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Combined and synergistic effects of climate change and urbanization on water quality in the Wolf Bay watershed, southern Alabama

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This study investigated potential changes in flow, total suspended solid (TSS) and nutrient (nitrogen and phosphorous) loadings under future climate change, land use/cover (LULC) change and combined change scenarios in the Wolf Bay watershed, southern Alabama, USA. Four Global Circulation Models (GCMs) under three Special Report Emission Scenarios (SRES) of greenhouse gas were used to assess the future climate change (2016–2040). Three projected LULC maps (2030) were employed to reflect different extents of urbanization in future. The individual, combined and synergistic impacts of LULC and climate change on water quantity/quality were analyzed by the Soil and Water Assessment Tool (SWAT). Under the “climate change only” scenario, monthly distribution and projected variation of TSS are expected to follow a pattern similar to streamflow. Nutrients are influenced both by flow and management practices. The variation of Total Nitrogen (TN) and Total Phosphorous (TP) generally follow the flow trend as well. No evident difference in the N:P ratio was projected. Under the “LULC change only” scenario, TN was projected to decrease, mainly due to the shrinkage of croplands. TP will increase in fall and winter. The N:P ratio shows a strong decreasing potential. Under the “combined change” scenario, LULC and climate change effect were considered simultaneously. Results indicate that if future loadings are expected to increase/decrease under any individual scenario, then the combined change will intensify that trend. Conversely, if their effects are in opposite directions, an offsetting effect occurs. Science-based management practices are needed to reduce nutrient loadings to the Bay.

Introduction

Land use/cover (LULC) and climate change have brought the issues of alteration in flow regimes and water quality deterioration to the forefront in many communities and countries around the world (Whitehead et al., 2009; Liu et al., 2013; Shaw et al., 2014; Chen et al., 2017). Changes in LULC, usually driven by increasing human population, are recognized as an important factor affecting water quantity and quality, often negatively. The most common cause of LULC change is urbanization. Urbanization usually affects water quality adversely. It causes increase in sediment and nutrient loads, heavy metals, and eventually blooming of toxic algae in receiving water bodies which can reduce dissolved oxygen

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levels (Bowen and Valiela, 2001; Bakri et al., 2008; Nagy et al., 2011; Gitau et al., 2016).

Besides LULC change, climate change is also a very important factor affecting water quantity and quality. Research suggests that increasing concentration of atmospheric CO_2 will change global climate systems, intensify the global hydrological cycle and have a major impact on regional water resources, which will affect both the distribution and quantity of water (Jha et al., 2006; Wu et al., 2012; Wang et al., 2017). Consequently, such changes will also affect fate and transport of sediment and chemicals (He et al., 2006; Strokal and Kroeze, 2013). Although both LULC and climate change play key roles for water resources and water quality, their combined effect and relative importance is not very clear, difficult to separate empirically, and varies from case to case and seasonally. Further, the combined effect resulting from the interaction of these two factors most likely is not a simple sum of each individual effect. In another words, there is a strong synergistic effect on hydrologic and water quality responses, when both LULC and climate changes are considered.

Hydrological and water quality modeling is often employed to assess the responses of water quantity and quality to environmental changes. Over the last two decades, models have greatly benefited from improved understandings of principles of eco-hydrologic systems, increased availability and accessibility of observed data, and substantial growth in computational power (Liu and Gupta, 2007). Compared to other estimation methods (paired catchments, approaches, time series analysis), modeling provides a framework to conceptualize and investigate impacts of climate and human activities jointly and separately, which is helpful to understand their relative importance well on water quantity and quality.

As an inherently probabilistic exercise (Praskievicz and Chang, 2009), there are uncertainties associated with models, which may come from variability of input data, parameter estimation and model structure (Beven and Binley, 1992; Clark and Slater, 2006; Yen et al., 2014). Proper consideration of uncertainty in hydrologic and water quality simulation needs to be seriously addressed in both research and operational modeling (Wagener and Gupta, 2005). When modeling the combined effects of future changes in LULC and climate on hydrology and water quality, variation in the model output mainly comes from the uncertainty of two input sources. One is related to the generation of future climate data to be used as model forcing data in the hydrologic models, such as the choice of the Global Circulation Models (GCMs), the choice of the Special Report Emission Scenarios (SRES; IPCC, 2001) of greenhouse gas, and different spatial and temporal downscaling methods to better represent climatology at regional scales. The second big source of uncertainty is associated with future LULC, which are quite hard to predict and are often affected by land use policy, economic development, population increasing/decreasing rate and natural environment.

Although several studies (*e.g.*, Olivera and DeFee, 2007; Guo et al., 2008; D'Agostino et al., 2010) focused on the combined effects of LULC and climate change on water quantity/quality, the following research gaps remain:

1. Most previous studies are focused on water quantity (Ma et al., 2009; Mango et al., 2010), with few studies thoroughly addressing the effect on various water quality indices, either due to data availability or model capacity.
2. Compared to future climate change scenarios, which usually contain various GCM outputs under different SRES, LULC change scenarios are too simplistic and do not consider the factors affecting LULC changes, such as land use policy, economic development, and natural environment.
3. Uncertainties, especially input uncertainties of both future climate and LULC projections are not satisfactorily addressed. As stated before, the uncertainty in the model output originates from many sources. Although some studies acknowledged the uncertainty caused by climate inputs (Wilby et al., 2006; Yen et al., 2015; Liu et al., 2015a, 2015b) Q4 there are limited studies (Chang, 2004; Wang et al., 2014) dealing with the uncertainties from climate combined with LULC change.
4. Individual effects from LULC and climate change are well established in previous studies, but the synergistic effect which is caused by the interaction of these two factors was rarely explored. Although some ecologic studies noticed the synergistic effect as multiple factorial contributions (Xu, 2010; Tian et al., 2011), in the field of hydrology, few studies pay attention to this important effect (*e.g.*, Molina-Navarro et al., 2014).

Inspired from these gaps, this study assessed responses of sediment and nutrient (N and P) loadings into a small bay in southeast U.S under predicted future climate and LULC conditions using the Soil and Water Assessment Tool (SWAT). Three study objectives are (i) explore the sediment and nutrient responses to combined effects of climate and LULC change; (ii) examine whether climate change exacerbates or offsets the impacts of LULC change and vice versa; synergistic effect is discussed when these two factors act simultaneously; and (iii) analyze climate and LULC induced future uncertainties on predicted sediment and nutrient loadings.

1. Methodology

1.1. *Study area*

Wolf Bay (Fig. 1) is nestled between the Perdido Bay to the east and Mobile Bay to the west, with its watershed covering about 126 km^2 in Baldwin County, coastal Alabama, USA. It is a sub-estuary of the Perdido Bay with a connection to the Intracoastal Waterway and includes various nutrient and sediment inputs from several sub-watersheds through Wolf, Sandy, Miflin and Hammock Creeks. The Wolf Bay watershed hosts a tremendous diversity of habitats that historically supported and may still support a large assemblage of plant and animal species. In December 2007, EPA designated Wolf Bay as an 'Outstanding Alabama Water', which provides additional protection for aquatic life.

Baldwin County experienced a 43% increase in population from 1990 to 2000, and another 30% increase from 2000 to 2010, and this trend is expected to continue according to the Baldwin County Planning and Zoning Commission (BCPZC). As a result of this population growth, there has been an increased demand for commercial, residential, and infrastructure development.

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