Science of the Total Environment 645 (2018) 806–816

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Assessment of hydrologic vulnerability to urbanization and climate change in a rapidly changing watershed in the Southeast U.S.

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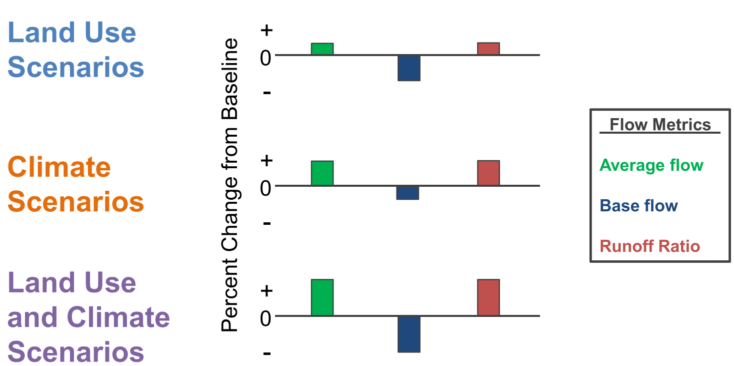
HIGHLIGHTS

- Land use (LU) models for the Southeast U.S. show rapid urbanization and forest loss.
- Streamflow was simulated using combinations of LU and climate models (2050–2070).
- Forests can buffer streamflow during hydrologic extremes, if they are large enough.
- Effects of urbanization and climate change were additive, amplifying change in flow.
- Risk of increased floods and drought must be considered in watershed planning.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 26 March 2018
Received in revised form 22 June 2018
Accepted 23 June 2018
Available online xxxx

Editor: Jay Gan

Keywords:
Forested watersheds
Streamflow
Land use models
Soil water assessment tool (SWAT)
Forest management, land use change

ABSTRACT

This study assessed the combined effects of increased urbanization and climate change on streamflow in the Yadkin-Pee Dee watershed (North Carolina, USA) and focused on the conversion from forest to urban land use, the primary land use transition occurring in the watershed. We used the Soil and Water Assessment Tool to simulate future (2050–2070) streamflow and baseflow for four combined climate and land use scenarios across the Yadkin-Pee Dee River watershed and three subwatersheds. The combined scenarios pair land use change and climate change scenarios together. Compared to the baseline, projected streamflow increased in three out of four combined scenarios and decreased in one combined scenario. Baseflow decreased in all combined scenarios, but decreases were largest in subwatersheds that lost the most forest. The effects of land use change and climate change were additive, amplifying the increases in runoff and decreases in baseflow. Streamflow was influenced more strongly by climate change than land use change. However, for baseflow the reverse was true; land use change tended to drive baseflow more than climate change. Land use change was also a stronger driver than climate in the most urban subwatershed. In the most extreme land use and climate projection the volume of the 1-day, 100 year flood nearly doubled at the watershed outlet. Our results underscore the importance of forests as

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https://doi.org/10.1016/j.scitotenv.2018.06.287
0048-9697/Published by Elsevier B.V.

hydrologic regulators buffering streamflow and baseflow from hydrologic extremes. Additionally, our results suggest that land managers and policy makers need to consider the implications of forest loss on streamflow and baseflow when planning for future urbanization and climate change adaptation options.

1. Introduction

Forested watersheds, which cover about 30% of the United States (US), contain >75% of the first-order streams (Sedell et al., 2000) and generate nearly 53% of total water yield (Brown et al., 2008). Forest ecosystems help mediate the episodic nature of storms and sustain reliable and clean freshwater supplies by storing water in soils and removing substantial amounts of soil water through evapotranspiration (ET; Bonan, 2008; Emanuel et al., 2010; Nippgen et al., 2016). Furthermore, forest soils act as a sponge and conduit for unused precipitation, thereby recharging groundwater and sustaining baseflow (Booth, 1991; Price, 2011; Singh et al., 2016).

Forested lands are particularly important in the Southeast US, because nearly two-thirds of its population receives a portion of its drinking water from surface and subsurface waters originating on public or private forested lands (Caldwell et al., 2014). Because many of the forests in the southern US are privately owned, they are vulnerable to urban development as the regional population grows (McNulty et al., 2013). In contrast to forests, urbanization restricts interactions between the stream and land while leading to increased runoff and subsequent higher peak flows, reductions in baseflows, and altered channel morphology (Boggs and Sun, 2011; Gagrani et al., 2014; Paul and Meyer, 2001; O'Driscoll et al., 2010). These issues, collectively referred to as "urban stream syndrome," can be attributed to "hydraulically efficient" storm water runoff systems (Walsh et al., 2005).

Since the mid-20th century, the Southeast US has been characterized by strong urban growth, often outpacing average urban growth rates across the US (Conroy et al., 2003). The spatial pattern of growth is characterized by low-density development outside the city center, also known as urban sprawl, which results in significant habitat fragmentation (Terando et al., 2014). The urban extent of 9 states in the Southeast is projected to increase 101–192%—leading to a fully connected megalopolis stretching from Atlanta, GA to Raleigh, NC by the year 2060 (Terando et al., 2014). The Central Appalachian Piedmont, the location of this megalopolis, is projected to lose 13–20% (1.5–2.4 million acres) of its forested lands to urbanization (McNulty et al., 2013). The intersection of increasing water demand and decreasing forested lands is particularly concerning in the context of climate change, which is expected to increase water stress throughout the Southeast US (Carter et al., 2014). Namely, the Southeast is expected to experience average annual temperature increases of as much as 4 °C by 2060 (Terando et al., 2014; McNulty et al., 2013). Changes in precipitation are more uncertain; however, the region is expected to experience greater frequency and severity of both drought and flood events (Easterling et al., 2000; Huntington, 2006). These changes, especially peak flows, may further exacerbate the effects of "urban stream syndrome."

Our goal was to identify the changes in streamflow amount and timing along trajectories of climate change and urban development in the Southeast to inform future forest management and land use planning. To accomplish this, we used an innovative fine scale (30 × 30 m) land use model for the Southeast US that incorporates both the National Land Cover Dataset (NLCD) and Forest Inventory Analysis data, combining both biophysical and socio-economic characteristics to project future (2060) land use (Martin et al., 2017; McNulty et al., 2013). Our approach provides fine scale detail compared to more generalized, simple land use projection models (Tu, 2009) at coarser spatial scales (250 m to 1 km; Caldwell et al., 2012; Viger et al., 2011). Differences in spatial detail have important implications for understanding the role of fine-scale land use patterns in regulating hydrologic processes. For example, at coarse-scales, the impacts of land uses that limit infiltration (e.g., urban areas) are "averaged out" among land uses that facilitate infiltration (e.g., forest areas).

The Yadkin-Pee Dee River watershed (YPDRW) in the Southeast US provides drinking water supplies and power generation, to over 3.6 million people within its approximately 17,000 km^2 drainage area. Changes in streamflow could impact the delivery of these critical services; therefore, the overall goal of this study was to assess the likely effects of future climate and land use change on water resources for the YPDRW. Specifically, this study focused on addressing the following research questions:

1. How might increasing urbanization in the YPDRW affect streamflow (average annual, low flow, baseflow, and runoff) in the future?
2. How might climate change (increased temperature and altered precipitation patterns) affect streamflow in the YPDRW?
3. Does one nonstationary factor (land use change or climate change) have a larger effect on streamflow than the other, and is there an interaction between factors?
4. How might the combined effects of land use and climate change impact extreme low and high flow quantiles (zero flow, 10-year flood, 100-year flood)?

To answer these questions, we used future land use datasets and future climate data as inputs to the Soil and Water Assessment Tool (SWAT) model to evaluate 12 future scenarios (4 each) of land use change only, climate change only, and combined climate and land use change. This study focused on streamflow and baseflow changes in the YPDRW and in three subwatersheds that represent a range of future forest land use patterns.

2. Methods

2.1. Study watershed

The Yadkin River begins in the Blue Ridge Mountains of western North Carolina (NC) and flows east for about 160 km, then turns south near Winston-Salem. In central NC, the Uwharrie River tributary joins the Yadkin River and forms the Pee Dee River. The Rocky River, another major tributary, joins the Pee Dee from the west and drains most of the area surrounding eastern Charlotte. In South Carolina, the Lumber River joins the Pee Dee River, which eventually empties into the Atlantic Ocean at Winyah Bay. The entire watershed above Winyah Bay is 29,137 km^2. However, for the purpose of this study, we focus on the Yadkin-Pee Dee River within NC (including the Upper, South, and Lower Yadkin, as well as the Rocky River and Upper Pee Dee HUC8 watersheds), which has an area of 17,780 km^2 (Fig. S1). The annual average precipitation based on 1981–2010 is 1137 mm (National Centers for Environmental Information, 2012).

2.2. SWAT model description

We used the ArcSWAT (2012 version) modeling software (Arnold et al., 2013) to simulate baseline and future streamflow dynamics. SWAT is a semi-distributed, watershed-scale hydrology model that was developed originally to model the impact of agricultural management practices on water quantity and quality (Arnold et al., 1998). It has been used to project the effects of climate and land use change on streamflow in both small watersheds and large river basins (Arnold et al., 1998; Douglas-Mankin et al., 2010; Gassman et al., 2007; Molina-Navarro et al., 2018; Wang and Kalin, 2017). SWAT has been used for urban and mixed use watershed modeling (Dixon and Earls, 2012; Eshtawi et al., 2016; Sisay et al., 2017) and is capable of simulating flashy urban storm runoff using sub-hourly time steps (Arnold et al., 2010; Jeong et al., 2010). Model performance has been comprehensively assessed over the last 30 years (Douglas-Mankin et al., 2010; Gassman et al., 2007).

The SWAT model delineates a watershed using a digital elevation model (DEM) and then divides the watershed into subbasins or subwatersheds based on the drainage area of the tributaries. Each subwatershed is further subdivided into hydrologic response units (HRUs), which are grouped together upon combinations of land use, soil, and topography. The SWAT model can simulate ET (we used the Penman-Monteith option; Monteith, 1965), surface runoff, lateral flow in the soil profile, groundwater flow, channel routing (Manning's equation for uniform flow in a channel), and reservoir storage (Arnold et al., 1998). Table S1 summarizes necessary data input files used in our model.

2.3. Land use models

We used a land use model to project fine scale (30 m × 30 m) spatial realizations of land use types from 2010 to 2060 (Martin et al., 2017). Briefly, a 2010 baseline was established by first translating current land cover to land use by implementing a random forest model that assigned pixels as forest or non-forest land use. Non-forested pixels were assigned their 2011 NLCD land cover class (i.e. developed, agriculture, or open water). Forested pixels were assigned forest attributes based on Forest Inventory and Analysis plots with similar climate, soils, topography, and phenology (McNulty et al., 2013). Land use projections incorporated social-economic (population and income growth; land, crop and timber prices), and ecological factors (tree species, vegetation) in a spatial allocation model. Socio-economic factors at the local level were consistent with the selected global IPCC SRES storylines. The A1B storyline assumes a higher rate of population (+60%) and economic growth and the B2 storyline assumes a lower rate of population (+40%) and economic growth (IPCC, 2007; Nakicenovic et al., 2000). Ecological projections including species projections were dependent on downscaled future climate projections (Coulson et al., 2010a; Coulson et al., 2010b). The selected scenarios produced a range of future climate conditions for the study area, with Cornerstone A (MIROC + A1B) expected to be hot and dry, Cornerstone B (CSIRO + A1B) warm and wet, and C (CSIRO + B2) and D (Hadley + B2) both warm and wet. Land use projection modeling also included assumptions of either increasing (Cornerstones A and C) or decreasing (Cornerstones B and D) timber prices (Table 1). Spatial imputations of future conditions were run 10 times and each pixel was assigned the mode land use for each of the four future scenarios (labeled as A, B, C, and D; Table 1). Land use classifications and the corresponding SWAT category for 2060 are defined in Table S2. For the purpose of this study, land use change refers to the conversion of forest land to urban land uses.

The baseline SWAT simulations used the 1992 NLCD, which is a land cover product, but the 2060 projections are land use products. One of the major distinctions between a land use classification and land cover classification in the Southeast US is how young forest is classified. Young forest (i.e., <5 m height) is classified as a forest land use in our land use model, whereas the NLCD classifies canopy heights <5 m as non-forested land cover (e.g., “shrubland”). A recent study in the same river basin (Martin et al., 2017), suggests that land use estimates derived from our models and NLCD-based land cover estimates are generally comparable. Furthermore <1% of the watershed was classified as transitional or shrubland, the categories most likely to be young forest land use, in the 1992 NLCD. In our study, land cover and land use classes were only used in the analysis if they occupied >5% of any subwatershed area. Therefore, only land cover and land use classes that were approximately equal (i.e. deciduous forest) were used in the analysis and subsequently compared.

2.4. Climate futures

We used CMIP5 (Taylor et al., 2012) daily climate data utilizing the Multivariate Adaptive Constructed Analogs (Abatzoglou and Brown, 2012) downscaling method, along with the METDATA (Abatzoglou, 2013) observational dataset as training data for the future simulations (downloaded through the USGS data portal: http://cida.usgs.gov/gdp). The land use model incorporated monthly climate data from CMIP3 into future projections of land use (described above), primarily to determine forest species groups, which were aggregated in this study to evergreen, deciduous, and mixed. CMIP3 projections incorporated socio-economic storylines of development and energy to project future climate (IPCC, 2007). CMIP5 used representative concentration pathways (RCPs) which are potential climate trajectories that can be achieved by multiple socio-economic and policy futures (IPCC, 2014; Van Vuuren et al., 2011). The role of policy and socio-economics in RCP trajectories is provided by Shared Socioeconomic Pathways (SSPs), which were not available at the time of the land use model implementation for this study (O'Neill et al., 2014). Further, SWAT requires daily weather data for precipitation, temperature, humidity, solar radiation, and wind speed and we could not identify an easily accessible source of daily downscaled CMIP3 data for our climate scenarios of interest. For consistency, we used the same GCM families (CSIRO, Hadley, and MIROC) and selected the Representative Concentration Pathway (RCP) scenarios that generally matched the CMIP3 climate scenarios used in the land use projection model (IPCC, 2014; Knutti and Sedláček, 2013). The A1B scenarios were matched with the RCP 8.5 scenarios and the B1 scenarios were matched with the RCP 4.5 scenarios. The climate scenarios used in our study are MIROC RCP 8.5, CSIRO RCP 8.5, CSIRO RCP 4.5, and Hadley RCP 4.5 (Table 1). The corresponding back-cast climate scenarios (MIROC, CSIRO, and Hadley) were used in the baseline simulations (Tables 2 and S1).

2.5. SWAT model set-up and evaluation

SWAT delineated the YPDRW into 28 subwatersheds within a total watershed area of 17,779.8 km^2. The outlet for this watershed is located at the USGS gage on the Pee Dee River (USGS Station ID 02129000,

Table 1
Overview of the paired land use models and climate models.

2060 land use cornerstone	Socio-economic growth	Timber prices	CMIP5 GCM and representative concentration pathway	Increase in average annual temp and precipitation
A	60% increase in population, high income growth	High	MIROC, RCP 8.5	Temperature: 3.2 °C Precipitation: 146 mm
B	60% increase in population, high income growth	Low	CSIRO, RCP 8.5	Temperature: 2.7 °C Precipitation: 131 mm
C	40% increase in population, low income growth	High	CSIRO, RCP 4.5	Temperature: 2.4 °C Precipitation: 219 mm
D	40% increase in population, low income growth	Low	Hadley, RCP 4.5	Temperature: 3.5 °C Precipitation: 73 mm

Table 2
SWAT scenarios: baseline, land use only, climate only, and combined.

Climate scenarios	NLCD 1992	Land use A 2060	Land use B 2060	Land use C 2060	Land use D 2060
MIROC 1982–2002	MIROC baseline	Land use A only			
CSIRO 1982–2002	CSIRO baseline		Land use B only	Land use C only	
Hadley 1982–2002	Hadley baseline				Land use D only
MIROC 8.5 2050–2070	Climate only	Combined A			
CSIRO 8.5 2050–2070	Climate only		Combined B		
CSIRO 4.5 2050–2070	Climate only			Combined C	
Hadley 4.5 2050–2070	Climate only				Combined D

Fig. S1). The 28 subwatersheds were further delineated into 193 HRUs, which were classified based on homogeneous land use types, soil types, and topography. The HRUs were defined by using percent thresholds of land use, soils, and slope of 5, 20, and 10%, respectively, within each of the 28 subwatersheds. These percentages were the lowest thresholds that did not create >200 HRUs.

The SWAT model was calibrated and validated using a split data approach that covered periods of high and low flow in each of the two time periods. Daily flow data from three USGS stream gages (02115360, 02116500, and 02129000, Fig. S1) were compared to the SWAT simulated data for the time period January 1, 1982 to December 31, 1996 for the calibration and from January 1, 1997 to December 31, 2008 for the validation. We chose those gage locations because they had long (>50 years) historical records that are necessary for robust calibration/validation of the model. The Nash Sutcliffe efficiency coefficient (NSE), ratio of root mean square error to the standard deviation (RSR), and percent bias (PBIAS) were calculated and represent measures of model performance. The NSE values were calculated as:

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

where
Q_i^{obs}, is the i^{th} observed discharge, Q^{mean} is the mean of observed discharges, and Q_i^{sim} is the i^{th} modeled discharge. The NSE can range from -∞ to 1. A value of 1 indicates a perfect fit between simulated and observed data and a value of 0 indicates that the average of the observed discharge would be a better fit than the model output (Nash and Sutcliffe, 1970). A NSE of 0.5 or higher is accepted as an indicator of satisfactory model performance for a monthly time step (Moriasi et al., 2007).

The RSR values are the ratio of root mean square error (RMSE) to the standard deviation of observed data and were calculated as:

$$RSR = \frac{RMSE}{STDEV_{obs}} = \left[\frac{\sqrt{\sum_{i=1}^{n} \left(Q_i^{obs} - Q_i^{sim} \right)^2}}{\sqrt{\sum_{i=1}^{n} \left(Q_i^{obs} - Q^{mean} \right)^2}} \right]$$

An RSR value of 0 indicates a perfect simulation, but values <0.70 are considered to be satisfactory for model performance at a monthly time step (Moriasi et al., 2007).

PBIAS quantifies whether the average tendency of the simulated data is greater or less than the observed data and expressed as a percentage, indicating a high or low bias in the modeled data. Positive PBIAS values indicate that the simulated data is lower than the observed data on average, but negative values indicate the reverse: simulated data is higher than the observed data on average. The PBIAS values were calculated using the following equation:

$$PBIAS = \left[\frac{\sum_{i=1}^{obs} \left(Q_i^{obs} - Q_i^{sim} \right) * 100}{\sum_{i=1}^{n} \left(Q_i^{obs} \right)} \right]$$

A PBIAS value <25% is considered satisfactory model performance and a PBIAS value of 0 indicates a perfect simulation for a monthly time step (Moriasi et al., 2007).

We used the SWAT-Calibration and Uncertainty Program (SWAT-CUP, version 2012) software, which integrates uncertainty analysis with the model calibration, and the generalized likelihood uncertainty estimation (GLUE) procedure at a daily timescale (Abbaspour, 2015; Beven and Binley, 1992). We selected 17 parameters and associated ranges based on the literature to conduct global sensitivity analysis where all parameters were changed at the same time and model performance (i.e., NSE) was assessed. After running 9100 simulations, the set of 7 parameters (i.e., available water capacity of the soil, soil evaporation compensation factor, depth of water for percolation to deep aquifer, average slope length, SCS curve number, groundwater delay, and depth of water for return flow) out of 17 that yielded the highest NSE during the calibration were considered the best parameters. Four parameters were changed for the entire watershed and the remaining 3 parameters were calibrated for the upper and lower portions of the YPDRW separately using USGS gages 02115360 (upper) and 02129000 (lower) (Table S3). The simulated daily streamflow from the calibration time period and validation time period was compared to the daily observed USGS stream gage data from three gage locations by calculating the NSE, RSR, and PBIAS values for each gage.

2.6. Simulation of land use and climate scenarios

SWAT model simulations were performed for two, 20-year time periods: baseline (1982–2002) and future (2050–2070). These time periods bracket the land use descriptions of 1992 and 2060. To simulate the effects of land use change and climate change we created three scenarios with the following input datasets:

1. Land use only scenarios: 2060 Land Use Cornerstones A–D with corresponding historical down-scaled climate data (1979–2002 with 3 years warm-up) from each of the 3 GCMs (MIROC, CSIRO, and Hadley).
2. Climate only scenarios: 4 future climate scenarios (MIROC 8.5, CSIRO 8.5, CSIRO 4.5, and Hadley 4.5) for 2047–2070 (with 3 years warm-up) with baseline 1992 land cover (NLCD).
3. Combined scenarios: 2060 Land Use Cornerstones A–D with corresponding future climate futures (MIROC 8.5, CSIRO 8.5, CSIRO 4.5, and Hadley 4.5) for 2047–2070 (with 3 years warm-up).

Thus there are 12 scenarios (4 each of land use only, climate only, and combined) and each scenario was compared to baseline data that reflected the baseline land cover (1992) and climate (1982–2002) (Table 2).

Model output from four focus areas was considered for detailed analysis: the Muddy Creek, the South Yadkin River, the Uwharrie River, and the YPDRW outlet (Fig. 1). We chose these three subwatersheds to represent different amounts of projected (2060) forest land use. Muddy Creek represents a mostly urban subwatershed and the Uwharrie River represents a mostly forested subwatershed at the baseline and in the future. The S. Yadkin River subwatershed is similar to the Uwharrie subwatershed at the baseline, but more forest will be converted to urban by 2060 (Table 3 and Fig. 1). The other major land use is agriculture and can be assumed to be the remaining fraction.

2.7. Analysis of modeled Streamflow response

We compared the 12 future scenarios to the baseline for each of the 4 watersheds by calculating relative percent change for the following streamflow response variables: average annual daily streamflow, the coefficient of variation (CV), mean annual runoff ratios, and the baseflow fraction. Average annual daily streamflow is the mean daily streamflow value for an average year. To calculate this value, we averaged daily streamflow for each day in the 20-year period (e.g., average streamflow at a gage on Jan 1). CV was estimated to measure the variability of annual streamflow and is calculated by dividing the standard deviation by the average annual daily streamflow. The annual runoff ratio is the ratio of streamflow (mm/year) to precipitation (mm/year). The ratio of baseflow to runoff was determined using the Baseflow Filter Program software, which is an adaptation of the automated Master Recession Curve procedure (Arnold et al., 1995; Arnold and Allen, 1999).

Table 3
Percentages of forest and urban land use at baseline (1992) and with projected scenarios A–D (2060).

Forest	1992 baseline	2060 A	2060 B	2060C	2060 D
Uwharrie river	81	66	66	68	68
S. Yadkin river	63	40	39	46	43
Muddy creek	45	12	12	22	22
Yadkin river	69	49	48	53	50
Urban					
Uwharrie river	0	20	20	15	16
S. Yadkin river	0	34	35	25	25
Muddy creek	34	88	88	71	70
Yadkin river	3	33	34	26	27

The two-sample Kolmogorov-Smirnov test (KS Test) (Massey Jr., 1951; Young, 1977) was used to compare flow duration curves of simulated streamflow to baseline observed daily streamflow. The KS test is based on the maximum difference between the two distributions. Two streamflow response variables were used to assess changes in high and low flow for the combined scenarios: 10-year (i.e., 10% change of occurring in an average year) and 100-year (i.e., 1% chance of occurring in an average year) recurrence intervals for streamflow (cms) and cumulative number of days of zero flow. We conducted the analysis for extreme flow quantiles on the combined scenarios only because the combined effects are most relevant (i.e., climate change will not occur independent of land use change and vice versa). Cumulative annual maximum and minimum recurrence intervals were calculated for the baseline time period and the future time period using the standard Log-Pearson Type III stream analyses (IACWD, 1982; Riggs, 1972).

Results were analyzed in ArcGIS (version 10.2.2), MatLab (R2016a version 9.0.0.341360) and R (version 3.4.3). All data and scripts

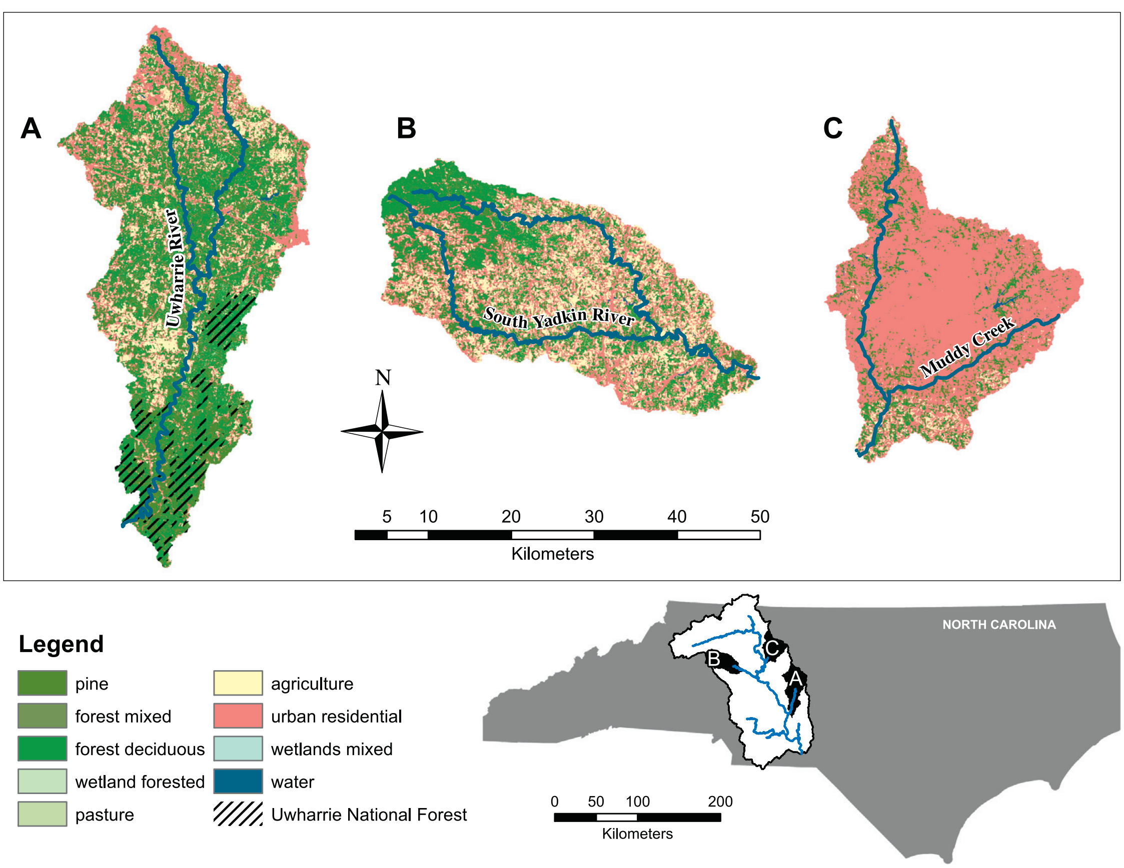

Fig. 1. Subwatershed land use and location map for the year 2060: A = Uwharrie River, B = South Yadkin River, C = Muddy Creek.

associated with this publication are available on GitHub at https://github.com/sheilasaia/paper-yadkin-swat-study and can be accessed via Zenodo (doi: https://doi.org/10.0.20.161/zenodo.1312628).

3. Results

3.1. Climate model projections

Average temperature is projected to increase over the baseline averages, ranging from 2.4 to 3.5 °C in the four climate futures (Table 1). The Hadley 4.5 model predicts the highest temperature increase at mid-century and the CSIRO 4.5 model predicts the least temperature increase. Precipitation is also projected to increase in all four climate scenarios, ranging from 73 to 219 mm annually (Table 1, Fig. S2). The CSIRO 4.5 model predicts the highest precipitation increase and the Hadley 4.5 model predicts the least precipitation increase. An important consideration is that we are using mid-century projections. In the latter half of the century, RCP 4.5 and RCP 8.5 are expected to diverge across all GCMs, with more rapid changes expected under RCP 8.5 (IPCC, 2014).

3.2. Land use change projections

The urban areas surrounding Winston-Salem and Charlotte, NC are projected to expand the most, and the Land Use A and B scenarios show a higher degree of growth compared to Land Use C and D (Fig. S3). Decreases in forest also surround those two urban areas, but the forest loss is most concentrated around Charlotte in Land Use B and D. The S. Yadkin River and Uwharrie River subwatersheds both began without significant developed land use at the baseline, but by 2060 their urban land use patterns diverge, in part due to land development restrictions within the Uwharrie National Forest (UNF), which accounts for 21% of the area in the Uwharrie River subwatershed. By 2060, the relative forest loss in the subwatersheds ranges from 51% to 73% in Muddy Creek, 27% to 37% in S. Yadkin River, and 16% to 19% in the Uwharrie River. Forest loss in the YPDRW is 22% to 29% in the four land use scenarios (A-D).

3.3. SWAT validation

The NSE, RSR, and PBIAS values for both the daily calibration and validation range from satisfactory to very good, using the evaluation criteria from Moriasi et al. (2007) at a monthly time step, and they are summarized in Table S4. Similarly, the natural logarithm of daily streamflow was estimated to understand model performance during extreme flow conditions (Table S4). Since model simulations for shorter time steps are typically not as good as simulations for longer ones (Moriasi et al., 2007), we assumed that our model performance at a daily time step is at least satisfactory or better. Observed vs. simulated streamflow were graphed as a scatterplot with associated R^2 values (Fig. S4) and as a time series (Fig. S5). The model systematically under-predicts flow in the 'dormant' season (November–April) and systematically over-predicts flow in the 'active' season (May–October). The systematic bias is greatest in January (−28%) and September (20%) based on mean monthly streamflow values.

3.4. Land use change effects on streamflow

Average annual daily streamflow increased by 6–24% in all four land use only scenarios in the YPDRW and the S. Yadkin and Uwharrie Rivers (less developed subwatersheds, 2050–2070). The largest increases in streamflow were from the Land Use A and C models in the S. Yadkin and Uwharrie Rivers (Fig. 2). Flow duration curves were significantly different for most land use scenarios compared to the baseline conditions (Fig. S6; KS Test, $P < 0.05$). They were not significantly different for the Muddy Creek subwatershed in the A–C land use only scenarios, the Uwharrie River subwatershed in the A, B, and D land use only scenarios, and the S. Yadkin River subwatershed in the Land Use D scenario (Fig. S6). In the significantly different Land Use A, B, and C scenarios, average daily streamflow is projected to increase. The CV between land use change only scenarios is low in general (<13% change from baseline), but Land Use B for the Muddy Creek shows a large decrease (23%) (Fig. 2).

Similar to average annual daily streamflow, mean annual runoff ratios increased (4–23%) in the two less developed subwatersheds (S. Yadkin and Uwharrie) and the YPDRW with the largest increases in Land Use C (Fig. 2). Future baseflow decreased from the baseline levels for all the watersheds and land use scenarios (4% to 27%), except for the Muddy Creek. However, the baseflow fractions for the Muddy Creek under baseline conditions ranged from 0.46–0.49 compared to almost 0.60 or higher in the other watersheds. The S. Yadkin River showed the highest decreases in baseflow (19% to 27%) (Fig. 2).

3.5. Climate change effects on streamflow

Three of the climate only scenarios (MIROC 8.5, CSIRO 8.5, and CSIRO 4.5) generated similar streamflow effects in both average annual daily streamflow (13–43% increase) and flow duration curves in the simulated period, 2050–2070. The highest increase in average daily streamflow (43%) was from CSIRO 4.5 for the YPDRW (Fig. 2). Flow duration curves were significantly different from the baseline conditions for all climate only scenarios (KS Test, $P < 0.05$), except for the Muddy Creek subwatershed for MIROC 8.5 and the Uwharrie River subwatershed for Hadley 4.5 (Fig. S6). Significantly different streamflow distributions for Hadley 4.5 are projected to decrease. The CV in streamflow increased for all the climate only scenarios (5–49%), except for CSIRO 4.5 in the Uwharrie and Yadkin River watersheds. Increases in CV were the highest (41–49%) under Hadley 4.5 across all watersheds (Fig. 2).

Consistent with the relative precipitation increases in the projected climate data (Table 1, Fig. S2), CSIRO 4.5 showed the largest increases (20–24%) and Hadley 4.5 showed the largest decreases (−5 to −12%) in the mean annual runoff ratio values (Fig. 2). The climate only scenarios decreased baseflow in all watersheds ranging from 3 to 12%. In the Muddy Creek subwatershed Hadley 4.5 produced a slightly larger decrease (12%) in baseflow than the other climate scenarios and subwatersheds (Fig. 2).

3.6. Combined land use change and climate change effects on streamflow

Similar to the climate only scenarios, the future combined scenarios (2050–2070) increased the average annual daily streamflow by 4–63% for all scenarios and all watersheds, except for the Muddy Creek subwatershed, which decreased in three combined scenarios (Fig. 2). The highest increases in streamflow (60–63%) for all watersheds were in the Combined C scenario. Flow duration curves for the combined scenarios followed the same pattern as the climate only scenarios: all combined scenarios were significantly different from the baseline except for the Muddy Creek subwatershed for the Combined A and the Uwharrie River subwatershed for the Combined D (Fig. S6). Average daily streamflow was projected to increase in the Combined A-C scenarios and streamflow was projected to decrease in the Combined D scenarios. The CV is predicted to increase for most of the future combined scenarios (6–54%) compared to the baselines, but the Combined D scenario increases in the CV are the highest (44–54%) in the YPDRW, and S. Yadkin and Uwharrie subwatersheds (Fig. 2).

Runoff ratio values increased (12–43%) in three watersheds for Combined A, B, and C scenarios, but there were decreases in these values most notably in the Combined D scenario in the Muddy Creek subwatershed (23%) due to both land use change and climate change (Fig. 2). The combined scenarios decreased baseflow in all watersheds ranging from (4 to 34%) from the baseline. The reductions in baseflow

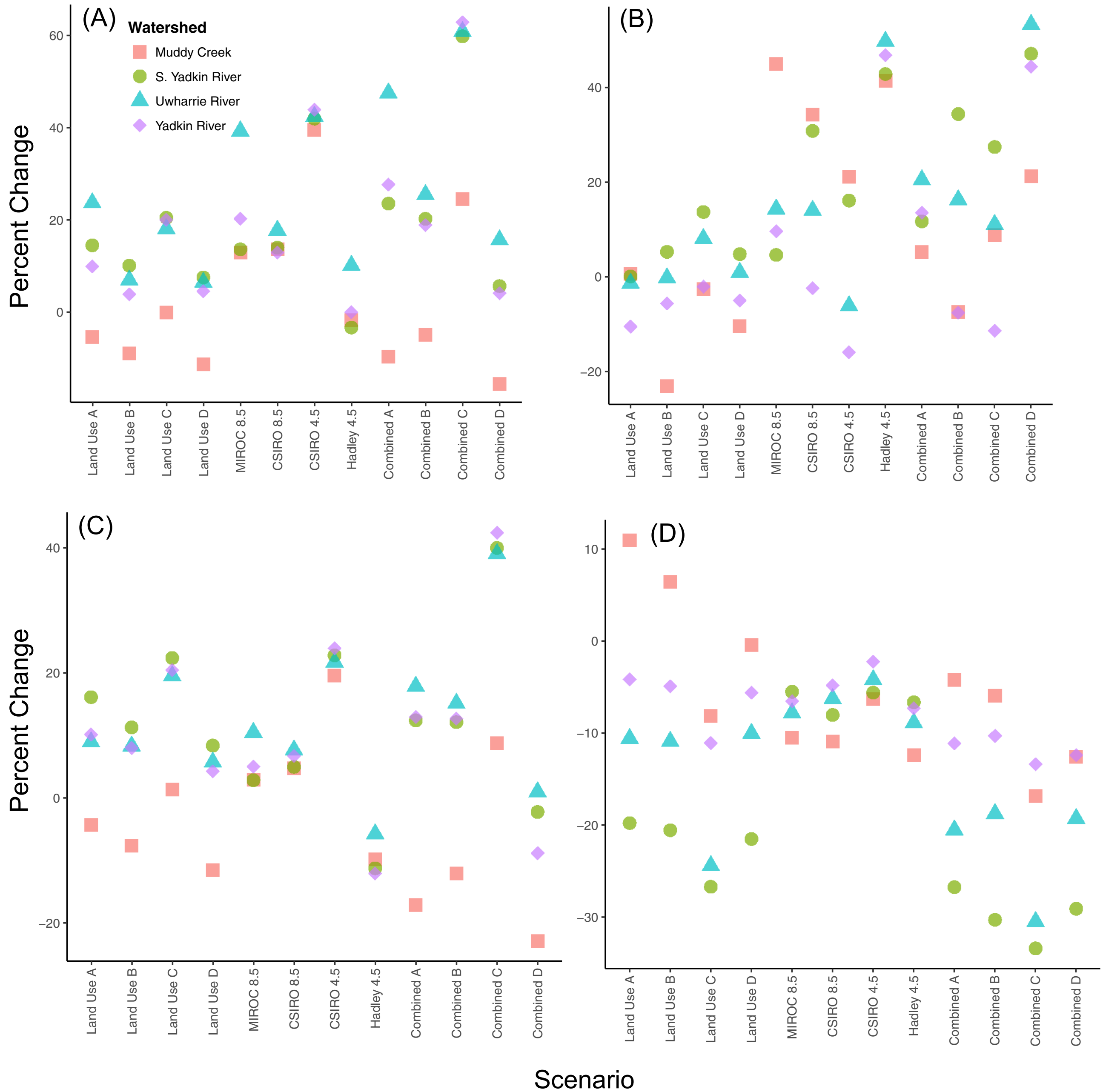

Fig. 2. (A) Percent change in average annual daily streamflow (cms) for each scenario (B) Percent change in the coefficient of variation for land use only, climate only, and combined scenarios. (C) Percent change in runoff ratios for land use only, climate only, and combined scenarios. (D) Percent change in baseflow fraction for land use only, climate only, and combined scenarios.

were greatest in the S. Yadkin River (26% to 34%) and the Uwharrie River (18 to 30%) subwatersheds (Fig. 2).

A decrease in spring streamflow, but increases in the summer and fall in the Combined A and B scenarios suggest a seasonal shift in climate and streamflow. The Combined C scenario is projected to increase streamflow in all seasons and in some cases flow duration curves are so steep that all future streamflow will be higher than the average baseline flow (e.g. fall for all watersheds and all seasons for the YPDRW). The Combined D scenario is much more variable among seasons and watersheds, but most of the decreases in streamflow occur in the spring, summer and winter months. This scenario also produces higher high flows and lower low flows in the spring and winter (Fig. S7).

3.7. Combined scenarios: effects on high and low flows

The combined scenarios show increases in the 100-year high flows, although the Combined A scenario shows some decreases, especially in the Muddy Creek watershed (54%). The 100-year high flows in the YPDRW are projected to increase by 73% (Combined A) to 151% (Combined B). Some of the largest increases in 100-year high flows are for the Uwharrie River subwatershed (Combined C: 247% and Combined B: 421%; Fig. 3). The results for the cumulative number of days of zero flow are variable. However, the Combined D scenario shows increases in the cumulative number of days of zero flow across all watersheds (63–225%) and the S. Yadkin River subwatershed is the only watershed to have consistent increases in all the combined scenarios (Fig. 3).

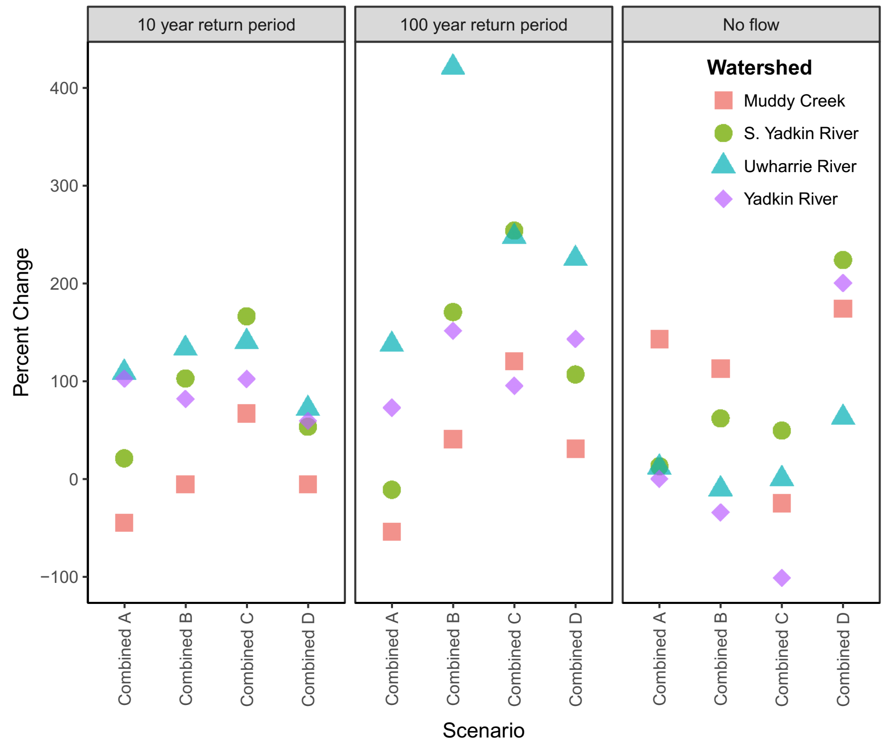

Fig. 3. (A) Percent change in streamflow (cms) for 10-year recurrence intervals for each subwatershed and combined scenario. (B) Percent change in streamflow (cms) for 100-year recurrence intervals for each subwatershed and combined scenario. (C) Percent change in the cumulative number of days of zero flow for each subwatershed and combined scenario.

4. Discussion

4.1. Land use change effects on streamflow

The effects of land use change on streamflow confirmed the importance of forests in minimizing runoff and maintaining baseflow (Boggs and Sun, 2011; Lockaby et al., 2013; Paul and Meyer, 2001; Rose and Peters, 2001; Singh et al., 2018; Stednick, 1996; Sun and Caldwell, 2015). In our study, the S. Yadkin River subwatershed particularly highlights the rapid transition from rural at baseline to a more developed watershed in 2060. With decreasing baseflow during periods of infrequent precipitation, the cumulative number of zero flow days increased in the S. Yadkin subwatershed in all combined scenarios. In the Southeast US, streamflow is impacted when the amount of urban land use reaches10–40% (Boggs and Sun, 2011; Paul and Meyer, 2001; Sun and Caldwell, 2015). In this study, increasing urban land use in watersheds such as the S. Yadkin (increase 25–35%) resulted in the largest changes in streamflow and baseflow. In contrast, land use change in the Uwharrie River subwatershed was buffered by the UNF and streamflow responses were less dramatic. However, the UNF is not large enough to prevent all future changes in streamflow due to forest loss in the remaining areas of the watershed (Fig. 2; Boggs and Sun, 2011; Booth, 1991). Forest loss at these levels may have significant implications for both high and low flows after urbanization in Piedmont rivers.

Comparing changes across and within the YPDRW yielded some useful insights about streamflow sensitivity to land use change. Without examining the subwatersheds, the complexity of effects would have been averaged out at the YPDRW scale. For example, in Fig. 2 the percent change in streamflow in each scenario for the YPDRW is intermediate compared to the results of the subwatersheds. Baseflow is particularly sensitive to changes in land use (Fig. 2), but this would have been hard to discern from just the YPDRW model results. Similarly, the change in zero flow days is variable depending on both the subwatershed and scenario (Fig. 3). Hence, our results suggest that it is critical to consider finer scale land use patterns when assessing the impacts of forest land use within the larger watershed ecosystem.

4.2. Climate change effects on streamflow

In the Southeast US, precipitation is the most important driver of streamflow (Caldwell et al., 2014), and in our study, this was evident as the CVs for streamflow were higher for the climate only scenarios than for the land use only scenarios (Fig. 2). Precipitation is also the most uncertain variable in climate change model projections (Luce et al., 2016). Three out of our four selected future climate scenarios (MIROC 8.5, CSIRO 8.5 and 4.5) resulted in model projections of increased streamflow (Fig. 2). Hadley 4.5 was the most variable climate model for all the watersheds (41–49% increase in CV) suggesting longer dry periods and more intense storms (Min et al., 2011).

Further, streamflow decreased under Hadley 4.5, likely due to increased ET resulting from increased temperature similar to results in Sunde et al. (2017). Mean annual runoff declined in all watersheds from 5 to 12% under Hadley 4.5 (Fig. 2), further indicating increases in ET that outpace precipitation (Sun, 2013; Vose et al., 2016). Conversely, under CSIRO 4.5, which predicted the largest increase in annual precipitation and the smallest increase in temperature, average annual daily streamflow increased by about 40% in all watersheds and mean annual runoff ratios increased by about 20%. A wetter climate with more moderate increases in temperature and ET might result in more flooding, highlighting the importance of forests as hydrologic regulators though both ET and soil water storage (Boggs and Sun, 2011; Emanuel et al., 2010; Hwang et al., 2012; Price et al., 2010).

4.3. Combined land use and climate change effects on streamflow

The results of our study on the combined effects of climate and land use change indicate future scenarios will exhibit increases in average annual daily streamflow and decreases in baseflow. Our findings are consistent with work by Wang et al. (2014) and Tao et al. (2014), but differ from others, including Sun (2013), Sunde et al. (2017), and Viger et al. (2011). Reasons for these differences are complex, but likely result from the use of different hydrologic models, and different approaches/models used to project future climate and land use. Consistent with examples including Caldwell et al. (2012); Lockaby et al. (2013); Martin et al. (2017); and Sun et al. (2008), the climate only scenarios had a larger effect on streamflow than land use change. Rice et al. (2015) suggest that the effects of urbanization increase sensitivity to climate change, especially for the magnitudes of high and low-flow events and intra-annual variability.

In the combined scenarios the effects of land use change and climate change on streamflow were additive, which is consistent with other research (Franczyk and Chang, 2009; Martin et al., 2017; Wang et al., 2014). The magnitude of response for land use only vs. climate only indicates which driver is the governing driver (Fig. 2). For baseflow land use is the stronger driver and at the subwatershed scale, land use change was the dominant driver in the Muddy Creek subwatershed. This is consistent with work by Tao et al. (2014) and Hejazi and Moglen (2008), who found that increased imperviousness (50% or more), could make land use changes a stronger driver of streamflow patterns. When the climate only and land use only responses are projected to go in different directions, the combined results are offset to some degree, consistent with Viger et al. (2011) (Fig. 2). Streamflow decreased relative to the baseline under Hadley 4.5, but when combined with land use change in Combined D, some of the effects were offset (e.g., average annual daily streamflow for the D scenarios in the S. Yadkin subwatershed increased by 8% for land use only, decreased by 3% for climate only, and increased by 6% for the combined). It is vital to note the importance of shorter-term fluctuations in precipitation and surface runoff to stream hydrology and ecology. For example the in the Combined D scenario the cumulative number of days of zero flow increased across all watersheds from 63 to 225%. As a result, temperature in the shallow, stagnant water may increase, stressing aquatic organisms (Richards et al., 1996).

4.4. Combined scenarios: hydrologic extremes

In addition to short term fluctuations, we found a trend in increasing extremes under the future Combined C and D scenarios. The Combined D scenario predicts the greatest change in the extremes: increased high and low flows (i.e., 100-year flood recurrence interval and cumulative days of zero flow, Fig. 3). Flow duration curves show longer periods of low flows, with 1–2 months lower than the baseline in an average year. While the S. Yadkin River subwatershed and YPDRW show modest decreases in low flow, the highest flows in an average year from the Combined D scenarios are much higher than the baseline, thus they raise the mean. The Uwharrie River subwatershed is projected to retain the most forest and this may offer some protective benefit.

The potential outcomes of the Combined C scenarios provide insight into potential impacts of land use and climate change on high flows that may result in flood events. Our results are conservative estimates, especially for extreme flow, because the model generally under-predicts flow as indicated by the positive percent bias values (Table S4) and the 7-day maximums (Table S5). Increases >60% in average annual daily streamflow (S. Yadkin, Uwharrie, and YPDRW) mean that streamflow for 9 months to 51 weeks out of the year would be much higher than the average baseline conditions. The highest 10% of streamflow (high flow) that would occur on the baseline average for one month a year is expected to occur more frequently: 3.5 months (S. Yadkin, Uwharrie Rivers) to six months (YPDRW) per year. Additionally, the 100-year high flow for the S. Yadkin and Uwharrie subwatersheds may increase by nearly 250% (Fig. 3). Most major infrastructure projects like levees are engineered for the 100-year recurrence interval (Shabman et al., 2014). Despite these conservative estimates, our set of plausible model projections suggests the highest floods would be unprecedented.

4.5. Implications and limitations

This work advances our understanding of how fine-scale land use models may generate insight into land use change at a scale useful for policy decisions. This modeling approach could be used in watersheds throughout the Southeast and would help identify "priority" watersheds under the greatest threat from future development should business as usual continue. More generally this research has implications for other places with rapid population growth displacing forests and similar effects from a warmer, wetter, and more extreme climate. While there is efficiency in using large scale modeling approaches, our research emphasizes the importance of finer-scale approaches when evaluating the effects of land use change. As with all modeling studies, uncertainty is inherent in all future projections of climate, land use, and their effects on hydrology. These results are based on assumptions that calibrated model parameters have well-constrained values and that model structures represent hydrological processes that are most important in this system.

While it is clear that climate change mitigation will take substantial international cooperation, conservation of forested areas could play a large role in climate adaptation strategies at the watershed scale. The increased risk of floods due to both heavier precipitation events and increased urbanization underscores the importance of forests as hydrologic regulators. Our models suggest that the hotter, wetter climate derived from the four climate scenarios for the YPDRW will overwhelm the ability of the projected extent of forest land use to efficiently buffer recurrent flooding or sustain baseflow during dry periods.

Prioritizing forest areas to conserve within a watershed could be the first step for local authorities or states working jointly on this issue (Gagrani et al., 2014; Olander and Young, 2016). Recognizing that urban development and population growth will continue, there are a variety of ways to protect surface water resources (i.e. Low Impact Development). By implementing these types of stormwater management strategies and forest conservation, at the start of a project or retrofitting existing infrastructure, many of the problems (i.e. the "urban stream syndrome") associated with traditional urban development could be mitigated. In light of these results it is critical that land managers and policy makers consider the implications of flooding and increased high and low flows when planning for future population growth and climate change adaptation options.

5. Conclusion

Our SWAT simulations project that streamflow will increase and baseflow will decrease in all the future scenarios of land use and climate change in the YPDRW in the SE US. We found that land use and climate change effects were additive, and that these impacts might lead to hydrologic extremes. Within the range of possible futures the extreme flow increases projected by the combined C scenario may result in high flows for half the year and unprecedented flooding while the combined D scenario may result in the greatest change in the extremes: increased high and low flows with longer periods of low flows.

Acknowledgements

This research was supported in part by an appointment to the U.S. Forest Service Research Participation Program administered by the Oak Ridge Institute for Science and Education (ORISE) through an interagency agreement between the U.S. Department of Energy (DOE) and the U.S. Department of Agriculture (USDA) Forest Service. ORISE is managed by Oak Ridge Associated Universities (ORAU) under DOE contract number DE-SC0014664. All opinions expressed in this paper are the authors' and do not necessarily reflect the policies and views of USDA, DOE, or ORAU/ORISE. The manuscript was improved by three anonymous reviewers and reviews from Devendra Amatya, Steven Brantley, and Jill Qi. We are thankful to our colleague, Theo Jass, who provided technical expertise that greatly assisted the research. All data and scripts associated with this publication are available on GitHub at https://github.com/sheilasaia/paper-yadkin-swat-study and can be accessed via Zenodo (doi: https://doi.org/10.5281/zenodo.1312628).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2018.06.287.

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