando et al., 2014; Van Metre et al., 2019). The effects on water resources caused by unchecked development can be further magnified by a changing climate.

As urbanization reroutes water across impervious surfaces and expanding population increases water demand, climate change will intensify the global hydrologic cycle, resulting in more infrequent and intense precipitation events which cause negative consequences to society, including increased flooding, drought, and soil erosion (O'Gorman & Schneider, 2009). Understanding the impact of a changing climate on water resources is of significant concern for areas where water supply may be stressed in the context of growing demand by an increasing population (G. Sun et al., 2008). In these areas, development impacts on water resources can be further exacerbated by a changing climate (Nagy et al., 2011; Ge Sun & Lockaby, 2012; G. Sun et al., 2008).

The effect that climate change will have on water resources in the SE hinges on its ability to alter stormflow, flooding, groundwater recharge, and baseflow (Vose et al., 2012). Precipitation is a helpful indicator of water yield in the SE, yet varied levels of evapotranspiration throughout the region often result in differing water yields (P. Caldwell et al., 2014). Therefore, it is important to better understand the main drivers of hydrologic change in the region to better inform water management, especially considering differing regional hydroclimates (Rice, Emanuel, Vose, & Nelson, 2015). Previous studies indicated that changes in climate across the SE created the greatest impact on water stress, followed by population and land use (G. Sun et al., 2008). Further, in portions of the Piedmont, climate change will have a more influential effect on future water yield, while development will demonstrate threshold behavior (Martin et al., 2017). Along with increased temperature stemming from climate change, Terando et al. (2014) noted that the burgeoning megalopolis between Atlanta and Raleigh will have a warmer climate as a result of the urban heat island effect. This study found that the average temperature of the Piedmont could be raised 2º– 6º C as a result of climate change, which will be exacerbated by the urban heat island effect that naturally makes urban areas 0.5º – 1.5º C warmer comparatively (Girvetz et al., 2009; Stone, Vargo, Liu, Hu, & Russell, 2013; Terando et al., 2014). With both climate change and development threatening watershed function and overall water resources, it can be daunting to consider the future of water supply in the Piedmont. Fortunately, numerous studies have revealed that forested areas can alleviate the anthropogenic effects of climate and land use change.

Forests and water resources

Research suggests that compared to all other land uses, forests continually provide the most stable water resources (Brown, Zhang, McMahon, Western, & Vertessy, 2005; Council, 2008; Ford et al., 2011) and supply more water than any other land cover (Ge Sun, Caldwell, & McNulty, 2015). Forests comprise around one-third of total US land area (Sedell, Sharpe, Apple, Copenhagen, & Furniss, 2000; Ge Sun et al., 2015), contribute 70-80% of total freshwater resources (Binkley, Ice, Kaye, & Williams, 2004; Sedell et al., 2000), and provide 40-50% of the total water yield (P. Caldwell et al., 2014; Ge Sun et al., 2015). Forests support watershed function and act as natural filtrations, cooling and cleaning water for both aquatic habitat and human use (Lockaby et al., 2013; Sedell et al., 2000). Large portions of the US population rely on forests to continuously provide clean water. In the SE, 34% of available water yield originates on forestland (P. Caldwell et al., 2014). When forests are converted to other land use types, water quality declines, critical habitat is lost, and flood hazards increase (P. Caldwell et al., 2014). Conversion of forest to urban and agricultural uses increasingly threatens water quality due to the increased loading of pollutants (Lockaby et al., 2013). Forested watersheds therefore provide an invaluable ecosystem service that is disrupted by land conversion.

The addition of impervious surface cover to a watershed significantly alters the natural landscape (Ge Sun & Caldwell, 2015), increases river flows in urbanized areas (P. V. Caldwell, Sun, McNulty, Cohen, & Moore Myers, 2012), reduces infiltration rates, and increases runoff velocity (Nagy et al., 2011). Vicars-Groening and Williams (2007) found that urbanization in the upper portion of White Rock Creek watershed in Dallas, TX suburbs reduced watershed infiltration capacity by 60%, causing significant increases in peak stormflow discharge. While the addition of impervious surface cover in water stressed regions may temporarily increase streamflow, its degrading effects on water quality and habitat diversity negate its potential for sustainably increasing water yield long term and it should therefore not be considered a proper management strategy (P. V. Caldwell et al., 2012).

Streams that run through urban areas are subject to “urban stream syndrome”, a condition that causes adverse effects such as disrupted channel morphology, increased nutrient and contaminant loading, and flashy hydrographs (Meyer, Paul, & Taulbee, 2005; Paul & Meyer, 2001; Walsh et al., 2005). There is strong evidence that urban water resources become vulnerable at a threshold of 20% imperviousness (C. L. Arnold & Gibbons, 1996; Paul & Meyer, 2001). However, recent literature suggest that the impervious threshold is dependent on ecosystem and development type (Ge Sun & Caldwell, 2015). Studies synthesized by Nagy et al. (2011) have found that urban streams in the Piedmont were degraded at less than 5% imperviousness. Ge Sun and Caldwell (2015) also note the 5-20% threshold, and have found watersheds with 43% imperviousness can double their runoff capacity. Because of this variation in the literature, it is important that watershed studies understand regional thresholds of impervious surface and its subsequent effect on stream ecosystems, especially in the context of land conversion (Schneid, Anderson, & Feminella, 2017).

Riparian Buffers as Mitigation Tools

Stemming from the positive relationship between forest and watersheds, riparian areas, vegetated zones along river and streambanks, are commonly used as best management practices (BMP) to mitigate the effects of anthropogenic activities and provide ecological stability (Blinn & Kilgore, 2001; Grace, 2005; Matteo, Randhir, & Bloniarz, 2006; Naiman & Decamps, 1997). Riparian areas represent a transition zone between terrestrial and aquatic ecosystems, making them a dynamic and diverse interface crucial to the function and organization of riverine systems (Naiman & Decamps, 1997). Riparian zones can enhance water quality by acting as biogeochemical and physical filters, catching harmful materials and substances before they enter the riverine system (Nagy et al., 2011). Further, these dynamic areas provide shading benefits along with bank stabilization and balanced dissolved oxygen levels, supporting habitat for aquatic organisms (Nagy et al., 2011).

Most states acknowledge the economic, environmental, and social value that riparian areas provide, and therefore have included them within forestry BMPs (Blinn & Kilgore, 2001). Grace (2005) synthesized research from across the 13 southern states that addressed non-point source pollution from forest operations and subsequent effect on watersheds. The study concluded that BMPs can protect water quality against intensive forest management, yet the full benefits are unknown given the variability in study scale. Riparian zones provide benefits in both urban and agricultural landscapes, and have long been used as BMPs for agricultural and forestry operations. A study analyzing the effectiveness of riparian areas (defined here as the zone between the edge of a cultivated field and a perennial stream) in trapping runoff sediment from agricultural fields over a 20 year period in two North Carolina Coastal Plain watersheds found that these buffers were able to retain 84-90% of runoff sediment within the watershed and out of the river systems (Cooper, Gilliam, Daniels, & Robarge, 1987). Since the study analyzed riparian areas of variable size the authors concluded that buffer zone width needs to proportionally increase with higher order streams, as the chances for transport increases (Cooper et al., 1987).

This notion of variable buffer zone width corresponds to “River Continuum Concept” (Vannote, Minshall, Cummins, Sedell, & Cushing, 1980), which implies that an entire river system is comprised of a continuous gradient of physical conditions and the “Flood Pulse Concept” (Junk, Bayley, & Sparks, 1989), which acknowledges the important role of floodplains in river systems. In the “Flood Pulse Concept”, floodplains are referred to as aquatic/terrestrial transition zones (Junk et al., 1989), which underscores the importance of riparian areas in explaining river system behavior. Riparian studies have since been conducted in the context of land use, especially pertaining to water and habitat quality.

Headwaters are regarded as important interfaces greatly influenced by riparian vegetation and are subsequently responsible for collecting and transporting material from the terrestrial landscape (Vannote et al., 1980). As a result, terrestrial changes can potentially have immediate effects on headwater systems and eventually disseminate to downstream portions. Sutherland, Meyer, and Gardiner (2002) studied the effect of terrestrial change on headwater systems by analyzing the effects of catchment land cover and sedimentation on fish assemblages in four (two disturbed and two reference) Appalachian headwater streams in North Carolina (Sutherland et al., 2002). The study found that disturbed streams with 13% to 22% non-forested land cover had higher suspended sediment concentration during both stormflow and base flow, although during base flow these streams always exceeded acceptable levels of turbidity (Sutherland et al., 2002).

Strategic management of headwater zones pose potential opportunities to mitigate the adverse effects of land use and climate change on watershed health. K. Duan, Sun, Caldwell, McNulty, and Zhang (2018) studied the availability of upstream flow and water supply stress levels across the CONUS and found that overstressed areas mostly occurred in headwater areas or areas isolated from other basins. While regional results can vary, the study also found climate variation and upstream consumption can increase downstream stress (especially in arid regions) (K. Duan et al., 2018). Ge Sun and Caldwell (2015) emphasize the need to both enact BMPs and protect source headwaters to conserve water resources in urbanizing areas. Accordingly, studies that focus on watershed health, especially in the context of changing conditions, should account for headwater regions.

Purpose of Study and Significance

The Albemarle-Pamlico Watershed system spans across the Piedmont of North Carolina and into Virginia. Home to over 3 million people, this watershed system has historically faced water quality and quantity issues stemming from population growth, specifically in the Neuse and Tar-Pamlico River basins (Borsuk, Clemen, Maguire, & Reckhow, 2001; Rashleigh et al., 2010). In an attempt to mitigate impairment within these basins, North Carolina has issued a state-mandated basin wide riparian buffer rule of 50-ft on each side of the water body throughout the entire Neuse and Tar-Pamlico Basins and in limited parts of other watersheds ("15A NCAC 02B .0233,"). Under this rule, the first 30-ft of the buffer must be undisturbed vegetation, while the next 20-ft can be managed vegetation. State level regulations for other watersheds vary. For example, the 50-ft buffer is mandated for the mainstem of the Catawba River basin, but is not required for headwaters. While the benefits of riparian buffers have been studied in the urban and rural context, it is unknown if the current state-mandated buffer widths will mitigate the potentially synergistic effects of land cover and climate change in the Piedmont region of North Carolina. To address this knowledge gap, this study examined the effects of current and expanded buffer widths on streamflow in the Upper Neuse watershed under changing land use and climate to assess the continuum of stable water resources for the region.

If current trends continue, watersheds located in exurban areas are particularly vulnerable to the effects of urbanization because of the large potential for development (Theobald, 2005). Matteo et al. (2006) noted that urbanizing watersheds responded particularly well to buffering BMPs, compared to watersheds that were already heavily urbanized. Similarly, Martin et al. (2017) found that forest conversion in an already highly urbanized watershed had minimal effects on water yield compared to the larger effect of forest conversion in a mixed-use watershed. Rapid land conversion rates in the mixed-use watershed pushed the land use distribution across a threshold, emphasizing the need to conserve forestland in urbanizing watersheds to prevent threshold effects (Martin et al., 2017). The SE is an important region to focus hydrologic studies as forestland provides drinking water to a large portion of the population (P. Caldwell et al., 2014), economic opportunity through the timber industry (Huggett et al., 2013; Oswalt, 2019), and potential mitigation of extreme hydrologic events, such as flooding (Ford et al., 2011). Therefore, knowledge on how changing conditions affect water resources in the SE is vital for maintaining these resources for both habitat and human use. Understanding the effectiveness of riparian buffers is crucial during a period of global change, where society is pressed to develop innovative strategies that promote adaptation to a changing climate and conservation of invaluable ecosystem services.

Our ability to anticipate the effectiveness of current and alternative riparian buffers in mitigating the continued effects of urbanization and climate change remains limited. Therefore, we investigated the central question: Do current or expanded riparian buffers mitigate more extreme flows expected under changing conditions?

To address this question, our study has three objectives:

1. Analyze the intensity and spatial distribution of land use change projected for a watershed within the Piedmont region of North Carolina.
2. Evaluate the magnitude and direction of changes in storm flow and base flow under future land use and climate conditions.
3. Compare the effectiveness of expanded riparian buffers compared to current buffers in mitigating storm flow and maintaining base flow under future conditions.

We addressed these objectives with a hydrologic modeling tool to assess how the riparian buffers effect water resources under a coupled land use/climate scenario in the Upper Neuse (HUC-8 watershed). Detailed further below, we used the Soil and Water Assessment Tool (SWAT), a semi-distributed conceptual and operational hydrologic model capable of simulating water quality and quantity on various watershed-scales (J. G. Arnold, Srinivasan, Muttiah, & Williams, 1998). We tested the benefits of three levels of buffer protection: no additional buffering (currently applied in most watersheds), 50-feet (the current policy applied throughout the Neuse), and 100-feet (applied in parts of the Chesapeake Bay watershed ("Critical Area Buffer Resources Guide," 2011; "Resource Protection Areas,") under a coupled land use/climate scenario extending to 2060. The parameters for the 2060 projections combined readily available, downscaled climate projections from the USGS data portal (cida.usgs.gov/gdp) with land use scenarios developed using the FUTure Urban-Regional Environment Simulation (FUTURES).

METHODS

Study Areas

SE Piedmont

Development patterns in the SE are influenced by the region's historic land use, with the majority of growth concentrated in the Piedmont. Historic and current land use trends predispose the SE to hydrologic challenges. Forests conversion in the SE is complex and dependent on global economic trends, as the region is the largest plantation forestry producer in the United States, and land is constantly fluctuating into and out of forest cover (Huggett et al., 2013; Wear, 2002). Following European settlement and widespread logging, the SE was historically dominated by intensive agriculture, which lead to significant topsoil erosion (up to 12.3 inches) (Daniels, 1987; Trimble, 1975) and declines in soil productivity (Lockaby et al., 2013). Around 1920, the mass abandonment of agriculture resulted in widespread reforestation (Huggett et al., 2013; Lockaby et al., 2013). The land has changed dramatically following this shift, giving rise to reforestation and development, especially in the Piedmont region.

From 1950 to present, the majority of development in the SE occurred in the Piedmont (Terando et al., 2014; Wear, 2002). The Piedmont, meaning "foot of the mountain", is the corridor between the Appalachian Mountains and the Coastal Plain (Rummer & Hafer, 2014). The region extends from central Alabama in the south to New York in the north (Fenneman & Johnson, 1946) and connects the largest SE cities, including Atlanta, Charlotte, and Raleigh-Durham (Terando et al., 2014; Wear & Greis, 2013). The Piedmont was subject to the agricultural abandonment that shaped the SE. Consequently, the majority of Piedmont forest are a result of secondary succession on fallow fields (Kim, Band, & Song, 2014).

The Upper Neuse

The Upper Neuse watershed (Figure 1) was chosen as a result of its mixed-land uses and proximity to growing urban areas in the rapidly developing SE Piedmont. The upper portion of this watershed was modeled based on surrounding urbanization, availability of long-term stream records, and inclusion of headwaters. Headwater areas control downstream transport, act as habitat for critical species, and are particularly sensitive to environmental and physical change (Fritz, Johnson, & Walters, 2008; U.S.EPA, 2015) and can therefore act as indicators for whole watershed health. The long-term record of stream discharge at subbasin outlets was crucial for the calibration process.

The Neuse, meaning "peace", was named for the Neusiok tribe, original occupants and stewards of the land (Hunt, 2018). The Neuse originates in Person and Orange counties and flows to the coast, connecting the Piedmont to the Pamlico Sound (*Neuse River Basin Restoration Priorities*, 2018). The headwaters, such as the Flat, Little, and Eno Rivers merge together in the Falls Lake Reservoir and form the Neuse River, which takes on brackish properties when it enters the Coastal Plain (*Neuse River Basin Water Resources Plan*, 2010). The Upper Neuse is a HUC-8 watershed that comprises 621,977.82-ha. According to the 2016 NLCD, land cover in the Upper Neuse is 38% forested, 21% developed, 24% pasture and cultivated crops, and 11% woody wetlands (Homer et al., 2020). All other land uses comprise ~6.2%.

The entire Neuse basin flows completely within state boundaries, comprises over 6,200 square miles, and incorporates all or portions of 77 municipalities such as Durham, Raleigh, Goldsboro, and New Bern (*Neuse River Basin Restoration Priorities*, 2018). The basin contains a growing population of over 2 million people, most of which live in the upper portions of the watershed (*Neuse River Basin Water Resources Plan*, 2010). Populations in the upper portion rely on surface water for both drinking supplies and recreational purposes (*Neuse River Basin Water Resources Plan*, 2010). As a result, the majority of reservoirs in the Neuse are located within the suitable topography of the Piedmont (*Neuse River Basin Water Resources Plan*, 2010). The Falls Lake Reservoir is the largest impoundment in the basin and supplies water for Raleigh and surrounding communities (*Neuse River Basin Water Resources Plan*, 2010). However, recent studies indicate that increased population growth will stress water supply in these areas (*Neuse River Basin Water Resources Plan*, 2010).

Urbanization has adversely affected the Neuse basin in the form of nutrient and sediment loading, downstream flooding, increased turbidity, and streambank erosion (Deamer, 2009). Nonpoint source runoff and subsequent excessive nutrient loading from land use activities is the main stressor responsible for the degradation of Falls Lake (Deamer, 2009). Accordingly, the Basin has been subject to multiple restoration activities and featured on American River's "*America's Most Endangered Rivers"* list ("Neuse River," 2017). Main restoration priorities in the Neuse, particularly in the upper regions, include nutrient and sediment reduction near municipal and agricultural areas along with targeting area for buffer restoration and preservation (*Neuse River Basin Restoration Priorities*, 2018).

The Neuse River Basin has a state-mandated, basin-wide riparian buffer requirement of 50-ft on each side of the waterbody where the first 30-ft of the buffer must be undisturbed vegetation, while the next 20-ft can be managed (15A NCAC 02B .0233). Buffers are defined based on surface waters that are prevalent on the NRCS Soil Survey map or the USGS 1:24000 quad topographic map. Surface waters that do not appear on either map are exempt from this rule. Additionally, uses and activities that existed before July 22, 1997 are also exempt (15A

NCAC 02B .0233). Restoration and preservation attempts are ongoing within the Neuse, with a high prioritization on reestablishing and protecting riparian buffers and corridors (*Neuse River Basin Restoration Priorities*, 2018). In the Upper Neuse watershed, 12% of land in the buffer area is developed, 44% is forested, 3% is non-forest vegetation, and 8.6% is agriculture (pasture/cultivated crops), according to the 2016 NLCD (Homer et al., 2020).

Hydrologic Modeling

Description of Model

The Soil and Water Assessment Tool (SWAT) is a hydrologic model created to assess alternative management impacts in large river basins (J. G. Arnold et al., 1998). The SWAT was originally developed by the USDA Agricultural Research Service (ARS) to simulate the effects of agricultural management practices on water resources, such as water quantity and quality (Gassman, Reyes, Green, & Arnold, 2007). The SWAT is a culmination of several different hydrologic models, including the Chemicals, Runoff, and Erosion from Agricultural Management Systems (CREAMS) and the Groundwater Loading Effects on Agricultural Management Systems (GLEAMS) models (Neitsch, Arnold, Kiniry, & Williams, 2011). The tool operates on a daily time step and uses spatially distributed data inputs (such as topography, soils, land cover/use, and weather) to predict water, sediment, and nutrient yields (Douglas-Mankin, Srinivasan, & Arnold, 2010). The SWAT is a commonly utilized hydrologic model because of its user-friendly interface and readily available input data (Karim C Abbaspour et al., 2007; J. G. Arnold et al., 1998).

Since its conception nearly 30 years ago, the SWAT has been widely used and verified by an extensive, interdisciplinary user community in both international and domestic studies (Gassman et al., 2007). The model is part of the U.S. Environmental Protection Agency Better

Assessment Science Integrating Point and Nonpoint Sources (BASINS) methodology and the U.S. Department of Agriculture Conservation Effects Assessment Project (CEAP) (Gassman et al., 2007). Additionally, the SWAT is advantageous as it is open source, allowing for transparency and replicability.

The SWAT simulates hydrologic processes by dividing the watershed into subbasins and hydrologic response units (HRU), which creates greater specificity and computational efficiency for modeling. The program first uses a digital elevation model (DEM) to fill pits and sinks, calculate flow direction and accumulation, create a stream network, and disaggregate the watershed into subbasins (Winchell, Srinivasan, Di Luzio, & Arnold, 2013). The creation of subbasins is useful when a watershed has differing land uses or soil properties, which can alter the hydrology (Neitsch et al., 2011). The subbasins are further divided into HRUs, which are comprised of areas containing similar biophysical characteristics such as land use, soil, and slope. As processes in the watershed are centered on the water balance (Neitsch et al., 2011), the SWAT simulates hydrologic processes in two phases: the land phase and the water or routing phase. Climate data such as precipitation and temperature are either derived from the built-in weather generator or provided by the user from nearby weather stations. Processes are first modeled within the HRUs and are then aggregated within the subbasins (Winchell et al., 2013). Flow is routed through the channel using the Muskingum method, or variable storage coefficient method (Neitsch et al., 2011). Once the model has been run, it is then calibrated and validated with historical streamflow records (Winchell et al., 2013). Calibration and uncertainty analysis can be completed using the standalone program SWAT-CUP (Calibration and Uncertainty Procedures), which lets the user chose from five calibration procedures to streamline the calibration process (Karim C. Abbaspour, 2015).

For this study, baseline scenarios were run using historical climate and land use records and compared against 2060 projections. Necessary input data for the SWAT includes digital elevation models (DEM), reservoir information (if applicable), land use/land cover, soil properties, observed weather data, and historical streamflow (used for calibration). A list of inputs and sources can be found in Table 1.

Projected Land Use

The FUTure Urban-Regional Environment Simulation (FUTURES) modeling framework was used for projected land use in the Piedmont region (Meentemeyer et al., 2013). FUTURES combines both spatial and temporal data to project regional urban change at the pixel level (Meentemeyer et al., 2013; B. Pickard, Gray, & Meentemeyer, 2017). FUTURES is advantageous to use as it is an open source model that integrates with GRASS GIS add-ons, allowing for greater replicability and transparency (Petrasova et al., 2016). When validated, this flexible, open-source framework has proven to have both consistent and even greater locational accuracy prediction compared to alternative land use models (Pickard et al., 2017). Further, FUTURES has been applied to forecast urban water demand on the state level under multiple land use and policy scenarios, making it a practical tool for urban planning (Sanchez et al., 2020). FUTURES can also be coupled with ecosystem services models, underscoring its capability of analyzing both social and ecological factors in management and conservation (B. R. Pickard, Van Berkel, Petrasova, & Meentemeyer, 2017). The FUTURES model provides an applicable scale for this study and also classifies urban land cover as impervious surface (Pickard, Van Berkel, Petrasova, & Meentemeyer, 2017).

The FUTURES framework aims to account for multiple drivers of land use change by integrating three submodels. First, the POTENTIAL submodel analyzes the probability of development by considering environmental, infrastructural, and socio-economical predictors to create a site suitability surface. Next the DEMAND submodel estimates per-capita land consumption in each subregion by analyzing how historical and projected population interact with observed development patterns. Lastly, the PGA (Patch-Growing Algorithm) simulates patches of urban development on the POTENTIAL surface that are informed by DEMAND outputs. (Meentemeyer et al., 2013)

For this study, the FUTURES model was run on GRASS version 7.6.1. A model tutorial, sample data, and further information on the below processes can be found on the main FUTURES hub (https://cnr.ncsu.edu/geospatial/research/futures/). The FUTURES model was run on the entire state of North Carolina (100 counties) plus portions of South Carolina that buffer the Upper Catawba watershed (4 counties). The POTENTIAL submodel was implemented by first finding possible predictors for urban growth, which include slope, amount of forest cover, distance from lakes/rivers, distance from protected areas, distance to main urban centers, and road density. The predictor variables were then used to inform development pressure, which analyzes past development patterns to drive future land change. Development pressure assumes that previous development in one cell will drive neighboring development. The most significant predictors that drove development in the study area were previous development, distance to city centers, distance to protected areas, distance to water, and slope. These predictors were then used to create the potential site suitability surface. Next, the DEMAND submodel predicted the expected quantity of land change by exploring the interaction between previous urbanization, projected population, and population trends, for each of the 104 counties. The submodel was left to choose which function (linear, exponential, or logarithmic) best suited the relationship between development and population, although the user can also specify. Before the final simulation was run, patch shapes were calibrated on Durham, Wake, Johnston, and Wayne counties within the Upper Neuse and Yancey, McDowell, Burke, and Catawba counties within the Upper Catawba. These counties were chosen for calibration as they represented an urban-rural gradient. The parallel-PGA was then enacted to produce 10 separate simulation runs predicting development patches in all 104 counties to the year 2060.

The simulations predicted development patches for each individual year as well as cumulative development from 2018 to 2060. All other land uses remained constant, including previous development. The simulation that represented the mode of the runs (simulation 5) was merged with the 2016 NLCD. Newly development patches from the FUTURES raster were classified as "low-intensity development" and all other land uses were assumed to remain constant. Riparian buffer scenarios were created on the future land use raster using the NHD+ dataset and R statistical software. The FUTURES simulation operated at the same 30-m resolution of NLCD. To apply the buffer scenarios, raster data was disaggregated to 15-m (49.2 ft). Buffers were applied to the raster as polylines of 50 or 100-ft that were then used to update the land cover data.

Future Climate

Studies on the relationship between water stress and climate change are challenging given the variability of climate prediction, but can be robustly estimated using global circulation models (GCM). The fifth phase of the Coupled Model Intercomparison Project (CMIP 5) (Taylor, Stouffer, & Meehl, 2012) daily future Multivariate Adaptive Constructed Analogs (MACA) statistically downscaled data (John T Abatzoglou & Brown, 2012) was used to inform future climate (downloaded from the USGS data portal: http://cida.usgs.gov/gdp). This study used the CSIRO GCM RCP 8.5 (high GHG concentration scenario). To download the data, centroids of each subbasin for the Upper Neuse (25 subbasins) were created to act as weather stations, replicating the process used to download historical climate from GRIDMET. These points were used to download both temperature and precipitation data (mean, min, max, sum, count) from January 1, 2018 to December 31, 2060. Solar radiation, relative humidity, and wind speed were left at SWAT simulation defaults.

Model Set-Up

The Upper Neuse HUC-8 boundary provided by the NHD Watershed Boundary Dataset ended ~13 meters away from the chosen watershed outlet (located at USGS gage 02089000 Neuse River near Goldsboro, NC), which would create uncertainties in hydrologic model set-up and subsequent calibration. Therefore, a new boundary was delineated using the USGS StreamStats tool to ensure proper drainage at the designated outlet (USGS, 2016). The boundary created in StreamStats was ~0.2% smaller compared with the NHD HUC-8 boundary. Using ArcSWAT 2012, the new Upper Neuse boundary was delineated into 25 subbasins and a stream network was created using a pre-processed DEM. HRUs were created by overlaying the 2011 NLCD, the SSURGO soils dataset, and slope. The 2011 NLCD was chosen over the newer 2016 dataset as 2011 fell closer to the middle of the baseline period (2000-2018). The suggested HRU default threshold is 20% for land use, 10% for soil, and 20% for slope (Winchell et al., 2013). However, default thresholds can potentially oversimplify the watershed landscape (Her, Frankenberger, Chaubey, & Srinivasan, 2015). Therefore, the HRUs were given threshold percentages of 5% for landuse, 10% for soil, and 10% for slope to create a total of 408 HRUs. Daily average precipitation and daily minimum and maximum temperature were then added from the GRIDMET data processed by Google EarthEngine (John T. Abatzoglou, 2013). Lastly, impoundment information was added for Lake Crabtree (subbasin 7), Falls Lake Dam (subbasin

8), and Lakes Wheeler and Benson (subbasin 11). The baseline SWAT model was run from January 1, 1997 to December 31, 2018 with a three year warmup period.

Calibration and Validation

The SWAT-CUP 2012 software package was used for the calibration and validation process (Karim C. Abbaspour, 2015). SWAT-CUP contains five calibration procedures (SUFI2, GLUE, ParaSol, MCMC, PSO) and can perform sensitivity and uncertainty analysis (K. C. Abbaspour et al., 2015). For this study, the GLUE (Generalized Likelihood Uncertainty Estimation) algorithm (Beven & Binley, 1992) was chosen for the calibration and validation process based on its ability to find behavioral parameter combinations and established use in similar studies (Kim et al., 2014; Suttles et al., 2018). The GLUE procedure recognizes non-uniqueness in model predictions (Kouchi et al., 2017) by assigning a likelihood value to each set of parameter values (Beven & Binley, 1992; Kouchi et al., 2017). Calibration and validation procedures followed the general guidelines proposed by K. C. Abbaspour et al. (2015), where parameters were given wide but realistic ranges that were subsequently narrowed down in an iterative process to optimize the objective function.

Model Experimental Design

The calibrated parameters that best optimized the objective function and future weather values were written back into the baseline SWAT model. From this calibrated model, three land use scenarios were each run from the time period 2047-2060 with a 3-year warmup period:

1. No Buffer – Business-as-Usual

While the state has enacted a 50-ft buffer rule throughout the Neuse River Basin, this scenario will indicate how water resources will be impacted if pockets of development occur within the existing buffer zone, which is consistent with the current situation, as explained above.

2. Current conditions: 50-ft buffer rule

The current Upper Neuse buffer rule seeks to protect and restore buffers on surface waters present on the NRCS Soil Survey map or the USGS 1:24000 quad topographic map. However, the Division of Mitigation Services (DMS) has listed a series of Targeted Local Watersheds (TLW) for buffer restoration and protection, highlighting ongoing efforts to standardize this rule across the basin (*Neuse River Basin Restoration Priorities*, 2018). Therefore, this scenario will hypothesize that by 2060, the 50-ft buffer rule will be enacted on all targeted stream segments throughout the basin.

3. Expanded buffer: 100-ft buffer rule

Expanded buffers have been enacted in watersheds that provide invaluable ecosystem services while simultaneously facing growing demand and development. Portions of the Chesapeake Bay watershed have a 100-ft buffer rule ("Critical Area Buffer Resources Guide," 2011; "Resource Protection Areas,"). Therefore, this scenario will hypothesize how a realistic, expanded buffer will affect water resources.

RESULTS

SWAT Calibration and Validation

Model calibration attempts to minimize the differences between model simulated output and observed flow (Karim C Abbaspour, Vaghefi, & Srinivasan, 2018). The baseline Upper Neuse SWAT model was calibrated from January 1, 2000 to December 31, 2012 and validated from January 1, 2013 to December 31, 2018 using daily flow data from USGS Gauge 02089000 (watershed outlet). Global calibration began with 19 parameters that were subsequently narrowed down to 15 based on the significance of p-values (Table 2). Of those 15 parameters, baseflow alpha factor for bank storage (ALPHA_BNK), groundwater "revap" coefficient (GW_REVAP), effective hydraulic conductivity in main channel alluvium (CH_K2), and average slope length (SLSUBBSN) were consistently significant when the objective function was maximized. The Nash Sutcliffe efficiency (NSE) coefficient was used to indicate model performance and is most frequently used in GLUE. The NSE is defined in Moriasi et al. (2007) as:

$$\mathrm{NSE} = 1 - \left[\frac{\sum_{i=1}^{n} \left(Y_i^{obs} - Y_i^{sim} \right)^2}{\sum_{i=1}^{n} \left(Y_i^{obs} - Y^{mean} \right)^2} \right]$$

Where Y_i^{obs} = *i*th observation for the component being evaluated. Y_i^{sim} = *i*th simulated value for component being evaluated (Moriasi et al., 2007). Y*mean* = mean of observed data for component being evaluated and *n* = total number of observations (Moriasi et al., 2007). The NSE ranges from -∞ to 1.0 where a value of 1 indicates a perfect fit between simulated and observed data and a value of <0.0 indicates that the observed data mean is the better predictor compared to that of the simulated data (Moriasi et al., 2007; Nash & Sutcliffe, 1970). An NSE value for monthly streamflow from 0.50-0.65 is satisfactory, 0.65-0.75 is good, and 0.75-1.00 is very good (Moriasi et al., 2007). Generally, when focusing on streamflow, NSE values are lower for daily time steps compared to monthly time steps and are better for calibration versus validation periods (Moriasi et al., 2007). The model was run 6,721 times and yielded an NSE of 0.67 and an R^2 of 0.67 for daily streamflow. Model validation is necessary to ensure that the calibrated model can make predictions with a certain degree of confidence on an independent dataset (Karim C

Abbaspour et al., 2018). To perform validation, the set of calibrated parameter ranges that best optimized the objective function were used to replace the default SWAT values. SWAT was then run for the validation period (January 1, 2013 – December 31, 2018) and yielded an NSE of 0.66.

Baseline and Future Climate Trends

Baseline precipitation and temperature cover the period from 2000 to 2018 while the future period ranges from 2050-2060. These two time periods correspond with the baseline and future SWAT models. Generally, future precipitation and temperature trends indicate a warmer and wetter future in the Piedmont region of North Carolina. Rainfall quantity will be similar between the baseline and future periods, but the distribution and intensity of these events will differ. Additionally, monthly minimum and maximum temperature will both be warmer in the future compared to the baseline (Figure 2).

For both baseline and future periods, daily rainfall across all subbasins was averaged to create one value for each day to represent precipitation across the entire Upper Neuse. Daily values were then summed to create monthly values used for seasonal analysis. To compare the two periods on the same scale, mean monthly precipitation was averaged across all months. The month-to-month comparison shows that average accumulated monthly rainfall is higher in the future period in all months expect April, May, June, and December (Figure 3). Despite this lower average, the future period growing season will be wetter compared to the baseline. For this study, the growing season is defined as April through October, while winter is defined as November through March. Total accumulated rainfall over the course of 7 months during the baseline growing season range from a low of 484.22 mm in 2007 to a high of 1,092.13 mm in 2018. Accumulated rainfall during the future growing season predicts a wetter future (in a shorter time period compared to the baseline) with a range from a low of 545.81 mm in 2052 to a high of 1,245.12 mm of accumulated precipitation in 2054. Special attention should be paid to the higher monthly averages during the future in August through October. These months also coincide with hurricane season in North Carolina, signifying the potential for more intense storm effects in the region.

Baseline and future winter seasons are more variable compared to the growing seasons. During the baseline period, the total accumulated rainfall over the 5-month winter season ranges from 303.19 mm in 2004 to 649.89 mm in 2018. The future period shows more variability, with a low of 240.03 mm in 2051 to a high of 822.96 mm accumulated in 2053. This trend indicates that the winter seasonal precipitation in the future will have a greater range compared to the baseline, with extreme low and high rainfall events.

Temperature was analyzed using the same methods as precipitation, except instead of summing daily events to generate monthly values, daily events were averaged to generate monthly averages. As noted previously, monthly maximum and minimum temperatures will be higher during the future period compared to baseline. Mean monthly temperature will also be higher in the future, with the largest percent change (43%) occurring in February, which jumps from 6.73 ºC in the baseline to 9.63 ºC in the future (Figure 4). Both future growing and winter seasons will be warmer compared to the baseline period.

FUTURES Urban Growth Model

The FUTures Urban Growth Model was used to predict patches of development across the entire state of North Carolina from 2019-2060. The “best run” output raster was merged with the 2016 NLCD to create the final raster representing land cover in 2060. Newly developed patches from the FUTURES raster were classified as “low-intensity development” (NLCD value 22) and all other land uses were assumed to remain constant. Low-intensity development is characterized as the 20-49% impervious cover typical of single-family housing developments in NLCD (Homer et al., 2015). The final output represents a base raster used to run future buffer width scenarios in the SWAT model from 2050-2060.

According to the 2016 NLCD, forestland, woody wetlands, and cultivated crops currently represent the top land covers in North Carolina. Deciduous forest remained the highest percent land cover in the state from baseline (19.58%) to future (19.13%) (Homer et al., 2020). Output from the FUTURES model shows low-intensity development doubling across the state from 2.92% in 2016 to 4.62% in 2060, representing a 58.3% difference (Figure 5). By 2060, development (in all forms) is predicted to comprise 12.96% of total land cover in the state, compared to 11.38% in 2016. Simulated future development occurs primarily on hay/pasture land (3.75% decline), indicating a gradual shift from agriculture to urban land use across the state. Increased development trends are evident in the Upper Neuse, which is presently considered an urbanizing, mixed-use watershed.

In the SWAT baseline model, open space development, forested land, cultivated crops, and woody wetlands comprised the top land covers in the Upper Neuse (Table 3). The FUTURES output showed low-intensity development doubling across the watershed to the year 2060 (Figure 6). Subbasins 2, 4, 5, 7, and 24 (watershed outlet) were further analyzed based on their baseline development and varying patterns of growth (Figure 6). Subbasin 2 has an area of 27,070-ha and is located north of Hillsborough in the headwater region of the watershed. FUTURES projections show a 28.57% increase in percentage of development from 8.23% in baseline to 10.5% in the future. Subbasin 4 (38,876-ha) contains the town of Hillsborough and surrounding area. This region had a greater percentage of development during the baseline period (19.8%) that also increased into the future (21.69%). Development in this subbasin seems to occur in both forested and agricultural land, dropping the percentage of these land covers by 2.65% and 1.06%, respectively. Subbasin 5 is slightly smaller at 13,663-ha and is of particular interest as it contains portions of Durham as well as the Falls Lake Reservoir, which supplies drinking water for the city of Raleigh and surrounding area. This subbasin is predicted to have a 90% increase in percentage of development, going from 7% development in the baseline to 13.3% in the future. Subbasin 7 (37,340-ha), which comprises the majority of Raleigh and parts of Research Triangle Park and William B. Umstead State Park, remained the highest developed subbasin from baseline (68%) to future (73%). Subbasin 24 (29,884-ha) had a 26% increase in percentage of developed land from baseline to future, putting it at the lower end of subbasins with a high rate of development. This subbasin contains the outlet. Therefore, outflow from this subbasin represents the cumulative effects of land cover change across the UN.

In all subbasins, future development results in a decrease in forest cover from the baseline to the future period. However, the 50-ft and 100-ft buffer scenarios successfully increase forest cover in all subbasins to exceed baseline levels. For example, in subbasin 7, development decreases forest cover from 23% in the baseline to 20% in the future. The added 50-ft buffers increase forest cover to 30% while the 100-ft buffers increase forest cover to 41.2%. The added forest cover by the 50-ft and 100-ft buffers results in a decrease in development by 13% and 27% respectively. In most subbasins, even with the addition of 100-ft buffers, future developed land will still exceed baseline levels. Future development also results in a decrease in agricultural land. The buffers have a different response to this land cover where the greater the buffer width, the less land there is for agriculture. For example, subbasin 2 is 24%

agricultural land in the baseline period. The un-buffered future shows a drop to 23% agriculture, while the 50-ft and 100-ft buffers decrease this cover further to 22% and 18%, respectively.

Baseline and Future Streamflow Trends

To compare baseline and future streamflow trends in all subbasins of interest, daily flow was averaged for each day across all years. Figures 7 – 11 show mean daily flow for each Julian day across all years for both the baseline (2000-2018) and future no buffer (2050-2060). In looking at the highest and lowest flow days between baseline and future period, subbasins 2 and 4 follow similar patterns, whereas subbasins 5 and 7 are similar. The outlet of the watershed behaves most similarly to subbasins 5 and 7. This grouping could result from the geographic proximity and land cover similarities between the subbasins. During the baseline period, subbasins 2 and 4 both have peak flows around November and low flows in late August. In the future period, the two subbasins have peak flows at the start of the growing season in April and low flows in late August. Subbasins 5 and 7 also have peak flows around November during the baseline period. However, the lowest flows occur in winter between December and January. In the future period, the highest flows occur in September and the lowest flows occur in July, suggesting seasonal flow differences between the two groupings. The outlet of the watershed indicates that baseline high and low flows occur in October and May, respectively. Future high and low flows both occur in September.

All subbasins and the outlet have a high percentage change in streamflow between baseline and future periods. For example, the highest percent change at the outlet was 66%, while subbasin 5 has over a 600% change that occurred during an event in October. The 10% highest and lowest percent change in streamflow events between the baseline and future period were pulled for each subbasin to represent extreme events. In subbasins 2 and 4, days with the highest percent change in streamflow occurred primarily in the growing season, while the lowest days were split between the growing and winter seasons. In subbasins 5 and 7, the trend reverses, where the highest events occur split between the growing and winter seasons and the lowest events occur primarily in the growing season. At the outlet, both high and low percentage change events occur primarily in the growing season. These results indicate the highest rates of change in streamflow across the watershed will potentially occur during the growing season. Figures 12 – 16 show the percent change in streamflow between baseline and future by season. Lastly, future streamflow during the growing and winter seasons is estimated to be higher compared to baseline levels in all subbasins but 5 and 7 (Table 4 and Table 5). In subbasin 5, streamflow during the growing season is slightly lower compared to baseline, while winter flow is slightly higher. In subbasin 7, both growing season and winter streamflow is predicted to be lower in the future compared to baseline.

Buffer Effect on Future Streamflow Trends

Along with the un-buffered future streamflow (FUTNB), daily flow was averaged for each day across all years for the 50-ft buffer future (FUT50) and 100-ft buffer future (FUT100). The percent change between FUTNB/FUT50 and FUTNB/FUT100 was then calculated to generate a general idea of how the buffers affected future streamflow across all days in the future period. In all subbasins, FUT100 generally had a higher percent change compared to FUT50, specifically in subbasins 2 and 7.

In subbasin 2, the FUT100 scenario increased streamflow at most by 3.8% compared to FUTNB levels, while FUT50 increased streamflow by 1.6% at the most. The buffers had a minimal effect across all Julian days in subbasin 4, increasing streamflow by 0.73% and 0.82% respectively. The buffers were more successful at decreasing streamflow in subbasin 4. FUT50 decreased flow by 2.1% and FUT100 decreased flow by 1.9%. In subbasin 5, FUT100 increased streamflow by 1.36% at the most while FUT50 increased flow by 0.97% at the most. The FUT50 scenario resulted in a decrease in flow by 1.34% and the FUT100 scenario decreased flow by 2.5% at the most in subbasin 5. In looking at the daily averages across all years, both buffer scenarios were most successful at decreasing FUTNB streamflow in subbasin 7. In this area, FUT50 decreased flow by 3% at the most and FUT100 decreased flow by 5.84% at the most. FUT50 and FUT100 increased flow at the most by 1.48% and 2.73%, respectively. At the outlet, the scenarios had a minimal effect. Both FUT50 and FUT100 increased and decreased flow by <1% at the most.

Buffer Effect during Extreme High and Low Flow Events

To analyze buffer effect on hydrologic extremes at a finer scale, the top 5% and lowest 5% daily streamflow events were pulled from each year (2050-2060) to represent extreme future peak and low flow events. For each date, daily streamflow was compared across the three scenarios (FUTNB, FUT50, FUT100) and percent change was calculated between FUTNB/FUT50 and FUTNB/FUT100 to analyze how the expanded buffers affected flow compared to the un-buffered future. The top 5% and lowest 5% streamflow events each generally comprised around 18 days every year. Streamflow percent change under the two scenarios during daily events across a given year were averaged to create a yearly snapshot of how buffers effected extreme flow in that given year.

In subbasins 4, 5, 7, and at the outlet, FUT50 and FUT100 on average decreased daily streamflow during the highest flow events in the majority of years. Across all years in subbasin 2, buffers increased daily flow by 0.20% (FUT50) and by 0.40% (FUT100) (Figure 17). Addition of the 50-ft buffers resulted in the largest percent change in daily streamflow in subbasin 4

(Figure 18). For instance, across all high flow events in 2058, FUT50 reduced daily streamflow by 4.42%. Across all years, the 100-ft buffers had the largest impact in subbasin 5 where they reduced daily streamflow by 2.15% (Figure 19). Subbasins 2, 4, and 5 all received comparable amounts of rainfall and showed similar streamflow patterns, albeit with different levels of flow. Subbasin 4 consistently had higher levels of daily streamflow compared to 2 and 5. Subbasins 2 and 5 hovered around similar levels of daily streamflow but basin 2 experienced lower low flows and higher high flows. The variation in buffer response during extreme high flows might be attributed to landuse of the subbasin. Subbasin 5 had the greatest percent change in level of urban development, while subbasin 4 remained one of the more forested areas of the watershed.

Buffer effects during the lowest daily flow events were also variable. In subbasins 2 and 5, the effects were minimal, with FUT50 and FUT100 both increasing and decreasing daily flow across all years by <1%. The buffers continued to effect subbasin 4, where FUT50 and FUT100 decreased daily streamflow across all years by 2.6% and 3%, respectively. Subbasin 7 shows diverging behavior, where across all years, FUT50 on average decreases flow and FUT100 increased flow (Figure 20). At the outlet, both buffers decreased daily flow on average across all years (Figure 21).

Buffer Effect on Water Resources

Water Yield

Across the watershed, FUT50 and FUT100 have variable impacts on FUTNB annual water yield (WY). The buffers had the greatest impact on annual WY in subbasin 4. In this area, the buffers decreased WY in every year but 2055 (FUT100 increases WY by <0.01%). FUT50 decreased annual WY at the most by 3.2% while FUT100 decreased at the most by 3.3%. In subbasin 2, the buffers mostly increased annual WY in all years but 2055 (FUT50 and FUT100) and 2056 (FUT100). However, the impact was marginal, both scenarios increased or decreased WY by <1% throughout the years. Subbasin 5 followed a similar pattern, where FUT50 and FUT100 both increased and decreased annual WY at the most by <1%. In subbasin 7, the buffers decreased annual WY at the most in 2058 by 1.06% (FUT50) and 2.12% (FUT100). At the outlet, WY varied by <1% except in 2058, where FUT100 decreased yield by 1.2%.

Runoff Ratio

Similar to WY, annual runoff ratio (RR) percent change between FUTNB/FUT50 and FUTNB/FUT100 was greatest in subbasin 4. In this subbasin, FUT50 and FUT100 decreased RR in all years but 2054 (FUT100 increased RR by 0.01%). FUT50 was more successful at decreasing RR compared to FUT100. FUT50 decreased RR from 0.33% – 3.18% across the years while FUT100 decreased RR from 0.18% – 3.08%. In subbasin 2, 5, and the outlet, RR was both increased and decreased depending on the year. In all instances, annual RR was only affected by ≤1%. In Subbasin 7, FUT50 decreased annual RR at the most by 1.06% and increased RR at the most by 0.61%. FUT100 had a greater impact, decreasing RR at the most by 2.12% and increasing at the most by 1.23%.

DISCUSSION

Future Climate Trends

The CSIRO GCM RCP 8.5 indicated an overall warmer future in the Piedmont, punctuated by more extreme precipitation events. This projection is consistent with the literature that indicate storms will be increasingly intense and infrequent in the future (O'Gorman & Schneider, 2009; Suttles et al., 2018). Generally, increases in both temperature and precipitation will have immediate effects on the hydrologic cycle. Broader trends across the CONUS project that temperature will surpass precipitation (the historic driver) in explaining runoff variation because higher temperature will trigger higher rates of evapotranspiration (Kai Duan et al., 2017). However increasing humidity and precipitation can potentially offset the effects of warming temperature on water resources resulting in a wetter future (Duan et al., 2017), as projected for the Piedmont.

I found that monthly average daily maximum and minimum temperature were higher in all months in the future compared to the baseline. Precipitation was more variable with noticeable seasonal differences. Analyses indicated that monthly average precipitation was higher in all months except April, May, June, and December. April, May, and June represent the beginning of the growing season in North Carolina. Lower precipitation and warmer temperatures during this time could put additional pressure on water resources. Further, while Atlantic hurricane season runs from June through November, some of the strongest hurricanes of record occur later in the season between August and October (U.S. Census Bureau, 2020). I found higher precipitation averages in these months, especially in September, which indicates the potential for hurricane events to occur under wetter conditions, potentially exacerbating flooding in the future. My results are consistent with Suttles et al. (2018), who analyzed mid-century climate in the Piedmont and found an increase in both precipitation and average temperature across four climate futures. Future precipitation across the winter season was more variable compared to the baseline. This trend indicates that future precipitation during the winter season might be characterized by more extreme low and high rainfall events.

Urban Growth Implications

I selected the FUTURES model to simulate future urban growth patches based on its high degree of customization, validation, and use in previous literature (Sanchez et al., 2020). Due to the uncertainty surrounding future human activity, land use projections should be interpreted as projections of one possible future (Van Metre et al. 2019). Results from the model showed low-intensity development doubling across the state by the year 2060, which increases total development by ~1%. This is intended to be a conservative estimate, as new development was assigned as low-intensity. On a smaller scale, the hydrologic intensification resulting from land use change will have immediate socioeconomic impacts on already vulnerable communities, such as communities with limited capacity to adapt to environmental change (Saia et al., 2019). Negative impacts from land use change, such as increased flooding, can impact property value and infrastructure (Carter et al., 2018; Saia et al., 2019), which can adversely affect a rapidly growing region such as the Piedmont.

Results from the FUTURES model extend beyond spatial implications and might be indicative of larger social and economic trends in North Carolina. Around 45% of future development occurs on forestland while 26% occurs on agricultural land. North Carolina has shifted from a largely agricultural state into an economy based in finance and biotechnology (*NC Economic Report*, 2018). As of 2018, job growth in the state was highest in the larger metropolitan areas at a level out-performing similar areas around the country (*NC Economic Report*, 2018). The shift in land cover change indicated by the FUTURES model suggests further development of these metropolitan areas, potentially fueled by population and job growth. Agricultural jobs in 2018 only comprised 0.6% of total jobs in the state (*NC Economic Report*, 2018). Therefore, losses in cultivated and pasture land could be an indicator of further shifts in the employment sector towards more urban-based jobs.

In all subbasins (excluding subbasin 13 which had no baseline development), forest cover decreased from baseline to FUTNB levels. In 22 of the 25 subbasins, the addition of the 50-ft buffer resulted in increased forest cover higher than baseline levels. Further, the 100-ft buffer increased forest cover beyond baseline levels in all subbasins. In the majority of subbasins, both FUT50 and FUT100 buffer scenarios increased forest cover beyond baseline levels while also maintaining urban land cover beyond baseline levels. Therefore, establishment and preservation of riparian buffers can potentially be a method to preserve forestland, support urban growth, and provide valuable ecosystem services.

Streamflow Trends

My SWAT model results indicated that compared to baseline, average future streamflow was higher in subbasins 2, 4, and across the UN (subbasin 24) and lower in subbasin 5 and 7. Across all subbasins, basin 5 had the highest percent change (90%) in development from baseline to FUTNB, while subbasin 7 maintained the highest percentage of development between both periods. These results highlight the potential for lower future flows in rapidly developing and already highly developed areas. For instance, Suttles et al. (2018) found that land use change coupled with changing climate resulted in infrequent precipitation events that decreased baseflow and increased the cumulative number of zero flow days in a rapidly urbanizing watershed. In that study, the SWAT model was employed to project streamflow response to land use and climate scenarios in the Yadkin River watershed in the NC Piedmont. Under a changing land use scenario, the Yadkin River watershed urbanized rapidly by 25-35% from baseline to 2060, similar to urbanization rates in the UN (Suttles et al., 2018). Therefore, my findings regarding flow in urbanized watersheds show a similar pattern to the findings of Suttles et al. (2018).

Peak and low flows in 2, 4, 5, and 7 differed between the baseline and FUTNB. In subbasins 2 and 4, peak flows occurred in November during the baseline and April during the future. Lower precipitation and warmer temperature was projected during April, which means these peak flows might be the result of land conversion altering the watershed landscape. In subbasin 5 and 7, low flows occurred around December/January during the baseline and are projected to occur in July during the future period. This shift indicates lower flow during peak summer months in these two developed areas, which can have negative impacts for aquatic habitat and water demand. Further, the highest rates of change in streamflow across the watershed were projected to occur during the growing season, meaning that streamflow could potentially be more variable during these warmer months.

Buffer Effect on Hydrologic Resources

FUT50 and FUT100 showed variable results during the most extreme high flow and low flow events. On average during the highest flow events across the future period, both buffer scenarios decreased streamflow in all subbasins except subbasin 2, and the largest decreases occurred in subbasin 4. These two basins follow similar patterns of development, but divergent stream flow responses. During the baseline period, subbasin 4 had a higher level of developed land compared to subbasin 2. However, subbasin 2 had a higher percent change from baseline to future development compared to subbasin 4. The difference in buffer response between these two subbasins might be attributed to their watershed positions. Subbasin 4 was downstream of subbasin 2, and, where upstream changes might have a cumulative effect in downstream areas. Buffer effect during low flow events was more variable. For example in subbasin 4, the buffers decreased streamflow during the lowest flow events. In subbasin 7, the buffers had variable effects, both increasing and decreasing flow during these events. The differences in these responses might be attributed to buffer response in developed vs. developing areas.

These findings indicate that buffer effect on daily streamflow is variable and potentially dependent on factors such as land use, climate, and watershed position of the individual subbasins. Expanded buffers might further exacerbate low streamflow in more forested areas, as seen in subbasin 4. Part of this behavior can be attributed to the offsetting impacts of expanded vegetation on water yield. Kim et al. (2014) used SWAT to retrospectively assess the effect of reforestation over the 20th century on watershed runoff in headwaters of the Neuse basin to determine why trends of increased precipitation did not result in increased runoff. The study found that water yield remained relatively constant throughout this period as a result of the offsetting impacts of forest regrowth (Kim et al., 2014). In developed areas, the buffers both increased and decreased streamflow during the lowest flow events, indicating more variability in highly developed subbasins. Hydrologic variability in urban watersheds can usually be attributed to factors like urban stream syndrome resulting from increased impervious surface cover.

Variable buffer effect in these subbasins highlights the need for further research into the placement of strategic buffers within the urban, suburban, and rural nexus depending on the management goal. While the aim of this study was to assess buffer effect on water quantity, vegetated/forested areas enhance water quality and help restore the natural water balance in urban areas (Fletcher, Andrieu, & Hamel, 2013). Matteo et al. (2006) found that incorporating more pervious cover through urban forestry practices greatly reduced sediment loading, nutrient contamination, and runoff rates, while increasing groundwater recharge in urban watersheds. Further, a rural watershed exhibited the greatest improvement in water quality when BMPs were enacted, as the greater amount of forest cover a basin contains, the greater capacity it has to adapt to changing conditions (Matteo et al., 2006). The study touched on similar conclusions to Cooper et al. (1987), noting that optimal riparian zones should vary with stream order. While our findings focus solely on water quantity, we drew similar conclusions to these previous studies in that buffer width should vary depending on the unique hydrologic characteristics of the watershed and overall management goal.

Water Yield and Runoff Ratio

Estimating future WY and the corresponding effect of buffers on this yield is important considering a broader context. Ge Sun et al. (2015) compared historical climate and four GCMs coupled with future greenhouse gas emission storylines and found that water yields are expected to decline for the entire CONUS by 2050, including in current water abundant regions such as the SE. These findings have direct implications for the Piedmont, which benefits from an availability of water resources. I found that buffers had differing effects on annual WY depending on the subbasin. In subbasin 2, the buffers marginally increase WY during all years while in subbasin 4, the buffers decrease WY in most years. In the remaining subbasins, WY is both increased and decreased by the buffers, depending on the year. Generally, while decreasing forest cover increases water yield and increasing forest cover decreases water yield, streamflow response is still largely influenced by climatic factors like precipitation (Brown et al., 2005).

Along with precipitation, WY is determined by the relationship between groundwater recharge and evapotranspiration (ET) (Gharibdousti Rasoulzadeh, Kharel, Miller, Linde, & Stoecker, 2019). Buffers play a unique role in assessing the water budget as they reroute precipitation and runoff from immediately entering the waterway and instead channel it towards groundwater percolation, plant uptake, and ET. The mid-century water budget of the Upper Neuse is projected to have increased precipitation in the region with decreases in ET, which coupled could result in increased WY and soil water (Ercan, Maghami, Bowes, Morsy, &

Goodall, 2020). Higher ET has been found to decrease total streamflow, flow rate, and groundwater recharge (Ge Sun et al., 2013) but is also variable by scale and season (Ercan et al., 2020). Therefore, to better manage and predict annual WY in the UN, the relationship between factors such as buffer, precipitation, and ET must first be well understood at the subbasin level.

Annual runoff ratio (RR) was most affected in subbasins 4 and 7. In subbasin 4, FUT50 and FUT100 decreased RR in all years but 2054, while in subbasin 7, the scenarios both decreased and increased annual RR. Annual RR is an important indicator of watershed health as coupled runoff decline and demand increase can put additional pressure on water resources, such as reservoirs (Ge Sun et al., 2013). Continual decreases in annual RR in subbasin 4 might be attributed to the basins greater amount of forest cover compared to subbasin 7. Buffers are meant to slow the process of runoff immediately entering the waterbody, and therefore might be more efficient at this process in areas that are surrounded by greater forest cover. Buffers supply the added benefit of improving water quality, which is of greater concern in urban areas with increased levels of runoff.

CONCLUSIONS

Using robust land use and climate change scenarios, this study analyzed the current and continued effectiveness of riparian buffers to stabilize water resources in a watershed that represents a microcosm of growing trends across the US. Therefore, the results of this study can potentially be extrapolated beyond the Piedmont to inform effective watershed management juxtaposed with rapid development and climate change. While there is a regional focus to this work, the potential for expanded buffers as mitigation tools has larger implications. Global water use continues to increase steadily in line with global population growth, consumption change, and economic trends (Stewart et al., 2020). These trends present a universal need to protect valuable water resources in a sustainable, cost-efficient manner. Effective management on the watershed scale must involve policies that balance land uses with watershed services (Postel & Thompson Jr, 2005). Under this framework, forest retention represents a natural and practical method for stabilizing water resources under climate and land use change in suitable areas (Postel & Thompson Jr, 2005; Ge Sun & Lockaby, 2012), as opposed to the conventional approaches such as reservoir construction and infrastructure retrofitting (Ge Sun & Lockaby, 2012).

Riparian buffers are a nature-based solution to maintaining the hydrologic balance in vulnerable watersheds and are regarded as BMPs in many forestry and agricultural practices. They are therefore already used in watersheds beyond the Piedmont. For example, a 100-ft buffer mandate in the Chesapeake Bay is a key component of both Virginia's Chesapeake Bay Preservation Act ("Resource Protection Areas,") and Maryland's Critical Area Program ("Critical Area Buffer Resources Guide," 2011). My results indicate that buffer preservation and retention could conserve forestland while also allowing for development to still occur at high levels in the UN. The buffer effect on streamflow during the most extreme flow events is variable and dependent on specific factors within each subbasin. While this study focused on water quantity, enhanced water quality is an additional benefit of riparian buffers. Restoring and expanding buffers in areas at risk of degraded water resources, such as areas subject to urban stream syndrome, could jointly improve water quality and maintain a stable water budget in context of land use change.

North Carolina's 50-ft mandated buffer rule aims to establish and preserve riparian buffers throughout the entire Neuse basin (15A NCAC 02B .0233). While buffer retention is a promising step towards maintaining overall watershed health, the width of these buffers should probably be determined by the overall management goal. For example, in some areas, a 50-ft buffer may suffice in mitigating high streamflow compared to a 100-ft buffer. In other areas, buffers expanded beyond 100-ft might be necessary in the context of changing land use and climate. Matteo et al. (2006) emphasize the need to establish “variable riparian zones” that are dependent on the degree of watershed impairment (151). The NC Division of Water Resources also stresses the need to establish buffers based on watershed and community needs (“Catawba River Basinwide Water Quality Plan”, 2010). Since most land within the buffer zones is residential, the Division also highlights the need for public education and outreach to ensure successful buffer implementation and preservation (“Catawba River Basinwide Water Quality Plan”, 2010). Therefore, further research is needed, perhaps at a smaller HUC-12 scale, into the benefits of variable riparian zone widths on water resources and corresponding public approval.

REFERENCES

15A NCAC 02B .0233, 0233 C.F.R.

Abatzoglou, J. T. (2013). Development of gridded surface meteorological data for ecological applications and modelling. *International Journal of Climatology, 33*(1), 121-131. Retrieved from https://rmets.onlinelibrary.wiley.com/doi/abs/10.1002/joc.3413. doi:https://doi.org/10.1002/joc.3413

Abatzoglou, J. T., & Brown, T. J. (2012). A comparison of statistical downscaling methods suited for wildfire applications. *International Journal of Climatology, 32*(5), 772-780. Retrieved from https://rmets.onlinelibrary.wiley.com/doi/epdf/10.1002/joc.2312. doi:https://doi.org/10.1002/joc.2312

Abbaspour, K. C. (2015). *SWAT Calibration and Uncertainty Programs -- A User Manual*. Retrieved from https://swat.tamu.edu/media/114860/usermanual_swatcup.pdf

Abbaspour, K. C., Rouholahnejad, E., Vaghefi, S., Srinivasan, R., Yang, H., & Klove, B. (2015). A continental-scale hydrology and water quality model for Europe: Calibration and uncertainty of a high-resolution large-scale SWAT model. *Journal of Hydrology, 524*, 733-752. Retrieved from <Go to ISI>://WOS:000354503300057. doi:10.1016/j.jhydrol.2015.03.027

Abbaspour, K. C., Vaghefi, S. A., & Srinivasan, R. (2018). A guideline for successful calibration and uncertainty analysis for soil and water assessment: A review of papers from the 2016 International SWAT Conference. In: Multidisciplinary Digital Publishing Institute.

Abbaspour, K. C., Yang, J., Maximov, I., Siber, R., Bogner, K., Mieleitner, J., . . . Srinivasan, R. (2007). Modelling hydrology and water quality in the pre-alpine/alpine Thur watershed using SWAT. *Journal of Hydrology, 333*(2-4), 413-430.

Arnold, C. L., & Gibbons, C. J. (1996). Impervious surface coverage - The emergence of a key environmental indicator. *Journal of the American Planning Association, 62*(2), 243-258. Retrieved from <Go to ISI>://WOS:A1996UA39200008. doi:10.1080/01944369608975688

Arnold, J. G., Srinivasan, R., Muttiah, R. S., & Williams, J. R. (1998). Large area hydrologic modeling and assessment - Part 1: Model development. *Journal of the American Water Resources Association, 34*(1), 73-89. Retrieved from <Go to ISI>://WOS:000072524100007. doi:10.1111/j.1752-1688.1998.tb05961.x

Beven, K., & Binley, A. (1992). The future of distributed models: model calibration and uncertainty prediction. *Hydrological Processes, 6*(3), 279-298. Retrieved from https://onlinelibrary.wiley.com/doi/pdf/10.1002/hyp.3360060305?casa_token=iXjO47hD9EEAAAAA:8154uPa73om6u9lh6fJwjhO92XJkLlIqa0l0jNChlc4yNLBo4nUl31vdgrTjRDPU0xUdCTEhgafjKw.

Binkley, D., Ice, G. G., Kaye, J., & Williams, C. A. (2004). Nitrogen and phosphorus concentrations in forest streams of the United States. *Journal of the American Water Resources Association, 40*(5), 1277-1291. Retrieved from <Go to ISI>://WOS:000224721900013. doi:10.1111/j.1752-1688.2004.tb01586.x

Blinn, C. R., & Kilgore, M. A. (2001). Riparian management practices: a summary of state guidelines. *Journal of Forestry, 99*(8), 11-17.

Borsuk, M., Clemen, R., Maguire, L., & Reckhow, K. (2001). Stakeholder Values and Scientific Modeling in the Neuse River Watershed. *Group Decision and Negotiation, 10*(4), 355-373. Retrieved from https://doi.org/10.1023/A:1011231801266. doi:10.1023/A:1011231801266

Brown, A. E., Zhang, L., McMahon, T. A., Western, A. W., & Vertessy, R. A. (2005). A review of paired catchment studies for determining changes in water yield resulting from alterations in vegetation. *Journal of Hydrology, 310*(1-4), 28-61. Retrieved from <Go to ISI>://WOS:000230436200003. doi:10.1016/j.jhydrol.2004.12.010

Caldwell, P., Muldoon, C., Miniat, C. F., Cohen, E., Krieger, S., Sun, G., . . . Bolstad, P. V. (2014). *Quantifying the role of National Forest System lands in providing surface drinking water supply for the Southern United States*: Government Printing Office.

Caldwell, P. V., Sun, G., McNulty, S. G., Cohen, E. C., & Moore Myers, J. A. (2012). Impacts of impervious cover, water withdrawals, and climate change on river flows in the conterminous US. *Hydrology and Earth System Sciences, 16*(8), 2839-2857. Retrieved from https://www.hydrol-earth-syst-sci.net/16/2839/2012/. doi:10.5194/hess-16-2839-2012

Carter, L., Terando, A., Dow, K., Hiers, K., Kunkel, K. E., Lascurain, A., . . . Schramm, P. J. (2018). Southest. In A. Jerolleman (Ed.), *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment,* (Vol. II, pp. 743-808). Washington, DC,USA: U.S. Global Change Research Program.

Cooper, J. R., Gilliam, J. W., Daniels, R. B., & Robarge, W. P. (1987). Riparian Areas as Filters for Agricultural Sediment. *Soil Science Society of America Journal, 51*(2), 416-420. Retrieved from http://dx.doi.org/10.2136/sssaj1987.03615995005100020029x. doi:10.2136/sssaj1987.03615995005100020029x

Council, N. R. (2008). *Hydrologic Effects of a Changing Forest Landscape*. Washington, DC: The National Academies Press.

Critical Area Buffer Resources Guide, 09 C.F.R. (2011).

Daniels, R. (1987). Soil erosion and degradation in the southern Piedmont of the USA. In M. G. Wolman & F. G. A. Fournier (Eds.), *Land Transformation in Agriculture* John Wiley & Sons Ltd.

Deamer, N. (2009). *Neuse River Basinwide Water Quality Plan*. Retrieved from https://files.nc.gov/ncdeq/Water%20Quality/Planning/BPU/BPU/Neuse/Neuse%20Plans/2009%20Plan/NR%20Basinwide%20Plan%202009%20-%20Final.pdf

Douglas-Mankin, K. R., Srinivasan, R., & Arnold, J. G. (2010). SOIL AND WATER ASSESSMENT TOOL (SWAT) MODEL: CURRENT DEVELOPMENTS AND APPLICATIONS. *Transactions of the Asabe, 53*(5), 1423-1431. Retrieved from <Go to ISI>://WOS:000284818500006.

Duan, K., Sun, G., Caldwell, P. V., McNulty, S. G., & Zhang, Y. (2018). Implications of Upstream Flow Availability for Watershed Surface Water Supply across the Conterminous United States. *Journal of the American Water Resources Association, 54*(3), 694-707. Retrieved from <Go to ISI>://WOS:000434120900009. doi:10.1111/1752-1688.12644

Duan, K., Sun, G., McNulty, S. G., Caldwell, P. V., Cohen, E. C., Sun, S., . . . Zhang, Y. (2017). Future shift of the relative roles of precipitation and temperature in controlling annual runoff in the conterminous United States. *Hydrology and Earth System Sciences, 21*(11), 5517-5529. Retrieved from https://www.srs.fs.usda.gov/pubs/ja/2017/ja_2017_sun_012.pdf. doi:https://doi.org/10.5194/hess-21-5517-2017

Ercan, M. B., Maghami, I., Bowes, B., Morsy, M. M., & Goodall, J. L. (2020). Estimating Potential Climate Change Effects on the Upper Neuse Watershed Water Balance Using the SWAT Model. *Journal of the American Water Resources Association, 56*(1), 53-67. Retrieved from <Go to ISI>://WOS:000502598600001. doi:10.1111/1752-1688.12813

Fenneman, N. M., & Johnson, D. W. (Cartographer). (1946). Physiographic divisions of the conterminous U. S. Retrieved from https://water.usgs.gov/lookup/getspatial?physio

Fletcher, T. D., Andrieu, H., & Hamel, P. (2013). Understanding, management and modelling of urban hydrology and its consequences for receiving waters: A state of the art. *Advances in Water Resources, 51*, 261-279. Retrieved from <Go to ISI>://WOS:000314105900014. doi:10.1016/j.advwatres.2012.09.001

Ford, C. R., Laseter, S. H., Swank, W. T., & Vose, J. M. (2011). Can forest management be used to sustain water-based ecosystem services in the face of climate change? *Ecological Society of America, 21*(6), 2049-2067. Retrieved from https://esajournals.onlinelibrary.wiley.com/doi/abs/10.1890/10-2246.1. doi:doi:10.1890/10-2246.1

Fritz, K. M., Johnson, B. R., & Walters, D. M. (2008). Physical indicators of hydrologic permanence in forested headwater streams. *Journal of the North American Benthological Society, 27*(3), 690-704. Retrieved from https://www.journals.uchicago.edu/doi/pdfplus/10.1899/07-117.1?casa_token=ZRJ-_Xi_01YAAAAA:IbrAsg1JeBeeyETnwKd4srPsZ-1tsZaqtP3wVl4xm6fIi8rQ37Gp7LZMzvMwQRTkeeLtg1PxZBE. doi:10.1899/07–117.1

Gassman, P. W., Reyes, M. R., Green, C. H., & Arnold, J. G. (2007). The soil and water assessment tool: Historical development, applications, and future research directions. *Transactions of the Asabe, 50*(4), 1211-1250. Retrieved from <Go to ISI>://WOS:000249466000012.

Gharibdousti Rasoulzadeh, S., Kharel, G., Miller, R. B., Linde, E., & Stoecker, A. (2019). Projected Climate Could Increase Water Yield and Cotton Yield but Decrease Winter Wheat and Sorghum Yield in an Agricultural Watershed in Oklahoma. *Water, 11*(1), 105. Retrieved from https://www.mdpi.com/2073-4441/11/1/105.

Girvetz, E. H., Zganjar, C., Raber, G. T., Maurer, E. P., Kareiva, P., & Lawler, J. J. (2009). Applied Climate-Change Analysis: The Climate Wizard Tool. *Plos One, 4*(12), 19. Retrieved from <Go to ISI>://WOS:000272833800015. doi:10.1371/journal.pone.0008320

Grace, J. M. (2005). Forest operations and water quality in the South. *Transactions of the Asae, 48*(2), 871-880. Retrieved from <Go to ISI>://WOS:000229031800046.

Her, Y., Frankenberger, J., Chaubey, I., & Srinivasan, R. (2015). Threshold Effects in HRU Definition of the Soil and Water Assessment Tool. *Transactions of the ASABE (American Society of Agricultural and Biological Engineers), 58*, 367-378. doi:10.13031/trans.58.10805

Homer, C., Dewitz, J., Jin, S., Xian, G., Costello, C., Danielson, P., . . . Riitters, K. (2020). Conterminous United States land cover change patterns 2001–2016 from the 2016 National Land Cover Database. *ISPRS Journal of Photogrammetry and Remote Sensing, 162*, 184-199. Retrieved from http://www.sciencedirect.com/science/article/pii/S0924271620300587. doi:https://doi.org/10.1016/j.isprsjprs.2020.02.019

Homer, C., Dewitz, J., Yang, L. M., Jin, S., Danielson, P., Xian, G., . . . Megown, K. (2015). Completion of the 2011 National Land Cover Database for the Conterminous United States - Representing a Decade of Land Cover Change Information. *Photogrammetric*

Engineering and Remote Sensing, 81(5), 345-354. Retrieved from <Go to ISI>://WOS:000354011600002. doi:10.14358/pers.81.5.345

Huggett, R., Wear, D. N., Li, R., Coulston, J., & Liu, S. (2013). Forecast of Forest Conditions. In D. N. Wear & J. G. Greis (Eds.), *The Southern Forests Futures Project: technical report* (pp. 73-101).

Hunt, K. (2018). Spotlight - The Lower Neuse River. Retrieved from https://soundrivers.org/spotlight-the-lower-neuse-river/

Junk, W. J., Bayley, P. B., & Sparks, R. E. (1989). The flood pulse concept in river-floodplain systems. *Canadian special publication of fisheries and aquatic sciences, 106*(1), 110-127. Retrieved from ftp://ftp.cs.ru.nl/pub/toinesmits/PDF_files_supporting_literature_24%2625-11-2009/1989JunkThe%20flood%20pulse%20concept%20in.pdf.

Kim, Y., Band, L. E., & Song, C. (2014). The Influence of Forest Regrowth on the Stream Discharge in the North Carolina Piedmont Watersheds. *Journal of the American Water Resources Association, 50*(1), 57-73. Retrieved from https://onlinelibrary.wiley.com/doi/abs/10.1111/jawr.12115. doi:doi:10.1111/jawr.12115

Kouchi, D. H., Esmaili, K., Faridhosseini, A., Sanaeinejad, S. H., Khalili, D., & Abbaspour, K. C. (2017). Sensitivity of calibrated parameters and water resource estimates on different objective functions and optimization algorithms. *Water, 9*(6), 384. Retrieved from https://www.mdpi.com/2073-4441/9/6/384/pdf. doi:http://dx.doi.org/10.3390/w9060384

Lockaby, G., Nagy, C., Vose, J. M., Ford, C. R., Sun, G., McNulty, S., . . . Myers, J. M. (2013). Chapter 13: Forests and Water. In *The Southern Forests Futures Project: technical report* (pp. 309-339).

Martin, K. L., Hwang, T., Vose, J. M., Coulston, J. W., Wear, D. N., Miles, B., & Band, L. E. (2017). Watershed impacts of climate and land use changes depend on magnitude and land use context. *Ecohydrology, 10*(7), 17. Retrieved from https://onlinelibrary.wiley.com/doi/abs/10.1002/eco.1870. doi:doi:10.1002/eco.1870

Matteo, M., Randhir, T., & Bloniarz, D. (2006). Watershed-scale impacts of forest buffers on water quality and runoff in urbanizing environment. *Journal of Water Resources Planning and Management, 132*(3), 144-152. Retrieved from <Go to ISI>://WOS:000237031700003. doi:10.1061/(asce)0733-9496(2006)132:3(144)

Meentemeyer, R. K., Tang, W. W., Dorning, M. A., Vogler, J. B., Cunniffe, N. J., & Shoemaker, D. A. (2013). FUTURES: Multilevel Simulations of Emerging Urban-Rural Landscape Structure Using a Stochastic Patch-Growing Algorithm. *Annals of the Association of American Geographers, 103*(4), 785-807. Retrieved from <Go to ISI>://WOS:000320300300003. doi:10.1080/00045608.2012.707591

Meyer, J. L., Paul, M. J., & Taulbee, W. K. (2005). Stream ecosystem function in urbanizing landscapes. *Journal of the North American Benthological Society, 24*(3), 602-612. Retrieved from <Go to ISI>://WOS:000231956900012. doi:10.1899/04-021.1

Moriasi, D. N., Arnold, J. G., Van Liew, M. W., Bingner, R. L., Harmel, R. D., & Veith, T. L. (2007). Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. *Transactions of the Asabe, 50*(3), 885-900. Retrieved from https://pubag.nal.usda.gov/download/9298/PDF.

Nagy, R. C., Lockaby, B. G., Helms, B., Kalin, L., & Stoeckel, D. (2011). Water Resources and Land Use and Cover in a Humid Region: The Southeastern United States. *Journal of*

Environmental Quality, 40(3), 867-878. Retrieved from <Go to ISI>://WOS:000289886000021. doi:10.2134/jeq2010.0365

Naiman, R. J., & Decamps, H. (1997). The ecology of interfaces: Riparian zones. *Annual Review of Ecology and Systematics, 28*, 621-658. Retrieved from <Go to ISI>://WOS:000070961400024. doi:10.1146/annurev.ecolsys.28.1.621

Nash, J. E., & Sutcliffe, J. V. (1970). River flow forecasting through conceptual models part I — A discussion of principles. *Journal of Hydrology, 10*(3), 282-290. Retrieved from http://www.sciencedirect.com/science/article/pii/0022169470902556. doi:https://doi.org/10.1016/0022-1694(70)90255-6

NC Economic Report. (2018). Retrieved from Raleigh, NC: https://files.nc.gov/nccommerce/documents/LEAD/Annual-Economic-Report/NC-2018-Economic-Report.pdf

Neitsch, S. L., Arnold, J. G., Kiniry, J. R., & Williams, J. R. (2011). *Soil and water assessment tool theoretical documentation version 2009*. Retrieved from

Neuse River. (2017). Retrieved from https://www.americanrivers.org/river/neuse-river/

Neuse River Basin Restoration Priorities. (2018). Retrieved from https://files.nc.gov/ncdeq/Mitigation%20Services/Watershed_Planning/Neuse_River_Basin/RBRP-Neuse-201807-.pdf

Neuse River Basin Water Resources Plan. (2010). Retrieved from https://www.ncwater.org/files/publications/Neuse_RB_WR_Plan_20100720.pdf

O'Gorman, P. A., & Schneider, T. (2009). The physical basis for increases in precipitation extremes in simulations of 21st-century climate change. *Proceedings of the National*

Academy of Sciences of the United States of America, 106(35), 14773-14777. Retrieved from <Go to ISI>://WOS:000269481000010. doi:10.1073/pnas.0907610106

Oswalt, S. N. (2019). National Forest Systems. In S. N. Oswalt, W. B. Smith, P. D. Miles, & S. A. Pugh (Eds.), *Forest resources of the United States, 2017: A technical document supporting the Forest Service 2020 RPA Assessment* (Vol. 97, pp. 63-68). Washington, DC: US Department of Agriculture, Forest Service, Washington Office.

Paul, M. J., & Meyer, J. L. (2001). Streams in the urban landscape. *Annual Review of Ecology and Systematics, 32*, 333-365. Retrieved from <Go to ISI>://WOS:000172908800012. doi:10.1146/annurev.ecolsys.32.081501.114040

Petrasova, A., Petras, V., Van Berkel, D., Harmon, B. A., Mitasova, H., & Meentemeyer, R. K. (2016). OPEN SOURCE APPROACH TO URBAN GROWTH SIMULATION. In L. Halounova, F. Sunar, M. Potuckova, L. Patkova, M. Yoshimura, U. Soergel, E. BenDor, J. Smit, G. Bareth, J. Zhang, S. Kaasalainen, U. Sorgel, B. Osmanoglu, M. Crespi, M. Crosetto, T. Blaschke, M. A. Brovelli, & B. Zagajewski (Eds.), *Xxiii Isprs Congress, Commission Vii* (Vol. 41, pp. 953-959). Gottingen: Copernicus Gesellschaft Mbh.

Pickard, B., Gray, J., & Meentemeyer, R. (2017). Comparing quantity, allocation and configuration accuracy of multiple land change models. *Land, 6*(3), 52. Retrieved from https://www.mdpi.com/2073-445X/6/3/52/pdf. doi:10.3390/land6030052

Pickard, B. R., Van Berkel, D., Petrasova, A., & Meentemeyer, R. K. (2017). Forecasts of urbanization scenarios reveal trade-offs between landscape change and ecosystem services. *Landscape Ecology, 32*(3), 617-634. Retrieved from https://doi.org/10.1007/s10980-016-0465-8. doi:10.1007/s10980-016-0465-8

Postel, S. L., & Thompson Jr, B. H. (2005). *Watershed protection: Capturing the benefits of nature's water supply services.* Paper presented at the Natural Resources Forum.

Rashleigh, B., Keith, D., Williams, D., Mangis, D., Schwede, D., Worthy, D., . . . McCutcheon, S. C. (2010). *Ecosystem Services Research Program (ESRP) Albemarle-Pamlico Watershed and Estuary Study (APWES) Research Plan*. Washington, DC: EPA/600/R-10/180 (NTIS PB2011-105281)

Resource Protection Areas.

Rice, J. S., Emanuel, R. E., Vose, J. M., & Nelson, S. A. C. (2015). Continental US streamflow trends from 1940 to 2009 and their relationships with watershed spatial characteristics. *Water Resources Research, 51*(8), 6262-6275.

Rummer, R. B., & Hafer, M. L. (2014). *Outlook for Piedmont forests: a subregional report from the Southern Forest Futures Project*. Retrieved from Asheville, NC: USDA-Forest Service, Southern Research Station: https://www.fs.usda.gov/treesearch/pubs/46307

Saia, S. M., Suttles, K. M., Cutts, B. B., Emanuel, R. E., Martin, K. L., Wear, D. N., . . . Vose, J. M. (2019). Applying Climate Change Risk Management Tools to Integrate Streamflow Projections and Social Vulnerability. *Ecosystems*, 1-17.

Sanchez, G. M., Terando, A., Smith, J. W., García, A. M., Wagner, C. R., & Meentemeyer, R. K. (2020). Forecasting water demand across a rapidly urbanizing region. *Science of the Total Environment*, 139050. Retrieved from https://doi-org.prox.lib.ncsu.edu/10.1016/j.scitotenv.2020.139050.

Schneid, B. P., Anderson, C. J., & Feminella, J. W. (2017). The influence of low-intensity watershed development on the hydrology, geomorphology, physicochemistry and macroinvertebrate diversity of small coastal plains streams. *Ecological Engineering, 108,* 380-390. Retrieved from <Go to ISI>://WOS:000423883000004. doi:10.1016/j.ecoleng.2017.05.052

Sedell, J., Sharpe, M., Apple, D. D., Copenhagen, M., & Furniss, M. J. F. P. (2000). Water and the forest service.

Stewart, B., Buytaert, W., Mishra, A., Zandaryaa, S., Connor, R., Timmerman, J., . . . Hada, R. (2020). Prologue: The state of water resources in the context of climate change. In U. W. W. A. Programme (Ed.), *The United Nations world water development report 2020: water and climate change* (pp. 219). Paris, France: UNESCO

Stone, B., Vargo, J., Liu, P., Hu, Y. T., & Russell, A. (2013). Climate change adaptation through urban heat management in Atlanta, Georgia. *Environmental Science & Technology, 47*(14), 7780-7786. doi:10.1021/es304352e

Sun, G., & Caldwell, P. (2015). Impacts of urbanization on stream water quantity and quality in the United States. *Water Resources Impact, 17*(1), 17-20. Retrieved from https://www.srs.fs.usda.gov/pubs/ja/2015/ja_2015_sun_002.pdf.

Sun, G., Caldwell, P. V., & McNulty, S. G. (2015). Modelling the potential role of forest thinning in maintaining water supplies under a changing climate across the conterminous United States. *Hydrological Processes, 29*(24), 5016-5030. Retrieved from <Go to ISI>://WOS:000368276600005. doi:10.1002/hyp.10469

Sun, G., Caldwell, P. V., McNulty, S. G., Georgakakos, A. P., Arumugam, S., Cruise, J., . . . Marion, D. A. (2013). Impacts of Climate Change and Variability on Water Resources in the Southeast USA. *NCA Southeast Technical Report 204-234*. Retrieved from https://www.fs.usda.gov/treesearch/pubs/44289.

Sun, G., & Lockaby, B. G. (2012). Water Quantity and Quality at the Urban–Rural Interface. In D. N. Labland, B. G. Lockaby, & w. Zipperer (Eds.), *Urban–rural interfaces: Linking people and nature* (pp. 29-48). Madison, WI: American Society of Agronomy, Crop Science Society of America, Soil Science Society of America.

Sun, G., McNulty, S. G., Myers, J. A. M., & Cohen, E. C. (2008). Impacts of Multiple Stresses on Water Demand and Supply Across the Southeastern United States. *Journal of the American Water Resources Association, 44*(6), 1441-1457. Retrieved from <Go to ISI>://WOS:000261334000008. doi:10.1111/j.1752-1688.2008.00250.x

Sutherland, A. B., Meyer, J. L., & Gardiner, E. P. (2002). Effects of land cover on sediment regime and fish assemblage structure in four southern Appalachian streams. *Freshwater Biology, 47*(9), 1791-1805. doi:https://doi.org/10.1046/j.1365-2427.2002.00927.x

Suttles, K. M., Singh, N. K., Vose, J. M., Martin, K. L., Emanuel, R. E., Coulston, J. W., . . . Crump, M. T. (2018). Assessment of hydrologic vulnerability to urbanization and climate change in a rapidly changing watershed in the Southeast U.S. *Sci Total Environ, 645*, 806-816. doi:10.1016/j.scitotenv.2018.06.287

Taylor, K. E., Stouffer, R. J., & Meehl, G. A. (2012). AN OVERVIEW OF CMIP5 AND THE EXPERIMENT DESIGN. *Bulletin of the American Meteorological Society, 93*(4), 485-498. Retrieved from <Go to ISI>://WOS:000303110900004. doi:10.1175/bams-d-11-00094.1

Terando, A. J., Costanza, J., Belyea, C., Dunn, R. R., McKerrow, A., & Collazo, J. A. (2014). The Southern Megalopolis: Using the Past to Predict the Future of Urban Sprawl in the Southeast US. *Plos One, 9*(7), 8. Retrieved from <Go to ISI>://WOS:000339614100034. doi:10.1371/journal.pone.0102261

Theobald, D. (2005). Landscape Patterns of Exurban Growth in the USA from 1980 to 2020. *Ecology and Society, 10*. Retrieved from https://www.ecologyandsociety.org/vol10/iss1/art32/ES-2005-1390.pdf. doi:10.5751/ES-01390-100132

Trimble, S. W. (1975). A volumetric estimate of man-induced soil erosion on the southern Piedmont Plateau. *Prospective technology for predicting sediment yields and sources*, 142-152.

U.S.EPA. (2015). Connectivity of streams and wetlands to downstream waters: A review and synthesis of the scientific evidence (final report). In: US Environmental Protection Agency Washington, DC.

United Nations, D. o. E. a. S. A., Population Division. (2014). *World Urbanization Prospects: The 2014 Revision, Highlights*: United Nations.

USGS. (2016). The StreamStats program: U.S. Geological Survey. Retrieved from http://streamstats.usgs.gov/

Van Metre, P. C., Waite, I. R., Qi, S., Mahler, B., Terando, A., Wieczorek, M., . . . Carlisle, D. (2019). Projected urban growth in the southeastern USA puts small streams at risk. *Plos One, 14*(10), e0222714. Retrieved from https://doi.org/10.1371/journal.pone.0222714. doi:10.1371/journal.pone.0222714

Vannote, R. L., Minshall, G. W., Cummins, K. W., Sedell, J. R., & Cushing, C. E. (1980). The river continuum concept. *Canadian journal of fisheries and aquatic sciences, 37*(1), 130-137.

Vicars-Groening, J., & Williams, H. F. L. (2007). Impact of urbanization on storm response of White Rock Creek, Dallas, TX. *Environmental Geology, 51*(7), 1263-1269. Retrieved from <Go to ISI>://WOS:000243819000018. doi:10.1007/s00254-006-0419-6

Vose, J. M., Ford, C. R., Laseter, S., Dymond, S., Sun, G., Adams, M. B., . . . Heartsill Scalley, T. (2012). *Can forest watershed management mitigate climate change effects on water resources %J In: Webb, Ashley A.; Bonell, Mike; Bren, Leon; Lane, Patrick N. J.; et. al., eds. 2012. Revisiting Experimental Catchment Studies in Forest Hydrology, Proceedings of a Workshop held during the XXV IUGG General Assembly in Melbourne, June–July 2011. IAHS Publ. 353:Oxfordshire, UK. 12-25*. https://www.fs.usda.gov/treesearch/pubs/41261

Walsh, C. J., Roy, A. H., Feminella, J. W., Cottingham, P. D., Groffman, P. M., & Morgan, R. P. (2005). The urban stream syndrome: current knowledge and the search for a cure. *Journal of the North American Benthological Society, 24*(3), 706-723, 718. Retrieved from https://doi.org/10.1899/04-028.1.

Wear, D. N. (2002). Chapter 6: Land Use. In *Southern Forest Resource Assessment*

Wear, D. N. (2013). Forecasts of Land Uses. In D. N. Wear & J. G. Greis (Eds.), *The Southern Forests Futures Project: technical report* (pp. 45-71).

Wear, D. N., & Greis, J. G. (2013). *The Southern Forest Futures Project: technical report*. Retrieved from https://www.fs.usda.gov/treesearch/pubs/44183

Winchell, M., Srinivasan, R., Di Luzio, M., & Arnold, J. (2013). ArcSWAT Interface for SWAT2012: User's Guide. In: Blackland Research and Extension Center and Grassland, Soil and Water Research Laboratory.

TABLES

Table 1. Input data for the Upper Neuse Watershed for the SWAT model.

Input Data	**Source**	**Resolution**	**Time period**
Digital Elevation Model	USGS National Elevation Dataset The National Map	1 arc-second = 30×30m	2013 and 2015
Land Cover (Calibration/Baseline)	National Land Cover Database	30×30m	2011 2016
Land Cover (Projected)	FUTURES Urban Growth Model	30×30m	2060
Soil Properties	USDA-NRCS Soil Survey Geographic Database (SSURGO) – 12 counties (UN) and 18 counties (UN) State Soil Geographic Data (STATSGO2) was used to substitute SSURGO MUSYM “UR” soil type. Web Soil Survey	Varies from 1:12,000 to 1:63,360	2018 – SSURGO 2016 – STATSGO2
Climate (Observed)	GRIDMET Daily precipitation and temperature created using Google Earth Engine	Txt file, point data	1979-2018
Climate (Projected)	CMIP5 MACA CSIRO RCP 8.5	Txt file, point data	2018-2060
Dams	U.S. Army Corps of Engineers National Inventory of Dams	Point data, Txt file	2013
Observed Streamflow	USGS stream gauges: 02089000 (located near Goldsboro, NC for Upper Neuse) and 02146000 (located in Rock Hill, SC for Upper Catawba)	Point, spreadsheet	2000 – 2018

Table 2. Calibrated SWAT parameters and default values

Parameter	Calibrated Value	Default Value
r__CN2.mgt	Original value multiplied by 0.61123	Varies with HRU
v__GW_DELAY.gw	104.05	31
v__GW_REVAP.gw	0.062	0.02
v__SLSUBBSN.hru	64.68	91.46
v__REVAPMN.gw	338.59	750
v__ESCO.hru	0.71	0.95
r__OV_N.hru	Original value multiplied by 1.10	0.14
r__CH_N2.rte	Original value multiplied by 1.101794	0.014
v__CH_K2.rte	175.05	0
v__ALPHA_BNK.rte	0.71	0
r__SOL_AWC(1).sol	0.21	0.17
r__SOL_K(1).sol	49.85	32.4
r__SOL_BD(1).sol	Original value multiplied by 1.26	1.35
v__RCHRG_DP.gw	0.11	0.05
v__SURLAG.bsn	10	2

Table 3. Land cover percentages across the Upper Neuse Watershed derived from the 2011 NLCD and the FUTURES putput overlaid on the 2016 NLCD.

Land Cover	**Baseline: 2011 NLCD**	**FUTURES Raster**
Open Water	1.85%	2.00%
Developed, Open Space	12.13%	11.89%
Developed, Low Intensity	5.39%	11.12%
Developed, Medium Intensity	2.33%	2.52%
Developed, High Intensity	0.67%	0.72%
Barren Land	0.21%	0.17%
Deciduous Forest	14.27%	13.05%
Evergreen Forest	12.14%	10.91%
Mixed Forest	11.84%	10.81%
Shrub/Scrub	1.24%	1.29%
Grassland/Herbaceous	2.52%	2.37%
Pasture/Hay	8.97%	8.17%
Cultivated Crops	14.65%	13.91%
Woody Wetlands	11.41%	10.80%
Emergent Herbaceous Wetlands	0.38%	0.27%

Table 4. Growing season average daily streamflow from baseline to FUTNB

Growing Season		
Subbasin	Baseline m^3/s mean	FUTNB m^3/s mean
2	1.66	2.07
4	2.77	3.21
5	1.99	1.78
7	5.24	4.06
24	64.01	69.86

Table 5. Winter season average daily streamflow from baseline to FUTNB

Winter Season		
Subbasin	Baseline m^3/s mean	FUTNB m^3/s mean
2	2.15	2.60
4	3.52	4.01
5	1.63	1.89
7	4.57	4.53
24	68.08	74.27

FIGURES

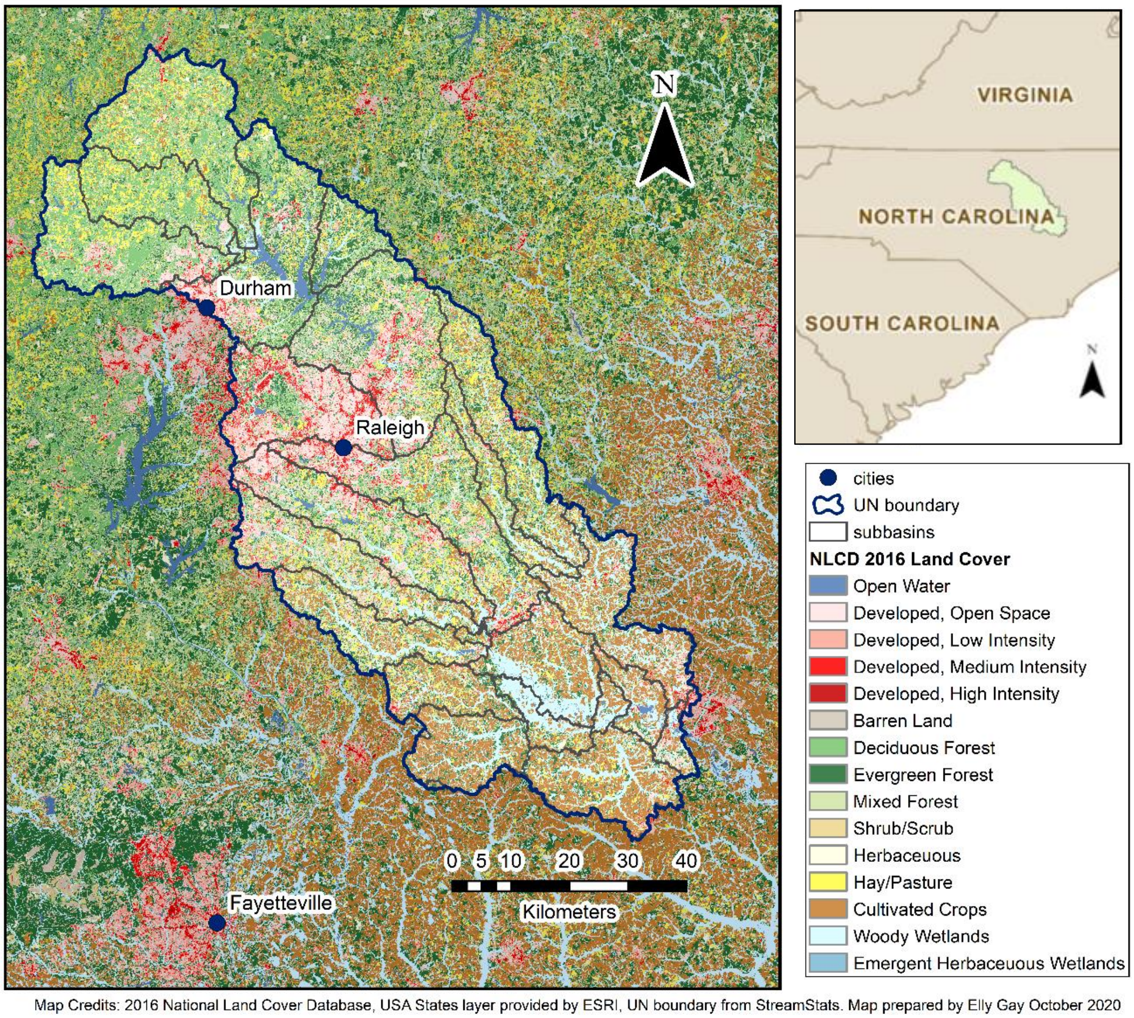

Figure 1 – The Upper Neuse Watershed showing NLCD 2016 land cover and subbasins created by the SWAT model.

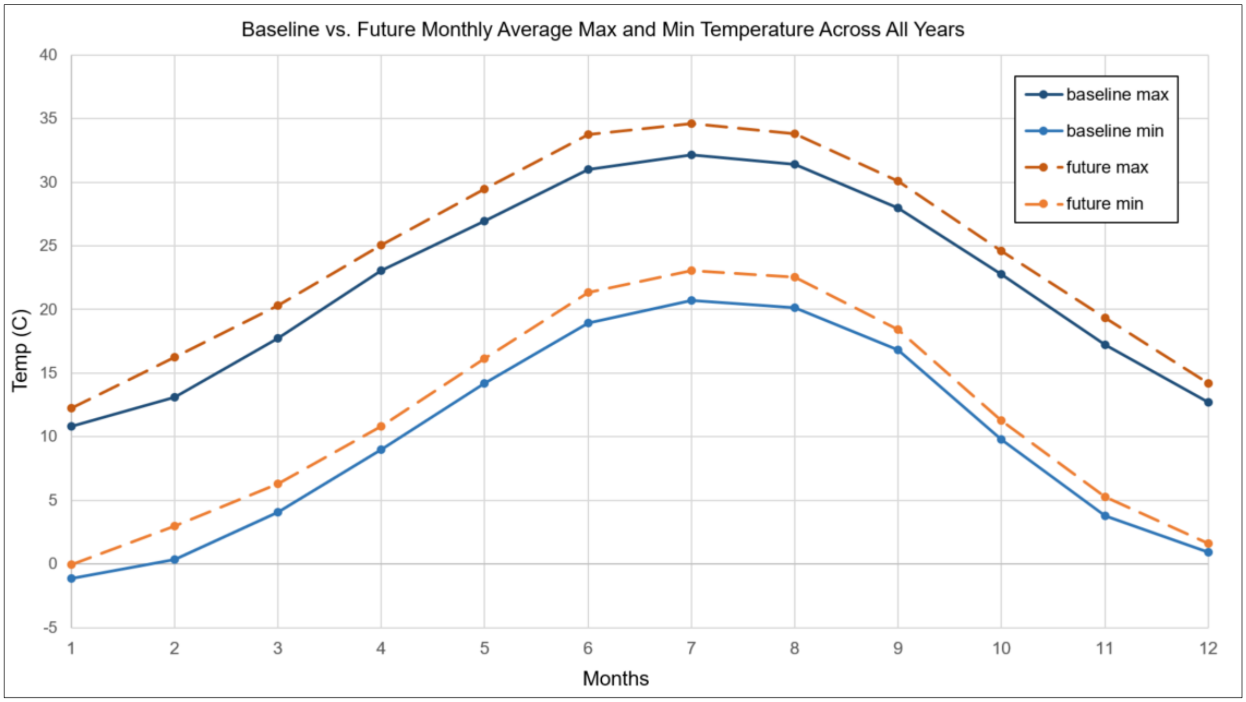

Figure 2 – Baseline and future monthly average maximum and minimum (c) temperature across all years. Values represent mean monthly temperature for the specific month across all years.

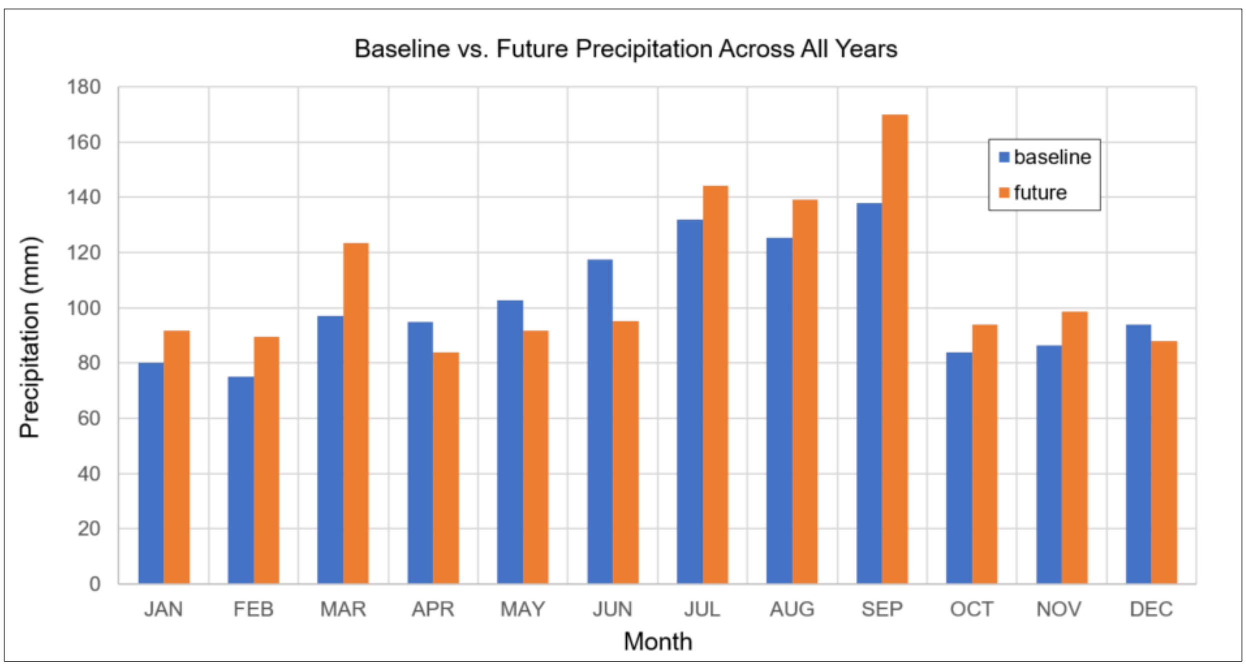

Figure 3 – Baseline and future average precipitation (mm) across all months. Values indicate average accumulated rainfall for the specific month across all years.

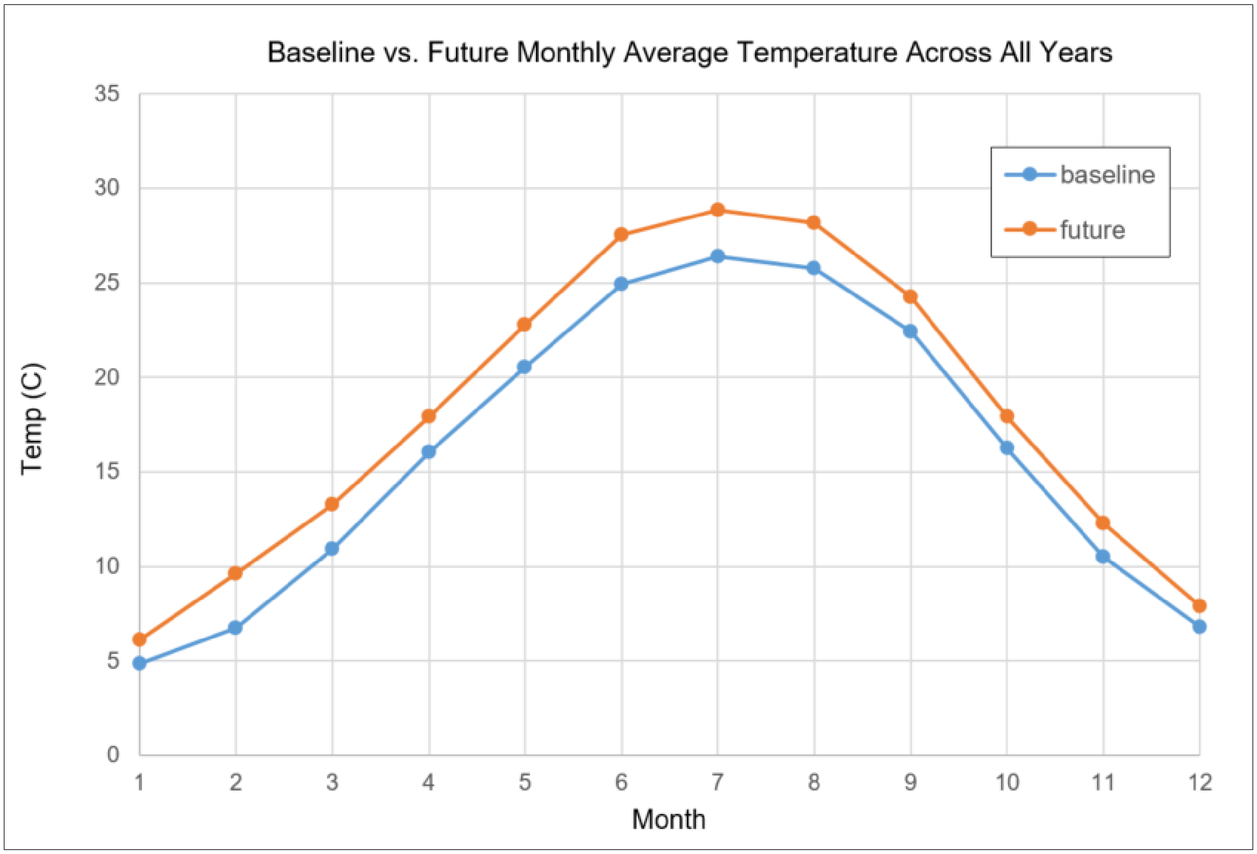

Figure 4 – Baseline and future monthly average (c) temperature across all years. Values represent mean monthly temperature for the specific month across all years

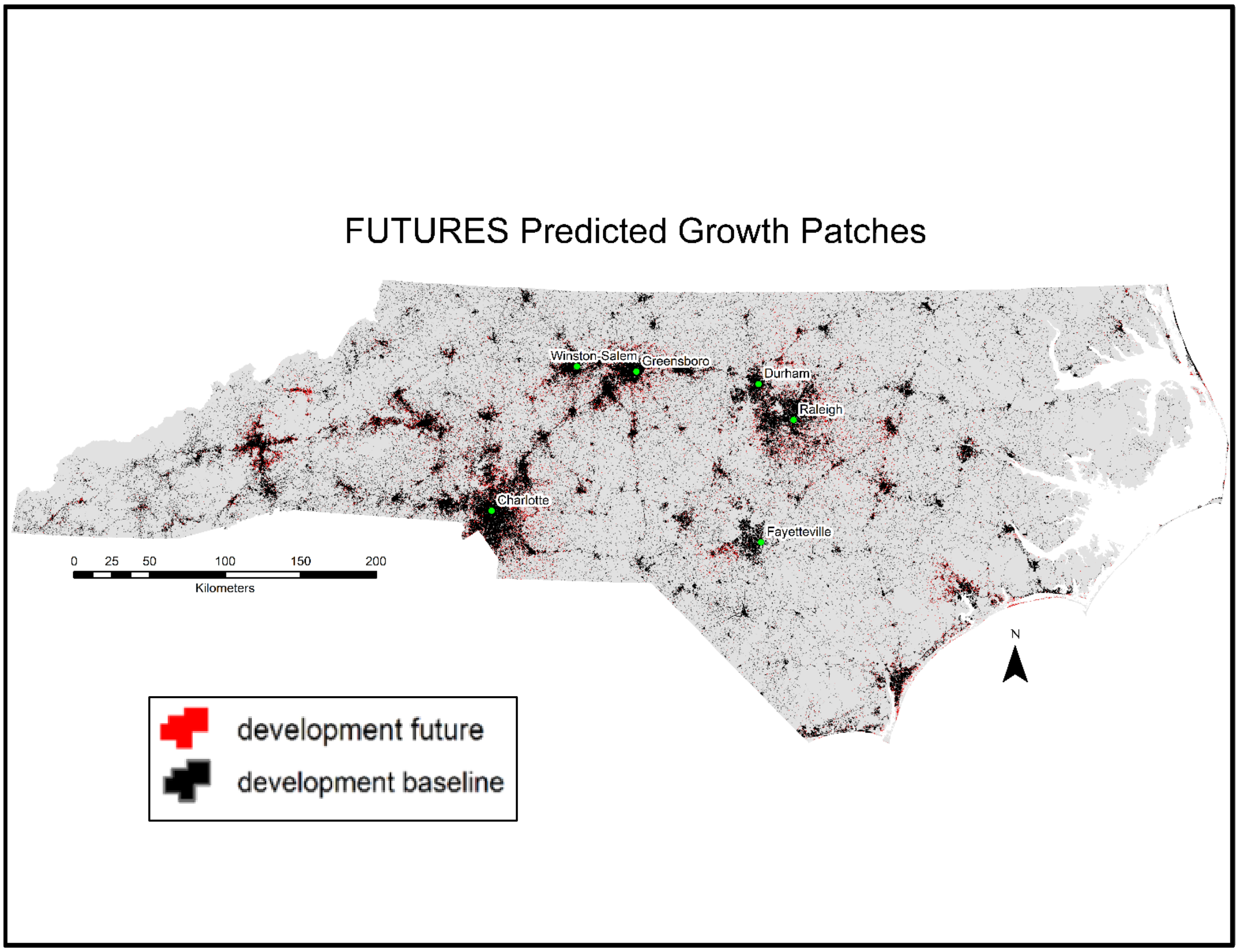

Figure 5 – Final FUTURES output showing development patches across NC. Black = pre-existing development from 2016 NLCD. Red = projected growth patches to 2060. Grey = all other landuses.

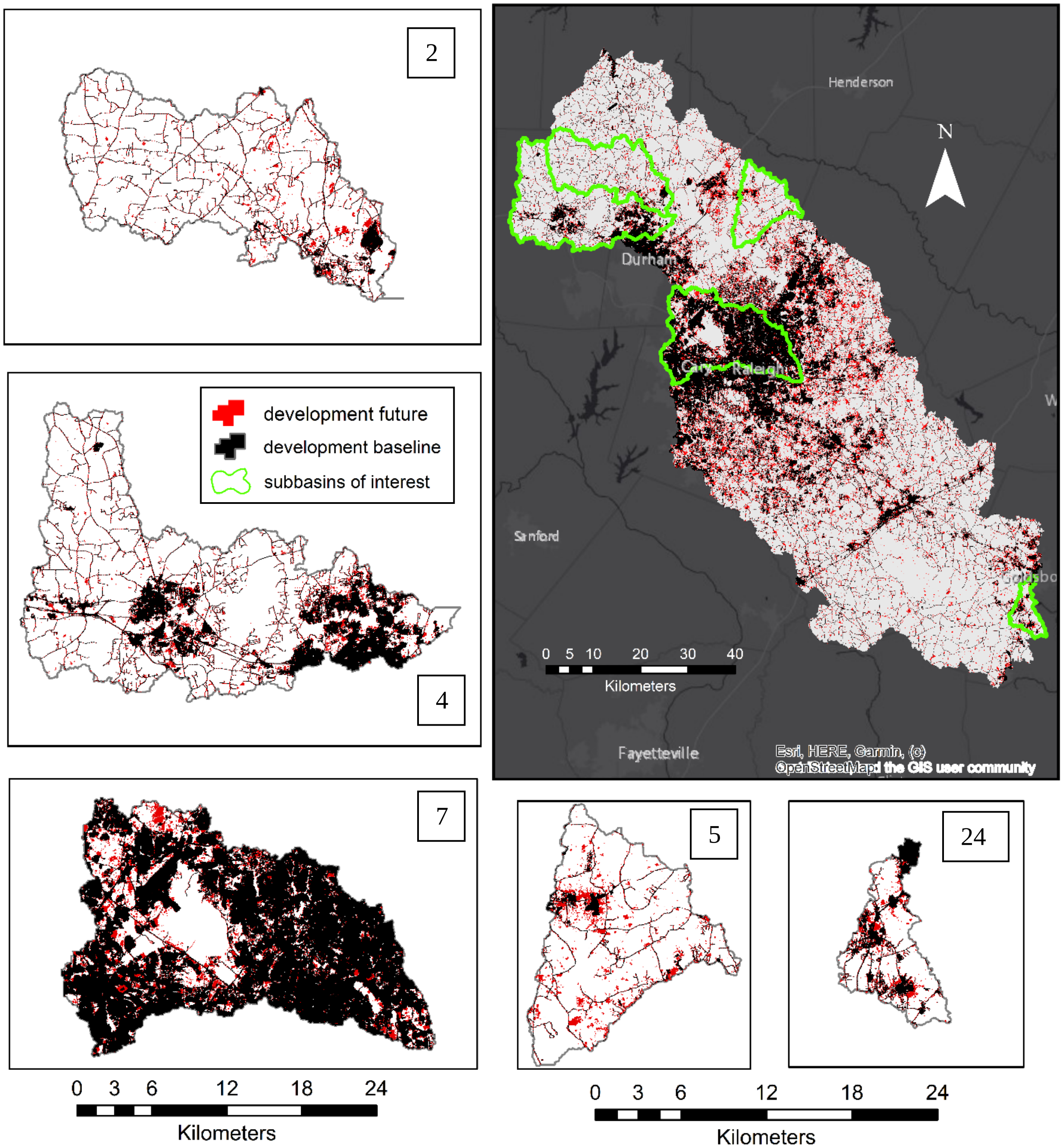

Figure 6 – Output of the FUTURES Urban Growth Model showing projected development patches across the Upper Neuse Watershed and subbasins of interest (2, 4, 5, 7, and 24 – the outlet).

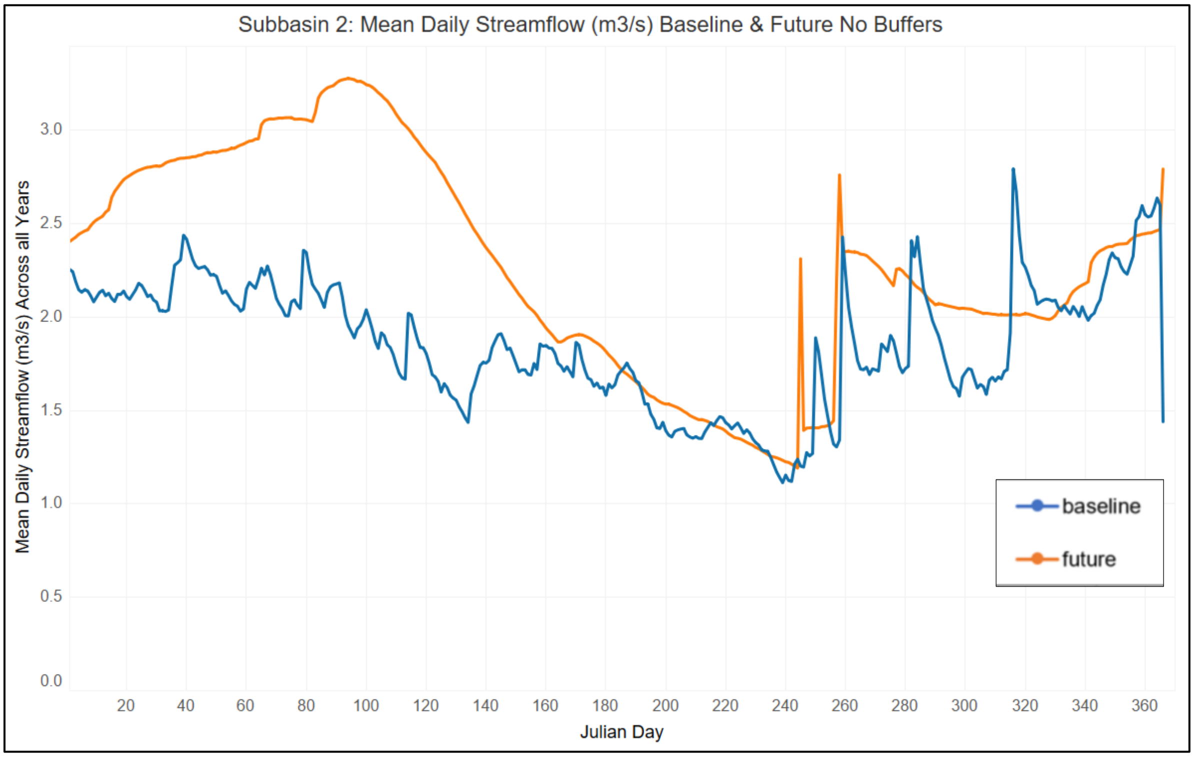

Figure 7 – Baseline and future (no added buffers) mean daily streamflow (m^3/s) on that Julian day across all years in subbasin 2.

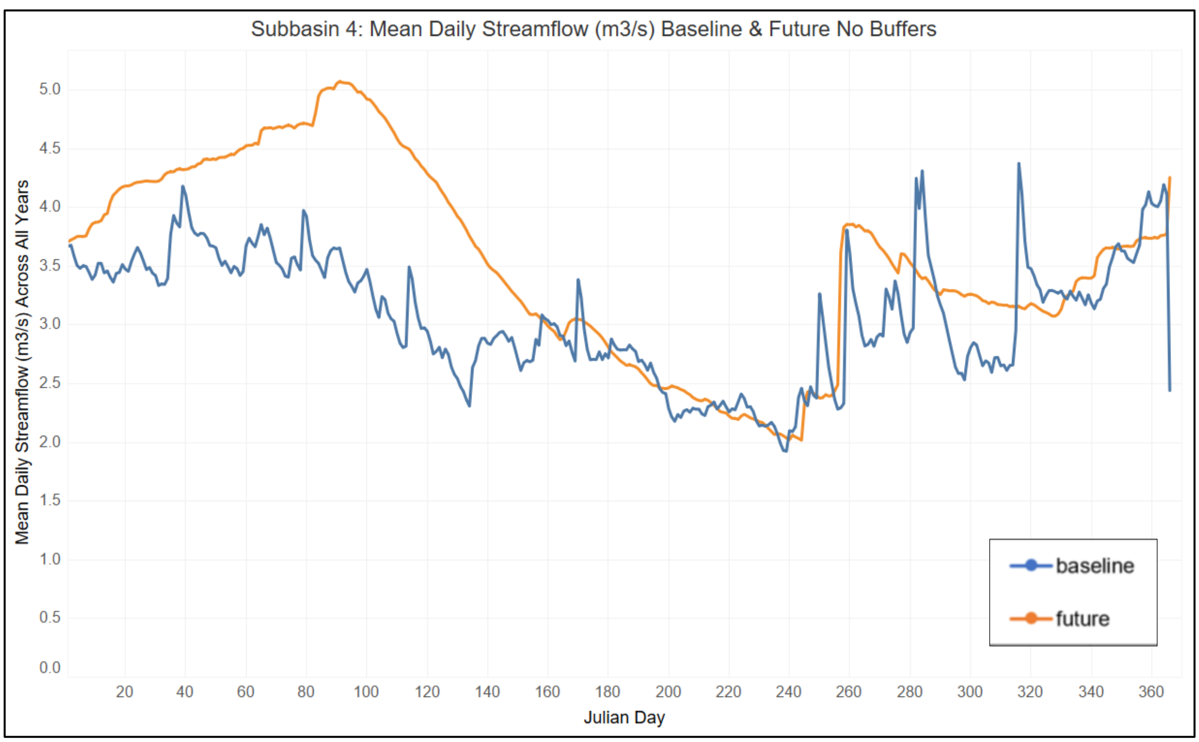

Figure 8 – Baseline and future (no added buffers) mean daily streamflow (m^3/s) on that Julian day across all years in subbasin 4.

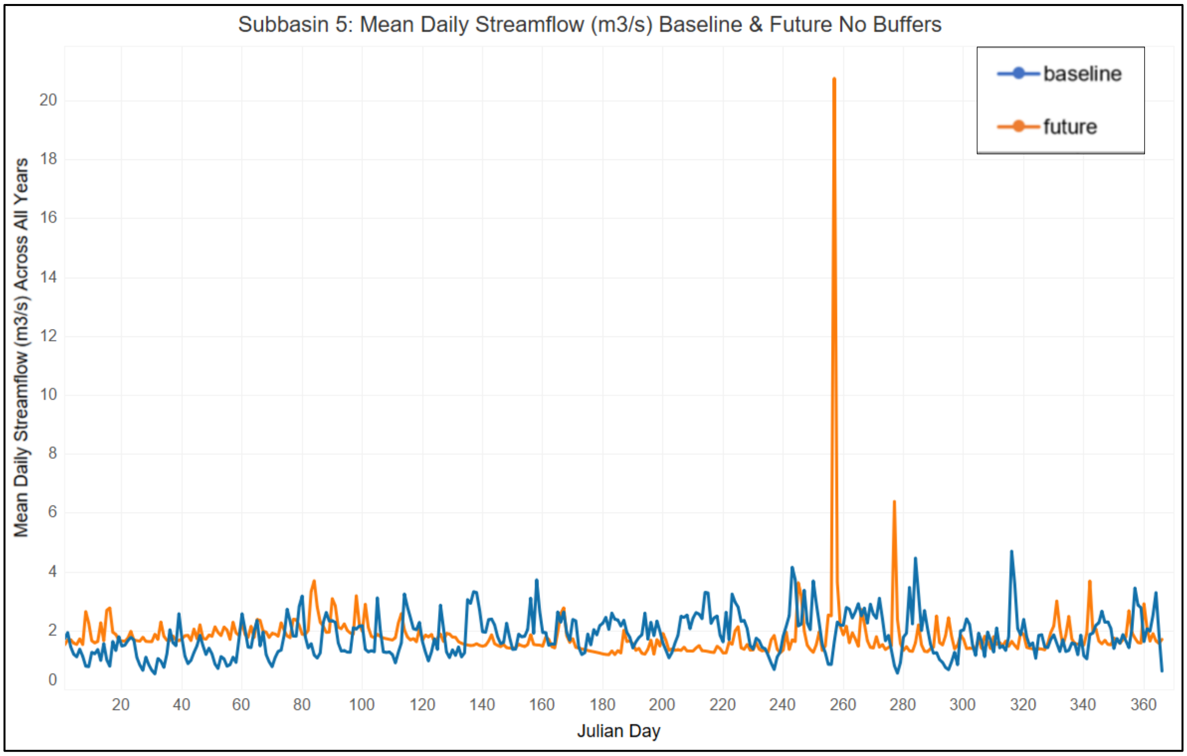

Figure 9a – Baseline and future (no added buffers) mean daily streamflow (m^3/s) on that Julian day across all years in subbasin 5.

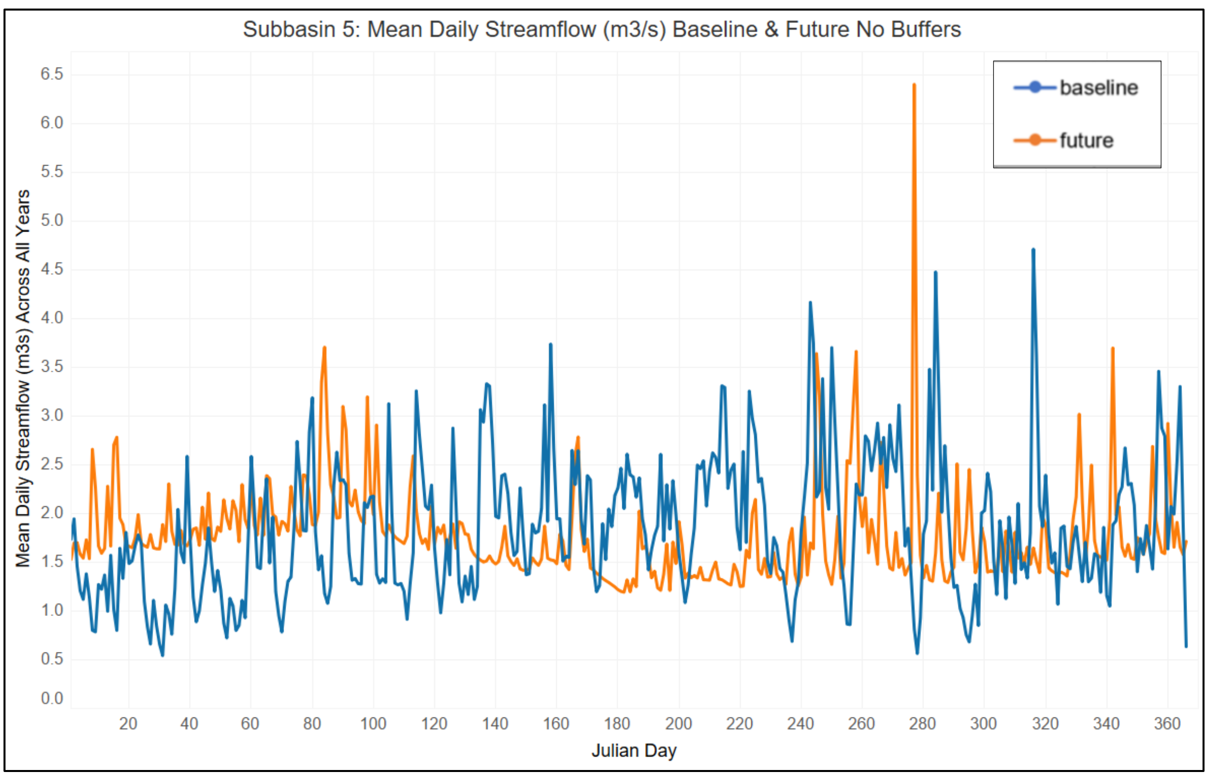

Figure 9b – Baseline and future (no added buffers) mean daily streamflow (m^3/s) on that Julian day across all years in subbasin 5. Extreme flow event on day 257 EXCLUDED.

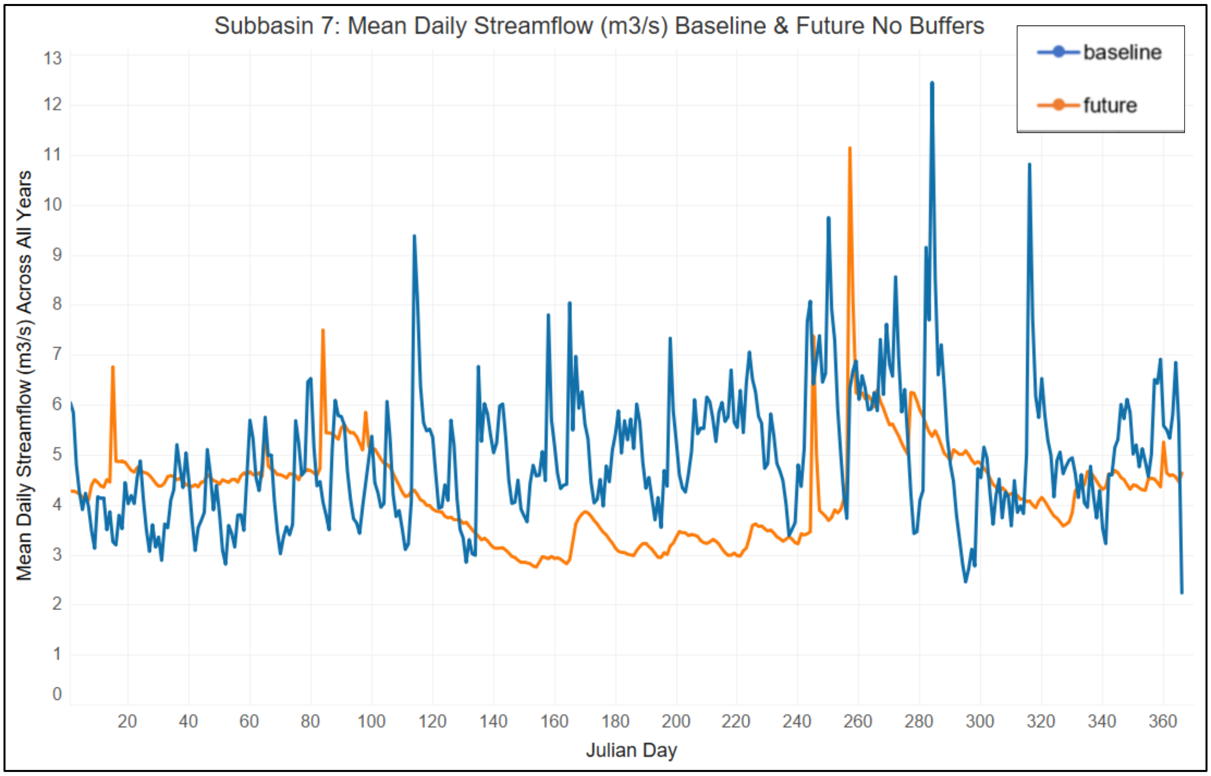

Figure 10 – Baseline and future (no added buffers) mean daily streamflow (m^3/s) on that Julian day across all years in subbasin 7.

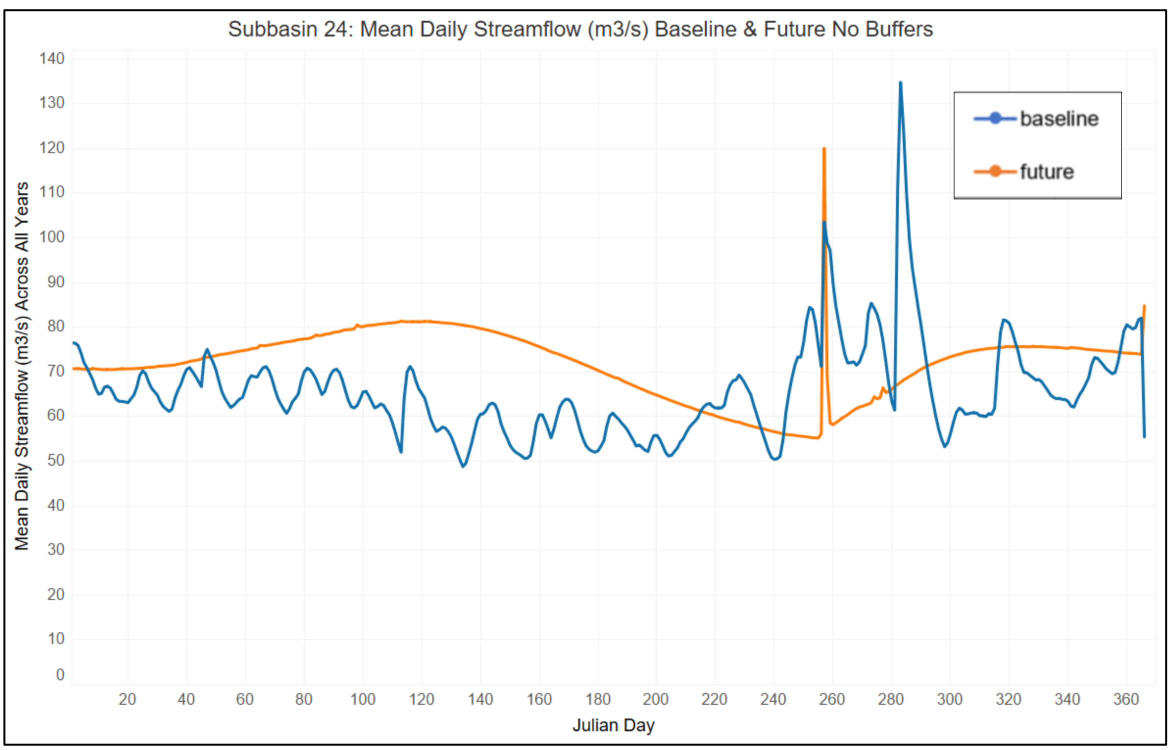

Figure 11 – Baseline and future (no added buffers) mean daily streamflow (m^3/s) on that Julian day across all years in subbasin 24.

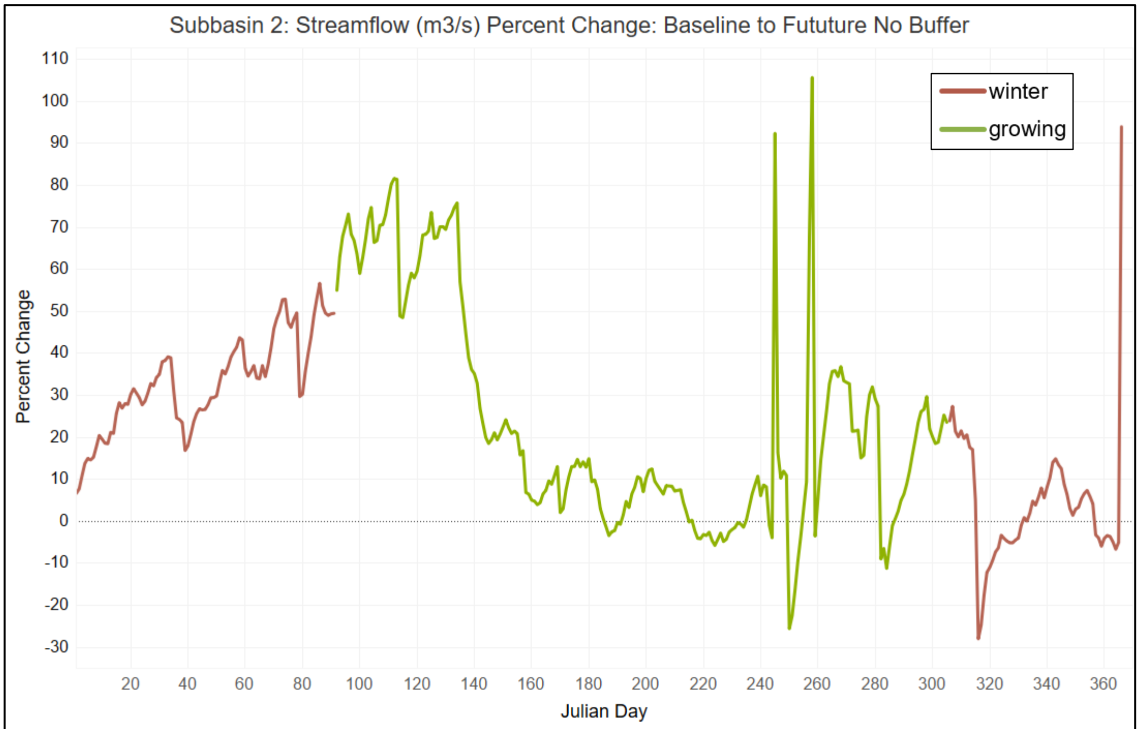

Figure 12 – Baseline and future (no added buffers) mean daily streamflow (m^3/s) on that Julian day across all years in subbasin 2 visualized by season.

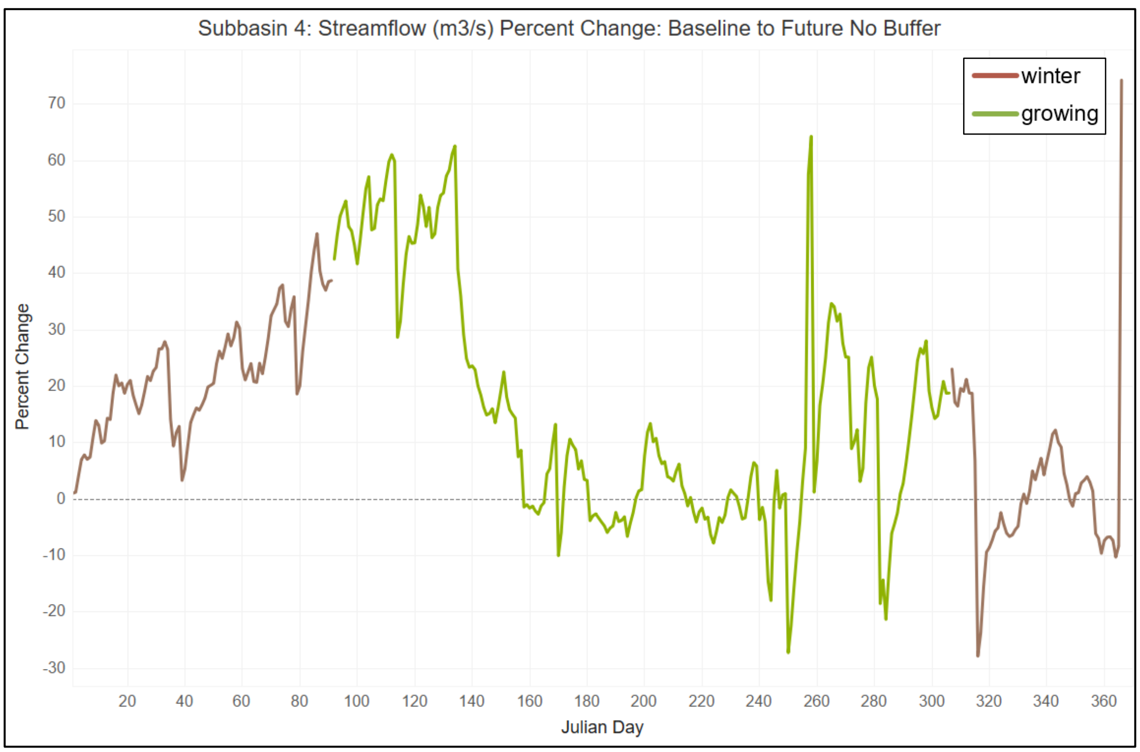

Figure 13 – Baseline and future (no added buffers) mean daily streamflow (m^3/s) on that Julian day across all years in subbasin 4 visualized by season.

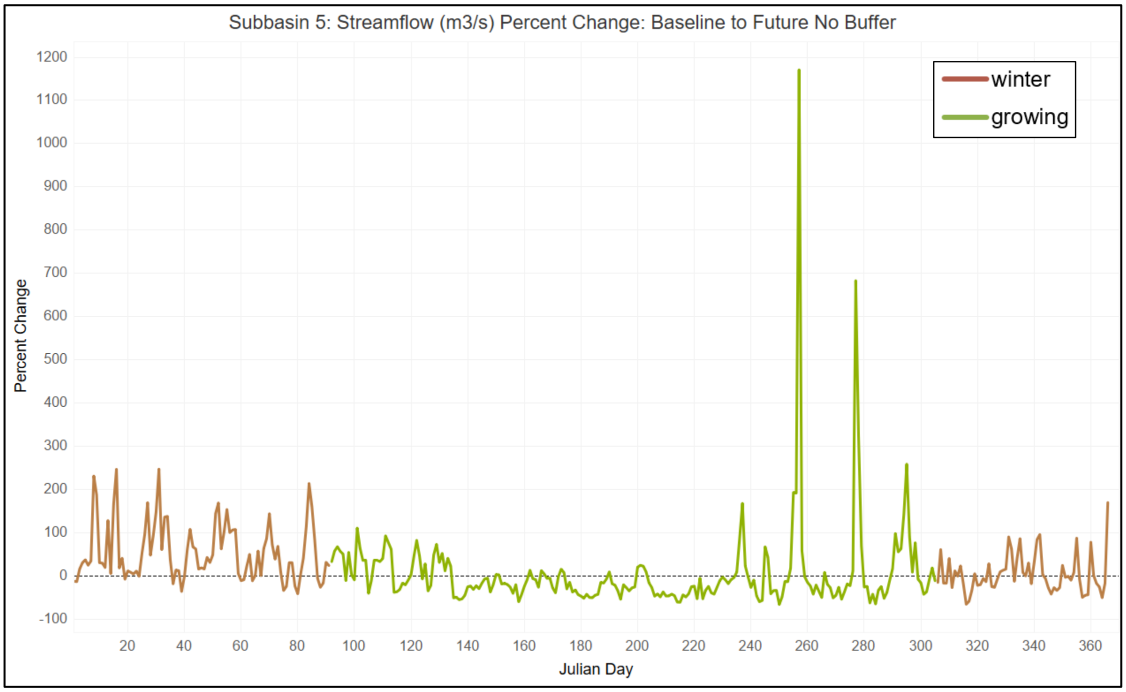

Figure 14 – Baseline and future (no added buffers) mean daily streamflow (m^3/s) on that Julian day across all years in subbasin 5 visualized by season.

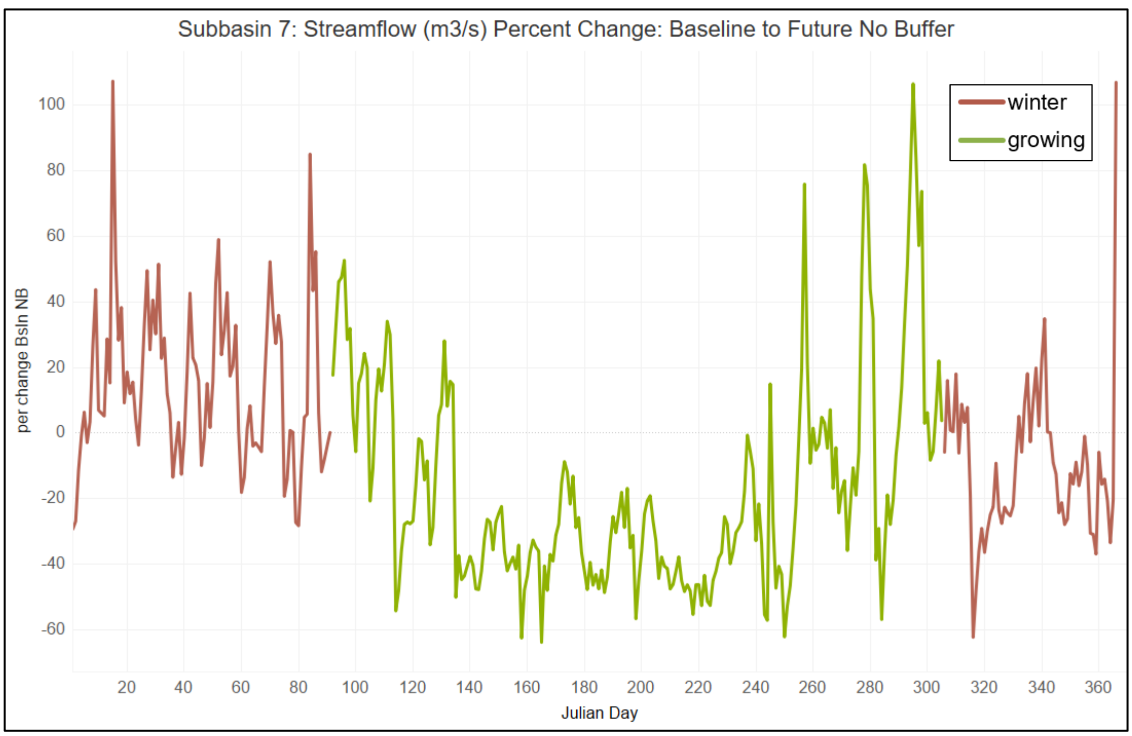

Figure 15 – Baseline and future (no added buffers) mean daily streamflow (m^3/s) on that Julian day across all years in subbasin 7 visualized by season.

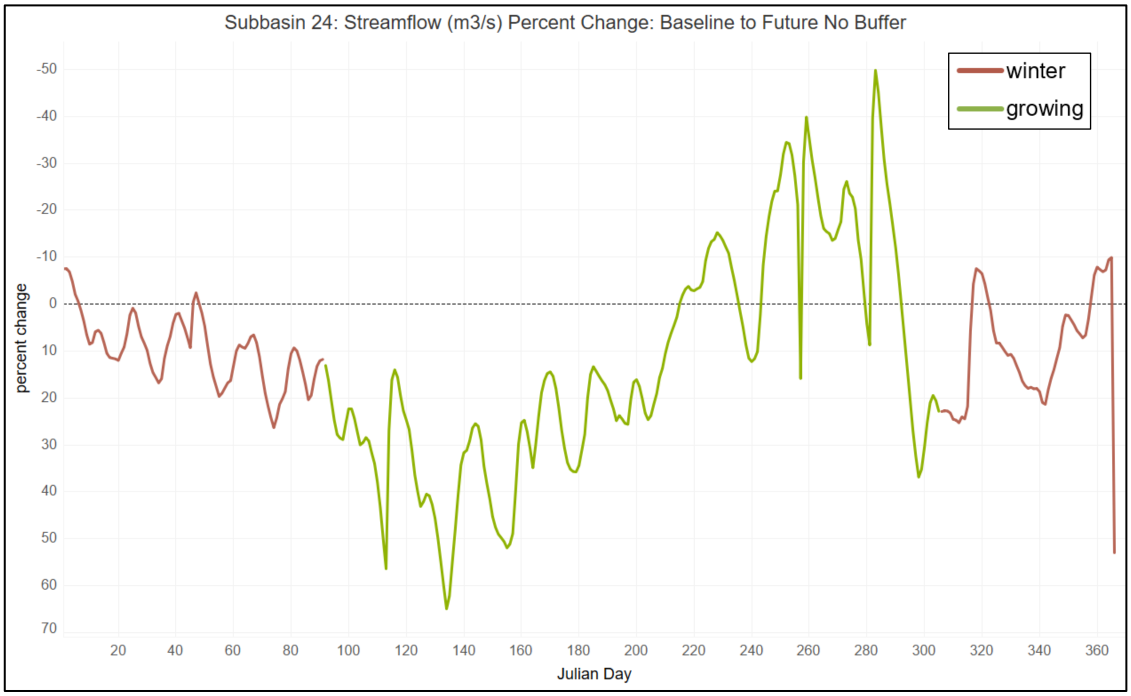

Figure 16 – Baseline and future (no added buffers) mean daily streamflow (m^3/s) on that Julian day across all years in subbasin 24 visualized by season.

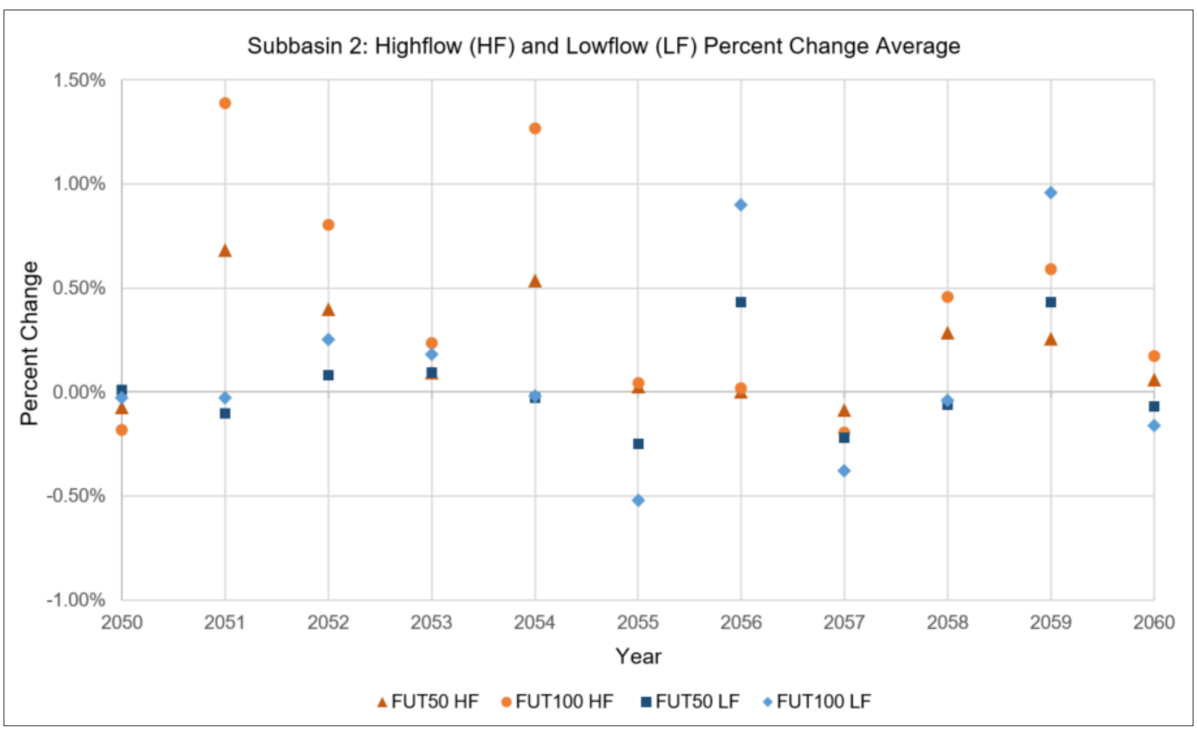

Figure 17 – Percent change in subbasin 2 streamflow from FUTNB to either FUT50 or FUT100. Values represent averages across all high or low flow events in that given year.

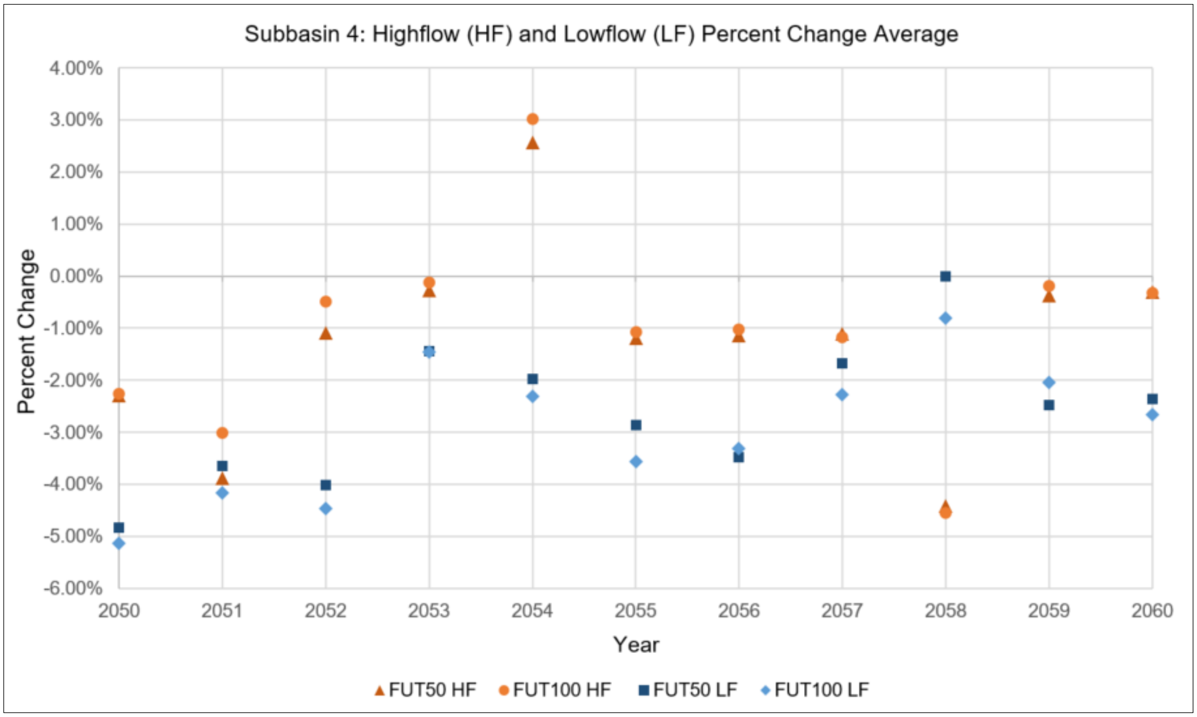

Figure 18 – Percent change in subbasin 4 streamflow from FUTNB to either FUT50 or FUT100. Values represent averages across all high or low flow events in that given year.

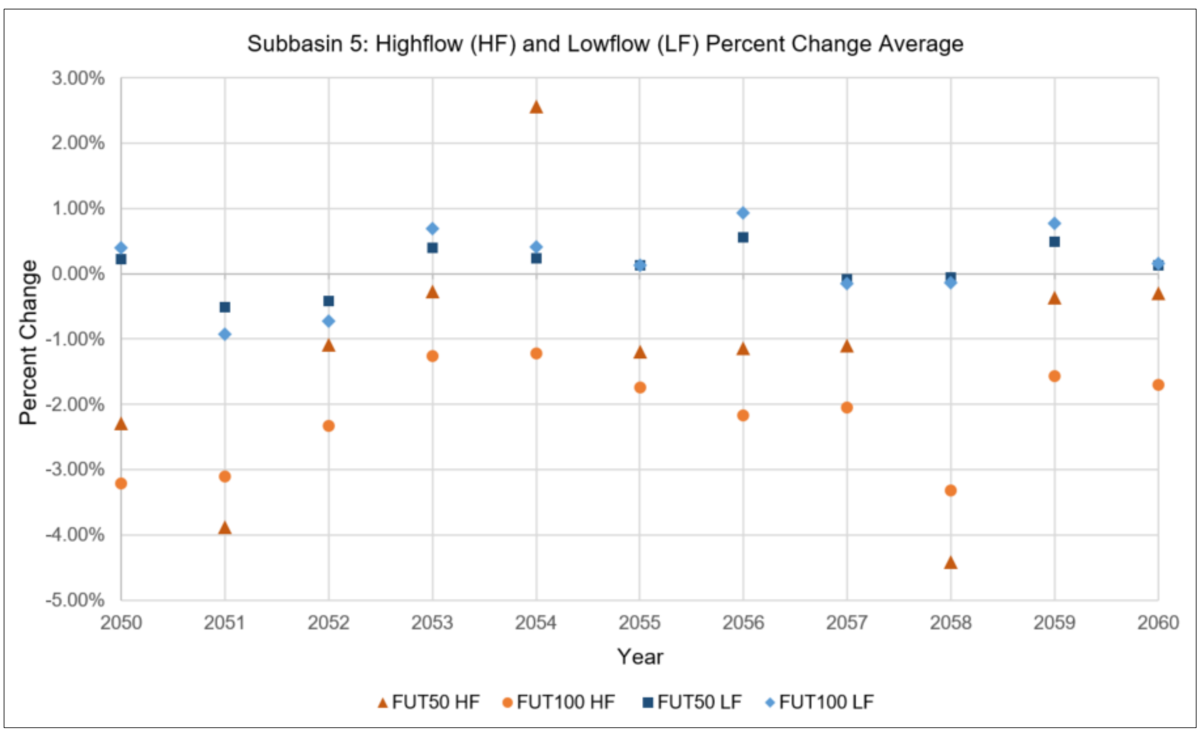

Figure 19 – Percent change in subbasin 5 streamflow from FUTNB to either FUT50 or FUT100. Values represent averages across all high or low flow events in that given year.

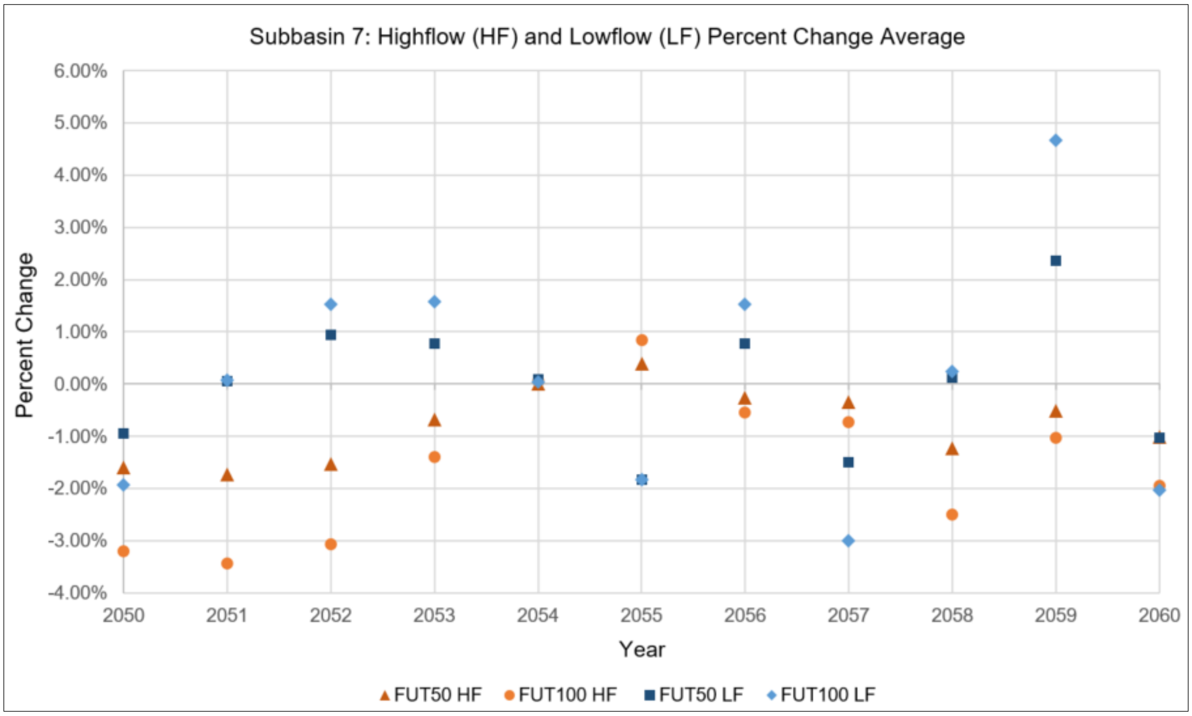

Figure 20 – Percent change in subbasin 7 streamflow from FUTNB to either FUT50 or FUT100. Values represent averages across all high or low flow events in that given year.

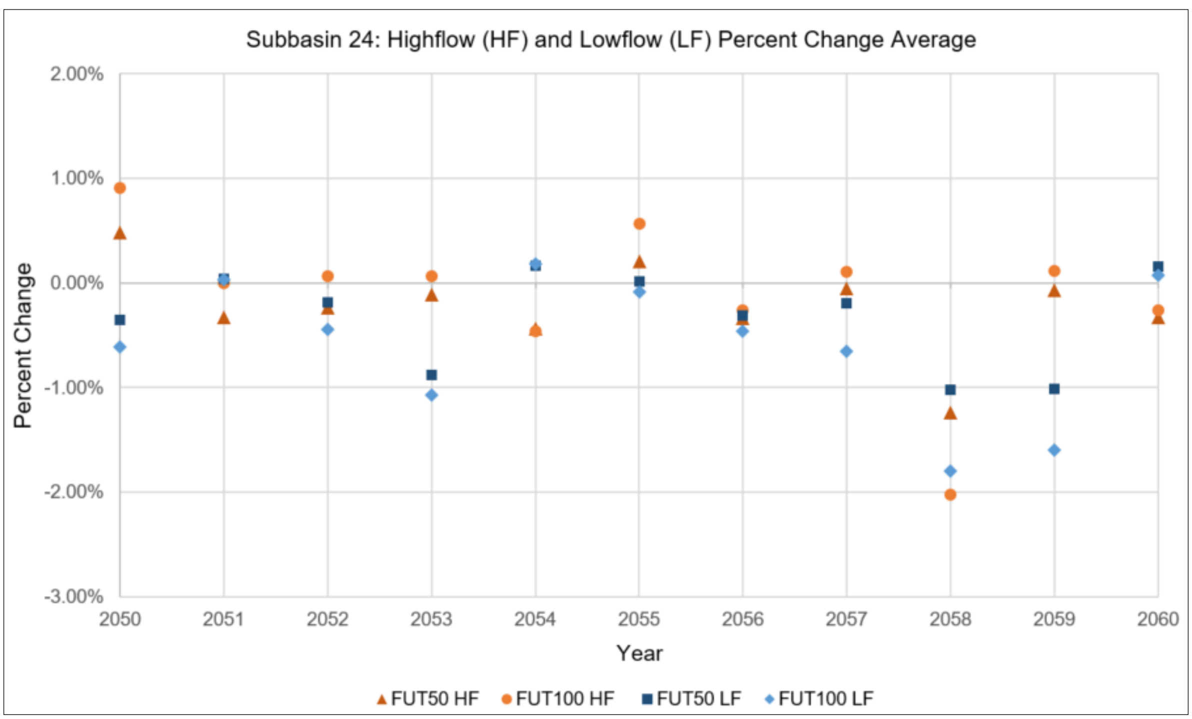

Figure 21 – Percent change in subbasin 24 streamflow from FUTNB to either FUT50 or FUT100. Values represent averages across all high or low flow events in that given year.