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Research Paper

Assessing climate change-induced flooding mitigation for adaptation in Boston's Charles River watershed, USA

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ABSTRACT

Climate change is projected to have increased temperature and more frequent and intense rainfalls in the northeast of the United States. Green infrastructure has been identified as a critical strategy for stormwater management and flooding mitigation as well as for climate change adaptation. Climate science plays an important role in understanding a range of climate change impacts and the effects of green infrastructure for climate change planning. Nevertheless, a lack of down-scaled climate change data and place-based assessment has discouraged local communities to pursue further climate change plans. This study proposed a transdisciplinary planning framework assessing the effects of detention in mitigating climate change-induced flooding, using a case in the Charles River watershed, Massachusetts, USA. Derived from a climate sensitivity test in the watershed, 36 climate change conditions were modeled using Soil and Water Assessment Tool (SWAT) and compared to IPCC scenarios. Statistical analyses revealed that detention is more efficient in reducing flooding hazards in low and moderate emission scenarios than those at high emission scenarios. A range of extra land area designated for detention would be needed for mitigating floods under various climate change scenarios. Planning implications include the needs for effective siting of detention areas combined with soil conservation in watershed planning, innovations in adaptive land planning and urban design, and a call for an integration of climate science and hydrological assessment in the transdisciplinary planning processes to better inform and facilitate decision-making using green infrastructure for climate change adaptation in local communities.

1. Introduction

Climate-related extreme weather has become more frequent and intense in the past decades. Trends of increased temperature and precipitation patterns are linked to increased intensity and duration of storm events in the Northeastern United States (IPCC, 2014; Rock et al., 2001). Erratic and intensified storm events have significantly impacted populated urban regions and shown the failure of conventional stormwater management practices that were designed based on past knowledge and climate trends (Booth & Jackson, 1997; Chizewer & Tarlock, 2013; Means, West, & Patrick, 2005). Consequently, planners and designers face challenges in managing climate change-induced flooding and adapting urban stormwater drainage systems to climate change.

Green infrastructure, an interconnected system composed of natural or man-made open space and landscape features that can provide multifunctional ecosystem services benefits, has been identified as a critical strategy for both climate change mitigation and adaptation (Benedict & McMahon, 2006; Gill, Handley, Ennos, & Pauleit, 2007) in addition to addressing climate justice in local communities (Cheng, 2016). Implementing green infrastructure requires both bio-physical capacity and social-institutional capacity (Matthews et al., 2015Matthews, Lo, & Byrne, 2015) in which the transdisciplinary planning approach plays a critical role in adaptive planning and design processes for building resilient communities (Ahern, Cilliers, & Niemelä, 2014; Cheng, 2014). Nevertheless, a lack of down-scaled climate change data and place-based assessment has discouraged smaller communities (e.g. Cedar Rapids, Iowa) to further pursue climate change adaptation actions (Chizewer & Tarlock, 2013). Due to uncertainty about projected climate change variation at the local scale, more empirical studies are needed to understand climate change impacts on hydrology within local watersheds (Bastola, Murphy, & Sweeney, 2011; Wood, Lettenmaier, & Palmer, 1997) in conjunction with understanding the

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effectiveness of particular climate change adaptation strategies.

Climate science plays an important role in preparing the public and decision-makers for anticipating a range of climate change impacts through understanding the effects of adaptation strategies (e.g., green infrastructure) and developing climate change action plans. Integrating climate science into hydrological studies has two primary approaches: scenario-based and scenario-neutral. The most well-known scenario-based case is by the Intergovernmental Panel on Climate Change (IPCC) derived from General Circulation Models (GCMs) that project greenhouse gas emission scenarios on a global scale. The advantage of using an IPCC scenario-based approach is that it has been widely accepted in science and policy realms as a 'top-down' assumption for climate change and is considered a defensible method for studying climate change impacts (Praskievicz & Chang, 2009). For example, using downscaled and bias-corrected GCM projections over studied regional watersheds has been applied to Ohio-Tennessee River Basin for evaluating water quality and crop productivity (Panagopoulos et al., 2015). Nevertheless, spatial mismatch and uncertainty inherent in major GCMs are known to exist. In order to study local watersheds as small as the Charles River watershed, recent efforts have been made to understand the range of uncertainty among downscaling methods, such as Regional Climate Models, by statistical downscaling in order to reflect climate change on the local scale (e.g., Corney et al., 2013; Mullan, Fealy, & Favis-Mortlock, 2012). However, the wide range of uncertainty among various GCMs and within the different downscaling methods remains a drawback of this 'top-down' approach (Brown, Ghile, Laverty, & Li, 2012; Praskievicz & Chang, 2009). The scenario-neutral method, on the other hand, is considered as 'bottom-up' approach using synthetic weather generation data for climate sensitivity tests (Prudhomme, Wilby, Crooks, Kay, & Reynard, 2010). This approach is advantageous for a grounded understanding of climate variability impacts on stormwater runoff and flooding hazards in a local basin, as part of a physical environment vulnerability assessment (Brown et al., 2012). The disadvantage lies in a lack of incorporating probable future global emission scenarios and climate change projections (Praskievicz & Chang, 2009).

This study aims to understand long term impacts of climate change on flooding and the potential of green infrastructure for climate change adaptation strategies, using the Charles River watershed as a study case. A planning framework is proposed for landscape and urban planners to incorporate climate science and green infrastructure assessment in the transdisciplinary planning processes for climate change adaptation (Fig. 1). This study adopted the merits of both 'bottom-up' (i.e., sensitivity tests) and 'top-down' (i.e., IPCC scenarios) approaches to assess climate change and green infrastructure strategies in answering the research questions: 1) to what degree does climate change influence flooding hazards? 2) to what degree can stormwater detention mitigate climate change-induced flooding hazards? 3) in what way can climate science be integrated into watershed planning using green infrastructure for climate change adaptation?

2. Study area

Charles River watershed drains an area of 778 km^2 and intersects 35 municipalities within the Boston Metropolitan Area with a total population of 1.2 million (City of Boston, 2016), including a large portion of Boston, Massachusetts, in the New England region of the United States (Fig. 2). The watershed is relatively flat and half of the watershed area is urbanized. The watershed can be described in three parts: upper, middle, and lower basins. The lower basin is the location of the most populous cities (i.e., Boston, Cambridge) and nearly all land is dedicated for urban uses (i.e., commercial, residential, transportation, urban parks). The upper basin consists of several suburban communities (MAPC, 2009). The middle and the upper basins have preserved over 3200 hectares of wetlands and open space as the "Charles River Natural Valley Storage" areas for flood control since the 1970's (US Army Corps of Engineers, 2016) and are dominated by natural lands (i.e., forests and wetlands). Isolated patches of agriculture and recreational land uses throughout the watershed make up 6% of the watershed area and are the areas chosen for modeling potential stormwater detention capacity in this study, because they are the easiest to convert and least impacted by additional water storage under current conditions.

3. Methods

3.1. SWAT model description and data source

Soil and Water Assessment Tool (SWAT) (ArcSWAT 2009.10.1) (Arnold, Srinivasan, Muttiah, & Williams, 1998; TAMU, 2011) was selected for several reasons. First, it incorporates climate change data and detention functions into stream flow impact simulation at watershed scale (e.g., Wu & Johnston, 2007). Second, it can incorporate climate data input from multiple GCMs and IPCC climate change scenarios for studying hydrologic cycles, stream flows and water availability (e.g., Bekele & Knapp, 2010; Takle, Jha, & Anderson, 2005). Finally, SWAT has been successfully applied for simulating stormwater best management practices (e.g., sedimentation-filtration basins) in urban watersheds (e.g., Wang & Qiu, 2014).

SWAT is a continuous, long-term, and semi-distributed processed based hydrological model (Arnold et al., 1998). The hydrological cycle is simulated based on the following water balance equation:

$$SW_t = SW_0 + \sum_{i=1}^{t} (R_{day} - Q_{surf} - E_a - w_{seep} - Q_{gw})$$

where SW_t is the final soil water content (mmH_2O), SW_0 is the initial soil water content on day I (mmH_2O), t is the time (days), R_{day} is the amount of precipitation on day i (mmH_2O), Q_{surf} is the amount of surface water on day i (mmH_2O), E_a is the amount of evapotranspiration on day i (mmH_2O), w_{seep} is the amount of water entering the vadose zone from the soil profile on day i (mmH_2O), Q_{gw} is the amount of return flow on day i (mmH_2O) (TAMU, 2011). This key equation is applied to each *Hydrologic Response Unit* (HRU) at each time step. Each sub-basin is composed of several HRUs based on unique land use, soil, slope, and management attributes. The water yield from each HRU is calculated separately and aggregated to each sub-basin outlet that is then routed downstream through the main channel. HRU allows a more accurate description of water balance at a smaller unit to provide a more robust modeling (TAMU, 2011).

Major inputs in SWAT included elevation, soil, land use, and weather data. The 30 m grid-based Digital Elevation Model generated by the USGS National Elevation Dataset was used for delineating the entire basin and sub-basins. Additional sub-basin outlets were added in order to be comparable with the size of census tract for associated study regarding social vulnerability (Cheng et al., 2013). A total of 54 sub-basins and 1470 HRUs were delineated. Land use data input is based on a state-wide land use dataset (MassGIS, 2005). Table 1 illustrates the corresponding land uses that were categorized into SWAT customized land use. Fig. 2 illustrated the distribution of generalized land uses. Urban land uses (i.e., commercial, industrial, residential, transportation, institutional, junkyard, and utilities land uses) were categorized into four SWAT urban land use types (urban commercial, urban residential-high density, urban residential-medium density, urban residential-low density), occupy 50% of the watershed area. Natural areas (i.e., forests, bushlands, successional forests, wetlands, bogs, water) were categorized into forest and wetland (41%) plus water (3%). The remaining area includes agricultural land use (i.e., croplands, orchards, nurseries, pastures) (3%) and recreational land use (i.e., recreation, golf course, cemetery) (3%). All agricultural (including 0.12% of orchards and nurseries) and recreational uses were categorized into general agricultural (AGRL) land use in SWAT for evaluating their potential for adaptive detention rather than for site-specific design recommendations. This categorizing method is justifiable because most of the