Original Research Paper

Future Water Budgets and Water Supply Stress under Climate Change and Urbanization in the Upper Neuse River Basin, North Carolina, USA

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Abstract: Urbanization and climate change are the two major threats to watersheds and the environment in the United States. It is imperative to understand the sensitivity of hydrologic responses to climate and urbanization across different physiographic regions in order to formulate sound watershed management strategies and policies. This study evaluated a watershed water balance model, Water Supply Stress Index (WaSSI), with measured historic streamflow data for the Upper Neuse River basin in central North Carolina. A user-friendly web version of the WaSSI model was applied to examine how climate change and potential urbanization over the next 50 years may affect streamflow (or water yield) of this river basin and water supply stress (water demand/water supply). Our simulation study suggested that urbanization could increase water yield (8%), while climate change could reduce (30%) water yield depending on future changes in precipitation and warming potential in the study basin. Climate change is likely to overwhelm the basin-wide impacts of urbanization in terms of its influences on water supply stress, but urbanization may aggravate the environmental problems by increasing stormflow and water quality degradation under a changing climate. Future climatic change models should reduce the uncertainty of climate projection in precipitation, a major control on watershed hydrology.

Keywords: Climate Change, Hydrologic Modeling, Urbanization, Water Yield, Water Supply

Introduction

Water is essential to life (McDonald *et al*., 2011). Water has been regarded as one of the most important natural resources, even more precious than oil in the future. Water sustains many economic activities including agriculture, transportation, manufacturing, recreation and tourism (Sun *et al*., 2008; 2013). In turn, humans have altered the water resource distribution, quality and availability directly through water use or indirectly through change in land use patterns, urbanization and local and global climate (Sun and Lockaby, 2012).

Climate change is the long-term change in weather patterns, including precipitation and temperature. It is caused by an increase in greenhouse gasses in the atmosphere (IPCC, 2014) and it is well known that climate change has profound impacts on stream hydrology, water quantity, water quality and water supply to ecosystems and humans (McDonald *et al*., 2011; NCA, 2014). Warmer temperatures caused by excess greenhouse gas emissions have been linked to acceleration of hydrologic cycles by increasing the rate of evapotranspiration. The results may leave some areas in drought and others with excess precipitation. Heavy downpours increase surface runoff which can wash pollutants and trash into water supply and recreational areas (Kundzewicz *et al*., 2007; CCSP, 2014). This could seriously impact water quality by causing problems for water infrastructure. In some areas of the country the effects of climate change can cause a shift in the

balance of water supply and demand (Sun *et al.*, 2008; Caldwell *et al.*, 2011; 2012). This shift will pressure managers to meet the changing needs of communities. We need to better understand and predict future climate change impacts on water resources.

The piedmont region, which contains the Research Triangle Park (RTP) area, in North Carolina is known for its vigorous economy accompanied by rapid population growth and land use change in the past two decades. For example, the Upper Neuse River Basin (UNRB) (in eastern North Carolina (Fig. 1) has a population of 190,000 people and it is projected that over the next 25 years, population will grow by 53% to 280,000 (http://unrba.org). Under uncontrolled growth, the watershed will see dramatic loss of forest land to urbanization. It was projected that urban and suburban areas could change from the current 18 to 60% in 25 years. The City of Durham, a major city within UNRB, has experienced a 40% population growth from the 1990 to 2010 s. Growth can lead to increased water pollution from storm runoff and non-point source pollution (O'Driscoll *et al.*, 2010) and is a major environmental concern in city planning in the southeastern US.

During the past decade, the waters of the UNRB have degraded and have been challenged to meet the demands of society and the environmental standards. Falls Lake is the primary source of drinking water for the City of Raleigh (Fig. 1). Concerns over water pollution and drinking supply for Raleigh have arisen amid the rapid population growth, urban sprawl and dynamic climate in the basin. The Falls Lake reservoir, constructed between 1978 and 1981, has emerging water quality and quantity issues. It has a surface area of around 12,500 acres and is the primary source of drinking water for Raleigh. The Falls Lake is a shallow Piedmont lake and thus it is difficult to maintain its water quality for chlorophyll-*a* because of its geology and topographic location downstream of urban areas. Now the water in Falls Lake is considered 'impaired,' meaning the water quality does not meet North Carolina standards.

Therefore, better understanding of the water budgets and water supply stress of the UNRB at present and in the future will allow policy makers to make informed management decisions. Decisions made on sound hydrological science will benefit local citizens and sustain the region's environmental resources.

The objectives for this study were to: (1) construct a water budget for the UNRB using the WaSSI hydrological model; (2) verify model performance with measured streamflow and ET data; and (3) assess the individual and combined potential impacts of future climate change and urbanization on the streamflow and water supply stress for the UNRB.
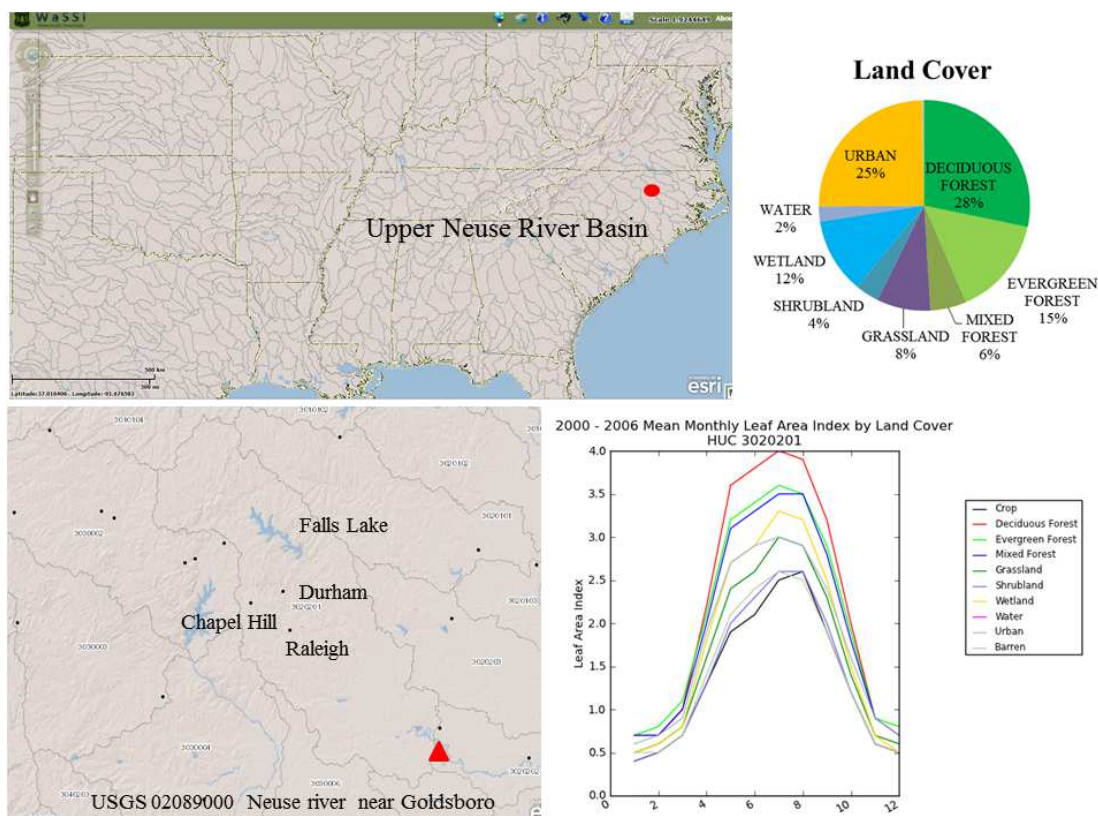

Fig. 1. Location, land use composition and leaf area index of the Upper Neuse River Basin (HUC 03020201) in North Carolina

Research Methods

The Upper Neuse River Basin (UNRB)

This study focuses on the Upper Neuse River Basin (UNRB) in North Carolina (Fig. 1). The UNRB intersects several counties from the headwaters (Person Orange), the middle reach (Durham, Granville), to the lower reach (Wake, Johnson, Wayne). The basin is identified with an 8-digit Hydrologic Unit Code (HUC) number of 03020201. The UNRB, located in the piedmont physiographic region, has a total catchment area of 6,232 km^2 and is comprised of several important tributaries such as the Flat, Eno and Little Rivers. The basin contains nine public drinking water supply reservoirs that serve about 500,000 people including Falls Lake Reservoir, Raleigh's major water source. The basin also contains many parks, such as the Eno River State Park, an important recreational area for North Carolina residents.

Watershed Land Cover Characteristics

The watershed is dominated by forest (56%), cropland (26%) and urban land (18%) use. The land cover data for this study were aggregated from the 2006 National Land Cover Dataset (30×30 m resolution based on Lands at imagery and classified into 17 cover types (http://www.mrlc.gov/nlcd06_data.php).

Climate Data for Model Validation and Predictions

The historic climate dataset (4×4 km resolution) for the 1961-2010 time period was derived from the Precipitation Elevation Regression on Independent Slopes Model (PRISM) database (Daly *et al.*, 2008). These data were used to validate the WaSSI model by comparing simulated streamflow with measured at one hydrologic gauging station maintained by the US Geological Survey (USGS).

Future climate data were acquired from downscaled by General Circulation Model (GCM) projections (Coulson *et al.*, 2010). Two climate change scenarios under greenhouse gas emission storyline SRES A1B were used to examine how future climate change may affect water resources in the UNRB. The two GCMs are CGCM3, developed by the Canadian Centre for Climate Modeling and Analysis and MIROC3.2, developed by the Center for Climate System Research, National Institute for Environmental Studies and Frontier Research Center for Global Change in Japan. These two GCMs represent two very different future climate conditions, warm (CGCM3) and drier and hot (MIROC3.2), in comparison to historic climate.

The WaSSI Model

This study used the USDA Forest Service Water Supply Stress Index (WaSSI) model (Fig. 2). WaSSI was designed and applied to the southeastern US at the 8-digit HUC watershed scale to estimate watershed water balances, carbon balances and water supply and demand on a monthly time step (Sun *et al.*, 2011a; Caldwell *et al.*, 2012; Sun *et al.*, 2015). A user friendly version of model is available online at http://www.forestthreats.org/research/tools/WaSSI. Users have the option to run multiple future scenarios to represent land use change (e.g., reforestation, urbanization) under historic climate (1961-2010) or 13 historic and future climate scenarios (1961-2099). Both model inputs and outputs can be viewed online and can be downloaded as charts, maps, or text files for additional analysis (Fig. 3).

The WaSSI model is an integrated, process-based simulator that describes key ecohydrological processes at a broad scale (Sun *et al.*, 2011b; Caldwell *et al.*, 2012; Sun *et al.*, 2015). It simulates water and carbon balances, including Evapotranspiraton (ET), soil water storage, runoff or water yield (Q) and ecosystem productivity (GPP) for each of eight land cover types within a given watershed and then aggregates these fluxes to the basin scale. Three sub-models are integrated within the WaSSI model framework. The water balance sub-model computes ecosystem water use (i.e., ET) and Q generated from each watershed. The carbon balance sub-model simulates monthly carbon gains (GPP) and losses (i.e., ecosystem respiration) in each watershed as functions of ET and GPP, respectively (Sun *et al.*, 2011a). The water supply and demand sub-model routes and accumulates Q through the river network according to topological relationships between adjacent watersheds, subtracts consumptive water use by humans from river flows and compares water supply to water demand to compute the water supply stress index. In this study, we focused on monthly and annual water yield (Q) and annual Water Supply Stress Index (WaSSI). By definition, water yield is the total flow generated from each basin as a function of monthly precipitation, ET and change in soil water storage. WaSSI is defined as the ratio of water demand over water supply. Water demand data were provided by periodic USGS water use surveys. The water use data for year 2005 was used in this study (Kenny *et al.*, 2009). Water supply refers to the sum of streamflow from the adjacent watersheds upstream, water yield generated from the current watershed and groundwater withdrawals in each month. For a complete description of the WaSSI model algorithms, readers are referred to the WaSSI User's Guide (http://www.forestthreats.org/research/tools/WaSSI/WaSSIUserGuide_english_v1.1.pdf).

The WaSSI model has been used to assess the combined or separate effects of climate change, land cover change and anthropogenic water use on historic and future water supply stress and ecosystem productivity over the US, Mexico, China and several African countries (Lockaby *et al.*, 2011; Averyt *et al.*, 2013; Tavernia *et al.*, 2013; Liu *et al.*, 2013; McNulty *et al.*, 2015). For this study, the focus is on the combined impacts of urbanization and climate change on annual and long term water yield.
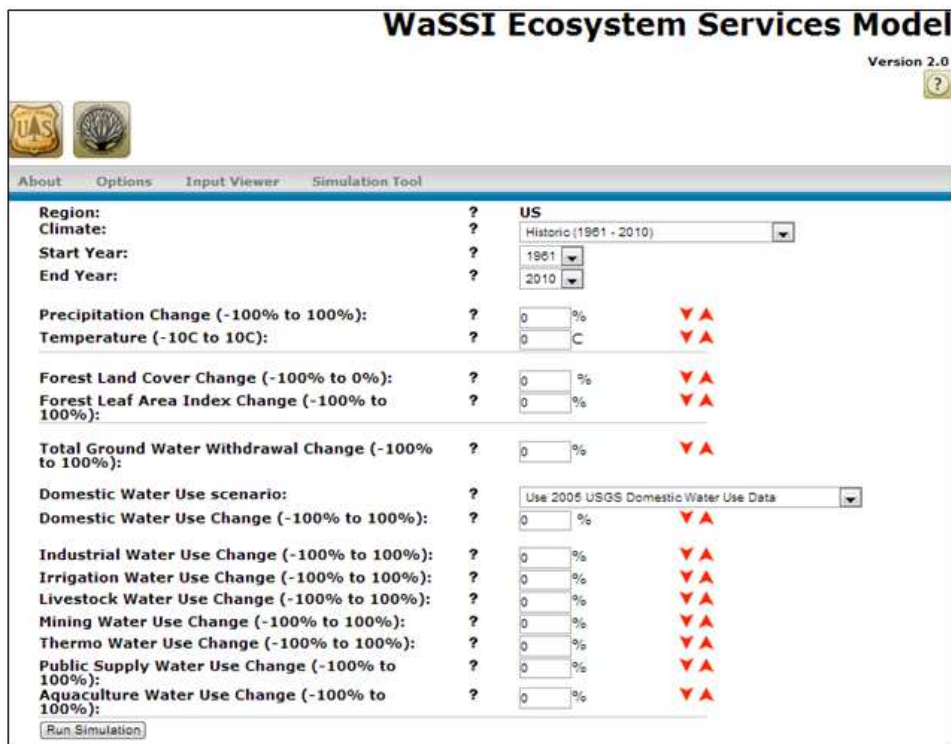
Fig. 2. A screenshot of the WaSSI online model user interface that allows the users to run the model online using different combinations of land covers and GCMs climate change scenarios or designed by the user
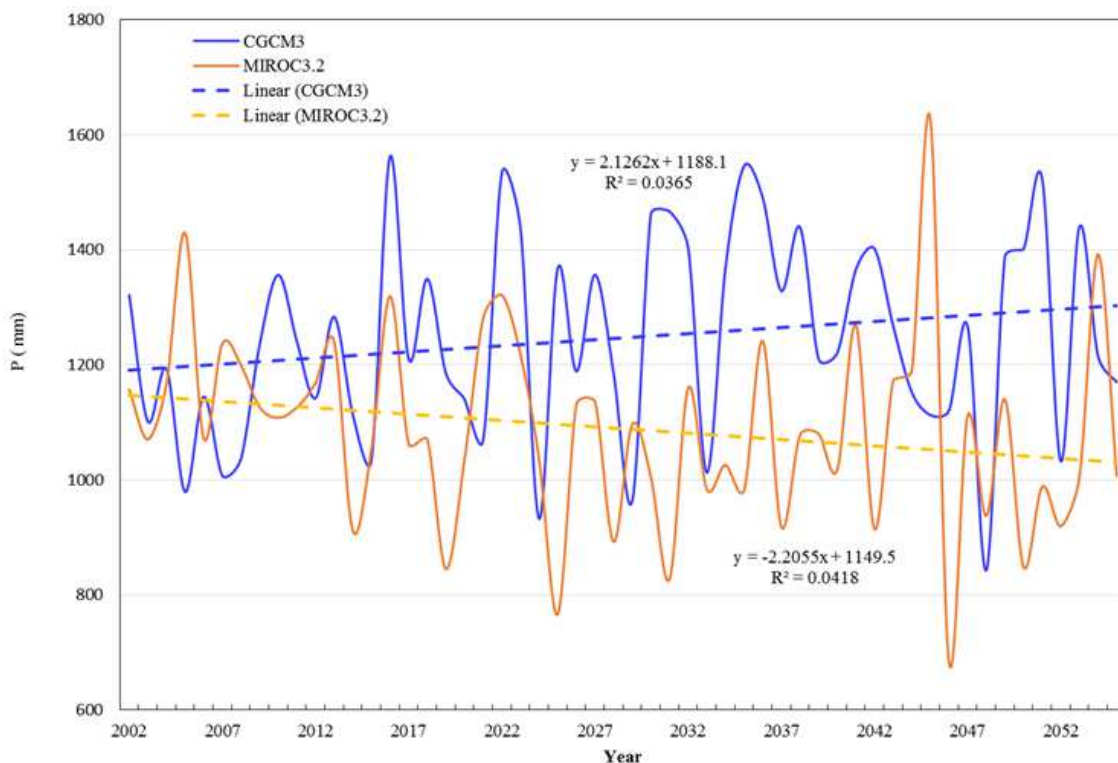

Fig. 3. Projected trend of annual precipitation for the Upper Neuse River Basin in North Carolina by two General Circulation Models (2002-2055)

Model Validation

The WaSSI model was designed for modeling watershed functions at the regional or continental levels. It is essential to evaluate the model's capability to simulate water balances locally and model uncertainty can be identified and quantified. Therefore, we first evaluated model performance using measured monthly streamflow data. However, the USGS Neuse River near Goldsboro (Station number: 02089000, Latitude 35°20'15", Longitude 77°59'51") started to operate only in 2007. Therefore we used reanalyzed monthly streamflow data by the USGS to represent flow measurements for the study basin (http://waterwatch.usgs.gov/index.php?id=romap3&sid=w__download). We evaluated the model performance in simulating monthly streamflow using Coefficient of Determination (R^2) and the slope of the linear regression model (simulated vs measured streamflow) and the Nash-Sutcliffe Efficiency (Nash and Sutcliffe, 1970).

Evapotranspiration (ET) is a major component of the watershed water balances and modeling errors of streamflow are often caused by model inadequacy in ET models (Sun *et al.*, 2011b). Therefore, the model's performance was also evaluated with published global MODIS ET by Mu *et al.* (2011) and modeled ET by from EC-MOD by Xiao *et al.* (2014). Both datasets have a 1×1 km grid resolution and were scaled to the HUC-8 watershed for model comparison purposes. The

MODIS ET data were developed using reanalysis of surface meteorological data with MODIS land cover, albedo, LAI and the Fraction of Absorbed Photo synthetically Active Radiation (FPAR). The ECO-MOD data represent 'scaled up' ET data of eddy covariance measurements with machine learning technique (Xiao *et al.*, 2014). The algorithms for regional and global ET mapping and monitoring have been evaluated with AmeriFlux flux datasets.

Model Applications

WaSSI was applied to six simulation scenarios derived from combinations of climate and urbanization projections that may represent future climate and land use conditions for the UNRB in 2050 (Table 1). The first scenario (S0) is the baseline, while S1 represents converting 50% forest land to urban and population from 1.2 million in 2010 to 1.9 million in 2050, a 62% increase (Zarnoch *et al.*, 2010). The percentage of forest land area was reduced from 56 to 28% and urban land area was increased from the current 18 to 48% in 2050.

The S2-S5 scenarios represent future climate combined with increased population and with or without land use change. The CGCM3 GCM predicted a slight increase in precipitation (2 mm per year) (Fig. 3) and in PET (1.7 mm per year) (Fig. 4), while the MICRO3.2 GCM predicted a decrease in P (2 mm per year) and a large increase in PET (2.6 mm per year).
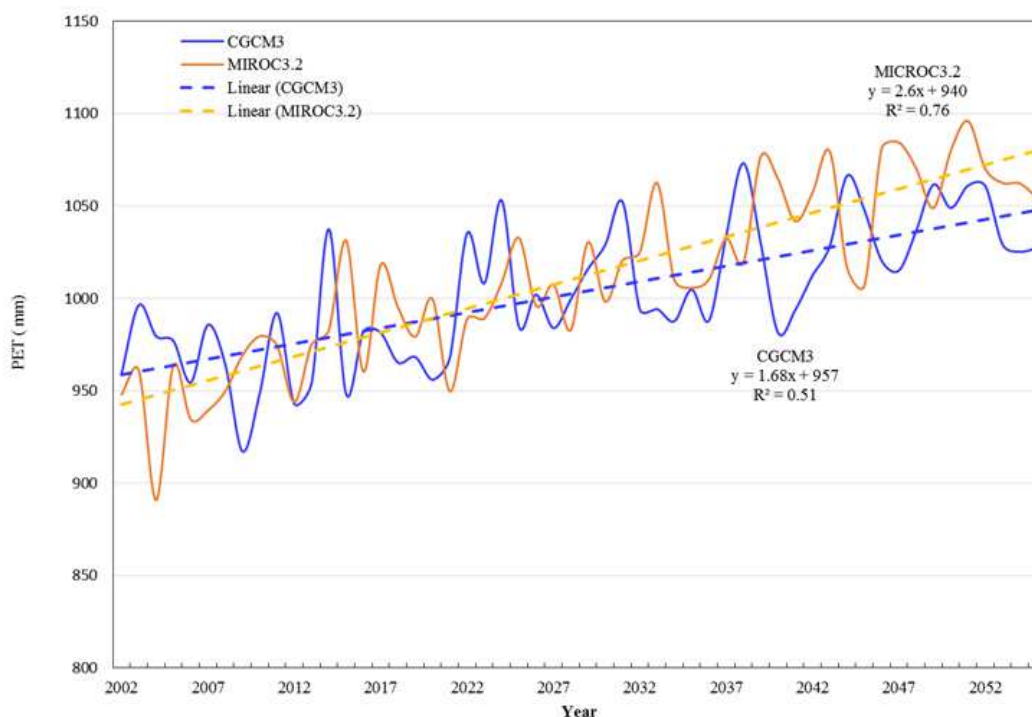

Fig. 4. Projected trend of annual potential evapotranspiration (PET) for the Upper Neuse River Basin in North Carolina by two General Circulation Models under the A1B emission storyline (2002-2055)

Table 1. Simulation scenarios by the WaSSI model to examine the combined hydrologic effects of climate change and urbanization

Scenarios	Climate	Land use	Population
S0	Historic (1961-2010)	Baseline (2006)	2005
S1	Historic (1961-2010)	50% Forest converted to urban	2050 IPCC SRES A1B scenario
S2	CGCM3	Baseline (2006)	2050
S3	MIROC3.2	Baseline (2006)	2050
S4	CGCM3	50% Forest converted to urban	2050
S5	MIROC3.2	50% Forest converted to urban	2050

Evaluation of Hydrologic Variables

In this study, we focused on two hydrologic variables, annual water yield (Q in mm/year) at the outlet of UNRB and water supply stress (WaSSI) under the six scenarios. Q indicates the water production capability of the watershed that is affected only by climate and land cover types while WaSSI reflects the influences of both nature (i.e., climate change and variability) and humans (i.e., urbanization and increased domestic water use accompanying population growth).

Results

Modeled Validation and Water Budgets

WaSSI captured monthly streamflow dynamics (Fig. 5) but overestimated the flow in September of 1999 when Hurricane Floyd hit North Carolina, resulting in widespread flooding in the UNRB. Similarly, the ET patterns modeled by WaSSI matched well with other ET estimates based on remote sensing techniques (Mu *et al.*, 2011) and ET data by Xiao *et al.* (2014). However, compared to MODIS-ET, WaSSI modeled ET rates were much lower during the growing season from April to September but much higher during the dormant season (Fig. 6).

At the annual time step, WaSSI modeled ET was lower than the MODIS-ET and the 'measured ET values'-the differences between measured P and Q, but higher than the estimated annual ET by Xiao *et al.* (2014) EC-MOD ET method (Fig. 7).

The measured mean annual precipitation (P) and streamflow (Q) for the 2001-2010 period was 1121 mm and 259 mm, respectively (Fig. 8). Modeled ET and water yield was 728 and 324 mm, or 65 and 35% of P, respectively. The WaSSI model overestimated Q by 91 mm per year or 27% on average when compared to measured Q. The overestimations were mainly found in wet years (2003, 2006) (Fig. 8). The simulated monthly Q was highly correlated with measured Q with a R^2 of 0.81 and Nash-Sutcliffe Efficiency of 0.71.

Impacts of Urbanization on Water Yield

The long-term baseline (S0, 1961-2010) mean annual streamflow was estimated as 437 mm (Fig. 8). As expected, converting 50% of forests to urban (S1) would increase Q by 34 mm per year or 8% due to the reduction in ET (Fig. 8). Urban land covers had lower Leaf Area Index (LAI) thus lower ET than forests (Sun *et al.*, 2011b; Sun and Lockaby, 2012).

Impacts of Urbanization + Climate Change on Water Yield

The mean annual water yield did not change much during 2002-2055 under the CGCM3 scenarios (S2, S4) (Fig. 10) although P increased by 2 mm per year (Fig. 3). This was because PET increased significantly at 1.7 mm per year (Fig. 4). In contrast, Q declined significantly under the MIROC3.2 climate scenarios (S3, S5) by 2.6 mm/year) (Fig. 10) as a result of decreases in P and increases in PET. Under the CGCM3 climate change scenario (S2), the mean water yield in 2050 (2045-2055) was almost identical (437 mm) to the baseline in 2005, although P increased 64 mm or 6%. This was due to the rise in air temperature and PET of 129 mm or 14%, resulting in a decrease in actual ET. However, water yield decreased greatly by 132 mm, or 25%, under the MIROC3.2 climate change scenario (S3). The change in water yield was a result of the combination of the 104 mm or 9% decrease in P and an increase in air temperature that resulted in an increase in PET of 154 mm or 17%. Because urbanization increased Q, the combination of urbanization and climate (S4, S5) resulted in a moderate increase in Q compared to S2 and S3. However, the urbanization effect could not compensate the large decline in Q for MIROC3.2 climate scenario (S3, S5).

Impacts of Urbanization and Climate Change on Water Supply Stress (WaSSI)

The baseline annual water stress index (WaSSI) was about 0.287, meaning 28.7% of the water supply was subject to water withdrawal from the basin (Fig. 9). This index was lower under the urbanization scenario (S1) as a result of increased Q and thus total water supply. Under S2, WaSSI increased slightly (from 0.287 to 0.3) as a result of population growth that required more water for domestic use. Due to the large decrease in Q, thus a decrease in water supply for the S3, WaSSI increased greatly to 0.458. Urbanization alleviated some of the water supply stress caused by MIROC3.2 to 0.40 (S5).
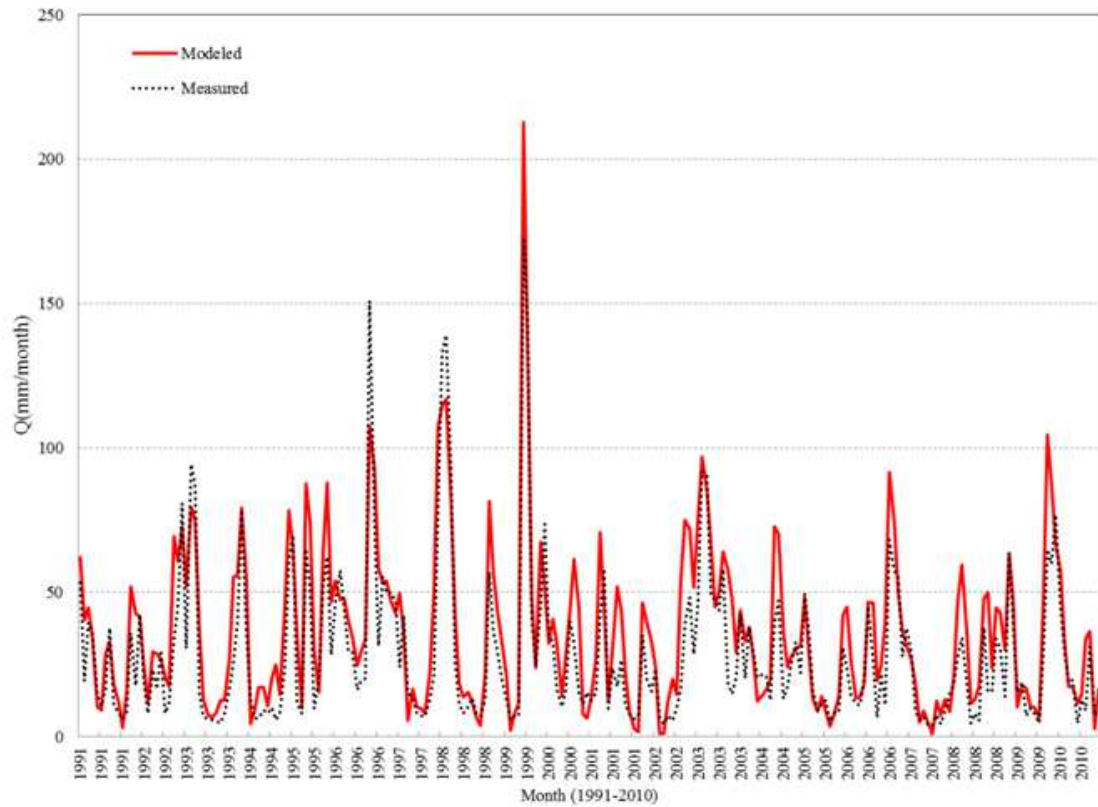
Fig. 5. Modeled and measured monthly streamflow for the Upper Neuse River Basin in North Carolina (1991-2010)
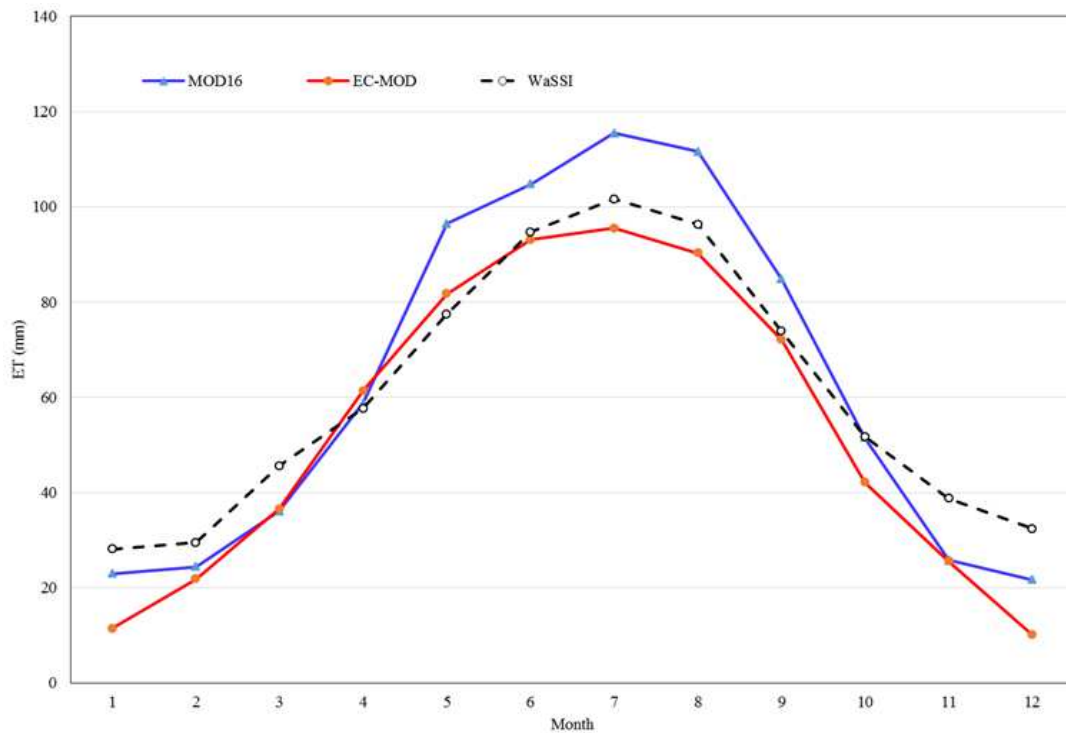

Fig. 6. A comparison of monthly modeled ET and estimated ET by the MODIS-ET (Mu *et al*., 2011) and EC-MOD by Xiao *et al*. (2014) for the Upper Neuse River Basin in North Carolina (2001-2010)
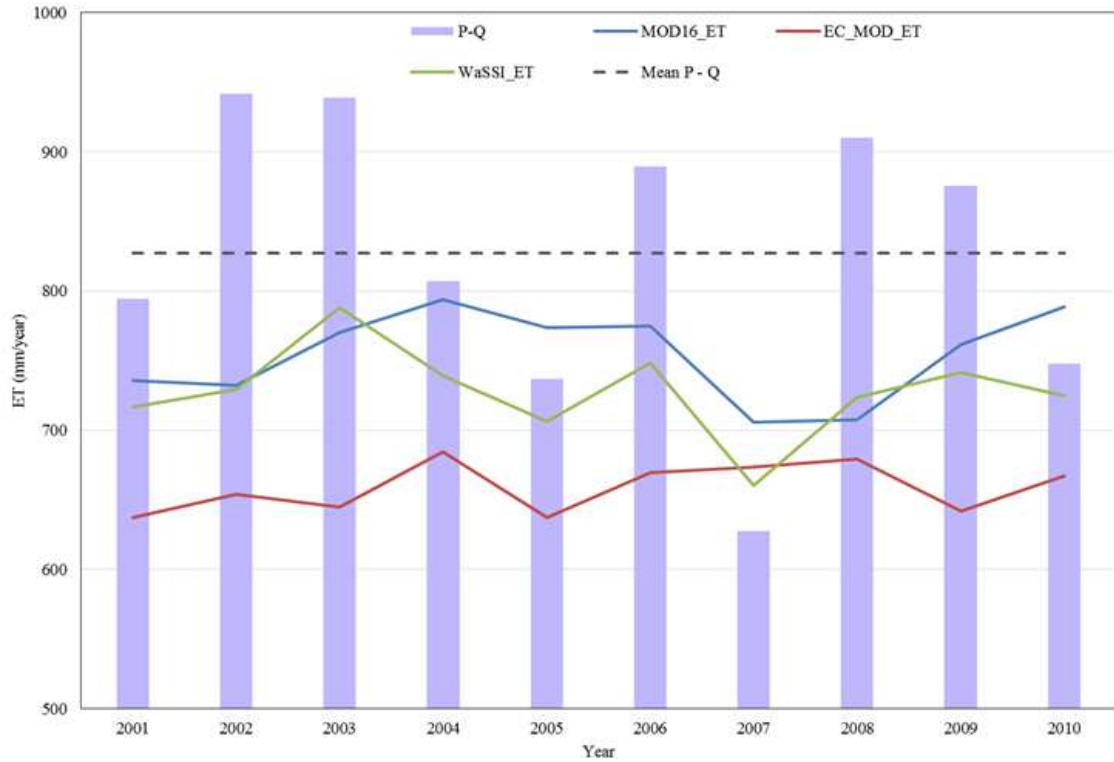
Fig. 7. Validation of annual evapotranspiration (ET) with different data sources for the Upper Neuse River Basin in North Carolina (2001-2010)
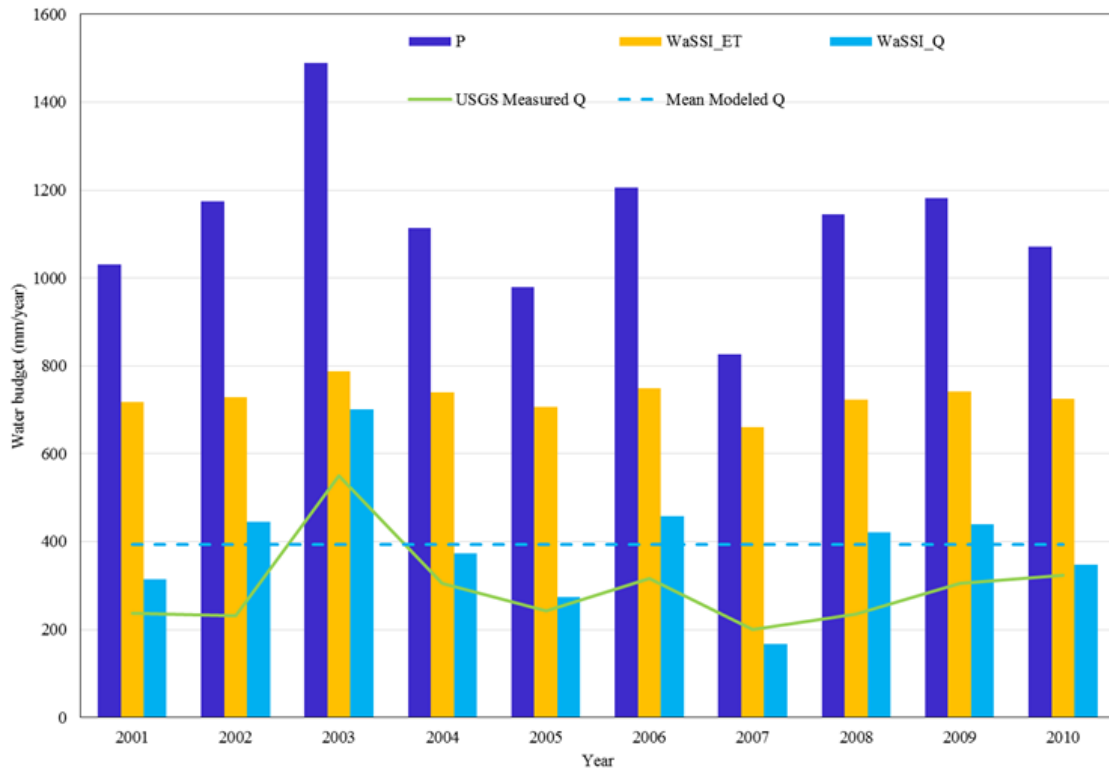

Fig. 8. Measured precipitation and streamflow and modeled water budgets for the Upper Neuse River Basin in North Carolina (2001-2010)
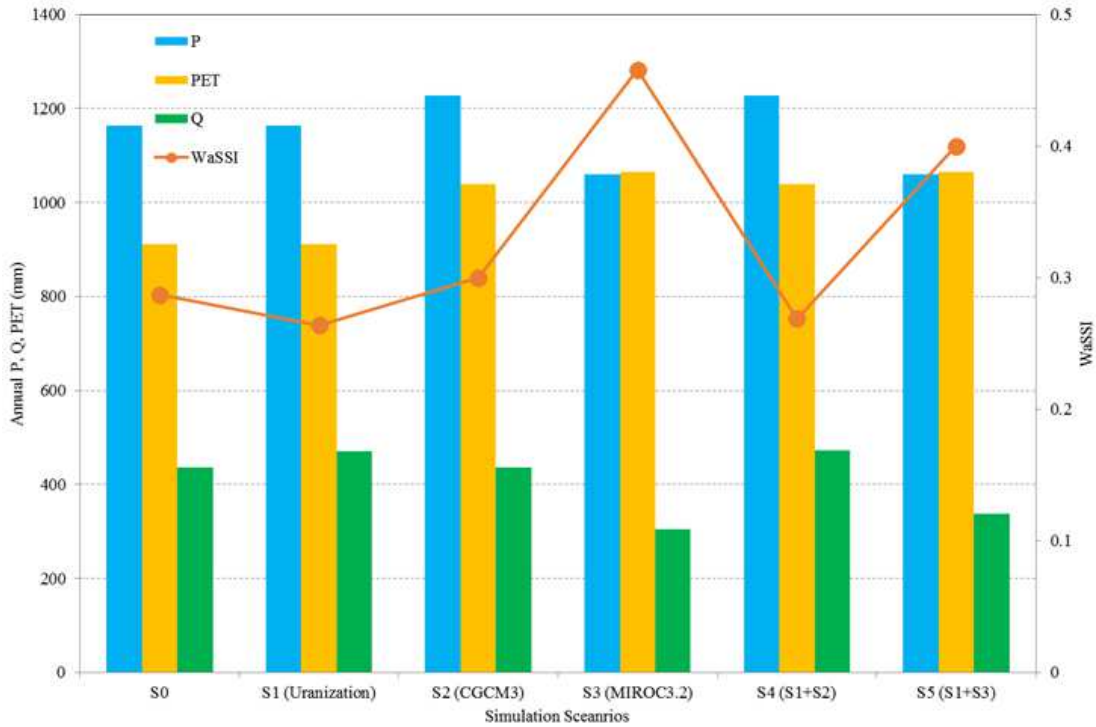
Fig. 9. Current and future (2050) annual water yield (Q) and Water Supply Stress Index (WaSSI = demand/supply) simulated by the WaSSI model
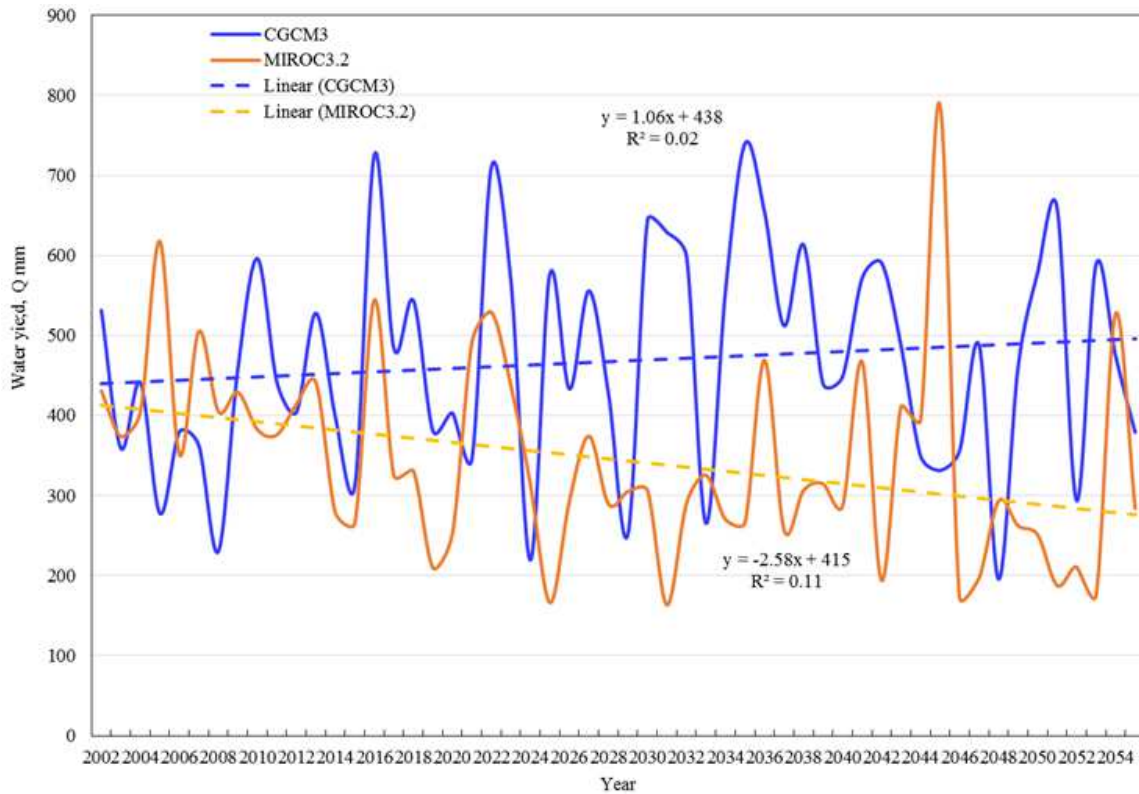

Fig. 10. Effects of climate change on annual water yield (Q) simulated by the WaSSI model

Conclusion

Our study indicated that some climate change scenario (MIROC3.2) could overwhelm the hydrological effects of urbanization by 2050. Large scale urbanization can cause substantial increases in runoff. However, the increase in flow was notable to alleviate water supply stress caused by severe future climate change as characterized by climatic variability (e.g., droughts or floods). In addition, urbanization may cause more water pollution due to higher runoff and water quality degradation. Therefore, urbanization would aggravate environmental concerns under future climate change.

Although most GCMs agree on the direction of air temperature change, large uncertainties remain in future precipitation changes and therefore inaccurate predictions of water budgets and water supply for cities. While the CGCM3 scenario predicted that runoff in the UNRB would not change much, the MIROC 3.2 scenario predicted that water yield would decrease and water supply stress would increase. Water resource managers should evaluate the risk of water supply shortages.

It is challenging to predict what impacts future climate change will have on water resources at a local watershed scale. Future climate change models should reduce model uncertainty in projected precipitation so that predictions of water resources will be more consistent and more useful for watershed planning and management.

Acknowledgement

Authors' Contributions

Michelle Tong Sun: Initiated the study, performed the model runs and drafted the paper while working as a USDA Forest Service Intern.

Ge Sun: Supervised Michelle Sun in WaSSI model runs; Helped research design, reviewed and revised the draft.

Chong Liu: Performed WaSSI model validation in modeling runoff and MODDIS ET while visiting the University of North Carolina-Chapel Hill.

Jennifer Anne Moore Myers: Supervised Michelle Sun and contributed manuscript writing and revisions.

Steven George McNulty: Provided advice to Michelle Sun on model runs, research design, hypothesis test and reviewed modeling results.

Ethics

The authors declare no conflicts of interest.

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