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Modeling the influence of climate change on watershed systems: Adaptation through targeted practices

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ABSTRACT

Climate change may influence hydrologic processes of watersheds (IPCC, 2013) and increased runoff may cause flooding, eroded stream banks, widening of stream channels, increased pollutant loading, and consequently impairment of aquatic life. The goal of this study was to quantify the potential impacts of climate change on watershed hydrologic processes and to evaluate scale and effectiveness of management practices for adaptation. We simulate baseline watershed conditions using the Hydrological Simulation Program Fortran (HSPF) simulation model to examine the possible effects of changing climate on watershed processes. We also simulate the effects of adaptation and mitigation through specific best management strategies for various climatic scenarios. With continuing low-flow conditions and vulnerability to climate change, the Ipswich watershed is the focus of this study. We quantify fluxes in runoff, evapotranspiration, infiltration, sediment load, and nutrient concentrations under baseline and climate change scenarios (near and far future). We model adaptation options for mitigating climate effects on watershed processes using bioretention/raingarden Best Management Practices (BMPs). It was observed that climate change has a significant impact on watershed runoff and carefully designed and maintained BMPs at subwatershed scale can be effective in mitigating some of the problems related to stormwater runoff. Policy options include implementation of BMPs through education and incentives for scale-dependent and site specific bioretention units/raingardens to increase the resilience of the watershed system to current and future climate change.

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1. Introduction

Climate change, through changes in timing and patterns of precipitation and temperature, is likely to impact water resources (IPCC, 2013). The global land and ocean surface temperature, shows a warming of 0.85 °C during 1880–2012 (IPCC, 2013), with recent decades warmer than prior decades. The Fifth Assessment Report (AR5) of IPCC observes that one of the most serious impacts of climate change is expected changes in surface runoff, especially in areas with impervious surfaces such as roads, parking lots and buildings (IPCC, 2013). Climate change impacts on runoff could be significant (Ekness and Randhir, 2015; Arnell and Gosling, 2013; Döll and Schmied, 2012). Some of the long-term effects of these changes on watershed ecosystems are increased stress to stormwater drainage systems and reduced habitat quality of aquatic ecosystems (Zoppou, 2001). There is a need for assessing impacts of climate change under varying future time scales and potential for adaptation through BMPs at a watershed scale.

Climate change impacts on watershed ecosystems and hydrologic processes are complex. Warming may cause shifts in the timing of streamflow in North America (Fritze et al., 2011) with implications in areas where water supplies are limited or overcommitted. Warmer temperatures in January and March may influence changes in the timing of runoff peaks. Changing climate can affect runoff patterns and timing in urban watersheds that have higher peak discharge and lower time-of-concentration in stormwater flows. This could have significant impact on stream ecosystems. In regions with higher expected precipitation, urban drainage systems receive volumes of water that could exceed their capacity to collect and redirect water to storage channels. Increases in precipitation intensity and duration can lead to increased flooding, eroded stream banks, widening of stream channels, polluted waters, impairment to aquatic ecosystems, changes in recreation use, threats to public health and safety, and economic impacts as well as increased costs of water and wastewater treatment. Land use changes through changes in impervious cover and alteration

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of watercourses (Zoppou, 2001) can further exacerbate climate induced problems in many watersheds (Marshall and Randhir, 2008).

Adapting to climate change is becoming a major part of the strategy to manage stormwater runoff in urban watersheds (California Climate Adaptation Strategy, 2009). Understanding the effectiveness of adaptation strategies and best management practices (BMPs) in order to mitigate hydrologic changes is critical for effective water resource management (Geosyntec Consultants, 2014).

Urban stormwater runoff is a significant source of pollution in estuaries and lakes (National Research Council, 2008). There are vast arrays of BMPs that can be effective in the managing pollutants. BMPs also have the added benefit of increasing infiltration and reducing overland flows. Implementation of more effective BMPs at the community level can help reduce the impact of climate change on stormwater runoff.

While the impact of climate change on watershed systems is well studied (Rahman et al., 2015; Ekness and Randhir, 2015; Luo et al., 2013; Marshall and Randhir, 2008), research on the efficiency of BMPs to mitigate these impacts is limited. The focus on subbasin-scale management options to reduce stormwater impacts from climate change is unique in the study. This need in research is critical in developing adaptation strategies that are local and site-specific to subbasins.

This study assesses the impacts of climate change on stormwater runoff in a coastal watershed and evaluates the impacts of BMPs to evaluate adaptation strategies at subbasin scale. We focus on hydrologic changes in the watershed ecosystems that result from climate change. In summary, this paper is unique in studying climate change impacts on watershed systems in near and far-future scenarios and in exploring opportunities for adaptation through targeted BMPs at subbasin scale using simulation modeling. The Ipswich Watershed is a focus of this study because of its severity in low flow conditions and poor water quality. The U.S. Environmental Protection Agency (USEPA) has identified the river as stressed and lists this river as impaired (under Clean Water Act's 303d list).

Specific objectives are to do the following: (1) Simulate baseline hydrologic conditions in the study watershed; (2) Examine the effects of near future and far-future climate change scenarios on watershed processes; and (3) Investigate the adaptation strategies using targeted placement of BMPs. The hypotheses specified are as follows: (i) Climate change in near and far-futures has significant effect on water quality and quantity of watersheds; and (ii) targeted BMPs in subbasins scale can be useful in adapting to climate change.

2. Methods

In this section, we provide an overview of the study area, conceptual and empirical models, and methods used in research.

2.1. Study area

The study area is the Ipswich River watershed (Fig. 1). The Ipswich River Watershed is located in northeastern Massachusetts and flows from its headwaters in Burlington, Wilmington and Andover, until reaching Plum Island Sound of the Atlantic Ocean in the town of Ipswich (Fig. 1). The river meanders and has a relatively flat course especially toward the end of the reach as it approaches the Ipswich Bay area. From the Ipswich headwater to the river's mouth, the elevation change is only about 35 m over about 64.37 km and has a drainage area of 401.45 square kilometers. The river itself is 56 km long and with its 45 tributaries, it covers an area of about 401.45 square kilometers. The Ipswich watershed has approximately 160,000 people that reside within its boundaries and includes all or portions of 21 towns (IRWA, 2013).

The Ipswich River has a history of problems with low flows and only recently has the watershed begun to improve. The American Rivers labeled the Ipswich River as the third most endangered river in 2003 (American Rivers Organization, 2003). The river is at a continually low state during the summer months as well going dry at multiple locations along the river. Through direct withdrawals from the river and excess ground water extraction, the river flows backwards at a particular location within the river.

The Ipswich watershed provides habitat for an array of wild life species including mammals, birds, amphibians, freshwater fish as well as anadromous fish. The forest of the Ipswich watershed is comprised primarily of white pine and mixed hardwoods, including red and white oak; sugar, red and silver maple; white ash, hickories and walnuts. There are considerable amounts of small mammals as well as larger ones including foxes, coyotes, bobcats, white tail deer, and moose (IRWA, 2013). The Ipswich river fish community is mostly generalist species that thrive in warm water and ponded conditions, as dams have changed the habitat available in the river. Seventy percent of the fish community is composed of three species: Redfin pickerel, American eel and Pumpkinseed. There are roughly 70 small dams and 500 crossings (culverts and bridges) in the river system, which has significantly altered the watershed from its natural conditions (IRWA, 2013). FTable in HSPF that defines channel geometry can model these structures.

2.2. Conceptual model

A conceptual model presents research flow in evaluating climate change effects on watershed systems (Fig. 2). Climate change includes temperature and precipitation, and both these impact the watershed hydrology. The watershed is composed of physical attributes that, in turn, influence water quality and quantity. Adaptation strategy policies can mitigate changes in watershed hydrology.

2.3. Simulation model

We use Hydrological Simulation Program (HSPF) Version 2.3 (Aqua Terra, 2014) to model the watershed system. This simulation model is an integration of several early simulation models that include Stanford Watershed (Crawford and Linsley, 1966), the Hydrologic Simulation Program Quality (Hydrocomp, 1977), and the Agricultural Runoff Management Model (Donigian, 1977), and other hydrologic models (Borah and Bera, 2003). HSPF is a continuous simulation model of watershed hydrology and water quality for both conventional and toxic organic pollutants, as well as pervious and impervious land surfaces and in streams and well-mixed impoundments. The HSPF simulates the storage and movement of water, by routing watershed surface and river processes (Donigian et al., 1984). U.S. EPA recommends the HSPF model as one of the models for total maximum daily load assessments nationwide (US EPA, 2014). The model is useful to analyze the long-term effects of hydrologic changes and water management practices (Borah and Bera, 2003). The model uses Philips method (Philips, 1957) and Chezy Manning equations to simulate infiltration (Migliaccio and Srivastava, 2007), and for overland runoff flows.

The shallow aquifer in the model considers active ground water storage and simulates fluctuations to deep percolation of ground water, ET, and baseflows. Kinematic wave equation (Migliaccio and Srivastava, 2007) models stream flow process. Other variables simulated in the model include soil and water temperatures, dissolved oxygen, carbon dioxide, nitrate, ammonia, organic nitrogen, phosphate and organic phosphorous. Woznicki and Nejadhashemi

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