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Riparian buffers increase future baseflow and reduce peakflows in a developing watershed

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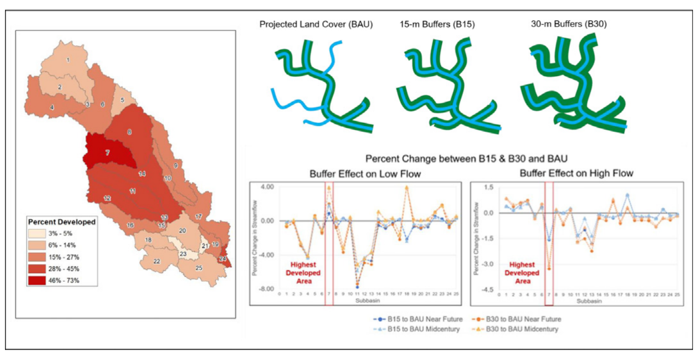
HIGHLIGHTS

- Riparian buffer treatments were tested across an urbanizing watershed.
- Streamflow was simulated under baseline (2000–2018) & future (2021–2060) periods.
- Simulations indicate a 4 % increase in frequency of high flow events to 2060.
- Buffer treatments dampen high flows in areas with the highest levels of development
- Buffers treatments also increase flow during low flow events in developed areas.

GRAPHICAL ABSTRACT



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ABSTRACT

Land conversion and climate change are stressing freshwater resources. Riparian areas, streamside vegetation/forest land, are critical for regulating hydrologic processes and riparian buffers are used as adaptive management strategies for mitigating land conversion effects. However, our ability to anticipate the efficacy of current and alternative riparian buffers under changing conditions remains limited. To address this information gap, we simulated hydrologic responses for different levels of buffer protection under a future scenario of land/climate change through the year 2060. We used the Soil and Water Assessment Tool (SWAT) to project future streamflow in the Upper Neuse River watershed in North Carolina, USA. We tested the capacity of riparian buffers to mitigate the effects of future land use and climate change on daily mean streamflow under three buffer treatments: present buffer widths and fully forested 15 m and 30 m buffers throughout the basin. The treatments were tested using a combination of a future climate change scenario and landcover projections that indicated a doubling of low-intensity development between 2017 and 2060. In areas with >50 % development, the 30 m buffers were particularly effective at increasing average daily streamflow during the lowest flow events by 4 % and decreasing flow during highest flow events by 3 % compared to no buffer protection. In areas between 20 and 50 % development, both 15 m and 30 m buffers reduced low flow by 8 % with minimal effects on high flow. Results indicate that standardized buffers might be more effective at a local scale with further research needing to focus on strategic buffer placement at the watershed scale. These findings highlight a

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novel approach for integrating buffers into hydrologic modeling and potential for improved methodology. Understanding the effects of riparian buffers on streamflow is crucial given the pressing need to develop innovative strategies that promote the conservation of invaluable ecosystem services.

1. Introduction

Urban land cover is expected to expand rapidly around the globe until at least mid-century (2040) across an envelope of possible socioeconomic futures, and 30–44 % of this new urban land will replace forest land cover (Chen et al., 2020). In the conterminous United States (CONUS), nearly half of the land cover changes between 2001 and 2016 occurred on forested land, and most of this was conversion to developed land (Homer et al., 2020). This shift represents a significant environmental change as forests provide the most stable water resources (Brown et al., 2005a; Ford et al., 2011; Sun et al., 2015) by acting as natural filters to improve water quality, supplying clean water for both aquatic habitat and human use (Lockaby et al., 2013; Sedell et al., 2000; Yazdi et al., 2021), and providing flood mitigation (Bradshaw et al., 2007; Tockner and Stanford, 2002). About 50 % of available water yield originates on forest land in the CONUS, supplying at least half of the surface water supply to 60 million people (Liu et al., 2021). The conversion of forest to developed land cover disrupts ecosystem services, decreases water quality, reduces critical habitat, and increases flood hazards over time (Caldwell et al., 2012; Delphin et al., 2016; Nelson et al., 2009). Climate change can further magnify the effects of land cover conversion on water resources (Caldwell et al., 2012; Martin et al., 2017; Miller and Hutchins, 2017) as it intensifies the global hydrologic cycle, resulting in more infrequent yet more intense precipitation events (O'Gorman and Schneider, 2009). The synergistic effects of land use and climate change cause increases in runoff, flashier streams, and flooding, while decreasing baseflows as dry periods lengthen and less precipitation percolates into the soil (Caldwell et al., 2012).

In watersheds where maintaining widespread forest land cover is an impracticable option, the conservation or restoration of streamside vegetation in riparian areas can support watershed function and ecosystem services (Riis et al., 2020). Riparian buffers are the resulting management strategy from this streamside conversion or restoration and are commonly defined as fixed-width areas immediately adjacent to streams measuring in the direction from the stream edge inland. Although depending on the size of the channel and position in the watershed, fixed-width streamside buffers may include portions of the ecosystem beyond the ecological riparian zone, or might exclude some areas of critical groundwater exchange (Kuglerova et al., 2014). Environmental managers and decision-makers have long used riparian buffers to mitigate the effects of anthropogenic activities across the watershed and provide stability to aquatic ecosystems (Blinn and Kilgore, 2001; Grace, 2005; Matteo et al., 2006; Naiman and Decamps, 1997). Riparian corridors can also foster ecological flows, i.e. the ecological integrity of the aquatic system, which have been progressively compromised by altered flow regimes from dams (Kuriqi et al., 2021), rapid land conversion, and increased water withdrawals (Hain et al., 2018). The economic, environmental, and social values that riparian buffers provide are widely recognized, especially regarding water quality protection (Lowrance et al., 1997; Orzetti et al., 2010).

The capacity of riparian buffers to minimize impacts on water resources under global change is a complex, pressing issue in watershed science and management (Riis et al., 2020). Growing areas have implemented riparian buffer mandates with the objective that riparian conservation and restoration will help mitigate the anthropogenic effects of development and land conversion on water resources. However, it is unclear if riparian buffers in isolation can attenuate the exacerbated effects of changing conditions. Specifically, the ability to anticipate the effectiveness of riparian buffers in mitigating the continued effects of urbanization and the extremes of precipitation expected under climate change remains limited. To address this knowledge gap, we examined the rapidly urbanizing Upper Neuse watershed in the Piedmont physiographic region of North Carolina, USA which supplies water to over 510,000 people (Allen et al., 2015). We first investigated climate and land use projections across the watershed and used these future conditions to compare the resulting future watershed hydrology (2021–2060) to a 2000–2018 Baseline period. *Our central objective was to quantify how streamflow may change in response to future climate and land use, and to examine how riparian buffers may effectively mitigate these changes*. We hypothesized that 1) extreme low flows will decrease and extreme high flows will increase, particularly in the most urbanizing watersheds, which will lead to more frequent and larger flooding events; and 2) riparian buffer protection can mitigate the effects of future conditions on streamflow across watersheds, increasing flow during low flows and decreasing flow during high flows, particularly in urbanizing watersheds. These hypotheses were tested by examining predicted future changes in average daily, extreme low, and extreme high flow portions of the hydrographs under three buffer scenarios including 1) no buffers, 2) 15 m (approximately 50 ft), and 3) 30 m (approximately 100 ft). This research aims to assess riparian buffer effectiveness under changing conditions, provide a replicable framework for hydrologic ecosystem service evaluation, and discuss the potential for an improved methodology.

2. Methods

2.1. Study watershed

The 6231 km^2 Upper Neuse River basin (Fig. 1) was selected as the study watershed due to its importance as a regional water supply, rapid expansion of urban land cover, and prevalence of riparian buffer mitigation efforts (Lebo et al., 2012). The Upper Neuse is classified as a USGS 8-digit watershed, equivalent to a medium-sized river basin. The Upper Neuse includes the headwaters of the Neuse River, which flows from the Piedmont physiographic region, through the Coastal Plain, and into the Pamlico Sound.

We used the 2011 National Land Cover Dataset (NLCD) (Homer et al., 2015) as the baseline for our study (see supplemental information for full list of acronyms). Resulting land cover in the watershed was 38 % forested, 21 % developed, 24 % pasture and cultivated crops, and 11 % woody wetlands (Homer et al., 2015). All other land covers comprised 6 %. The Upper Neuse watershed includes a number of artificial impoundments, the largest of which is the Falls Lake Reservoir that supplies water for Raleigh and surrounding communities.

The Piedmont is characterized by a gently rolling topography, resulting in an elevation ranging from 15 to 270 m in the Upper Neuse watershed. Soils in the Upper Neuse are predominately silt and sandy loam with moderate infiltration rates (Soil Survey Staff, 2018). The most common soil type in the Piedmont is the well-drained Cecil soil. As the Upper Neuse moves towards the Coastal Plain, soils turn sandier and drier (Gatiboni, 2018). Annual average accumulated precipitation from 1991 to 2020 at the watershed outlet was 1320 mm and mean air temperature was 17 °C (Arguez et al., 2010).

2.2. Hydrologic modeling approach

Our multi-model framework integrates the Soil and Water Assessment Tool (SWAT) to simulate streamflow and the FUTure Urban-Regional Environment Simulation (FUTURES) to project future land change (Fig. 2). SWAT is a semi-distributed hydrologic model capable of simulating water, sediment, and nutrient yields at various watershed-scales (Arnold et al., 1998). We followed the methods of Wu et al. (2021) and de Mello

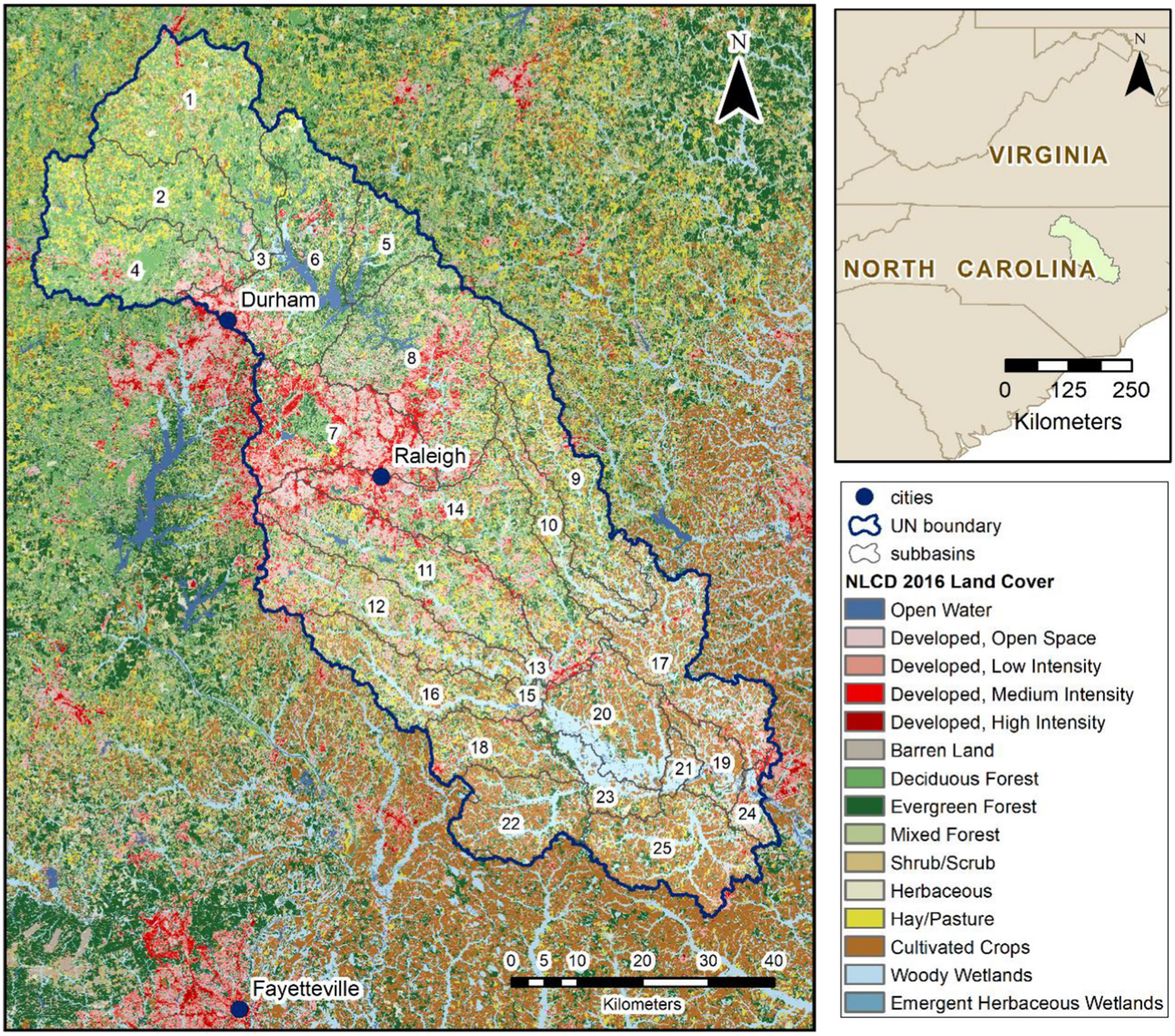

Fig. 1. The Upper Neuse watershed and 25 subbasins delineated by the SWAT model shown with the 2016 NLCD.

et al. (2017) to manipulate land cover in riparian buffers, detailed below. While SWAT has difficulty resolving some spatially explicit hydrological processes related to riparian buffers within subbasins, it remains a robust tool available for evaluating the effects of streamside buffer management on watershed flow regimes at a large scale.

The climate parameters for the future projections combined readily available, downscaled climate projections from the USGS data portal (cida.usgs.gov/gdp) and we simulated future land cover using FUTURES described below (Meentemeyer et al., 2013). The hydrologic model yielded future streamflow projections from 2021 to 2060 under three buffer treatments. These future scenarios and were also compared to Baseline (2000–2018) climate and land cover conditions. All necessary input data for the baseline SWAT model (elevation, land cover, and soil data) were in a 30 m resolution.

2.2.1. Future climate data

Baseline climate data were derived from the gridMET dataset (Abatzoglou, 2013). For future climate conditions we used the Coupled Model Intercomparison Project (CMIP5) CSIRO general circulation model with representative concentration pathway 8.5 (RCP 8.5). This climate scenario assumes increasing greenhouse gas emissions and projects warmer and wetter future conditions (Taylor et al., 2012). Future projections of average daily precipitation and temperature were obtained from the Multivariate Adaptive Constructed Analogs (MACA) statistically downscaled climate database (Abatzoglou and Brown, 2012) (data portal: http://cida.usgs.gov/gdp).

We used data from the Upper Neuse watershed outlet for our climate comparisons to provide context for the streamflow predictions. The time series was broken into three periods for comparison: 2000–2018 (Baseline), 2021–2040 (Near Future), and 2041–2060 (Midcentury). Mean precipitation (mm) and temperature (°C) obtained from the MACA database were compared on a seasonal, monthly, and annual basis. Extreme high precipitation and consecutive dry days, daily extreme temperature, and climatic change in the growing season (April through October) and winter (November through March) were also examined.

2.2.2. Land cover change model

We simulated urban driven land change from 2017 through 2060 using the FUTURES model (Meentemeyer et al., 2013) to account for future population growth and urban development. FUTURES is an open source urban growth model using GRASS GIS add-ons (Petrasova et al., 2016). We simulated land cover using GRASS version 7.6.1 for the entire state of North Carolina (NC; 100 counties) and adjacent parts of South Carolina (SC; 4 counties). The framework simulates spatially and temporally explicit patterns of urbanization by integrating three submodels that consider where (POTENTIAL submodel), how much (DEMAND submodel), and what form (Patch Growing Algorithm [PGA]) newly developed land is likely to occur. Submodels were parameterized and calibrated following previous

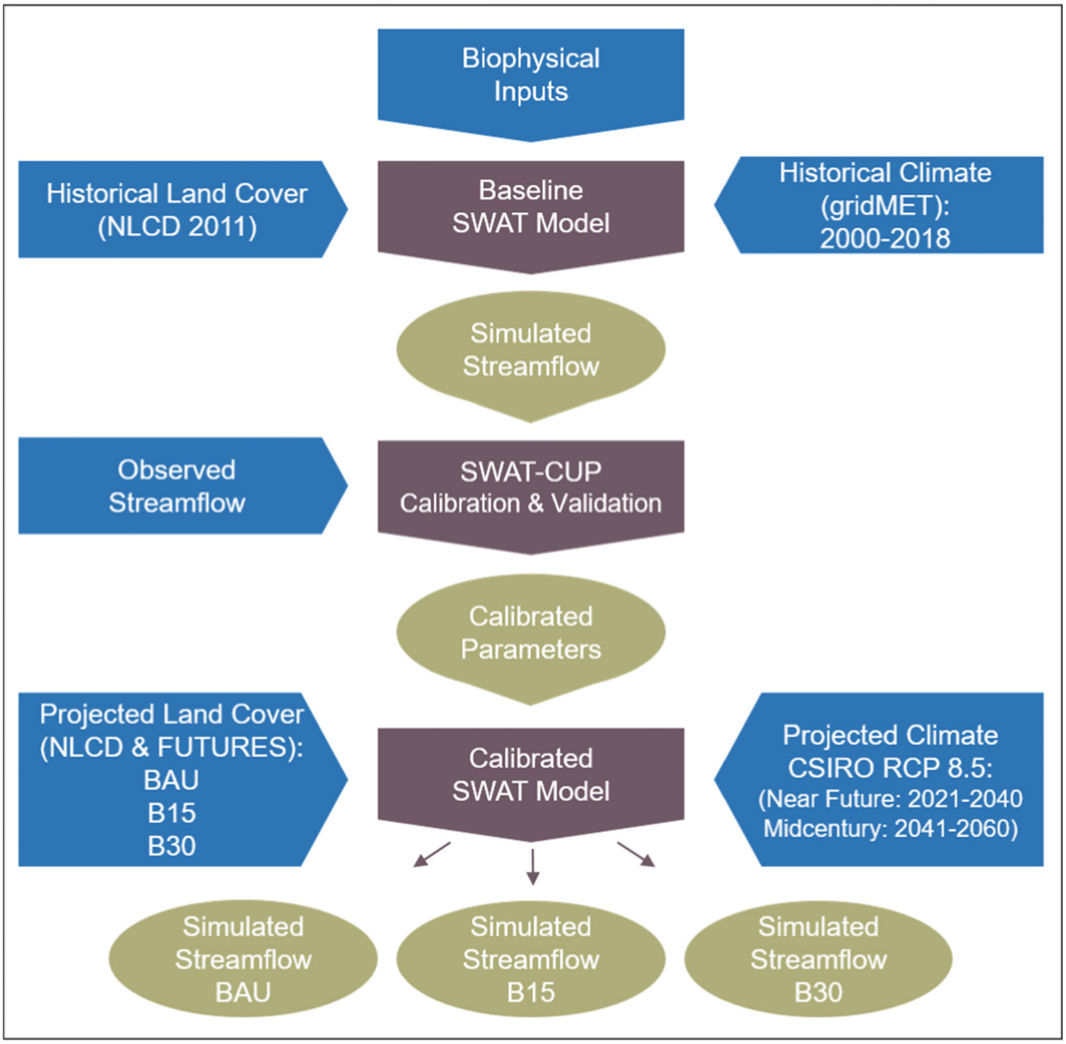

Fig. 2. Conceptual workflow of our multi-model approach. SWAT was used to simulate Baseline and future streamflow while SWAT-CUP was used to calibrate the Baseline SWAT model for future conditions. The FUTURES model generated a forecasted land cover raster that was used for future SWAT scenarios.

studies (Dorning et al., 2015; Meentemeyer et al., 2013; Sanchez et al., 2020; Smart et al., 2021). We calibrated patch size and shape parameters on four counties (i.e., Durham, Wake, Johnston, and Wayne counties) located within or near the Upper Neuse in the eastern part of NC as well as four counties (i.e., Yancey, McDowell, Burke, and Catawba counties) that represented an urban-rural gradient in different areas of the state. We computed 10 iterations under the Status Quo trajectory of growth to capture the variability in development patterns between individual simulations. The simulation of cumulative development (2017–2060) that had the highest agreement among iterations (simulation 5) was merged with the 2016 NLCD. Simulations of newly developed patches where assumed as "low-intensity development" (i.e., NLCD value 22) and all other land covers were assumed to remain constant (i.e., maintained 2016 land use land cover conditions). "Low-intensity development" is characterized as the 20–49 % impervious cover typical of single-family housing developments in the NLCD (Homer et al., 2015). This was selected as a conservative estimate, as not all future development will be classified as low-intensity. More information can be found on the main FUTURES hub (https://cnr.ncsu.edu/geospatial/research/futures/).

2.2.3. Riparian buffer treatments

Riparian buffer protection treatments were imposed on the future land cover raster using the stream network from the National Hydrography Dataset (NHD) and R statistical software. The three tested levels of buffer protection included: business as usual buffers (BAU), fully forested 15 m buffers (B15), and fully forested 30 m buffers (B30). The state of North Carolina has issued a state-mandated, basin-wide riparian buffer rule requiring 50 ft. (15.24 m) of buffer on each side of surface water bodies throughout the entire Neuse Basin under state administrative code 15A NCAC 02B 0.0714/0.0734, although the rule includes exemptions resulting in a mix of streamside land uses. Within the present mandated buffer zone in the Upper Neuse, land cover remained consistent from the 2011 to 2016 NLCD, ranging from 44 % forested, 29 % wetlands (woody or emergent), 11 % developed, 6 % agriculture (pasture/cultivated crops), and 10 % other land covers (open water, herbaceous shrub/scrub, barren). Therefore, the BAU treatment represents a future where all exemptions would carry forward and no additional buffer protection would be added. Pockets of development were still allowed to occur within the mandated buffer zone in the FUTURES model and no changes were made to this future land cover raster for the BAU treatment.

We manipulated the future land cover raster by re-categorizing values within the specified buffer area as forest cover, similar to the methods of Wu et al. (2021) and de Mello et al. (2017). To accomplish this, buffer areas for B15 and B30 scenarios were overlaid on the future land cover rasters as polylines after first resampling the rasters from 30 m to 15 m. Buffer scenario rasters remained in the 15 m resolution. Next, the land cover within these areas was converted from the NLCD classification (Baseline period) or FUTURES model classification (BAU scenario) to "mixed forest" (NLCD value 43). The buffer distances represent the horizontal distance from the stream edge versus a slope distance, therefore, areas that are steeply sloped might have an overrepresentation of riparian area whereas flatter areas might better capture the mandated buffer zone. We used the SWAT model to assess the effect of fixed-width buffers at this watershed scale as SWAT is advantageous to use for simulating hydrologic processes at this larger extent. However, this scale of a model might not perfectly capture detailed hydrologic routing processes that occur in riparian areas under empirical conditions.

2.2.4. SWAT model set-up and calibration

SWAT operates on a daily time step and uses spatially distributed data inputs such as topography, soils, land cover/use, and weather to predict water, sediment, and nutrient yields using a water balance approach (Neitsch et al., 2011). Baseline and future streamflow were simulated using the ArcSWAT 2012 interface (version 10.7). SWAT first uses elevation data to calculate flow direction and accumulation, create a stream network, and disaggregate the watershed into subbasins (Winchell et al., 2013). The subbasins are further divided into Hydrologic Response Units (HRUs), which are comprised of areas containing similar biophysical characteristics such as land cover, soil, and slope. Processes are first modeled within the HRUs and are then aggregated within the subbasins (Winchell et al., 2013).

The unique combinations of land cover, soil, and slope comprised by HRUs represent the smallest level of computation within the model. This method aims to robustly simulate complex hydrologic processes while maximizing computational efficiency. As a result, HRUs comprise lumped areas within a subbasin that are not spatially oriented with each other (White and Chaubey, 2005) and therefore do not account for hydrologic connectivity within HRUs (Her et al., 2015). Subsequently, the addition of riparian buffers to the subbasin translates to added forest cover, but the adjacency to the stream is not specifically modeled. Despite this method of water routing, the SWAT model remains a robust tool for simulating future streamflow under buffer treatments at a regional watershed scale for this study. We delineated the 6231 km^2 Upper Neuse watershed by creating a watershed outlet at USGS gage 02089000 Neuse River near Goldsboro, NC using the USGS StreamStats tool (https://streamstats.usgs.gov/). The watershed was then divided into 25 subbasins, and a stream network was created using pre-processed elevation data from a 30 m Digital Elevation Model. HRUs were created by loading in the 2011 NLCD (midpoint of the 2000–2018 Baseline), a modified SSURGO soils dataset, and manually defining two slope classes by creating a percent rise raster classified with the Jenks natural breaks method (0–5.37, 5.37–999).We used threshold percentages of 5 % for land cover, 10 % for soil, and 10 % for slope for HRU definition to maximize computational efficiency while avoiding oversimplification of the watershed landscape, resulting in a total of 408 HRUs.

We simulated weather input for SWAT by creating centroids of each subbasin for the Upper Neuse (25 subbasins). We found the statistically downscaled grid cell containing each centroid, and for each grid cell we downloaded 2020–2060 CSIRO RCP 8.5 GCM daily temperature and precipitation data for future projections, as well as 1997–2018 daily gridMET mean precipitation and daily minimum and maximum temperature for the Baseline period and model calibration (Abatzoglou, 2013). Solar radiation, relative humidity, and wind speed were estimated using the SWAT built-in weather generator. Lastly, reservoir information was added for Lake Crabtree (subbasin 7), Falls Lake Reservoir (subbasin 8), and Lakes Wheeler and Benson (subbasin 11). Reservoirs were simulated through a target release approach by altering reservoir characteristics, such as initial reservoir volume and surface area when reservoir is filled to the principal spillway using. These parameters were derived from the US Army Corps of Engineers National Inventory of Dams (https://nid.usace.army.mil/). The Baseline SWAT model was run from January 1, 1997 to December 31, 2018 with a three-year warmup period.

The model was calibrated from January 1, 2000 to December 31, 2012 and validated from January 1, 2013 to December 31, 2018 at the watershed outlet using the SWAT-CUP 2012 software package (Abbaspour, 2015) with the GLUE (Generalized Likelihood Uncertainty Estimation) algorithm (Beven and Binley, 1992). The GLUE procedure recognizes non-uniqueness in model predictions (Kouchi et al., 2017) by assigning a likelihood value to each set of parameter values (Beven and Binley, 1992; Kouchi et al., 2017). Global calibration began with 19 parameters that were commonly used in similar watershed studies in the region (Ayivi and Jha, 2018; Ercan et al., 2020; Suttles et al., 2018). After several iterations, the parameter set was subsequently narrowed down to 15 based on the significance of p-values and effect on overall calibration performance. Of the 15 parameters baseflow alpha factor for bank storage (ALPHA_BNK), SCS runoff curve number (CN2), effective hydraulic conductivity in main channel alluvium (CH_K2), average slope length (SLSUBBSN), Manning's "n" value for the main channel (CH_N2), saturated hydraulic conductivity (SOL_K), threshold depth of water in the shallow aquifer required for return flow to occur (GWQMN), moist bulk density (SOL_BD), and the groundwater "revap" coefficient (GW_REVAP) consistently had a significant p-value (<0.05) during the sensitivity analysis and when the objective function was maximized. All parameters were changed for the entire watershed except the SCS runoff curve number, which was changed separately for the upper, middle, and lower portion of the watershed, as illustrated in Table 1. The final fitted parameter values fall within recommended published ranges.

The Nash Sutcliffe efficiency (NSE) (Nash and Sutcliffe, 1970) coefficient was used as the main indicator of model performance, defined in Moriasi et al. (2007) as:

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

where Y_i^{obs} = ith observation for the component being evaluated. Y_i^{sim} = ith simulated value for component being evaluated. Y^{mean} = mean of observed data for component being evaluated and n = total number of observations. The NSE ranges from negative infinity to 1, with a NSE of 1 indicating perfect fit between the observed and simulated data. A NSE ≤ 0 indicates that the observed data provides a better fit than model output. An NSE ≥ 0.5 is an acceptable indicator of satisfactory model monthly performance (Moriasi et al., 2007). From the calibrated model, three future coupled land cover and climate scenarios were each run from January 1, 2018 to December 31, 2060 with a 3-year warmup period.

2.2.5. Model calibration and validation

The watershed outlet (USGS 02089000) has a long-term observed daily discharge record starting in 1985. The observed mean was 54.14 m^3/s during the calibration period and 83.63 m^3/s during the validation period. We ran 3820 calibration simulations in SWAT-CUP and achieved both a NSE and R^2 of 0.65 for daily streamflow prediction (Fig. 3).The ratio of root mean square error to the standard deviation (RSR) for daily calibration was 0.59 (good model performance rating) and percent bias (PBIAS) was −3 % (very good performance rating) according to the calibration standard set by Moriasi et al. (2007). Once the satisfactory performance metric was achieved, the set of calibrated parameter ranges that best optimized the objective function were used to replace the default SWAT values. The calibrated SWAT model was run again for the validation period and the daily flow output was compared to historical daily flow data. NSE was 0.75, R^2 was 0.75, RSR was 0.5, and PBIAS was −0.40 % for daily predictions during the validation period which correspond to very good model performance (Moriasi et al., 2007). For the entire baseline period (2000–2018), daily model performance had a NSE of 0.72, R^2 of 0.72, PBIAS of −1.9 %, and RSR of 0.53. The calibrated baseline model estimated mean flows with lower bias compared to the extreme high and low flows; however, this pattern is expected as hydrologic models have a difficult time estimating the empirical extremes of flow (Caldwell et al., 2015). A negative PBIAS for both the calibration and validation periods indicates that the Upper Neuse SWAT model underestimates high flows and potentially overestimates low flows. The same calibrated parameter set was used to run all future scenarios.

Table 1
Subbasin percent developed, forest, and agricultural cover from the Baseline and future BAU, B15, and B30 treatments. The tables are organized by the upper, middle, and lower portions of the watershed and are sorted in descending order based on baseline percent development. The BAU values represent the percent change in land cover from BAU to Baseline. The B15 and B30 values represent percent change in land cover from buffer treatments to BAU. All land cover change refers to change within the subbasin boundary versus the change of all upstream subbasins.

Upper	Development				Forest				Agriculture			
Subbasins	Base	BAU	B15	B30	Base	BAU	B15	B30	Base	BAU	B15	B30
7	70	+5	−13	−27	23	−12	+50	+106	2	−14	−12	−30
8	35	+26	−12	−27	48	−14	+15	+32	8	−17	−5	−18
6	21	+28	−13	−27	54	−8	+9	+22	9	−9	−9	−28
4	20	+9	−11	−24	60	−3	+7	+16	15	−1	−8	−23
3	9	+33	−10	−19	46	−4	+4	+9	8	−8	−3	−11
2	8	+28	−12	−25	62	−3	+5	+14	24	−2	−8	−22
1	8	+9	−10	−22	59	−1	+5	+15	25	−1	−7	−23
5	7	+88	−15	−30	67	−7	+5	+13	12	−8	−7	−25

Middle	Development				Forest				Agriculture			
Subbasins	Base	BAU	B15	B30	Base	BAU	B15	B30	Base	BAU	B15	B30
11	37	+23	−11	−24	35	−14	+20	+45	15	−13	−5	−15
14	32	+26	−11	−23	37	−12	+16	+37	17	−11	−4	−14
12	29	+37	−12	−26	33	−16	+22	+52	20	−15	−5	−17
16	12	+50	−12	−26	30	−7	+17	+48	33	−8	−6	−21
10	12	+62	−10	−23	33	−9	+12	+32	32	−9	−5	−15
15	10	+53	−11	−23	22	−5	+26	+67	45	−5	−8	−23
9	9	+78	−12	−26	40	−8	+11	+30	34	−8	−5	−18
13	0	NA	−9	−13	17	+1	+5	+7	19	−4	−3	−3

Lower	Development				Forest				Agriculture			
Subbasins	Base	BAU	B15	B30	Base	BAU	B15	B30	Base	BAU	B15	B30
24 (Outlet)	24	+26	−8	−19	15	−8	+33	+76	21	−10	−7	−17
17	13	+29	−9	−19	13	−4	+29	+74	42	−4	−5	−14
19	12	+40	−8	−18	11	−4	+48	+110	40	−6	−9	−22
18	10	+31	−11	−23	27	−3	+21	+52	41	−4	−8	−22
20	7	+34	−9	−20	15	−2	+26	+63	35	−3	−8	−20
25	6	+31	−8	−17	15	−2	+27	+65	50	−2	−6	−15
22	6	+27	−11	−23	21	−2	+25	+61	47	−2	−8	−20
21	3	+48	−8	−16	7	−1	+44	+103	39	−2	−7	−16
23	2	+69	−11	−22	17	−1	+12	+31	25	−4	−5	−14

2.3. Scenario analyses

We assessed differences between Baseline (2000–2018) and future (2021–2060) daily streamflow (m^3/s) by comparing Baseline output to the BAU treatment. Average daily streamflow values were averaged to create single values to compare across years for each subbasin, which indicated shifts in the timing of peak and low flow events, especially between growing and winter seasons across all scenarios.

We then compared the relative difference in average daily streamflow between the BAU and two buffer protection treatments (B15 and B30) over the Near Future (2021–2040) and Midcentury (2041–2060) periods. To assess these relative differences, we examined future low flows (below 10 percentile) and high flows (above 90 percentile). These percentiles were calculated in R statistical software by calculating the future (2021–2060) average daily streamflow in each percentile for each subbasin during the BAU treatment. Those daily events were then compared across

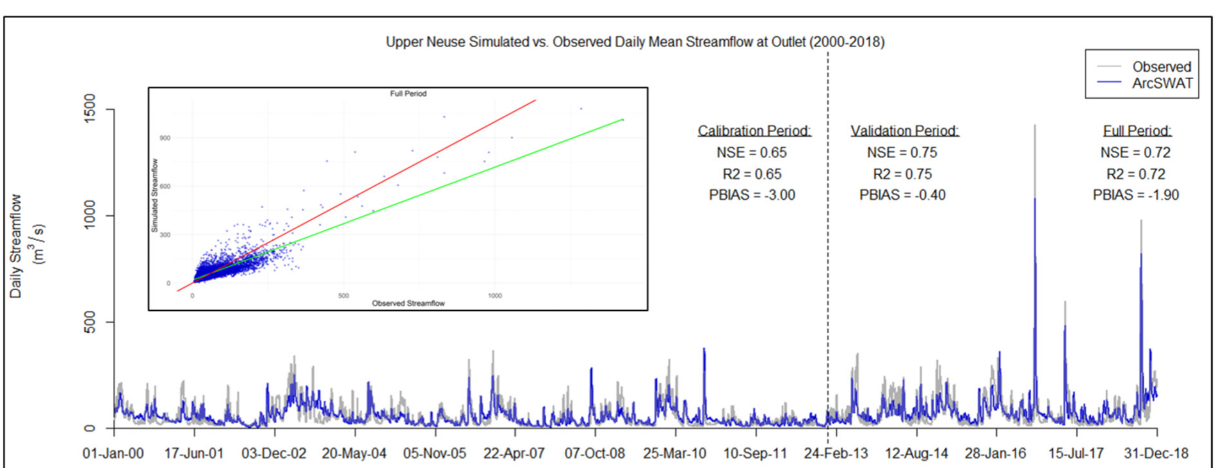

Fig. 3. Hydrograph of observed vs. simulated daily flow during the calibration, validation, and full periods. Inset graph is a scatterplot of observed (x-axis) vs. simulated (y-axis) daily flow during the full period.

the B15 and B30 treatments to reveal how the buffer treatments affected BAU streamflow. The low flow calculations also included an examination of daily mean baseflow across all years and the high flow calculations included a Log-Pearson Type III analysis. Baseflows were calculated using the baseflows function of the hydrostats package in R (Bond, 2022). The baseflows function uses the Lynne-Hollick filter to find the measure of central tendency and baseflow indices. The Log-Pearson Type III analysis is a flood frequency analysis commonly used by Federal agencies to estimate the probability of streamflow during different return periods (Thomas, 1985). We used this analysis to assess buffer effect on extreme stormflow in the most developed area of the watershed (subbasin 7) and at the watershed outlet.

3. Results

3.1. Future climate conditions

The climate scenario we selected describes an overall warmer and wetter future for the study area (Fig. 4). The annual mean temperature at the watershed outlet gradually increased across the three periods from 17 °C Baseline to 18 °C in the Near Future to 18.8 °C in the Midcentury. The annual mean maximum temperature also increased from 22.8 °C Baseline to 24.2 °C Near Future to 24.9 °C Midcentury. The average minimum temperature also increased from 11 °C in the Baseline to 12 °C Near Future to 12.7 °C in the Midcentury. The Midcentury growing season temperature was projected to increase from an average of 23 °C to 25 °C across the periods. Temperatures in the dormant season also increased from Baseline (9 °C) to Midcentury (11 °C). The Near Future followed this pattern, where the only decrease during the dormant season was for December, where the average dropped <1 °C relative to the Baseline. Daily extreme high temperature increased as well, with an increase from 4 % of days above 35 °C during Baseline to 9 % of days in the Near Future and 12 % of days in the Midcentury.

The mean annual precipitation at the watershed outlet during the Baseline period was 1309 mm, which increased by 2.4 % during the Near Future (1340 mm) and 6.5 % during the Midcentury (1393 mm), relative to the Baseline. Mean annual precipitation values ranged from 1173 to 2366 mm across the watershed, with the lower portion of the basin receiving the highest rates (Supplementary Fig. 1). Following the trend in historical data, monthly average accumulated precipitation values decreased from September to October (Fig. 4C) across all periods (Arguez et al., 2010). The greatest increases in monthly precipitation between the Baseline and future periods occurred in July and August. While mean annual precipitation increased from Baseline to the future periods, December was drier, by 16 % from Baseline (100 mm) to Near Future (84 mm) and 20 % from Baseline to Midcentury (80 mm). During the Baseline period, 0.19 % of days (0.7 days per year) exceeded the 76 mm (3-in.) extreme precipitation threshold (Frankson et al., 2022). This value drops to 0.12 % of total days in the Near Future, and in the Midcentury, 0.16 % of total days exceeded this threshold. The number (as percentage of days over a time period) of consecutive dry days (two plus days with <1 mm of precipitation) decreased from 16.2 % at the Baseline, to 14.9 % in the Near Future, and 14.6 % in the Midcentury. The length of the consecutive dry days also decreased. The Baseline had the longest period of 40 consecutive dry days. This stretch drops to 29 consecutive days in the Near Future and 27 consecutive days in the Midcentury.

We also examined water balance components such as evapotranspiration "ET" and water yield (Supplementary Fig. 2). To compare these values,

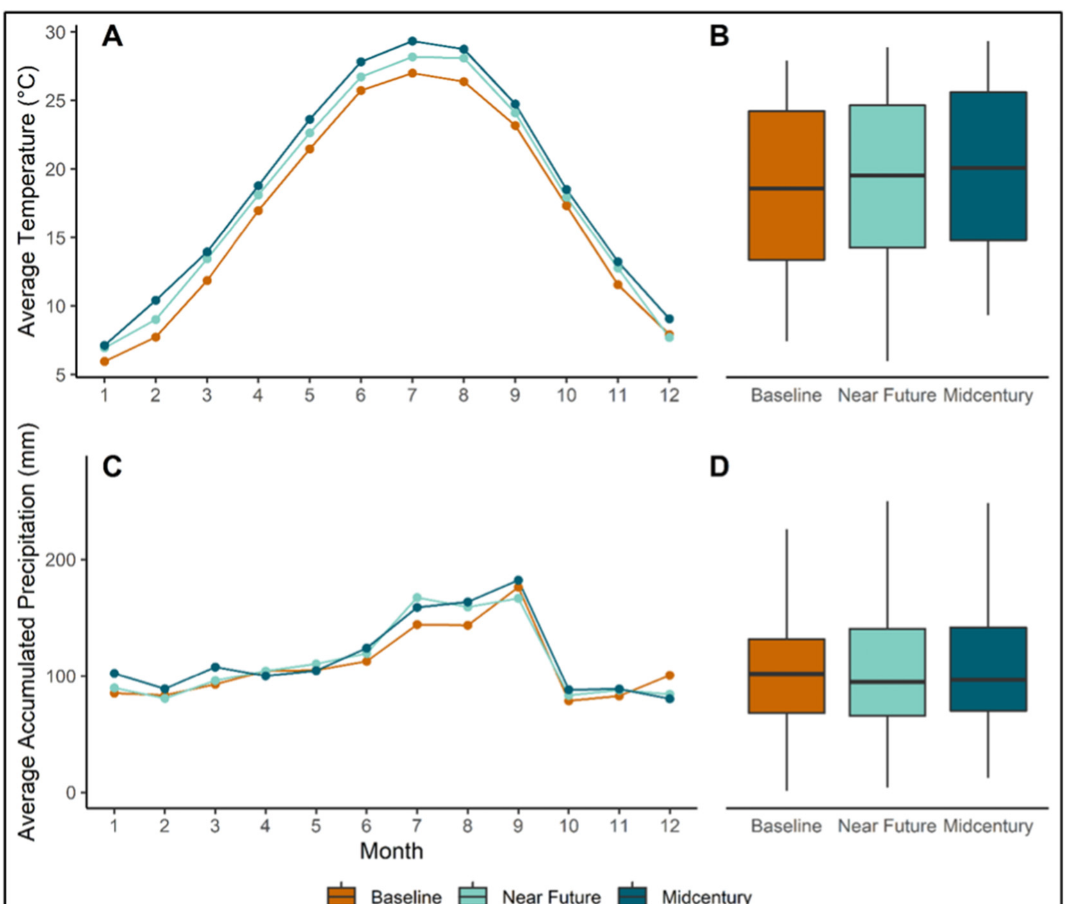

Fig. 4. (A) Average monthly temperature (°C) across all years for the Baseline (2000 – 2020), Near Future (2021–2040), and Midcentury (2041–2060) periods and (B) distribution of monthly values. (C) Average monthly accumulated precipitation (mm) across all years and time periods and (D) distribution values.

we assessed average annual ET (mm) and water yield (mm) across the watershed from the Baseline, BAU, B15, and B30 treatments. We found no significant difference in ET rates between the future scenarios. However, future ET (BAU, B15, B30) is projected to be on average higher than Baseline ET. The largest change occurs in February, where future ET is projected to be 13 % higher than Baseline ET. Future ET is projected to be lower compared to the Baseline during the end of the growing season from July to October. The water yield values show more of a difference between the future scenarios. The BAU has a higher water yield from January to April compared to the Baseline and buffer treatments. However, during most of the growing season, the buffer treatments have a higher water yield compared to the BAU. This difference is most evident in June and July, where BAU water yield is 13 % lower compared to B15 and B30 water yield.

3.2. Future land cover conditions

Land use projections suggested a 5.5 % to 11.2 % increase of low-intensity development across the watershed by 2060, which vary in location and quantity across the study watershed (Table1; Fig. 5). The highest density of development occurred around Raleigh, spanning across subbasins 7, 8, 11, and 14, suggesting an increase in urban sprawl. Subbasin 2 (271 km^2) in the headwater region of the watershed and was projected to increase from 8.2 % developed land cover to 10.5 %. Also in the headwater region, Subbasin 4 (389 km^2), which included the rapidly expanding town of Hillsborough, increased in development from 19.8 % to 21.7 %. Development in this subbasin occurred on both forested and agricultural land, reducing these land covers by 2.7 % and 1.1 %, respectively. Subbasin 5 (137 km^2) contained the town of Creedmoor as well as the Falls Lake Reservoir, which supplies drinking water for the city of Raleigh and surrounding area. This subbasin was predicted to develop from 7 % in the Baseline to 13.3 % in the Midcentury period. Subbasin 7 (373 km^2), which was comprised of the majority of Raleigh, parts of Research Triangle Park, and William B. Umstead State Park, remained the highest developed subbasin from Baseline (70 %) to BAU Midcentury (73 %). Across the entire Upper Neuse, developed land cover increased from a total of 21 % to 26 %.

Land cover within the 50-ft (15.24 m) state mandated buffer zone under baseline conditions was 11 % developed. Because development was allowed to occur under the BAU scenario with no consideration of buffer protection, developed land cover within the 50-ft (15.24 m) zone increased to 18 % developed, while forest (39 %) and agriculture (7 %) decreased across the watershed to 2060. We assumed a complete reforestation of buffers for both levels of protection (B15 and B30), these future condition treatments resulted in increased forest cover relative to Baseline conditions across all subbasins. For example, in subbasin 7, forest cover decreased from Baseline (23 %) to BAU (20 %), but increased for future treatments where buffer reforestation was applied (B15 30 %, B30 41.2 %). Even with the complete reforestation of the buffers, future developed land cover exceeded Baseline levels, indicating that the majority of development

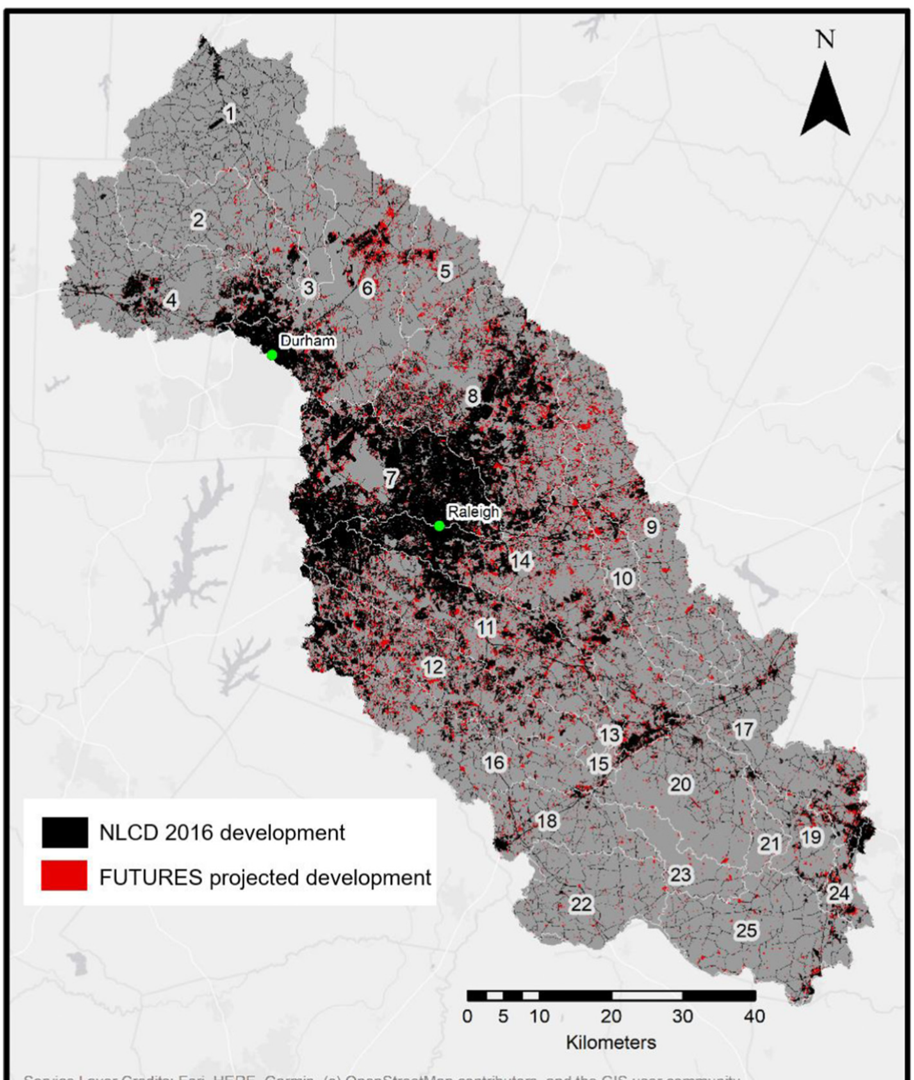

Fig. 5. Output from the FUTURES Urban Growth Model showing projected development patches across the Upper Neuse Watershed.

occurred outside of the buffer zones. This could also indicate that buffer addition replaced other land covers, such as agriculture. For example, subbasin 2 contains 24 % agricultural land in the Baseline period. BAU showed a decrease to 23 % agriculture, while B15 and B30 decreased agricultural land cover to 22 % and 18 %, respectively.

3.3. Projected streamflow

Average daily streamflow across the watershed is projected to be higher from Baseline to the BAU future periods. Compared to the BAU treatment, buffer treatments slightly impacted average daily streamflow (< ± 1.2 %) but did not result in a consistent response across subbasins. (Fig. 6). Further, in some subbasins, B15 and B30 showed diverging responses; however, the response was a < 1 % change in average daily streamflow. Average daily streamflow increased from the Baseline to the BAU future periods by 1.3 % to 28 % among subbasins, with the Midcentury as the wettest period ranging from 4.7 % to 27 %. Without buffer protection (BAU treatment), select subbasins experience a high increase in average daily streamflow relative to Baseline levels. Subbasin 5 underscores this finding with average daily streamflow levels ranging from 30 % higher in the Near Future and

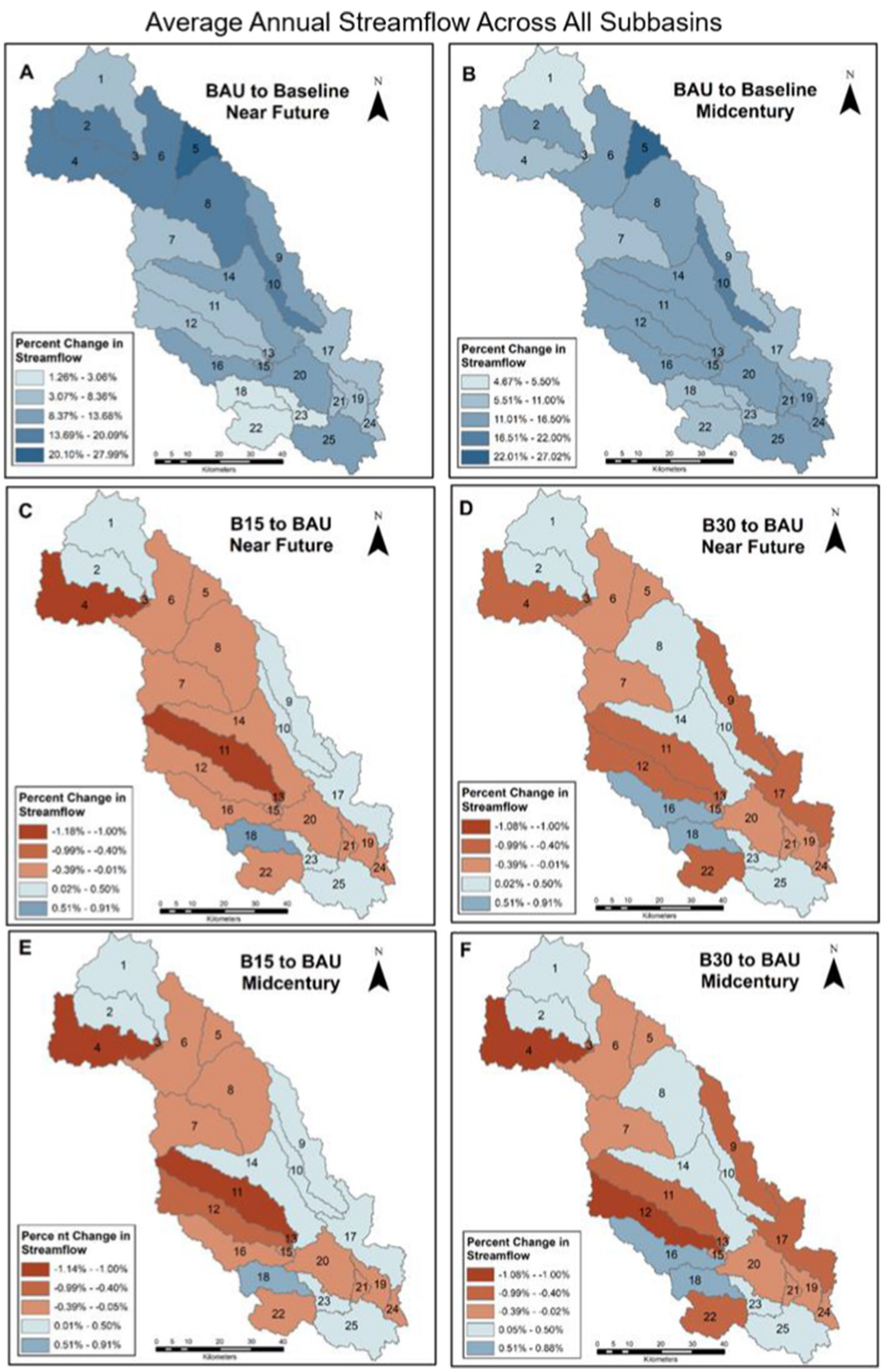

Fig. 6. Percent change in daily streamflow based on the Baseline, BAU, and buffer treatments (B15 and B30). The subbasin maps represent average percent change in streamflow between (A) BAU and Baseline in the Near Future, (B) BAU and Baseline Midcentury, (C) B15 and BAU Near Future, (D) B30 and BAU Near Future, (E) B15 and BAU Midcentury, (F) B15 and BAU Midcentury.

27 % higher in the Midcentury. The outlet, representing the entire watershed, experienced an 8 % (Near Future) to 11 % (Midcentury) increase in average daily streamflow from the Baseline to BAU future periods. The buffers treatments slightly decreased (<1 %) average daily streamflow at the outlet.

The trend of increased mean daily flow is similar when examined seasonally. The entire watershed had 8 % (Near Future) to 13 % (Midcentury) higher growing season average daily streamflow rates in the BAU scenario compared to Baseline in all subbasins but subbasin 7, the most developed subbasin (70 % Baseline, 73 % BAU). There, growing season average daily streamflow was projected to decrease 6 % to 4 % in the BAU Near Future and Midcentury, respectively and the addition of the buffers did not increase or decrease streamflow from Baseline levels. The winter season shows a more variable responses across the watershed. During the winter season, percent change in average daily streamflow rates from the BAU to Baseline ranged from −0.33 % to 32 % in the Near Future and 3 % to 29 % Midcentury. Subbasin 7 was an outlier here too, where winter streamflow rates were 12 % higher during both of these scenarios.

At the watershed outlet, the highest mean daily flows across the year occurred mid-October during the Baseline period, with a shift to mid-November during both future periods. Baseline lowest mean daily flows occurred mid-February while future lowest mean daily flows shifted several months to early July. Buffer treatments had no detectable impact on the timing of lowest mean daily flows. In general, streamflow became more extreme in future climate scenarios; annual maxima were larger and annual minima were smaller in Near Future and Midcentury scenarios compared to the Baseline period (Supplementary Fig. 3).

3.4. Buffer effect on low flow

The number of low flow events (i.e., the lowest ten percentiles of average daily streamflow) for the entire Upper Neuse watershed remained consistent from the Baseline to the future BAU as low flow calculations at the outlet showed a 1 % increase in the frequency of events from the Baseline to future periods. Buffer treatments decreased flow magnitude at the outlet

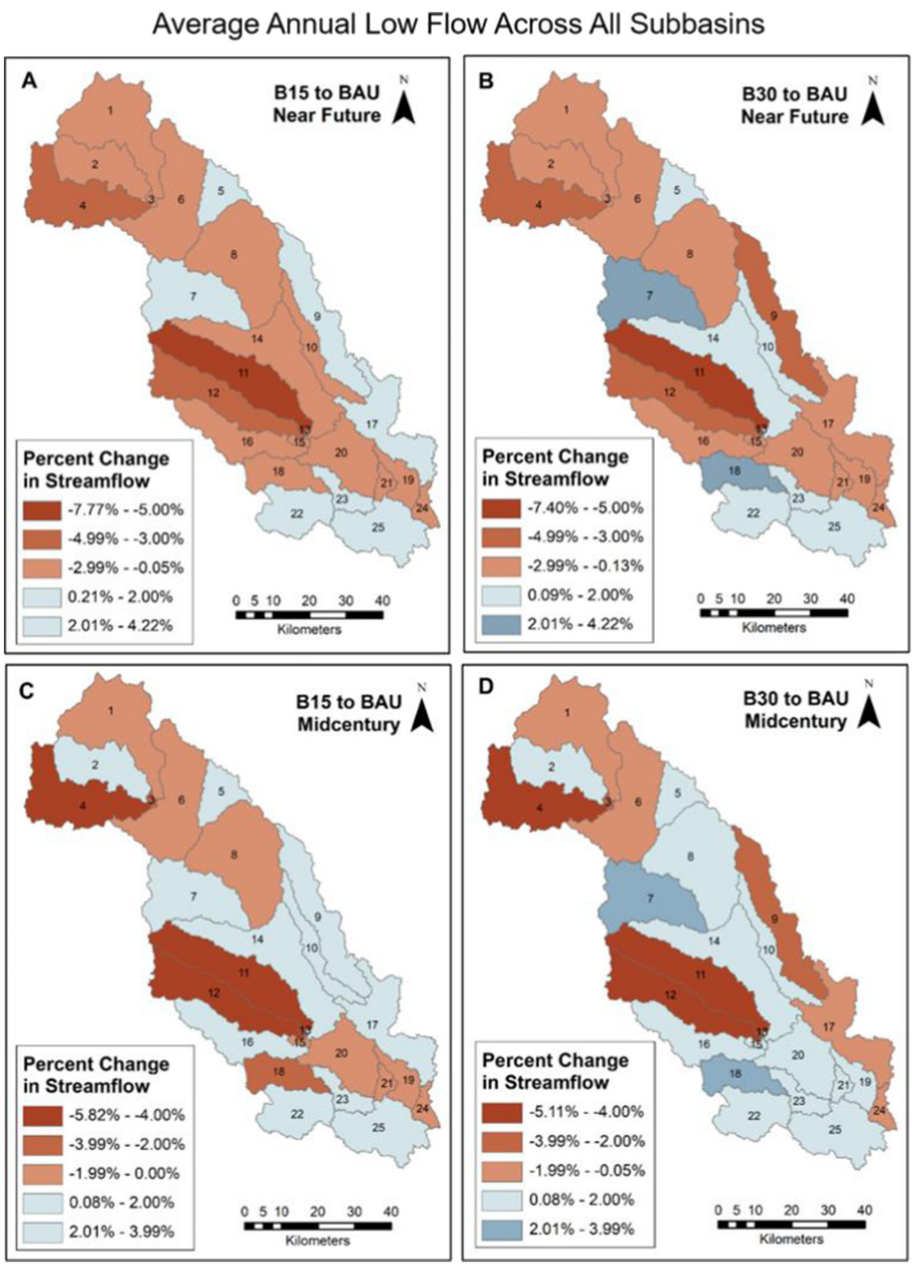

Fig. 7. Average percent change in low flow events (lowest 10 percentiles). The subbasin maps represent average percent change in low flows between (A) FUT15 and BAU Near Future, (B) FUT30 and BAU Near Future, (C) FUT15 and BAU Midcentury, (D) FUT30 and BAU Midcentury.

during low flow events by <1 %. However, the results for individual subbasins reveal a more nuanced story (Fig. 7).

During the Near Future, in subbasins where development ranged between 16 % and 40 %, buffer treatments were associated with decreasing average daily streamflow during low flows compared to the BAU. During the Near Future, buffer treatments decreased flow 0.1 % to 7.8 % among subbasins. During the Midcentury, this trend persisted but the effect of buffers decreased (reducing flow by up to 5.8 % versus 7.8 %). Buffer treatments were particularly associated with reducing low flows in subbasins 4 (headwater subbasin), and subbasins 11 and 12 (downstream of high development). Developed land ranged from 20 % to 36 % in these subbasins during the Baseline period. The exception to this pattern is subbasin 18, which was 10 % developed in the Baseline. In subbasin 18, the BAU and B15 treatments pushed land cover past the 10 % development threshold (14 % and 12 % respectively), while the B30 treatment reduced development to Baseline levels (10 %). Resultantly in this subbasin, buffer treatments had a diverging response where B15 decreased flow by 2 % and B30 increased flow by 4 % during both future periods.

Subbasin 7 remained the highest developed subbasin across all land cover scenarios, ranging from 70 % (Baseline) to 53 % (B30). In subbasin 7, B30 buffers substantially increased flow during low flow events up to 2 % (Near Future) and 4 % (Midcentury), while B15 increased flow 1 % (Near Future) and 2 % (Midcentury). In subbasins where development was <16 %, buffer response was variable and associated with both increasing and decreasing low flows relative to the BAU by ≤1 % (excluding subbasin 18).

Buffer effects on baseflows also varied by Baseline and BAU subbasin development. Where both Baseline and future development exceeded 20 %, buffers were associated with future increases in mean daily baseflow only during times outside of the peak growing season. During the future peak growing season, baseflow values were lowest, and in some cases, lower than the Baseline (Supplementary Fig. 4). Overall, buffer treatments had little effect on baseflow at the whole watershed scale.

3.5. Buffer effect on high flow

For the Upper Neuse watershed as a whole, high flows (i.e., the top ten percentiles of average daily streamflow) increased by 4 % during both BAU future periods compared to the Baseline period (Fig. 8). The buffer treatments were most successful at decreasing flow during the highest flow events relative to the BAU. While the treatments increased flow in select subbasins during the highest flow events, this increase was <1 % and was concentrated in subbasins 1–4 and 6 in the headwater region, which remained the highest forested area of the watershed from Baseline (>46 %) to BAU (>44 %). Buffer treatments produced the largest reduction in mean daily high flow in subbasins 7, 11, and 12. These subbasins were among the highest developed areas during the Baseline and remained >30 % developed in all future scenarios. At the whole watershed scale, the buffer scenarios were associated with reductions in high flow by <1 %.

Log-Pearson Type III analyses at the outlet (Table 2) showed a large change in magnitude of the most extreme stormflows between the Baseline and BAU future, with little difference between future buffer treatments. B30 decreased extreme flows in all return periods more than B15, but these decreases were minor (<1 % reduction). Percent change in flow from the Baseline to BAU increased during all return periods but the 5-year and 10-year periods. During these periods, there was a 3.6 % (5-year) and 2.8 % (10-year) reduction in flow magnitude from the BAU to Baseline. The flood stage height for the USGS gauge at the study watershed outlet is 18-ft, which corresponds to 257.7 m^3/s (9,100 ft^3/s). During the baseline, 63 days (0.91 % of total days) exceeded this threshold, increasing to 81 days (1.1 %) in the Near Future and 118 days (1.6 %) in the Midcentury BAU scenarios. Peak flow rates in the Near Future were lower compared to the Baseline despite the minor increase in flood events. During the Midcentury, peak flow rates nearly doubled from the baseline. Both findings indicate a more variable future with more flooding.

The Log-Pearson Type III analyses was repeated for subbasin 7 (Table 3), which is the subbasin with the highest fraction of developed land cover. Here, the buffer treatments had a larger effect compared to the outlet, particularly during the 2-year return period. Buffer treatments were associated with a 1.3 % flow reduction (B15) and 2.8 % reduction (B30) compared to the BAU. The buffers did not reduce high flow at the 25, 50, 100, and 200-year return periods. During the 200-year return period, analysis revealed a 28.8 % increase in flow from the Baseline to BAU.

4. Discussion

Our scenarios of future climate and land use change indicate a warmer, wetter future with more frequent and higher magnitude flooding in the Upper Neuse River basin, supporting our hypothesis that extreme high flows will increase in magnitude and frequency. We found that there will be a 4 % increase in frequency of high flows from Baseline (2000–2018) to future periods (2021–2060). Coupled with expected urbanization, this finding suggests that more people will live in flood prone areas of the Upper Neuse watershed by Midcentury. Aside from increases in extreme flows, our results indicate that hydrologic responses to changing conditions are more complex than we initially hypothesized. Specifically, the fixed-width 15 m and 30 m riparian buffer treatments that we tested did not substantially mitigate changing conditions at the watershed level; however, we found evidence that these buffers could reduce the frequency of local flooding in some developed subbasins and increase flow rates during low flow periods in the highest developed subbasins.

4.1. Future climate and urban growth implications

For our study area, the CSIRO RCP 8.5 climate scenario predicts a warmer future with less extreme precipitation events. Monthly precipitation was greater for the future period compared to the Baseline; however, lower precipitation and warmer weather during the start of the growing season in April, May, and July could put additional pressure on water resources. Further, while Atlantic hurricane season runs from June through November, some of the strongest hurricanes of record occur later in the season between August and October (U.S. Census Bureau, 2022). We found higher precipitation in these months under the future climate scenario. These results suggest the potential for hurricane events to occur under wetter conditions thereby potentially exacerbating flooding in the future. These results are consistent with regional projections that indicate a warmer future of more extreme precipitation (Carter et al., 2018b; McNulty et al., 2013).

The impacts of a changing climate on hydrological processes cannot be viewed in isolation of expanding urban land use, which also affects hydrological processes associated with streamflow. Results from the FUTURES land use model show low intensity development doubling across the state by the year 2060. This projection is a conservative estimate, as all new development was assigned as “low-intensity” corresponding to 20–49 % impervious surface, typical of single-family housing (Homer et al., 2020). Attributable to the uncertainty surrounding future human activity, land cover change can have immediate socioeconomic impacts on already vulnerable communities, such as communities with limited capacity to adapt to environmental change (Saia et al., 2019). Negative impacts from land cover change, such as increased flooding, can impact property value and infrastructure (Carter et al., 2018a), which can adversely affect rapidly growing regions such as our study area.

Re-establishment or preservation of riparian buffers can potentially preserve forest land, support urban growth, and provide valuable ecosystem services. Our model of land cover change projects a decline in forest land cover from Baseline to 2060 in all but one subbasin, which had no urban development in the 2011 NLCD and no additional development in the future owing to its smaller size and location in the headwater region. Adding buffer treatments increased overall forest land cover across the watershed. In 22 of the 25 subbasins, B15 resulted in increased forest cover higher than Baseline levels. Further, the B30 increased forest cover beyond Baseline

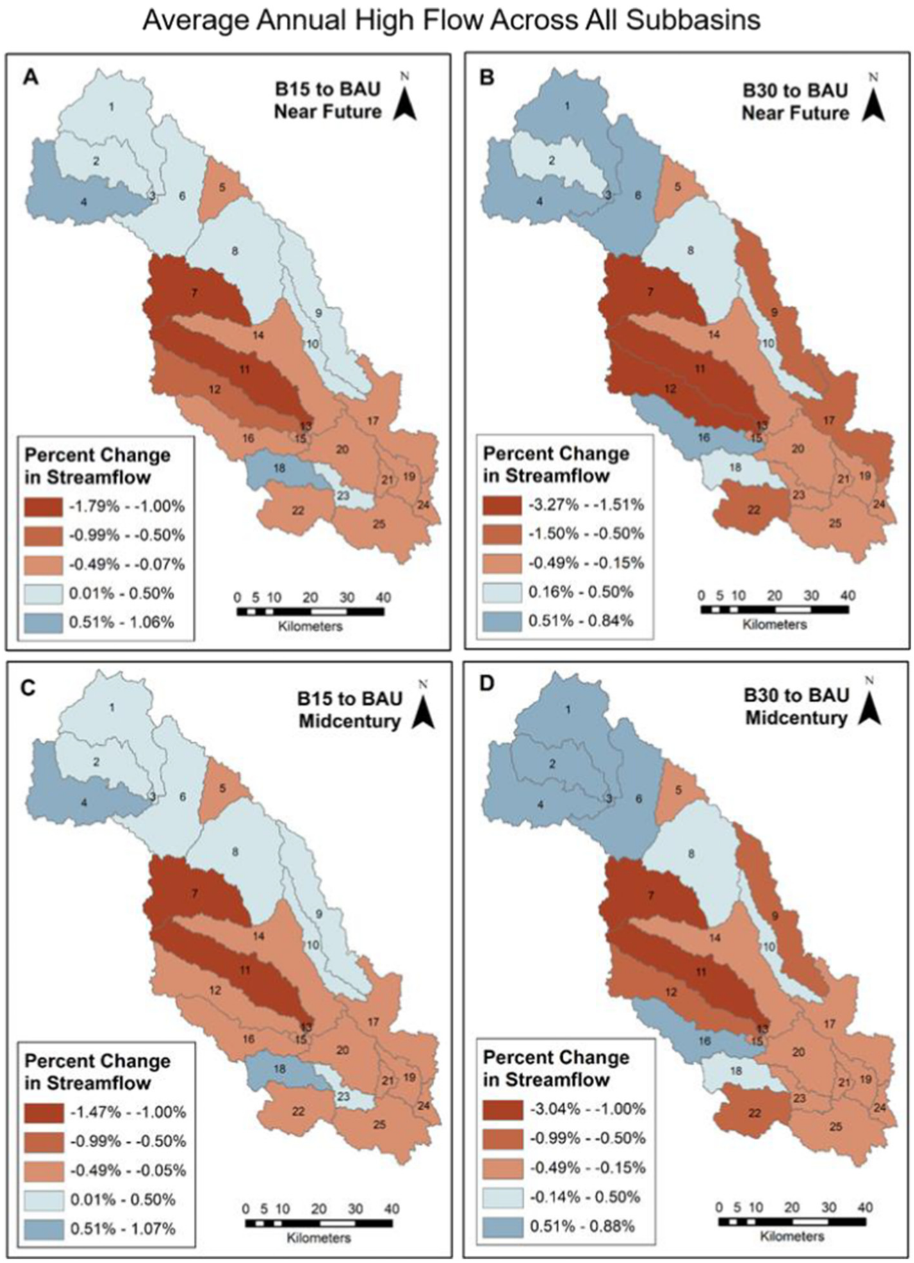

Fig. 8. Average percent change in high flow events (highest 10 percentiles). The subbasin maps represent average percent change in high flows between (A) FUT15 and BAU Near Future, (B) FUT30 and BAU Near Future, (C) FUT15 and BAU Midcentury, (D) FUT30 and BAU Midcentury.

levels in all subbasins. In the majority of subbasins, both B15 and B30 buffer scenarios increased forest cover beyond Baseline levels while also maintaining urban land cover beyond Baseline levels. The BAU scenario represents a future where existing buffer exemptions and development patterns continue into the future. Therefore, these fully-forested buffer scenarios demonstrate both the potential benefits of buffers for regulation of the streamflow regime and a future where the state-mandated rule is fully enacted. In practice, however, it may not be feasible to convert prior

Table 2
Daily streamflow (m3/s) output from the Log-Pearson Type III analysis at the outlet, where FUT30 lowers extreme flow but only by <1 %.

Log-Pearson Type II analysis at outlet								
TR	Probability	Q Base	Q BAU	Q B15	Q B30	Percent Change: BAU to Base	Percent change: B15 to BAU	Percent change: B30 to BAU
2	50 %	211.32	215.76	215.13	213.68	2.10 %	−0.29 %	−0.96 %
5	20 %	391.82	377.84	377.14	374.98	−3.57 %	−0.18 %	−0.76 %
10	10 %	565.65	550.11	549.36	546.60	−2.75 %	−0.14 %	−0.64 %
25	4 %	867.17	877.53	876.72	873.15	1.20 %	−0.09 %	−0.50 %
50	2 %	1165.25	1232.23	1231.37	1227.22	5.75 %	−0.07 %	−0.41 %
100	1 %	1540.95	1716.79	1715.96	1711.36	11.41 %	−0.05 %	−0.32 %
200	0.5 %	2012.35	2377.14	2376.34	2371.60	18.13 %	−0.03 %	−0.23 %

Table 3
Daily streamflow (m3/s) output from the Log-Pearson Type III analysis in subbasin 7. The buffers had a larger effect on this scale compared to the watershed scale.

Log-Pearson Type II Analysis Subbasin 7								
TR	Probability	Q Base	Q BAU	Q 15	Q 30	Percent Change: BAU to Base	Percent change: B15 to BAU	Percent change: B30 to BAU
2	50 %	43.08	39.71	39.21	38.62	−7.83	−1.26	−2.75
5	20 %	75.43	70.65	70.20	69.57	−6.34	−0.63	−1.52
10	10 %	102.23	99.93	99.63	99.06	−2.25	−0.30	−0.87
25	4 %	142.57	149.99	150.05	149.71	5.21	0.04	−0.19
50	2 %	177.44	198.94	199.46	199.44	12.12	0.26	0.25
100	1 %	216.82	260.09	261.28	261.77	19.96	0.46	0.65
200	0.5 %	261.12	336.21	338.35	339.61	28.76	0.64	1.01

developed or agricultural areas in these buffers to forested land. In these cases, particularly in agricultural areas, grass and herbaceous vegetation can be utilized in buffer zones and still provide benefits such as filtering runoff and providing bank stabilization (Riis et al., 2020).

4.2. Changes in general streamflow from baseline to future periods

Our scenarios of projected daily streamflow values from 2000 to 2060 revealed an increase in daily flow rates with an evident shift in of timing low flow events. At the outlet, lowest flow occurrence shifts from February during the Baseline to early July in the future. This finding is important, as ET in SE watersheds is sensitive to changes in temperature and precipitation (Younger et al., 2020). Higher future temperature patterns could increase ET, which causes reductions in baseflow. Therefore, this shift in timing at the outlet means low flows in the growing season will potentially be exacerbated by variable future precipitation patterns and higher temperature. Further, other climate models in the CMIP5 ensemble project more extreme changes to temperature and precipitation compared to the CSIRO model used in this study (Suttles et al., 2018). This response could also suggest developing basins are succumbing to urban stream syndrome once they hit the 10 or 20 % development threshold and start displaying flashier hydrographs (Bledsoe and Watson, 2001; Walsh et al., 2005). Urban stream syndrome describes a condition that can affect water bodies flowing through developing and developed areas, characterized by increased nutrient and contaminant concentration, physical disruptions to the channel network, and loss of aquatic biodiversity (Meyer et al., 2005; Paul and Meyer, 2001). Future projected development in several subbasins pushed the percent of developed land past a 5, 10, or 20 % threshold, resulting in differing hydrologic responses potentially linked to the variability of urban stream syndrome. Subbasin 18 underscores this point, where buffers exacerbated low flows when future development surpassed a 10 % threshold and alleviated low flows when development was reduced to 10 %.

4.3. Buffer effect on maintaining low flow

Adding buffer treatments resulted in small hydrological changes for low flow at the watershed outlet, and overall the differences between the protected buffer treatments were small. Ecologically, the percentage of additional forest cover in each subbasin relative to the basin size might have been too small to alter extreme hydrologic events at the outlet. Cole et al. (2020) suggest that forested buffer strips should comprise between 20 % and 40 % of the total catchment to attenuate natural flooding. Our findings are consistent with Knouft et al. (2021), who found that the addition of 30.5-m riparian buffers did not significantly alter streamflow under changing climate. Likewise, (Wu et al., 2020) found riparian buffers more effective at reducing sediment load versus a significant reduction in streamflow. Caldwell et al. (2015) also found that a suite of fine-scale and regional-scale hydrologic models in the SE over predict low flows.

The percent change in low flow (lowest 10 percentile) across the watershed indicates buffer treatments decrease flow rates during low flow events in developed areas (development >20 %) but can potentially increase flow in developing areas (<20 %) and areas with >50 % development. This finding suggests that buffers have a more variable and localized effect on low flow that is likely connected to subbasin Baseline land cover. One important implication of this finding is that standardized buffer treatments may not stabilize low flows in areas that already experience urban stream syndrome during the Baseline (>20 % development), supporting evidence that land cover change is less impactful on streamflow for highly developed watersheds (Martin et al., 2017). However, buffers may help alleviate or avoid urban stream syndrome in newly developing basins (subbasin 18), and might have water quality benefits we did not assess in this study (Lebo et al., 2012).

Understanding the baseflow component of hydrograph separation is an important factor towards understanding overall hydrologic behavior in a watershed, as baseflow is the sustaining force for streamflow between rainfall events (Bosch et al., 2017; Singh et al., 2019). In our study, mean daily baseflows in developed areas were higher in the future period except during mid-summer. During these months, we found that either 15-m or 30-m riparian buffers could increase or decrease mean daily baseflow compared to the Baseline depending on the subbasin; however, the change in flow was minor ($\leq$ 1 %). The positive relationship between increased forest cover from the buffers and increased baseflow could also be explained by ET reduction from forest loss associated with development (Price et al., 2011; Teuling et al., 2019). However, changing temperature and precipitation patterns during the future period could negate the offsetting effects development has on forest ET. At the outlet, future mean daily baseflow rates dropped during peak growing season compared to the Baseline. Precipitation and temperature were projected to be higher during peak growing season from Baseline to future periods. Higher temperature usually increases growing season transpiration rates. Higher transpiration rates in riparian zones could result in decreased groundwater availability and lower baseflow contribution to overall streamflow (Li et al., 2020). Some of the potential effects of an increase in transpiration on streamflow might be offset by increased precipitation.

Decreased baseflow in mid-summer months may suggest a need for management interventions in areas threatened by water scarcity, as stable baseflow levels are often perceived as indicators of stable water resources (Tan et al., 2020). Our findings indicate that expanded riparian buffers have the potential to maintain higher baseflow levels in certain areas compared to the BAU scenario. This finding would benefit from expanded research on variable or strategic buffer widths in highly developed areas. The notion of strategic buffer strips and the subsequent effect of buffers on watershed processes in more forested areas corresponds to the Bond et al. (2002) notion of the "zone of vegetation influence" on the streamflow regime. Management activities that utilize buffer zones for mitigating the effects of land conversion on baseflow would also benefit from an examination on water demand by different vegetation types, as forested areas have a greater capacity for soil moisture extraction (Brown et al., 2005b).

4.4. Buffer effect on high flows

We found that high flows (flows in the highest 10 percentiles of daily flows) will increase by 4 % across the watershed for both the BAU, Near Future, and Midcentury periods under our chosen climate/land cover change scenario. Buffer treatments were particularly effective at decreasing flow rates during high flow events in subbasins with the highest levels of Baseline development (>30 %). The buffer effect was more variable at lower development thresholds, but generally buffers did not counteract the effect of increased impervious surface cover in areas near the 10 % or 20 % development threshold. Buffers minimally affected flow during high flow events (<1 % decrease) at the watershed outlet, indicating again that buffer addition is potentially more impactful at the localized versus watershed scale, especially in highly developed areas.

Flood analyses at the outlet revealed an increase in percentage of flow during the 2, 25, 50, 100, and 200-year return periods and a decrease during the 5 and 10-year periods from BAU to Baseline. In subbasin 7, flow decreased during the 2, 5, and 10 year periods and drastically increased in the 25, 50, 100, and 200-year periods, with B30 decreasing flow by 2.8 % at the 2-year period. The minimal effect of buffers at the outlet compared to subbasin 7 underscores that buffers in this study have a larger hydrologic impact at smaller scales. Further, buffer treatments can successfully mitigate flow rates during smaller magnitude floods, but need to be coupled with other management strategies at larger return periods.

The increased number of flood days during the future period corresponds to the more extreme and variable precipitation patterns that occur over the future period. Our findings are consistent with Martin et al. (2017), where increased water availability during some future periods did not compensate for the prevalence of increased drier periods, and planners should be prepared for both extremes. There is an inextricable relationship between forests and flooding, specifically in that robust, connected riparian corridors (and the floodplains they contain), can attenuate flood magnitudes during periods of high flows (Gurnell, 2014; Hupp and Osterkamp, 1996; Stallins et al., 2010; Tockner and Stanford, 2002). Specifically, increased vegetation in the riparian zone creates greater physical resistance to floodwaters and reduces flow velocity, which increases infiltration rates and allows for greater groundwater recharge (Riis et al., 2020). These effects can dampen downstream flood peaks, delay the timing of peaks, and allow for a slower release of water in dry periods (Riis et al., 2020; Thomas and Nisbet, 2007).

However, simply expanding buffers to manage stormflow in isolation of other mitigation activities might not be effective or practical across a heterogeneous landscape. Boggs and Sun (2011) underscore this point through their finding that even watersheds with similar climatic characteristics produce differing hydrologic responses based on a series of controlling factors, including forest prevalence. Differences in landscape structure have been attributable to differences in mean response time among catchments (Nippgen et al., 2011) and explanatory control on runoff source area (Jencso et al., 2009). While the flood analyses at the outlet indicated that B15 and B30 buffers decreased flow during the return periods and reduced the number of flooding days in the future relative to the BAU, this effect was small. Buffer effect in individual subbasins, such as subbasin 7, might be more impactful as a result of internal landscape structures, versus across a heterogeneous landscape at the watershed scale.

4.5. Hydrologic model limitations

SWAT is one of the most widely used hydrologic models, and its open-source nature, computational efficiency, extensive user community, and GIS interface were all advantageous for this research. It is possible that the SWAT representation of hydrologic routing does not fully capture riparian buffer benefits on runoff. SWAT interprets buffer addition in the subbasin as a general land cover change but does not specifically account for spatially explicit riparian processes.

Fully distributed models such as MIKE-SHE might better represent the spatial extent of riparian area within the watershed. MIKE-SHE has been used successfully to model river basin scale dynamics (Zhang et al., 2021) and assess riparian buffer reforestation (Botero-Acosta et al., 2018; Fabris et al., 2018). However the complex structure of such models make them computationally intensive and prone to overparameterization (Neumann et al., 2021), which could affect processing at the regional watershed-scale that was used in this study. The US EPA SWMM model is a common tool for urban drainage infrastructure that has been applied across watersheds (Kachholz and Tranckner, 2020; Tsai et al., 2017), and has the capability of simulating riparian buffers (Wright et al., 2021). While recent developments have helped the model better estimate ET (Hornschemeyer et al., 2021) and evaluate thermal mitigation practices (Ketabchy et al., 2019), it remains most practical for primarily urbanized versus mixed use areas. Further, Golmohammadi et al. (2014) evaluated the performance of SWAT, MIKE-SHE, and APEX models in a small-sized watershed and found both SWAT and MIKE-SHE outperform APEX, with MIKE-SHE slightly outperforming SWAT during the validation period. However, the study notes that the distributed nature of MIKE-SHE requires a large amount of input data that limits its usage in watersheds lacking measured observations (Golmohammadi et al., 2014). SWAT has the flexibility to address management practices owing to continual model development, making it one of the leading watershed-scale models nationally and abroad (Gassman et al., 2014). Therefore, SWAT was chosen for this study based on the scale, accessibility, and replicability of the model.

Previous SWAT studies have incorporated riparian buffers using a filter strip option, which applies a vegetative buffer at the HRU level. SWAT uses filter strips to remove contaminates such as sediment, nutrients, and pesticides, but does not affect surface runoff. Filter strips were not applied in this study as the focus was on water quantity. Recent studies have had success coupling SWAT outputs with models such as the Riparian Ecosystem Management Model (REMM) to better account for the ecological function of riparian areas in SWAT (Jiang et al., 2020). Future riparian buffer research using the SWAT model could benefit from this coupled approach.

5. Conclusions

We tested the effects of land cover and climate change on daily streamflow in the Upper Neuse watershed and the potential for riparian buffers to mitigate these changing conditions. We found that buffer treatments have a minimal impact on streamflow at the watershed scale but could be impactful at more localized levels, as buffers were associated with an increase in flow during the lowest flow events and a decrease in flow during the highest flow events in the most developed parts of the watershed. Buffers may also help alleviate the effects of urban stream syndrome in developing areas. This research aimed to present a novel approach for riparian buffer assessment by using a multi-model approach consisting of SWAT and FUTURES to provide a scientific analysis of a common management practice increasingly utilized to mitigate anthropogenic effects on water resources. Further research on riparian buffers using hydrologic models could benefit from linking SWAT outputs with ecological models and focusing on the effect of strategically placed versus standardized buffer zones.

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CRediT authorship contribution statement

Following the CRediT format, author contributions include: Elly Gay: conceptualization, writing- original draft, methodology, data analysis, data collection, Katherine Martin: Conceptualization, Writing- data analysis, methodology, review & editing, Supervision, Peter Caldwell: Writing- data analysis, methodology, review & editing, Ryan Emanuel: Writing - Review & Editing, Georgina Sanchez: Methodology, writing - Review & Editing, Kelly Suttles: Writing - Review & Editing.

Data availability

Data will be made available on request.

Declaration of competing interest

The authors declare there are no conflicts of interest.

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