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RESEARCH ARTICLE

Watershed impacts of climate and land use changes depend on magnitude and land use context

Katherine L. Martin[1,2,3] | **Taehee Hwang**[4] | **James M. Vose**[2] | **John W. Coulston**[5] | **David N. Wear**[2] | **Brian Miles**[6] | **Lawrence E. Band**[6]

[1] Oak Ridge Institute for Science and Education (ORISE), Oak Ridge, TN, USA
[2] Center for Integrated Forest Science, USDA Forest Service Southern Research Station, Raleigh, NC, USA
[3] Department of Forestry and Environmental Resources, North Carolina State University, Raleigh, NC, USA
[4] Department of Geography, Indiana University, Bloomington, IN, USA
[5] Forest Inventory and Analysis Program, USDA Forest Service Southern Research Station, Blacksburg, VA, USA
[6] Institute for the Environment, University of North Carolina at Chapel Hill, Chapel Hill, NC, USA

Correspondence
Katherine L. Martin, Department of Forestry and Environmental Resources, North Carolina State University, Campus Box 8008, Raleigh, NC 27695, USA.
Email: katie_martin@ncsu.edu

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Abstract

Human population growth and urban development are affecting climate, land use, and the ecosystem services provided to society, including the supply of freshwater. We investigated the effects of land use and climate change on water resources in the Yadkin–Pee Dee River Basin of North Carolina, United States. Current and projected land uses were modeled at high resolution for three watersheds representing a forested to urban land use gradient by melding the National Land Cover Dataset with data from the U.S. Forest Service Forest Inventory and Analysis. Forecasts for 2051–2060 of regional land use and climate for scenarios of low (B2) and moderately high (A1B) rates of change, coupled with multiple global circulation models (MIROC, CSIRO, and Hadley), were used to inform a distributed ecohydrological model. Our results identified increases in water yields across the study watersheds, primarily due to forecasts of increased precipitation. Climate change was a more dominant factor for future water yield relative to land use change across all land uses (forested, urban, and mixed). When land use change was high (27% of forested land use was converted to urban development), it amplified the impacts of climate change on both the magnitude and timing of water yield. Our fine-scale (30-m) distributed combined modeling approach of land use and climate change identified changes in watershed hydrology at scales relevant for management, emphasizing the need for modeling efforts that integrate the effects of biophysical (climate) and social economic (land use) changes on the projection of future water resource scenarios.

KEYWORDS

climate change, ecosystem services, forest management, land use change, RHESSys, urbanization, water resources

1 | INTRODUCTION

Land use–land cover (LULC) changes, together with climate change (CC), will continue to affect the ability of shrinking and more fragmented natural areas to provide ecosystem services, including freshwater availability. Water availability for expanding urban areas will be affected by up to a 4.8 °C increase in the global average temperature by the end of the century and an expected increase in more extreme hydrologic events, including droughts and floods (Field & Van Aalst, 2014; O'Gorman & Schneider, 2009). Clean, abundant freshwater is a critical ecosystem service for which consumption is likely to increase with population growth. The 2014 National Climate Assessment identified water availability as one of the key impacts of CC on the Southeastern United States (Carter et al., 2014), and forecasts indicate that much of the region will experience an increasing deficit between human demand and supply (Lockaby et al., 2013). Consistent with global trends, the U.S. Southeast is expected to experience a doubling of urban area by 2060 and average annual temperature increases of 2–4 °C (McNulty, Myers, Caldwell, & Sun, 2013; Terando et al., 2014; Wear, 2013). In the U.S. Southeast, there are discrepancies among climate models with regard to total precipitation; however, the region is expected to experience greater frequency and severity of both drought and flood events, consistent with trends emerging across several regions of the Unites States in the recent decades (Easterling et al., 2000; Field & Van Aalst, 2014; Huntington, 2006).

Forests are an important LULC for clean, stable water supplies. In the Southeast, forest LULC has fluctuated with periods of development and in response to changes in timber and agricultural markets

(Wear, 2013). Between 2010 and 2060, up to 21% of the forest in the Piedmont, an extensive region that includes most of the major cities in the Southeast, is projected to transition to urban development (Wear, 2013). When forests are converted to urban LULC, the increase in impervious cover tends to increase high flows, whereas baseflows are reduced through the decrease in groundwater recharge and storage due to reduced infiltration (Calhoun, Frick, & Buell, 2003; Rose & Peters, 2001; Schoonover, Lockaby, & Helms, 2006; Wang, Lyons, & Kanehl, 2001). The effects of conversion to urban LULC on hydrologic behavior are thought to exhibit threshold effects, whereby small changes have minimal effects, but at a certain point, additional impervious surface causes runoff and water yield to increase dramatically (Wang et al., 2001; Sun & Caldwell, 2015; Walsh, Fletcher, & Ladson, 2005; Walsh et al. 2005). On regional scales, urban development alters both temperature and precipitation because of its effects on local energy balances and heat exchanges, hydrology, and atmospheric chemistry (Zhang et al., 2005; Zhou et al., 2004). When compared to urban LULC, conversion of forest to agriculture has more moderate effects but can also increase overland flow and water yield (Schoonover et al., 2006).

Forecasting the concurrent and interactive effects of climate and LULC changes on water yield is a challenging task that requires models drawn from multiple disciplines. Estimating future LULC patterns requires projections of economic growth, agricultural and timber markets, population growth, and methods to distribute urban development spatially. Further, LULC change models must be matched in scales appropriately in time and space to be informative for investigations of ecological and hydrological processes. In complex and mixed-use landscape characteristic of the Piedmont region of the Southeast, LULC change (Terando et al., 2014; Wear, 2013) and hydrologic models, for example, Caldwell, Sun, McNulty, Cohen, and Myers (2012) and Sun, McNulty, Moore Myers, and Cohen (2008), applied at larger spatial scales illustrate broad future patterns but cannot account for the fine-scale complexities that influence localized hydrologic processes (Miles & Band, 2015). This scale mismatch limits the ability of hydrologic models to quantify how different LULC patterns interact, respond to CC and variability, and influence ecosystem processes, and in turn, water availability. Furthermore, hydrologic models must be sufficiently process based and appropriately scaled (temporally and spatially) to quantify these fine-scale complexities. We address these challenges by combining a novel approach for quantifying and projecting future LU at high resolution (30 m) with a spatially distributed and process-based ecohydrologic model (Regional Hydro-Ecological Simulation System [RHESSys]; Tague & Band, 2004) to examine the interactions between climate and LU change at fine temporal and spatial scales (Figure 1). Using coupled climate and LU scenarios, we determined the magnitudes and spatial distributions of LU and CCs across the watersheds in the Yadkin River Basin of North Carolina. These projections were combined with the RHESSys model to answer the following questions: (a) What are the respective effects of changes in LU and climate on watershed hydrology? (b) Are there important interactions between simultaneous

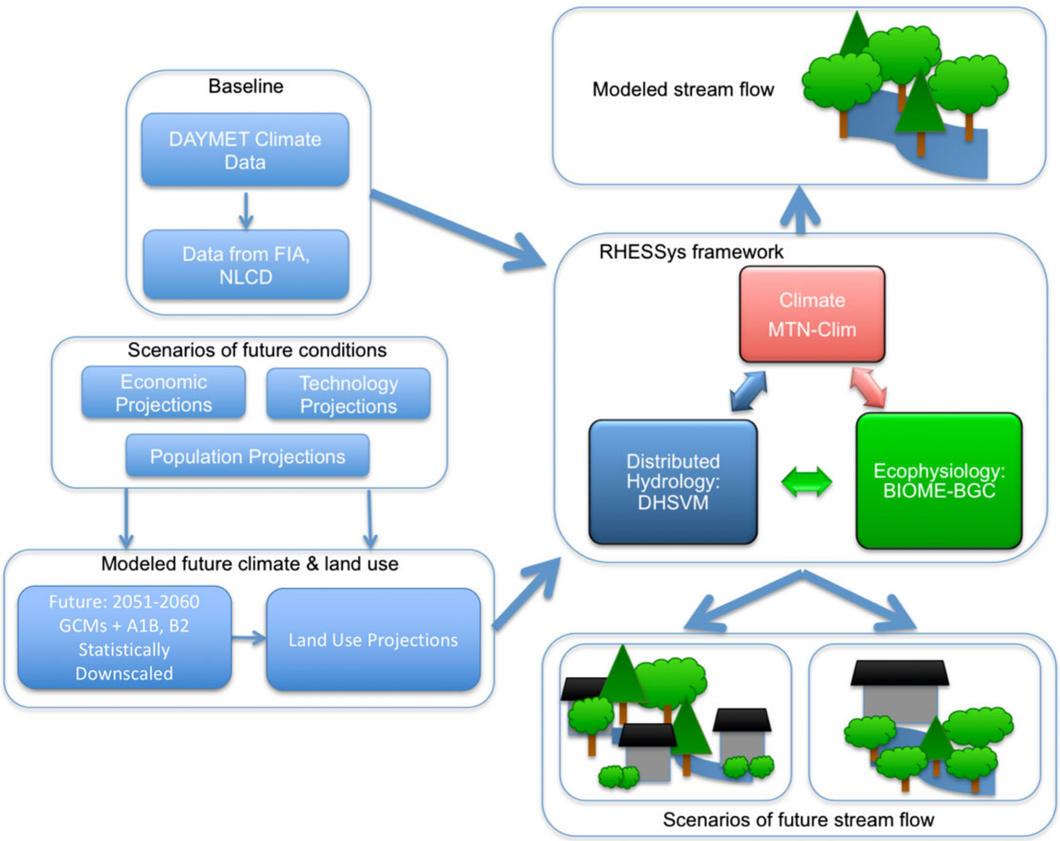

FIGURE 1 Conceptual diagram of multimodel approach to examine the effects of changes in climate and land use on water yield. DHSVM = Distributed Hydrology Soil Vegetation Model; FIA = Forest Inventory and Analysis; GCM = Global Circulation Model; NLCD = National Land Cover Dataset; RHESSys = Regional Hydro-Ecological Simulation System

changes in LU and climate? (c) How do responses vary across watersheds with different current LUs and expected rates of future change?

2 | METHODS

2.1 | Study site

As the first component of a larger project examining ecohydrologic changes across the Yadkin–Pee Dee River Basin from the mountains to the coast, study watersheds were selected as representative of physiographic conditions, including LULC and topography, across the Mountain and Piedmont regions. From the available watersheds with active U.S. Geological Survey (USGS) stream gages with a long-term (preferably >10 years) dataset, three headwater catchments along a LU gradient from predominately forested to predominately urban were selected; details of the study watersheds are found in Table 1. Briefly, Elk Creek is a primarily forested watershed located in the Crystalline Ridges and Mountains subsection of the Blue Ridge Mountains, characterized by high relief and acidic, well-drained loamy soils underlain by Precambrian-age igneous and high-grade metamorphic rock (Griffith et al., 2002). Soil survey data (Soil Survey Geographic Database) indicated soils are predominately fine sandy loams, gravely fine sandy loams, and sandy loams (Soil Survey Staff, Natural Resources Conservation Service, United States Department of Agriculture, n.d.). County-level data from the United States Department of Agriculture (USDA) Forest Service Forest Inventory and Analysis (FIA) database collected from Watauga, Caldwell, and Wilkes counties using the Forest Inventory Data Online tool suggested a species composition dominated by deciduous hardwoods including oaks (*Quercus prinus*, *Quercus alba*, and *Quercus coccinea*), tulip poplar (*Liriodendron tulipifera*), red maple (*Acer rubrum*), and American beech (*Fagus grandifolia*), with inclusions of white pine (*Pinus strobus*). The West Branch of Rocky River (Rocky River) is a mixed LU watershed currently in the exurban area adjacent to Charlotte and Kannapolis, NC, characterized by forest, agriculture, and some developed LUs. Mallard Creek is a predominantly urbanized watershed in the Charlotte metropolitan area. Both Rocky River and Mallard Creek are located in the Southern Outer Piedmont, characterized by mixed oak forests and old fields of pine growing on red, clayey subsoils underlain by deep saprolite over gneiss, schist, and granite (Griffith et al., 2002). Web soil survey data (Soil Survey Staff, Natural Resources Conservation Service, United States Department of Agriculture, n.d.) indicated soils in the Rocky River watershed are predominantly sandy clay loams, clay loams, loams, and fine sandy loams. In the Mallard Creek watershed, soils are similar, predominately fine sandy loams, sandy clay loams, sandy loams, and loams. FIA data extracted for Iredell and Mecklenburg counties indicate that the forests across both watersheds are dominated by deciduous hardwoods, including oaks (*Quercus rubra*, *Q. alba*, and *Quercus falcata*), Sweetgum (*Liqidambar styraciflua*), hickories (*Carya glabra* and *Crassula ovata*), tulip poplar, and red maple, with scattered pine (*Pinus taeda* and *Pinus echinata*).

2.2 | Climate datasets

Baseline climate data for each of the study watersheds were established using the Daymet climate dataset, which provides gridded datasets of daily temperature and precipitation interpolated from ground-based meteorological observations dating from January 1, 1980 (Thornton et al., 2014). Daymet was selected as the baseline climate data source due to the availability of data, particularly precipitation data, at fine spatial and temporal resolutions. Using Daymet data, we selected three points from each study watershed at the approximate upper watershed boundary, watershed midpoint, and USGS stream gage locations were collected. The points were chosen as representative of the elevation gradient within each watershed to

TABLE 1 Detailed land use information of three study watersheds

Watershed	Size	Elevation range (median)	NLCD 2011 land cover	Modeled land use, 2010 (baseline)	USGS stream gage record
Elk Creek USGS 02111180	132	327–1254 (602)	85% deciduous forest 3% evergreen forest 2% mixed forest 2% hay/pasture 3% developed 3% other	82% deciduous forest 4% evergreen forest 8% mixed forest 4% hay/pasture 2% developed, open	1965–current
Rocky River USGS 0212393300	54	194–271 (229)	36% deciduous forest 8% evergreen forest 1% mixed forest 20% hay/pasture 24% developed 6% grassland 5% other	38% deciduous forest 11% evergreen forest 6% mixed forest 19% hay/pasture 14% developed, open 7% developed, low 2% developed, medium	2004–current
Mallard Creek USGS 0212414900	90	168–270 (220)	17% deciduous forest 5% evergreen forest 5% hay/pasture 68% developed 5% other	20% deciduous forest 8% evergreen forest 3% mixed forest 5% hay/pasture 26% developed, open 25% developed, low 11% developed, medium 3% developed, high	1994–current

Note. "Size" refers to km^2, elevation in meters. "Other" refers to land cover categories that represented <1% of the watershed and include the NLCD categories: open water, barren land, shrub/scrub, grassland/herbaceous, cultivated crops, woody wetlands, and emergent wetlands. NCLD = National Land Cover Dataset; USGS = U.S. Geological Survey.

provide the most accurate estimate of precipitation distributions across the watershed and to inform MT-Clim model (Running, Nemani, & Hungerford, 1987), the mountain microclimate module of the ecohydrological model framework implemented in the study (Tague & Band, 2004), described below. The inclusion of precipitation data at multiple points within the watersheds allowed us to implement more accurate calibration of the distributed ecohydrologic model.

Internally consistent climate, economic, social, and LU future scenarios were chosen from the library used in the 2010 Resources Planning Act Assessment (USDA Forest Service, 2012) to maintain consistency across future projections from multiple models. These scenarios were adopted from the IPCC Fourth Assessment Report (IPCC, 2007). We chose two contrasting social economic storylines, A1B and B2, each of which was coupled with two different global circulation models (CSIRO and MIROC or Hadley). These four combinations: Scenario A (A1B + MIROC), Scenario B (A1B + CSIRO), Scenario C (B2 + CSIRO), and Scenario D (B2 + Hadley) were also used in the Southern Forest Futures Project, a large technical report on the future of the region produced by the USDA Forest Service (Wear & Greis, 2013). These scenarios were chosen as representative of moderately low to moderately high changes in LU and climate (Table 2). Scenarios A and B, using the A1B storyline, describe futures of high population growth and high energy use, whereas Scenarios C and D use the B2 storyline of low population growth and low income growth. These futures translate into a range of climate projections for the 2010–2100 period across the Southeast, with Scenario A expected to be hot and dry, B warm and wet, and C and D both warm with average annual precipitation similar to historic averages (McNulty et al., 2013).

2.3 | Climate downscaling

The study used a dataset of spatially downscaled climate projections published by the USDA Forest Service (Coulson, Joyce, Price, & McKenney, 2010; Coulson et al., 2010). Climate projections were spatially downscaled from global forecasts using the ANUSPLIN software package to the 5-arc minute grid scale at a monthly time step for the 2010 USDA Forest Service Resources Planning Act (Coulson, Joyce, Price, & McKenney, 2010; Coulson, Joyce, Price, McKenney, Siltanen, et al., 2010; USDA Forest Service, 2012). ANUSPLIN is a downscaling technique developed by the Australian National University that uses a thin-plate smoothing spline-interpolation technique (Hutchinson, 2010). Change factors were then imposed on 1961–1990 monthly climate normals from the PRISM dataset (PRISM Climate Group, Oregon State University, http://prism.oregonstate.edu). By incorporating climate records, change factor methods produce projections with what Ekström, Grose, and Whetton (2015) termed high "climate realism," which is useful in impact studies. For further information, see Coulson, Joyce, Price, and McKenney (2010) and Coulson, Joyce, Price, McKenney, Siltanen, et al. (2010). We do not consider there to be a conflict between the use of baseline daily climate series from the Daymet climate dataset and the projection dataset to explore the potential impacts of CC, which was created by combining spatially downscaled global circulation model output with PRISM derived 30-year historic monthly climatology. The 5-arc minute grid point closest to the midpoint of each study watershed was selected to create a monthly climate record for 2051–2060. These climate projections used to inform the LU model were scaled at a monthly time step; however, our hydrologic model required daily climate data (see description of RHESSys below). Therefore, a temporal downscaling process was also implemented. We created a daily climate record for each projected month based on a similar month from the historic record. First, we determined which month from the historic record was most similar to each projected month, in terms of monthly maximum temperature, monthly minimum temperature, and total monthly precipitation. This was accomplished by comparing each projected month with every historic record from the same month; for example, January 2051 was compared to each January from the 1980–2010 record. From

TABLE 2 Overview of LULC and climate change scenarios

Scenario	GCM + SRES	Social economic	Timber prices	Regional LULC change[a]	Regional climate change[b]
A	MIROC + A1B	60% increase in population, high income growth	High	143% increase in urban land; 8% loss of forested land	Minimum temperature increase 0.3 °C, maximum temperature increase 1.9 °C, and average annual precipitation decrease 224 mm
B	CSIRO + A1B	60% increase in population, high income growth	Low	143% increase in urban land; 13% loss of forested land	Minimum temperature increase 1 °C, maximum temperature increase 4.5 °C, and average annual precipitation increase 31 mm
C	CSIRO + B2	40% increase in population, low income growth	High	98% increase in urban land; 7% loss of forested land	Minimum temperature decrease 0.21 °C, maximum temperature increase 2.3 °C, and average annual precipitation decrease 53 mm
D	Hadley + B2	40% increase in population, low income growth	Low	98% increase in urban land; 12% loss of forested land	Minimum temperature increase 0.3 °C, maximum temperature increase 2.9 °C, and average annual precipitation decrease 30 mm

Note. GCM = global circulation model; LULC = land use–land cover change.

[a]Change in LULC across the Southeastern region (including all states between Virginia and Texas) as reported by Wear (2013).

[b]Change in annual minimum and maximum temperatures and average annual precipitation across the Southeastern region (including all states between Virginia and Texas) compared to 2001–2009 historical climate, as reported by McNulty et al. (2013).

each comparison, an index of difference was created, defined as the sum of the absolute values of the difference between each of the temperature variables (monthly average maximum and minimum) and twice the absolute value of the difference in monthly precipitation, so that matches would be weighted for the closest precipitation match (Equation 1).

$$D_i = \text{abs}\left(\text{Max}T_p - \text{Max}T_h\right) + \text{abs}\left(\text{Min}T_p - \text{Min}T_h\right) + 2\ \text{abs}\left(P_p - P_h\right). \quad (1)$$

Then, the historic record with the smallest index of difference was selected as the match. After selecting the most similar historic record, an adjustment factor was applied to the daily record to create a projected daily climate dataset. For example, if the difference between the projected mean maximum monthly temperature and the closest mean maximum monthly match from the historic record was 0.4°, this was added to the daily historic record. For precipitation, the difference between the projected monthly precipitation and the historic monthly precipitation was divided by the number of precipitation events in the historic record and added to each one. Records were checked and corrected to ensure daily minimum temperatures did not exceed daily maximum temperatures.

2.4 | Land use model—baseline

A model of current and projected future LU scenarios in the Yadkin River Basin was developed in this study, extended from the Southern Forest Futures Project (Wear & Greis, 2013) but resolved at a finer spatial scale (30 m) so that we could examine future hydrologic changes at scales relevant to land management. LU categorizes the landscape based on its social or economic purpose, in contrast to approaches such as the National Land Cover Dataset (NLCD; Homer et al., 2015), which define land cover categories by interpreting the spectral properties from remote sensing datasets (Coulston, Reams, Wear, & Brewer, 2014). Evaluations of LU or land cover data can lead to differing estimates of forest extent and change, for example, vegetation canopy heights must exceed 5 m to be classified as forest in NLCD, even if the LU is young forest (Coulston et al., 2014).

The LU model was refined from methodologies and scenarios of future conditions used for multiple explorations of changes in LU, including the Southern Forest Futures Project (Wear & Greis, 2013) and the USDA Forest Service 2010 Resources Planning Act Assessment (USDA Forest Service, 2012). In particular, county-level estimates of LU change available in Wear (2013) were further refined to a 30-m spatial scale, consistent with the resolution of the NLCD. The ecohydrological model (RHESSys) used in the study is often used at a 30-m or finer scales (Mittman, Band, Hwang, & Smith, 2012; Mohammed & Tarboton, 2014; Shields & Tague, 2015). Due to a combination of available data on land cover, digital elevation models and processing time (smaller spatial scales are more computationally intensive) resolutions of <30 m are generally used in smaller watersheds. LU assignment began with a base layer where the 30-m grid pixels were first classified as forest or non-forest from a random forest model developed to translate current land cover to a forest LU map. This model was developed using the FIA sample observations (across all LUs and covers), a time series of NLCD land cover, and current NLCD percent tree canopy cover (Coulston, Jacobs, King, & Elmore, 2013). FIA data include vegetation measurements (species, size, condition, etc.) across public and private ownerships and include both forest and non-forest. All pixels identified as forest were then assigned attributes including forest type (later consolidated to deciduous, evergreen, or mixed) from a plot in the FIA database with similar characteristics (such as climate, topography, soil, and phenology) using an ensemble imputation approach, leading to multiple spatial realizations. Non-forest LUs (e.g., developed, agriculture, open water, and wetland) were then assigned a baseline LU using the NLCD 2011 dataset, remaining consistent with the base year spatial realizations. To facilitate projections, each forest pixel was assigned the "plot number" of its imputed plot for each realization. Each pixel was assigned the mode LU (including forest type) from a set of 20 realizations for the base LU layer.

2.5 | Land use model—future projections

Projecting future LU required a multimodel and multidisciplinary approach because LU depends on biophysical factors (climate, vegetation type, and species) as well as social economic factors (e.g., rates of population and income growth and thus development; land prices based on agricultural and timber markets). Incorporating timber markets is an especially important component of LU models in areas with active forest management, such as the Southeastern United States. For Scenarios A and B, the A1B economic storyline projects a future of overall moderate population growth and high income growth, suggesting by 2060, there would be about a 60% increase in population and per capita income of $80,000 (in 2006 dollars) on average across the Southeast. Thus, Scenarios A and B represent futures with higher rates of LULC change, where more forest is converted to developed urban area (Wear, 2013). Both population and income growths are more moderate in Scenarios C and D, based on the B2 storyline, resulting in lower rates of LULC change and urban development. Averaged across the Southeast, Scenarios C and D result in 2060 with a 40% increase in population and per capital income of $60,000 (2006 dollars). Scenarios A and B were downscaled to the county level based on the spatial econometric approach defined by Woods and Poole (Woods and Poole Economics, 2007; Zarnoch, Cordell, Betz, & Langner, 2010). The same spatial pattern of population change was applied to generate county-level estimates for Scenarios C and D but were adjusted to so that the county-level projections added up to the storyline's total.

Once population and income growth were established, they were combined with estimates of agricultural and timber market forces to determine LU futures, as described in Wear (2013). National Resource Inventory data from 1987 to 1997 were used to estimate a county-level change model for the 13-state Southeast region using panel-data statistical methods and to validate the models consistency with observed changes (Wear, 2013). Then, projections of LU change for each county were made for both scenarios based on the population, income, and economic variables described above. Scenarios C and D (B2) show spatial patterns of population and income growth similar to Scenarios A and B (A1B) but at lower rates. A projection of the amount of development was based on population and income growth and then rural LU was projected based on urbanization rates, rural land rents, and crop and timber prices.

Forest LU projections were developed using the US Forest Assessment System (US-FAS), a modeling framework used by the USDA Forest Service to predict future forest conditions that incorporates climate and LU changes, forest succession, and market-driven timber harvesting (USDA Forest Service, 2012). FIA is a baseline for this system. The US-FAS provides future conditions for every plot in the FIA database based on projected climate conditions, forest age, forest type, and whether the plot will likely be harvested. The extent and type of forested LU also varies with timber prices. Scenarios A and C were assigned a future of increasing timber prices, whereas timber prices decreased in Scenarios B and D. Harvest projections were defined by estimating the growth on each plot using a conditional logit model based on historical plot records, then the resulting timber volume was combined with projected timber prices to determine harvest probabilities. Random draws from the associated distributions define the harvest events. Detailed plot conditions were then determined by selecting an FIA measurement plot with conditions (climate, forest age, harvest type, and forest type) matching the future conditions at the plot location.

County-level LU projections for all LUs were refined to a 30-m scale by developing a spatial allocation model. The spatial allocation model assigned the probability of each pixel converting to a different LU and remaining in the same use. These probabilities were then used to determine which pixels to change in order to reflect projected LU change from the county-level projection. This step allocated LU transitions among forest, developed, agriculture, water, and wetlands to the 30-m map. Forest transitions (changes in forest types, forest management impacts, etc.) were allocated separately. As noted above, forest projections are modeled in the US-FAS, which projects forest transitions, growth, forest management, and so forth consistently with chosen scenarios at the FIA plot level. In effect, this system moves plots forward in time. The spatial allocation of these forest dynamics is driven by the plot-level spatial imputation described earlier. The set of pixels assigned to each plot during the spatial imputation follow the trajectory of that plot as projected in the US-FAS. Each pixel was then assigned the modal LU drawn from 10 imputation solutions for each of the Scenarios A–D. The 10 imputations represent a future LU projection for 2060 that incorporates the degree of social economic and CC that occurred over the 50-year period from the baseline; changes were not grown continuously.

The LU model projections did not include degree of development (open, low intensity, medium intensity, and high intensity) or agriculture (hay/pasture and cultivated crops) that were used in the baseline layer from NLCD categories. However, these categories were required to assign levels of imperviousness and leaf area index values within the ecohydrological modeling framework (described below). To provide these values, all pixels that had been developed in the baseline LU layer were assigned the same value (e.g., all low-intensity development remained low intensity) in the 2060 projection, and all pixels that had transitioned to developed LU were assigned as medium intensity. Current suburban, exurban, and development LUs intensities in the study watersheds tended to be medium, so it was assumed that future development would follow a similar pattern. This medium level of development intensity is described in the NLCD legend as areas with a mixture of constructed materials and vegetation, where impervious surfaces cover 50–79% of the area, commonly areas of single-family housing units. Pixels that were previously agriculture were assigned into the same category, and all pixels that had transitioned to agriculture became hay/pasture, the predominant agricultural LU within the study watersheds. As with the base model, future LU maps were also created from the modal LU for each pixel from a set of 10 spatial imputation solutions for each of the four scenarios.

2.6 | Distributed ecohydrological model

RHESSys is a geographic information system-based, distributed ecohydrological modeling framework that synthesizes climate, LULC, topography, and soil to simulate carbon and water exchange with the atmosphere, water runoff through streams, and nitrogen cycling and export with either prescribed species or functional vegetation patterns (Band et al., 1993; Tague & Band, 2004). The RHESSys framework partitions a landscape into a hierarchical spatial structure with levels that are associated with different ecological and hydrological processes (Tague & Band, 2004). Each level is defined as a particular class type that has specific storage, flux, and default variables appropriate for that level. In this way, associated processes are simulated at the appropriate scale, so that photosynthesis takes place within canopy strata, soil nutrient cycling occurs within a patch, and water is routed between patches at the hillslope scale within a basin (Tague & Band, 2004). RHESSys includes a climate module adapted from MT-Clim that distributes input climate data according to variations in radiation and topography (Running et al., 1987). At the patch (30-m pixel in this study) level, an ecophysiological model adapted from BIOME-BGC (Running & Coughlan, 1988; Running & Hunt, 1993) estimates carbon, water, and nitrogen fluxes from different canopy cover types, whereas representation of soil organic matter and nutrient cycling is largely based on the CENTURY model (Parton et al., 1993; Parton et al., 1996). At the hillslope scale, the Distributed Hydrology Soil Vegetation Model (Wigmosta et al. 1994) distributes soil moisture laterally through topographic gradients within drainage areas on each side of a defined stream link. Detailed explanations of this model can be found in Tague and Band (2004). Inputs for RHESSys were prepared using *Ecohydrolib* (https://github.com/selimnairb/EcohydroLib) and *RHESSysWorkflows* (https://github.com/selimnairb/RHESSysWorkflows). *Ecohydrolib* includes tools to acquire and format data from publicly available databases (e.g., soils from NRCS Soil Survey Geographic Database, SSURGO; NLCD; elevation data from the USGS National Elevation dataset, NED), whereas *RHESSysWorkflows* translates these spatial datasets into parameter files required by the model (Miles, 2014). Ecophysiological and soil parameters were refined from previous studies in the Southern Appalachians (Hales, Ford, Hwang, Vose, & Band, 2009; Hwang, Band, & Hales, 2009; Hwang, Band, Vose, & Tague, 2012).

RHESSys requires estimates for the leaf out and senescence timing of deciduous species. As the climate warms, growing season length is increasing due to both earlier green-up and delayed senescence (Jeong, Ho, Gim, & Brown, 2011). Phenology data derived from long-term remote sensing data products, GIMMS NDVI 3 g (Pinzon &

TABLE 3 Evaluation of modeled water yield using NS efficiency of log-transformed daily water yield for the calibration (2011–2013) and validation (2008–2014) periods

	Calibration—daily		Validation—daily		Validation—weekly		Validation—monthly	
	Log NS	NS	Log NS	NS	Log NS	NS	Log NS	NS
Elk Creek	0.77	0.58	0.68	0.61	0.70	0.49	0.89	0.83
Rocky River	0.44	0.43	0.53	0.56	0.66	0.70	0.71	0.84
Mallard Creek	0.52	0.58	0.46	0.45	0.68	0.43	0.80	0.32

Note. NS = Nash–Sutcliffe.

Tucker, 2014), from the Upper Yadkin watershed including Elk Creek, suggest that from 1982 to 2009, spring green-up advanced 8 days, and autumn senescence was delayed by 11 days (T. Hwang, unpublished data). Phenological changes were assumed to continue at a comparable rate, and hence, leaf out was advanced 15 days in the spring, and senescence was delayed by 20 days in the autumn of 2060 compared to 2010.

2.7 | Model calibration

The hydrological module of RHESSys was calibrated using a Monte Carlo approach on seven key hydrological parameters: decay rate of saturated hydraulic conductivity with soil depth for both vertical and lateral dimensions, saturated hydraulic conductivity at soil surface (both vertical and lateral dimensions), soil depth, and two conceptual groundwater storage and release parameters: one controlling bypass flow from the soil surface directly into the linear groundwater store (representing macro-pores or preferential flows) and the other control the first-order release of water from deep groundwater storages to the stream (Tague & Band, 2004). Calibrations were performed using *RHESSysCalibrator* (https://github.com/selimnairb/RHESSysCalibrator), which uses a modular architecture to support Monte Carlo simulations in parallel, on the *KillDevil* computing cluster at the University of North Carolina at Chapel Hill. The period from January 2011 to October 2013 was used for calibration with a 2-year spin-up period to most align with the baseline LU layer in 2010. This period included years of normal, above average, and below average annual precipitation (1980–2014 mean annual precipitation: 1,172 ± 189 mm (*SD*), totals in 2011: 1,272 mm; 2012: 1,015 mm; and 2013: 1,508 mm). Model daily streamflow results were evaluated with the USGS stream gage records. Generalized Likelihood Uncertainty Estimation methodology was used to estimate model uncertainty in the prediction of future water availability (Beven & Binley, 1992; Freer, Beven, & Ambroise, 1996). Rather than use a single optimum parameter set, the top 100 parameter sets were selected as behavioral runs, which were then ranked to generate a cumulative distribution function from which the uncertainty bounds were selected. The Nash–Sutcliffe efficiency (NSE) of log-transformed daily water yield data (Nash &

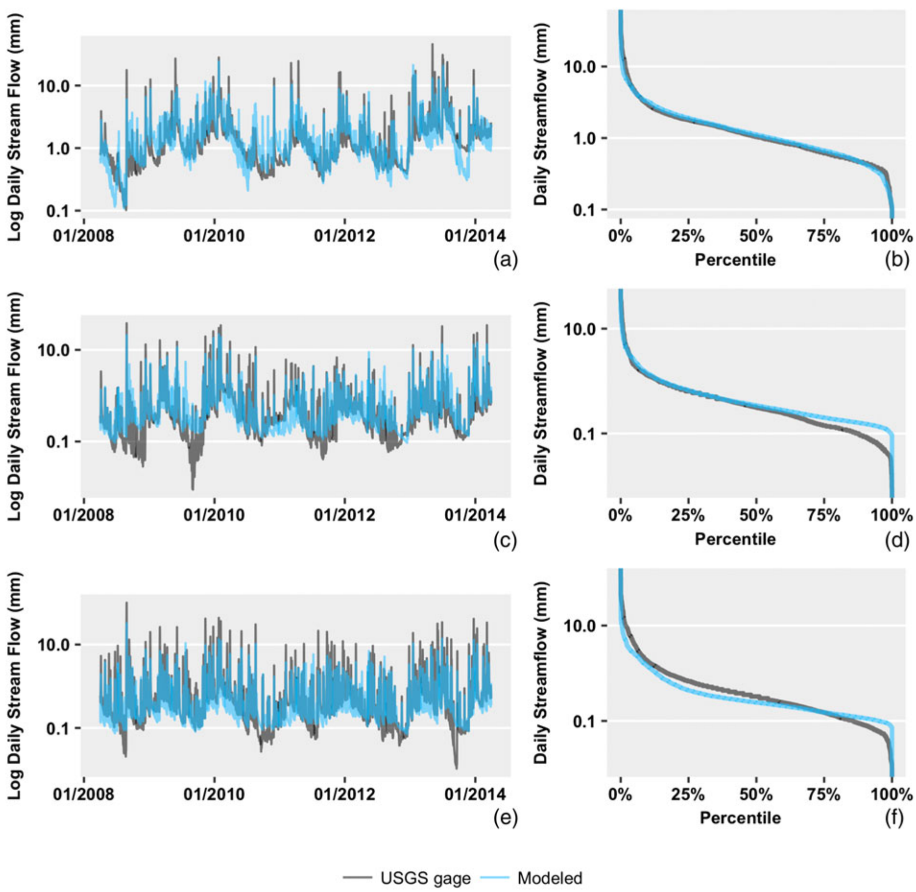

FIGURE 2 Modeled results for the 2008–2014 validation period compared to U.S. Geological Survey (USGS) stream gage data, shown as log daily streamflow (a, c, and e) and flow duration curves shown at log scale (b, d, and f) for Elk Creek (a and b), Rocky River (c and d), and Mallard Creek (e and f). Detailed model fit results appear in Table 2

Sutcliffe, 1970) was used as the likelihood measure. The selection processes using log-transformed daily water yield emphasizes model fit primarily on low flows because we were primarily interested in how climate and LU changes impact water yield during critical periods of surface water supply. In addition, low flows are also closely coupled with vegetation water use in this region (Hewlett & Hibbert, 1963), which is in turn determined by factors including climate and the extent of forest cover. Following calibration, model fit was validated from the 2008–2014 period. Calibration and validation model results are presented in Table 3. Validation results suggest RHESSys model results matched daily stream discharge records relatively well (log NSE >0.5; Beven & Binley, 1992; Freer et al., 1996), although simulated daily water yields were overestimated during the very low flows (<0.1 mm/day; Figure 2). Additionally, the model largely underestimated the peak flows in the predominantly urbanized watershed (Mallard Creek; Figure 2e,f). Although the model has been successfully applied to suburban watersheds in previous studies (Mittman et al., 2012; Shields & Tague, 2015), this underestimation might be due to lack of detailed data on rainfall intensity and storm drainage networks in our simulation, both of which would impact flow generation in this watershed.

2.8 | Simulations of future water yield

The calibrated model was further applied to assess the potential effects of scenarios of LU and CCs on water yield dynamics at each

TABLE 4 Modeled land use changes (percent change) from the 2010 model baseline to 2060 across the three study watersheds for four future scenarios

		Baseline	A	B	C	D
Elk Creek	Forest	94	−3	−4	−2	−2
	Agriculture	4	−1	−1	−1	−1
	Developed	2	+4	+5	+3	+3
Rocky River	Forest	55	−16	−27	−14	−27
	Agriculture	19	0	−3	−1	+1
	Developed	23	+18	+31	+16	+27
Mallard Creek	Forest	31	−11	−21	−12	−21
	Agriculture	5	+1	+1	+1	+1
	Developed	63	+11	+21	+12	+20

Note. Scenarios can be thought of as (A) moderate population and high income growth with high timber prices; (B) moderate population and high income growth with low timber prices; (C) low population and low income growth with high timber prices; and (D) low population and low income growth with low timber prices. Further details in Table 2.

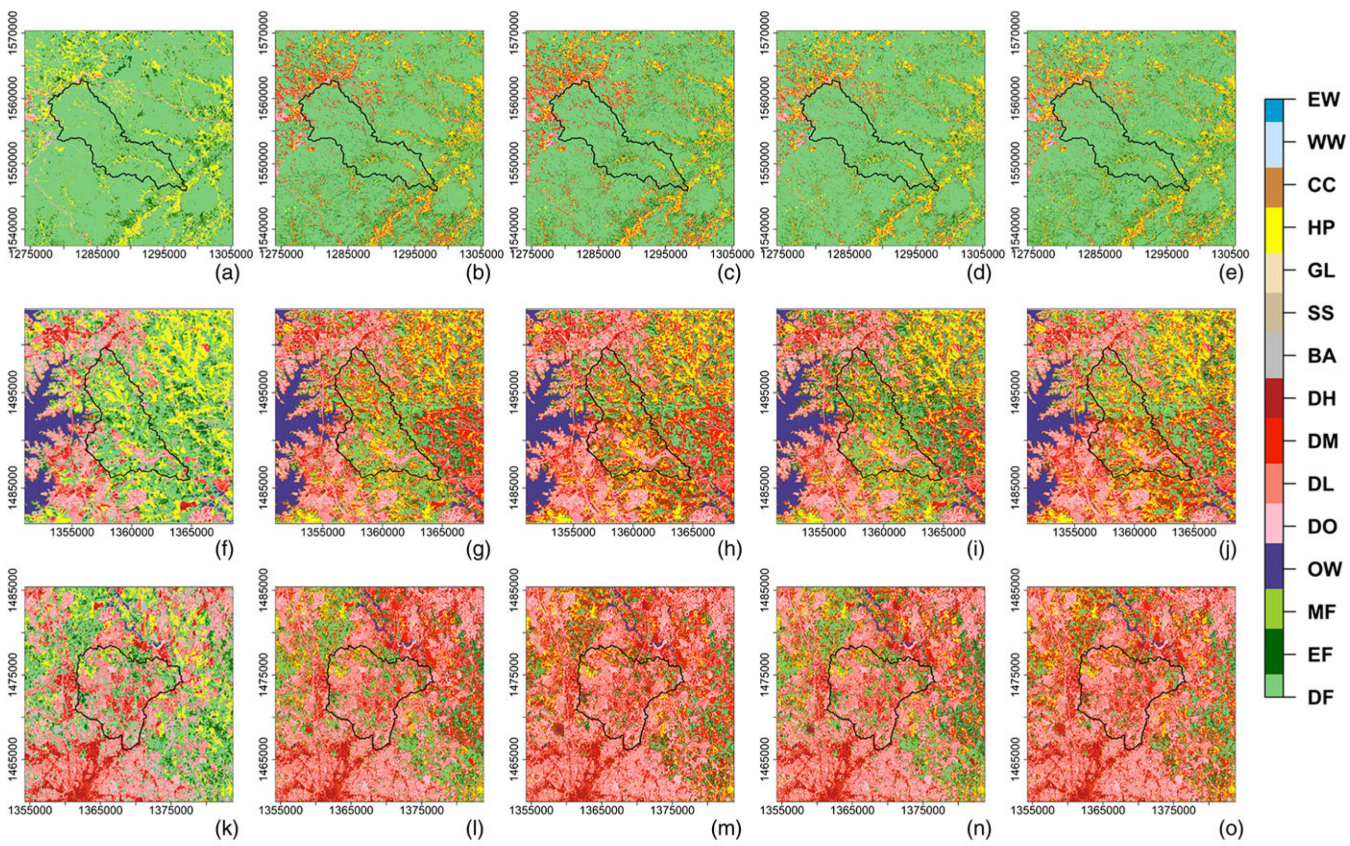

FIGURE 3 Baseline and projected (for 2060) land use results across the three study watersheds under four scenarios of change: (a) Elk Creek, baseline (2010); (b) Elk Creek, LU-A (MIROC + A1B); (c) Elk Creek, LU-B (CSIRO + A1B); (d) Elk Creek, LU-C (CSIRO + B2); (e) Elk Creek, LU-D (Hadley + B2); (f) Rocky River, baseline; (g–j) Rocky River watershed, baseline, LU-a, LU-B, LU-C, and LU-D; and (k–o) Mallard Creek, baseline, LU-A, LU-B, LU-C, and LU-D. Land cover is coded as BA = barren; CC = cultivated crops; DF = deciduous forest; DH = developed, high intensity; DL = developed, low intensity; DM = developed, medium intensity; DO = developed, open; EF = evergreen forest; EW = emergent wetlands; GL = grassland; HP = hay/pasture; MF = mixed forest; OW = open water; SS = schrub/shrub; WW = woody wetlands. Details of the degree of land use changes can be found in Table 3

of the three study watersheds. Future LU (2060) and climate (2051–2060) effects were first tested independently (LU-A, LU-B, LU-C, LU-D, CC-A, CC-B, CC-C, and CC-D) then the combination scenarios (LUCC-A, LUCC-B, LUCC-C, and LUCC-D) were run. All 12 scenario-based simulations were run with a 5-year spin-up period. In both the baseline and future projections, one LULC map input was used for the duration of the 10-year simulation. For LU-only scenarios, the baseline climate record (2001–2010) was used, and likewise, CC-only scenarios were run using the baseline LU layer (2010). Changes in water yield dynamics were assessed using monthly flow duration curves, highlighting changes in both high- and low-flow regimes. Monthly and annual water yield for the scenarios of change over the 2051–2060 simulation period were also examined to deconvolve the relative influence of simultaneous climate and LU changes on water yield.

3 | RESULTS

3.1 | Land use change model

LU characterization in the baseline model (Table 1), was similar to the land cover data from the NLCD. Elk Creek is a heavily forested watershed, categorized as 82% deciduous in the LU model, with an additional 3% evergreen and 8% mixed forest. The remaining LU was 4% hay/pasture and 2% developed. There was also a high level of agreement between NLCD and the baseline model in Rocky River (Table 1), a mixed-use watershed categorized as 38% deciduous forest, 11% evergreen forest, 19% hay/pasture, and 23% developed. At Rocky River, the LU model indicated 3% mixed forest compared to <1% mixed forest in NLCD. This is likely due to methodological differences in how the landscape is classified, that is, in the LU model, young forest is classified as forest, whereas in NLCD, canopy heights <5 m are assigned a non-forested land cover. The model also closely matched NLCD at the urban watershed (Table 1). Mallard Creek, categorized by the LU model as 65% developed, 20% deciduous forest, 8% evergreen forest, 3% mixed forest, and 5% hay/pasture.

The amount and direction of LU change from the baseline to the 2060 projections was highly variable across the study watersheds (Figure 3; Table 4). The mountainous Elk Creek watershed remained heavily forested (~90% forested) with little difference between the scenarios (conversion of 2–4% forest and 1% agriculture to developed LU). The Rocky River watershed, located just outside the metropolitan areas of Charlotte and Kannapolis, NC, in the Piedmont, will experience the greatest LU transition in the projections. Timber prices likely had a strong influence on projected forest conversion in the Rocky River watershed, as the greatest conversion of forest (27%) occurred in scenarios of decreasing timber prices (LU-B and LU-D) despite different economic and population storylines. Forest conversion was more moderate under LU-A and LU-C scenarios (16% and 14%, respectively) where timber prices were projected to increase. Furthermore, the loss of forested LU was reflected in a roughly equivalent gain in developed LU (16–31%), with some minor conversion of agriculture (3%) in LU-B. The heavily developed Mallard Creek watershed was

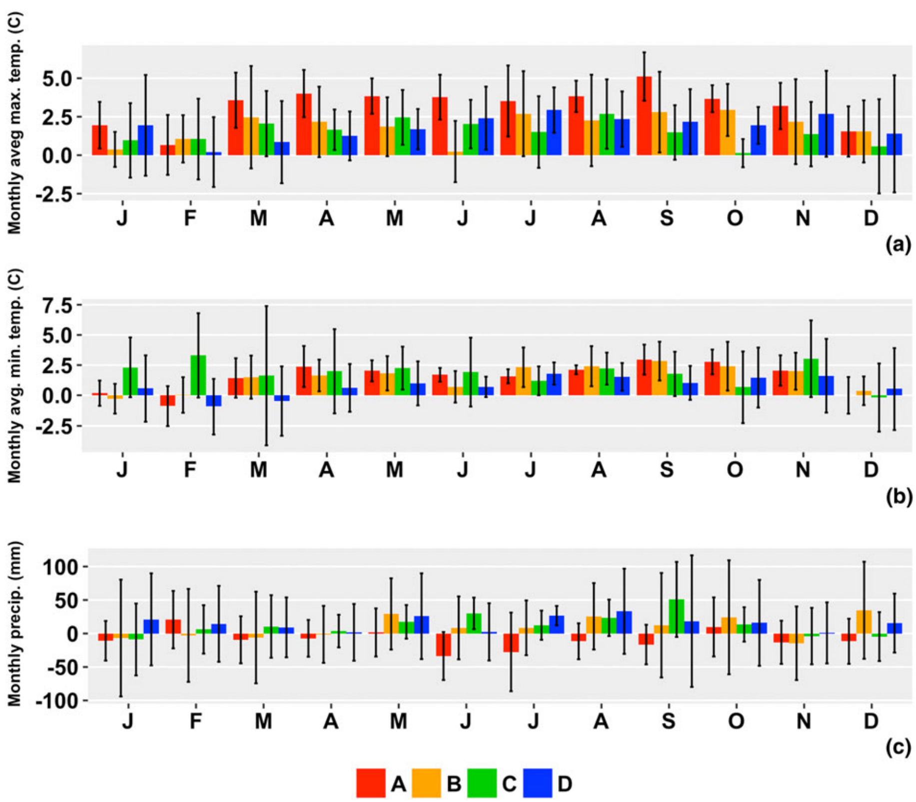

FIGURE 4 Changes in climate from 2055 to 2060 for four scenarios (A, B, C, and D), compared to monthly average climate from Daymet climate data 1980–2014, averaged across three study watersheds. Scenarios can be thought of as (a) moderate population and high income growth with high timber prices; (b) moderate population and high income growth with low timber prices; (c) low population and low income growth with high timber prices; and (d) low population and low income growth with low timber prices. Further details in Table 2

projected to experience a further loss of 11–21% of forested LU. This was also influenced by decreasing timber prices, as forest conversion was more moderate with increasing timber prices (11–12% in LU-A and LU-C) and greater under scenarios of decreasing timber prices (27% under LU-B and LU-D). All scenarios included an increase of 1% in agriculture in the Mallard Creek watershed, but the remaining transition of forest LU was to developed (11–21%).

3.2 | Climate change

When compared to the climate averages over 1980–2014, climate projections for 2051–2060 indicate a generally warmer future across all the study watersheds in terms of both maximum and minimum temperatures (Figure 4). Greater increases occurred in maximum and minimum temperatures during the approximate growing season (March–November) compared to the winter (December–February). Monthly maximum temperatures increased more under CC-A, but there was not clear separation between CC-B, CC-C, and CC-D for maximum temperatures or any of the projected changes in minimum temperatures. Precipitation also trended higher compared to the 1980–2014 monthly averages under CC-B, CC-C, and CC-D, but like changes in temperature, varied by month (Figure 4c). On an annual basis, precipitation increased most under CC-B 1,327 ± 114 (*SD*) and CC-D 1,367 ± 255 mm but also increased under CC-C, 1,289 ± 170 mm (*SD*), compared to mean annual precipitation of 1,177 ± 187 mm (*SD*) from 1980 to 2014. CC-A suggests a drier future, with mean annual precipitation 1,068 ± 173 mm (*SD*).

3.3 | Respective and combined modeled effects of land use and climate changes on water yield

LU change effects on water yield varied by watershed (Table 5). Effects were minimal for the Elk Creek watershed (<4-mm change in average annual water yield under all scenarios), which remained >90% forested in all future scenarios (Figure 5a–d). In Rocky River, all LU change scenarios, where forested LU was converted to developed, increased water yield, particularly high flows (Figure 5e–h). All future scenarios were more variable, particularly at high flows, as indicated by the wide uncertainty boundaries for high flows. LU-B (i.e., a future of high population growth, high income growth, and low timber prices) resulted in

TABLE 5 Difference monthly and annual streamflow between baseline (2001–2010) and four scenarios of land use change (2060), climate change (2051–2060), and simultaneous land use and climate change across three watersheds

			J	F	M	A	M	J	J	A	S	O	N	D	Annual	Annual (mm)
Land use change	A	Elk	−1	−1	−1	−1	0	0	0	0	0	0	−1	−1	−1	−2.64
		Rocky	26	20	28	31	38	31	37	28	37	41	51	36	43	62.10
		Mallard	5	4	4	6	12	9	8	7	7	9	9	5	7	10.06
	B	Elk	−1	−1	−1	−1	0	0	0	0	0	0	−1	−1	−1	−3.31
		Rocky	74	62	74	74	83	87	105	84	95	101	111	91	94	135.76
		Mallard	28	31	34	34	47	55	50	45	43	32	41	39	40	59.11
	C	Elk	0	0	0	0	0	0	0	0	0	0	0	0	0	−0.07
		Rocky	52	42	51	50	51	44	50	43	50	45	72	61	55	79.77
		Mallard	7	6	6	8	14	12	11	10	10	11	12	8	9	13.71
	D	Elk	−1	−1	0	0	0	0	0	0	0	0	0	−1	0	−0.97
		Rocky	40	31	42	43	51	50	60	47	57	62	70	53	48	68.89
		Mallard	14	12	13	15	24	25	25	23	22	24	22	17	19	28.86
Climate change	A	Elk	−25	15	1	2	9	−29	−39	−21	−31	−17	−23	−30	−16	−72.54
		Rocky	42	148	110	125	148	−5	−15	11	3	61	38	36	61	88.08
		Mallard	32	64	22	1	9	−16	−6	−16	−35	6	2	8	6	8.52
	B	Elk	22	81	23	2	42	23	28	87	75	107	15	27	41	188.89
		Rocky	180	186	114	49	103	68	7	34	43	130	95	132	97	140.04
		Mallard	109	99	61	16	59	37	40	47	11	66	18	77	53	79.06
	C	Elk	−8	47	49	23	53	57	25	76	62	134	42	6	43	195.75
		Rocky	261	319	275	250	202	116	81	183	338	300	163	141	220	316.16
		Mallard	78	111	108	55	35	35	43	66	47	85	20	6	58	85.85
	D	Elk	28	67	45	21	73	19	28	41	77	106	15	−7	40	184.27
		Rocky	392	291	248	255	384	116	89	120	330	277	146	168	235	337.79
		Mallard	123	119	100	35	73	24	41	72	55	82	27	36	66	97.63
Land use and climate change	A	Elk	−26	14	−2	1	9	−29	39	−21	−31	−17	−24	−31	−16	−74.96
		Rocky	80	194	125	142	198	29	21	65	46	143	87	68	100	143.46
		Mallard	32	62	19	−2	10	−12	−3	−13	−31	11	3	8	7	10.00
	B	Elk	20	78	21	2	42	22	27	84	72	104	13	25	39	181.58
		Rocky	218	202	123	75	215	144	96	128	122	250	144	202	156	225.33
		Mallard	111	87	55	17	84	62	67	66	28	93	31	84	64	95.67
	C	Elk	−8	47	49	22	53	57	25	75	62	133	41	5	42	193.06
		Rocky	257	309	265	242	258	182	134	242	405	367	195	148	246	353.92
		Mallard	76	104	99	49	45	46	54	72	56	97	25	7	61	90.44
	D	Elk	27	66	45	21	73	19	28	40	76	104	14	−8	39	180.85
		Rocky	388	277	226	238	399	172	168	194	374	326	188	175	256	368.02
		Mallard	114	104	80	25	77	42	64	88	72	93	32	37	68	101.86

Note. Monthly values are reported in percentages and annual values in both percentage and mm.

the greatest increase in water yield in Rocky River, with an average annual increase of 135.8 mm (94%; Table 5). High flows (highest 10 percentiles) increased the most under LU-B, by an average of 29.2 mm (88%) and the least under LU-A (average of 12.1 mm or 37%). LU-A and LU-D had similar effects on high and low (lowest 10 percentiles) flows. Under LU-A, high flows increased an average of 12.1 mm (37%) and low flows increased 0.9 mm (29%), whereas under LU-D, high flows increased 14.6 mm (44%) and low flows increased 1.2 mm (37%); LU-C had greater effects on high flows (average 19.6-mm increase, 59%) than on low flows (0.7-mm increase, 23%). LU change in the Mallard Creek watershed resulted in very moderate increases in water yield (10- to 59-mm increase in average annual water yield; Table 5), which were most prominent under LU-B (Figure 5j; high flow increase of 14.2 mm or 45% and low flow increase of 1.1 mm or 27%) and LU-D (Figure 5l; high flow increase of 5.4 mm or 45% and low flow increase of 1.2 mm or 27%).

Compared to the LU change, the effects of CC were greater and more variable across all watersheds (Figure 6). CC-A, which represents a hot, dry future, resulted in water yields that were at times below the baselines across the watersheds. At Elk Creek, CC-A resulted in a 16% reduction in average annual water yield (−73 mm; Table 5), which was characterized by reduced high flows (average reduction 28.4 mm or 29%) but similar low flows (+0.4 mm, 4%). Results were similar at Mallard Creek, where high flows were slightly reduced (−4.0-mm decrease, −13%) and low flows that were slightly increased (1.0-mm increase, 25%), and overall, average annual water yield increased slightly (9 mm or 6%; Table 5). In Rocky River, CC-A resulted in water yields that were higher than the baseline scenario (average annual water yield +61% or 88 mm; Table 5), due to increased high flows (61% or 20.2 mm). The remaining scenarios (B–D) all resulted in increased water yields relative to baseline (Table 5). The highest high flows occurred under CC-B and CC-D, which increased at Elk Creek by 49% and 47% (47.5 and 45.8 mm), respectively, 149% and 267% (49.5 and 88.6 mm) at Rocky River, and 54% and 68% (17.2 and 21.5 mm) at Mallard Creek. CC–C resulted in the greatest increase in low flows across all watersheds; at Elk Creek, there was a 180% (18.7 mm) increase; at Rocky River, where there was a 294% (9.1 mm) increase; and at Mallard Creek a 123% (5.2 mm) increase. CC-B had similar effects to CC-D in Elk Creek (increase of 189–184 mm or 41–40% in average annual water yield, respectively) and Mallard Creek (respective increase of 79–97 mm or 53–66% in average annual water yield). For Rocky River, CC-B had a similar effect to CC-C at high flows (49.5-mm increase under CC-B compared to 60.4-mm increase under CC-C) but was more similar to CC-A at low flows (1.2-mm increase CC-B and 2.0-mm increase CC-A), so that overall, water yield increases were more moderate under CC-B (140 mm or 97% increase in average annual water yield) than CC-C (316 mm or 220% increase in average annual water yield) or CC-D (338 mm or 235% increase in average annual water yield).

Results from the combined LUCC scenarios resulted in similar effects to the CC-only scenarios in both the heavily forested Elk Creek and the predominantly developed Mallard Creek watersheds (Figure 7; Table 5). In Elk Creek, there was almost no difference between the combined effect LUCC- and the CC-alone scenarios at either high or low flows; all differences were within 2%. At Mallard Creek, results were also similar for high flows (less than a 3.5-mm increase for all scenarios), but the combined effects of LUCC increased base flows slightly more than CC alone, particularly in scenarios LUCC-B (increase of 2.2 mm or 53% LUCC-B compared to 1.3 mm or 32% increase under CC-B) and LUCC-D (increase of 4.0 mm or 94% under LUCC-

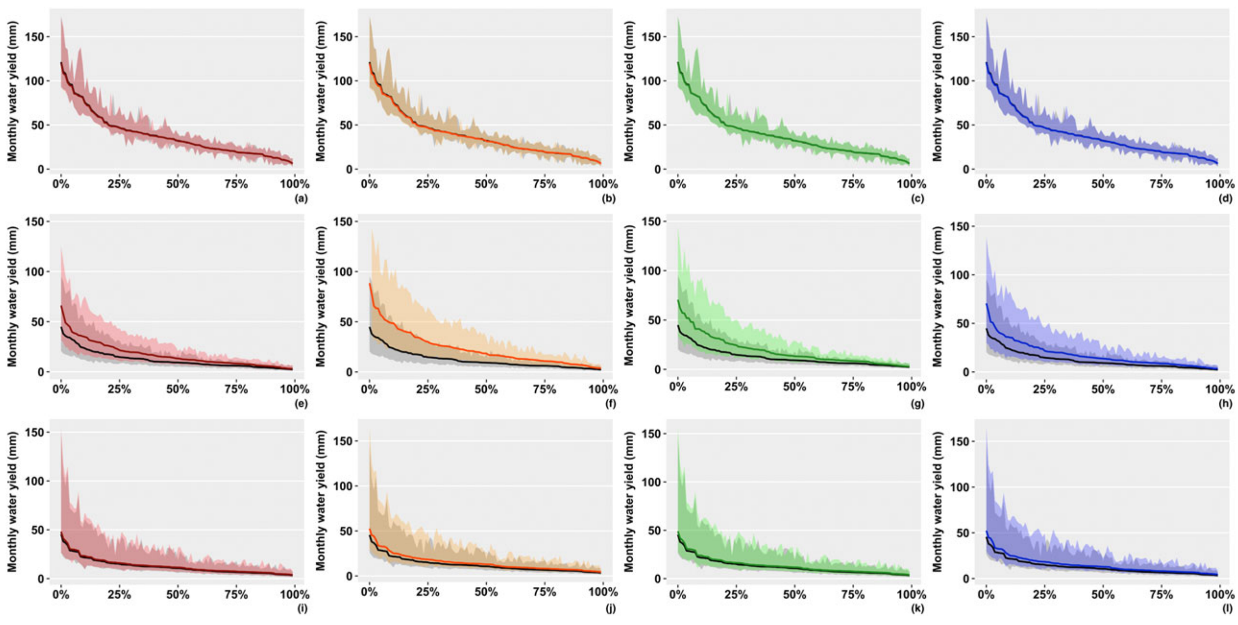

FIGURE 5 Flow duration curves under baseline (black) and land use change scenarios (LU-A: red, LU-B: orange, LU-C: green, and LU-D: blue) for 2060. Curves represent the median of 100 behavioral model runs and shading bounds the 95% confidence intervals determined by Generalized Likelihood Uncertainty Estimation. Each watershed is represented by four horizontal panels, representing Scenarios A–D, including (a–d) Elk Creek, primarily forested; (e–h) Rocky River watershed, exurban; and (i–l) Mallard Creek, urban. Details of land use change can be found in Table 3. Further details of future scenarios are detailed in Table 2

D compared to a 3.0 mm or 70% increase under CC-D). In the mixed LU watershed, Rocky River, the combined effects of LUCC increased high flows slightly when compared to CC only, with the greatest increase under Scenario B (increase of 55.3 mm or 166% for LUCC-B compared to an increase of 49.5 mm or 149% for CC-B; Figure 7 e–h). The combined LUCC had more of an effect on low flows when compared to CC alone. Changes in low flows were greatest in LUCC-C (12.4 mm or 402%) and LUCC-D (6.4 mm or 208%). Aggregated to annual water yield, results further indicate little difference between the effects of CC and LUCC at Elk Creek and Mallard Creek, but the beginnings of a separation of CC and LUCC effects at Rocky River, particularly for scenarios of high LU change (Figure 8). Annual water yield particularly increased under scenarios LUCC-B (average increase 225.3 mm or 156%) compared to CC-B (average increase 140.0 mm or 97%) and LUCC-A (average increase 143.5 mm or 100%) compared to CC-A (average increase 88.1 mm or 61%).

4 | DISCUSSION

A key challenge for deconvolving the relative impacts of climate and LU changes and their interactions has been an inability to project future LU in a rational and robust way, particularly at spatial scales relevant to ecosystem processes, watershed management, and water supply management (Sun & Vose, 2016). The LU model developed as a part of this study represents a significant advancement for evaluating the potential consequences of the combined effects of climate and LU changes at scales necessary to inform policy and management decision-making. In addition, our study highlights several key points for future water yield and in turn, water resource availability in the study region. Although previous studies (Lockaby et al., 2013; Sun & Caldwell, 2015; Sun, Caldwell, & McNulty, 2015) suggest that the Southeast will be affected by a continuation or acceleration of the conversion of forest to urban LU and by CCs, our study indicates that it is less clear how these changes will be spatially and temporally distributed within and across watersheds and how these fine-scale changes impact total water yield. Consistent with other studies in the region (Caldwell et al., 2012; Lockaby et al., 2013; Sun et al., 2008), our results indicate that CC will be more influential on future water yield than changes in LULC and that the effects of development on hydrologic processes may show threshold behavior; however, our results suggest that responses are highly dependent on fine-scale LU patterns that have not been accounted for in previous modeling studies. For example, we found that even a moderate amount of conversion of forest to developed use in a mixed-use watershed had a large effect on water yield dynamics. From 2010 to 2060, the primary change in LU was the conversion of forest to developed LU in the mixed-use Rocky River watershed. In contrast, forest to developed conversion had minimal effects in the already heavily urbanized Mallard Creek. Further, the combined effects of LU and CCs were very similar to the climate-only scenarios across the Elk Creek and Mallard Creek watersheds, indicating the dominant role of CC in both forested and highly developed watersheds. In the Rocky River watershed, the combined effects of LU and CCs resulted in higher water yields than the climate-only scenario, particularly in A-LUCC and B-LUCC but less so in C-LUCC and D-LUCC. Hence, by combining a fine-scale LU change model that included social economic drivers and statistically downscaled climate scenarios, we were able to identify changes in watershed hydrology at scales relevant for local water supply management. For example, the metropolitan area of Charlotte, NC, is

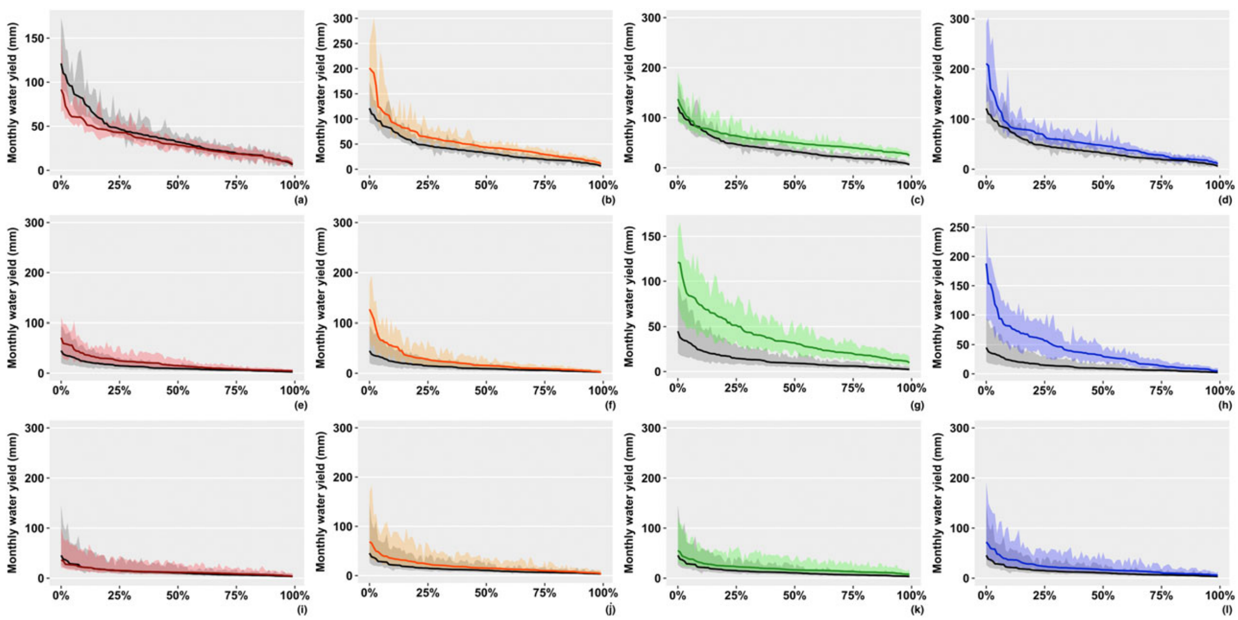

FIGURE 6 Flow duration curves under baseline (black) and climate change scenarios (CC-A: red, CC-B: orange, CC-C: green, and CC-D: blue) for 2060. Curves represent the median of 100 behavioral model runs and shading bounds the 95% confidence intervals determined by Generalized Likelihood Uncertainty Estimation. Each watershed is represented by four horizontal panels, representing Scenarios A–D, including (a–d) Elk Creek, primarily forested; (e–h) Rocky River watershed, exurban; and (i–l) Mallard Creek, urban. Details of land use change can be found in Table 3. Further details of future scenarios are detailed in Table 2

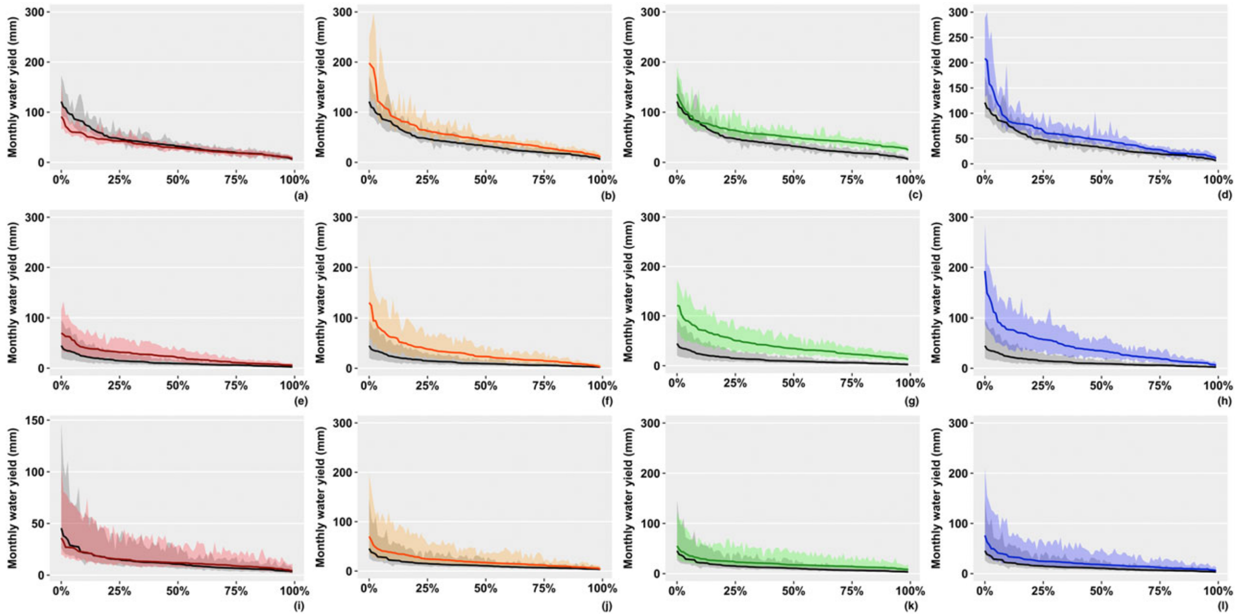

FIGURE 7 Flow duration curves under baseline (black) and scenarios of combined land use and climate changes (LUCC-A: red, LUCC-B: orange, LUCC-C: green, and LUCC-D: blue) for 2060. Curves represent the median of 100 behavioral model runs and shading bounds the 95% confidence intervals determined by Generalized Likelihood Uncertainty Estimation. Each watershed is represented by four horizontal panels, representing Scenarios A–D, including (a–d) Elk Creek, primarily forested; (e–h) Rocky River watershed, exurban; and (i–l) Mallard Creek, urban. Details of land use change can be found in Table 3. Further details of future scenarios are detailed in Table 2

8,280 km^2, spread across four Hydrologic Unit Code (HUC) 8 watersheds. The Rocky River and Mallard Creek watersheds are part of the same HUC 8 watershed, but we found they were subject to different levels of changes in climate and LULC and thus responded quite differently. At the HUC 8 or larger scales, it is unlikely the strong regional dependence of LU change at Rocky River would have been identified (Figure 1).

It should be noted that many of the differences in water yield projections between future scenarios are heavily influenced by precipitation patterns. Because projections of future precipitation are among the most uncertain aspects of climate modeling, caution should be taken in evaluating model projections that apply CC scenarios in absolute terms. Although our study suggests that more water might be available in the future during some years, water managers should also anticipate periods of reduced water availability in drought years. Many of the forecasts, including the National Climate Assessment, suggest the Southeast will experience increasing water stress (Carter et al., 2014). For example, if future precipitation across the region decreases, in accordance with some projections (McNulty et al., 2013; Sun et al., 2008), climate is likely to have very different effects on watershed hydrology and might become increasingly dependent upon the interactions among LU change and vegetation responses. In our case, the reductions in precipitation under Scenario A might not have been sufficiently severe or sustained to cause great changes at mid-century but could become increasingly influential over time. It is possible that in a future of reduced precipitation, LU conversion might reduce vegetation water use and thus have a mitigative effect on overall water availability (Ford, Laseter, Swank, & Vose, 2011). However, this study suggests this is unlikely except in areas of where the degree of LU conversion results in a threshold effect, thought to be when total imperious surface cover exceeds approximately 20% across the watershed (Wang et al., 2001; Sun & Caldwell, 2015; Walsh, Fletcher, et al., 2005; Walsh, Roy et al., 2005). At the same time, if precipitation events become more intense (higher rainfall intensity), as predicted by climate projections and consistent with available observations (Groisman et al., 2005; Min, Zhang, Zwiers, & Hegerl, 2011; Trenberth, Dai, Rasmussen, & Parsons, 2003; Zhou et al., 2011), the negative effects of urban development and increases in impervious surface cover are likely to increase. Combined futures of extreme precipitation and increases in impervious surface cover would likely increase high flows and decrease low flows, resulting in flashier hydrographs, greater erosion, and declining water quality (Lockaby et al., 2013). Our study did not indicate lower base flows. This might be due to conservative estimates of impervious surface cover or an inability of the groundwater component of RHESSys to simulate low dynamics. Finally, our study did not include estimates of anthropogenic water use, which will increase with population increases. At the current time, we did not find any data indicating that the watersheds used in this study are sources for significant water withdrawals. However, overall water stress could increase regionally as water use increases, even if some portions of the watershed do not reflect this.

Our findings that LU change was particularly influential in a mixed LU watershed is especially important for identifying areas where hydrologic responses are most sensitive to LU change. Although CC is a global phenomenon, LU change is local and thus presents options for mitigation. The model development scenarios used a spatial pattern based on a continuation of historic urban growth. However, there are opportunities to apply different future growth scenarios and to inform LU strategies to reduce the impacts of development. Oftentimes, low

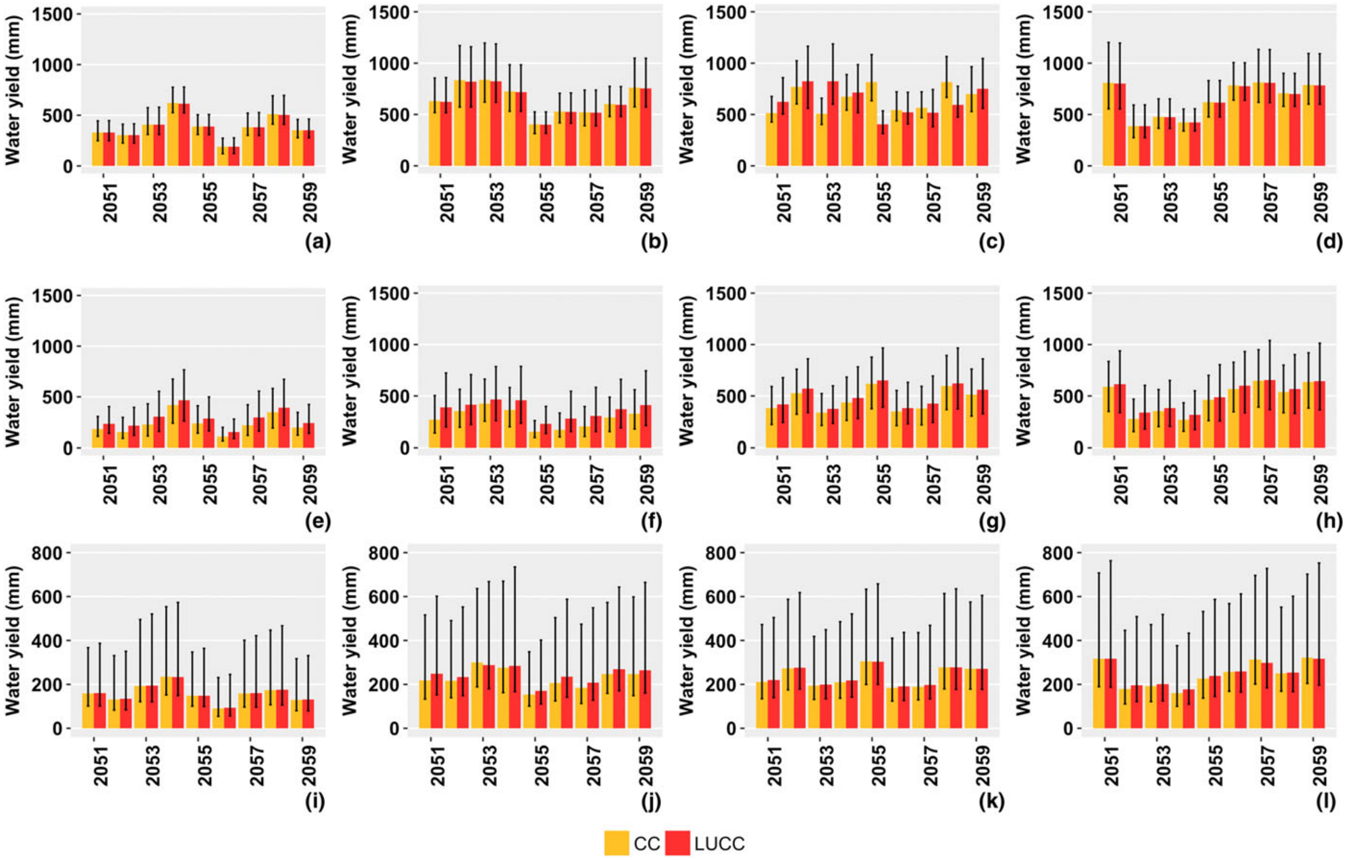

FIGURE 8 Annual water yield under four scenarios of climate change (CC) only and combined land use and climate change (LUCC) at the three study watersheds: (a) Elk Creek, Scenario A; (b) Elk Creek, Scenario B; (c) Elk Creek, Scenario C; (d) Elk Creek, Scenario D; (e) Rocky River, Scenario A; (f) Rocky River, Scenario B; (g) Rocky River, Scenario C; (h) Rocky River, Scenario D; (i) Mallard Creek, Scenario A; (j) Mallard Creek, Scenario B; (k) Mallard Creek, Scenario C; and (l) Mallard Creek, Scenario D. Scenarios can be thought of as (A) moderate population and high income growth with high timber prices; (B) moderate population and high income growth with low timber prices; (C) low population and low income growth with high timber prices; and (D) low population and low income growth with low timber prices. Further details in Table 2

impact development strategies are implemented opportunistically (Elliott & Trowsdale, 2007; Martin-Mikle, de Beurs, Julian, & Mayer, 2015), but this study suggests prioritizing areas of expected high change might be more beneficial than areas where urban development is already intense and thus exceeded a threshold. Furthermore, if large areas of forest remain on the landscape, they can be managed to mitigate undesirable future conditions, for example, thinning forests to increase water yields (Douglass, 1983; Ford et al., 2011; Sun et al., 2015). The high-resolution LU change model leveraging the FIA database provided greater details and accuracy about the spatial extent of forests. Importantly, the model suggests that forested land cover is likely to remain stable in the critical mountain headwater areas of the Yadkin–Pee Dee Basin, but that change is highly responsive to timber prices in the Piedmont. This knowledge suggests that future studies could test scenarios of forest management and conservation programs across the landscape. For example, conservation programs might mitigate the influence of global market fluctuations on the extent of forested land most effectively in the Piedmont, whereas forest management to increase water yield might be more effective in the Mountains.

We recommend that strategies for watershed management are more likely to be successful if they adopt risk-based assessments of a range of future senarios and include regular updating (Golladay et al., 2016). It is likely that the simultaneous effects of LULC and CCs will impact critical water supplies before many of the model uncertainties, particularly for precipitation projections, will be resolved; therefore, planning will need to incorporate risk (Vose, Martin, & Barten, in press). The complexities of LU and CCs are likely to result in a range of possible futures across ecosystem processes, including productivity, carbon, and nutrient cycling, as vegetation responds to multiple factors of change and increased variability. For example, leaf area index and thus vegetation water use might increase in response to increased growing season length and increased atmospheric CO_2 concentration but might also decrease during periods of drought (Ainsworth & Rogers, 2007; Angert et al., 2005; Ford et al., 2011; Gedney et al., 2006; Jeong et al., 2011; Novick et al., 2015).

Changes in LU and climate scenarios that are relatively straightforward in summary had complex effects on total and seasonal hydrologic behavior in this study. Although future scenarios are often selected to bracket high and low changes in atmospheric CO_2 concentration and thus temperature, precipitation is more complex and uncertain. At the same time, precipitation is a key component of hydrological processes and subsequent ecosystem responses, including vegetation productivity. In light of the uncertainty of future change, the inclusion of more extreme possible futures might be illustrative. Three of the four climate futures selected for this study suggest a wetter future at midcentury (2051–2060), but the interactions of LU and a future of more severely reduced precipitation could indicate different interactions. Similarly, our assignments of future development intensity were somewhat conservative. More extreme development futures that result in greater loss of forest and an increase in impervious cover would further synchronize precipitation and water yield responses due to a reduction in forest water absorption and storage.

5 | CONCLUSION

Overall, this study emphasizes the importance of integrated modeling efforts for the prediction of future water resources, including LULC, CC, forest dynamics, and hydrological processes under a unified modeling framework. The full range of possible futures is difficult to capture all in one analysis. However, the inclusion of LU change, CC, and the combined effects across four scenarios of the future and three watersheds representative of conditions across the landscape allows us to identify areas where impacts may be greatest and prioritize management and policy responses to mitigate or prevent undesirable outcomes. Although CC occurs over broad scales due to complex global processes, there are opportunities to (a) manage the magnitude and spatial pattern of LU change, (b) manage rural, forested areas for CC adaptation and mitigation, and (c) incentivize forest conservation to prevent threshold effects in urbanizing watersheds.

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