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

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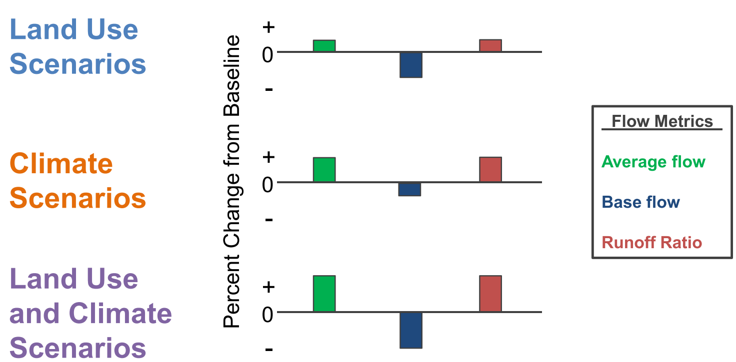
HIGHLIGHTS

- 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



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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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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