Landscape and Urban Planning 167 (2017) 25–36

Contents lists available at ScienceDirect

Landscape and Urban Planning

journal homepage: www.elsevier.com/locate/landurbplan

Research Paper

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

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A R T I C L E I N F O

Keywords:
Green infrastructure
Climate change-induced flooding
SWAT
Watershed planning
Climate change adaptation
Climate change scenarios

A B S T R A C T

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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http://dx.doi.org/10.1016/j.landurbplan.2017.05.019
Received 1 October 2016; Received in revised form 24 May 2017; Accepted 28 May 2017
0169-2046/ Published by Elsevier B.V.

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

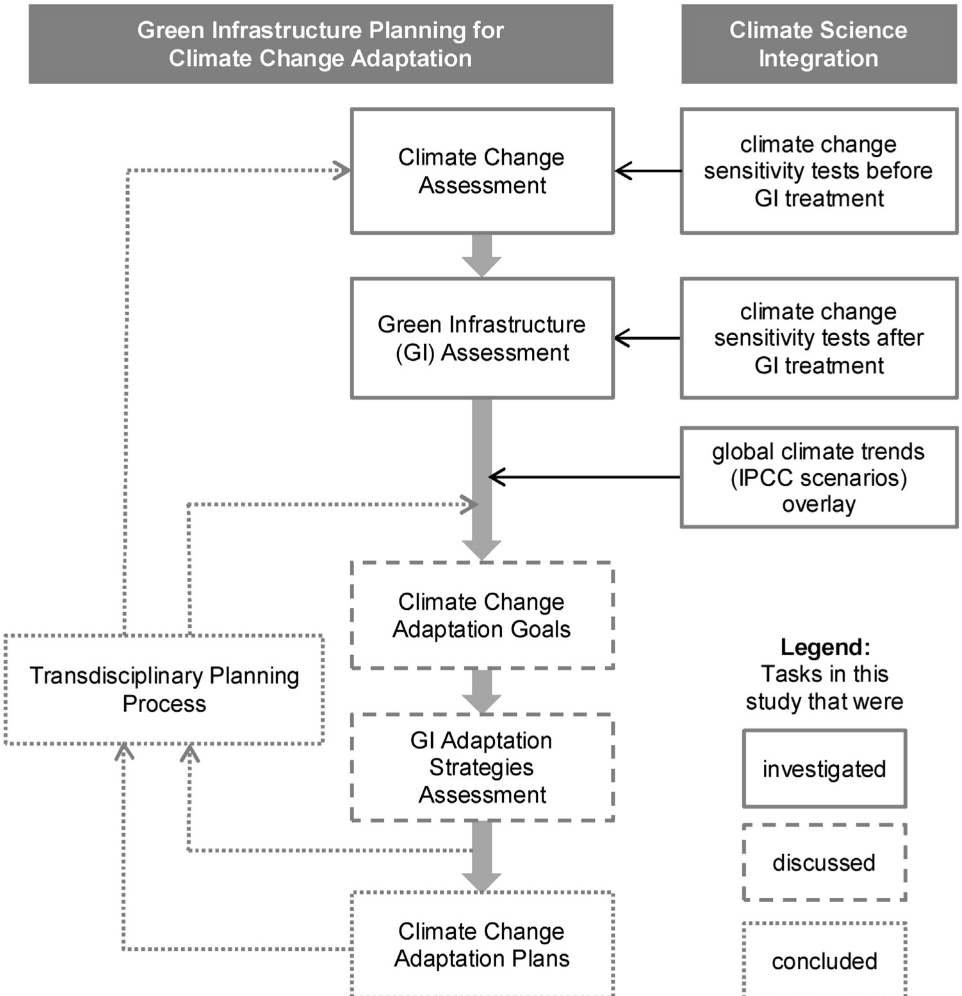


Fig. 1. A transdisciplinary planning framework of integrating climate sciences and place-based assessment in green infrastructure planning for climate change adaptation planning.

agricultural and recreational areas have relatively large grassy type of permeable surfaces compared to urban built areas, which affect how much water can be infiltrated into the soil layer, in addition to their relatively small percentage of area in the watershed. Moreover, our flooding hazard index disregards land uses in the calculation. Therefore, we combined agricultural and recreational uses into one category for hydrological modeling.

The hydric soil groups were derived from the Soil Survey Geographic-certified soil datasets approved by the United States Department of Agriculture Natural Resources Conservation Service. The Charles River watershed consists of hydric soil group A (35%), B (30%), C (24%), and D (11%), in which group A has the highest infiltration rate and group D has the highest runoff potential.

Daily observed weather data between 1990 and 2011 was obtained from the National Climatic Data Center at three stations—Walpole 2 (USC00198757), East Milton Blue Hill Observatory (USW00014753), and Boston Logan International Airport (USW00014739). The weather stations were chosen because they had complete historical daily records and were located in close proximity to the watershed (Fig. 2). Even though those weather stations are not located within the watershed boundary, they do not significantly affect the modeling results since the weather pattern in the greater Boston metropolitan area is relatively homogenous. The climate input data were maximum temperature, minimum temperature, and total precipitation. The observed daily streamflow data between 1990 and 2011 was obtained from the United States Geological Survey database at stream gage number 01104500 located in the lower basin (Fig. 2). No large reservoirs are located along the main channel of the river and thus were not included in the model.

3.2. SWAT calibration and validation

SWAT is a comprehensive model encompassing interactions between various processes of parameters. Table 2 lists parameters used and their calibrated values for calibration of hydrological balance and streamflow in various SWAT processes. Parameters that affect surface runoff included curve numbers (CN2), available soil water capacity (Soil_AWC), saturated hydraulic conductivity (SOL_K), soil evaporation compensation factor (ESCO), and surface runoff lag coefficient (SURLAG). SWAT input variables that affect baseflow included base-flow recession constant (Alpha_BF), base-flow alpha factor for bank storage (ALPHA_BNK), effective hydraulic conductivity in main channel alluvium (CH_K2), groundwater delay (GW_Delay), the threshold depths of water in the shallow aquifer required for return flow to occur (GWQMN) and for re-evaporation to occur (REVAPMN), groundwater re-evaporation coefficient (GW_REVAP), deep aquifer percolation fraction (RCHRG_DP). Those parameters plus the plant uptake compensation factor (EPCO) were routinely adjusted and identified as significant parameters throughout the literature (Arnold et al., 2012). Two additional parameters – fraction of transmission losses partitioned to the deep aquifer (TRNSRCH) and maximum amount of water trapped by fully developed canopy (CANMX) – were adjusted for this study.

Fig. 3 demonstrates the results of SWAT model calibrated with a 14-year period (1992–2005) and validated with a 6-year period (2006–2011) at daily time steps. In addition, three calibration and validation metrics—Nash-Sutcliffe model efficiency coefficient (NSE), the ratio of the root mean square error to the observation standard deviation (RSR), and percent bias (PBIAS)—were used. The results are

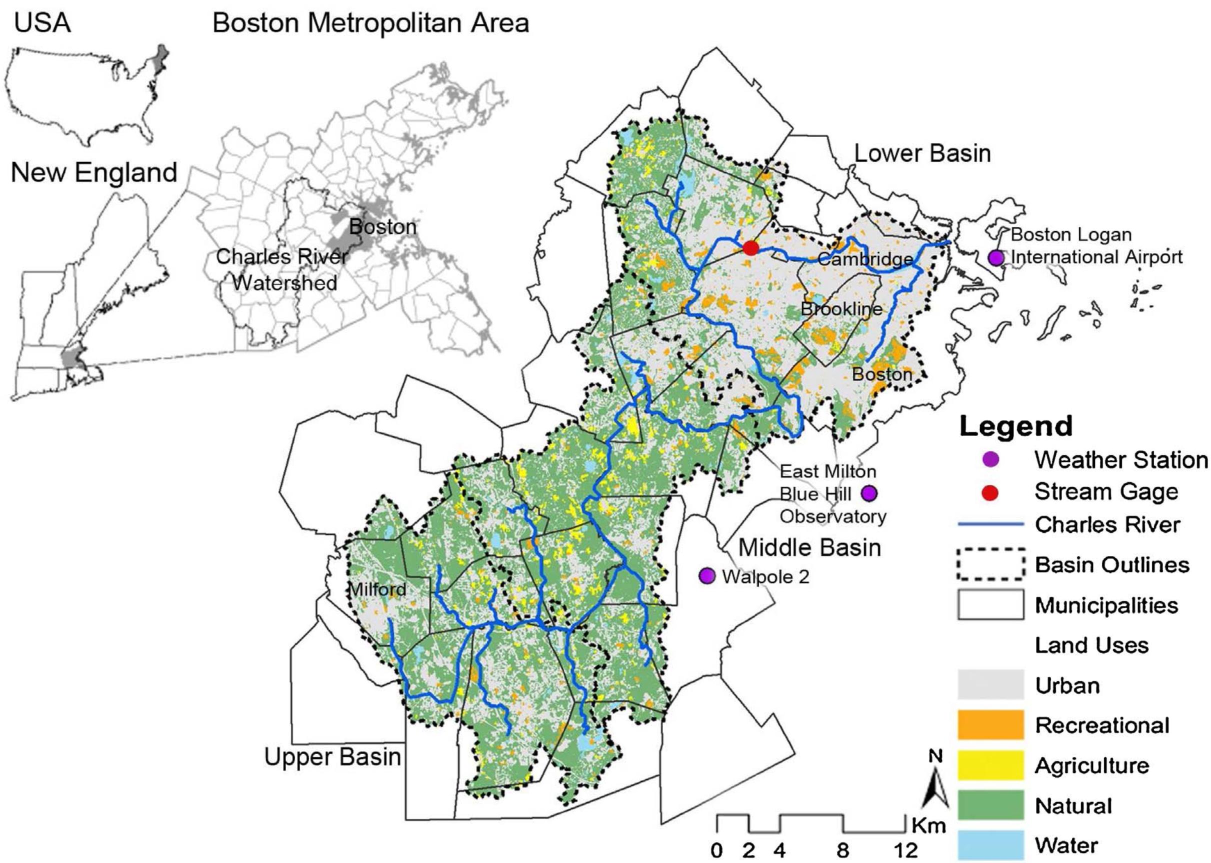


Fig. 2. Study area of Charles River watershed consists of 35 municipalities with urban land uses dominating the lower basin and more natural areas in the middle and upper basins. Historical data from three weather stations and the stream gaging station were used to generate weather inputs and calibration for SWAT modeling.

NSE = 0.76 for calibration and NSE = 0.77 for validation; RSR = 0.49 for calibration and RSR = 0.48 for validation; PBIAS = −0.12 for calibration and PBIAS = −0.17 for validation. A NSE value of 1 represents a perfect match and NSE ≥ 0.50, RSR ≤ 0.70, and PBIAS within ± 0.25 are considered as satisfactory model performance (Moriasi et al., 2007). Thus our study represented a reasonable model in simulating hydrological processes in the Charles River watershed.

Sub-daily modeling was not considered in this study for several reasons. First, calibrating the SWAT model under daily scale and use it for sub-daily scale is not a justifiable method (Wi, Yang, Steinschneider, Khalil, & Brown, 2015). Second, the climate change scenario data is also at a daily scale. Sub-daily future climate data has even larger uncertainty than monthly or daily scale and they are not always available from all GCMs. Third, sub-daily scale applied in the 50-year time period of our study would have resulted in too many data points to practically calculate. This might require running a supercomputer for the calibration purpose. Finally, the daily data and results for over decades are better served for the long range watershed planning purpose of this study.

3.3. Flooding hazard index (FHI)

The output of stream outflow from SWAT modeling was used to compute the flooding hazard index (FHI) under climate change conditions. FHI was defined as the probability (P) of number of days in a study period when the simulated stream outflow (Q_i) in respective climate change conditions would exceed the bankfull discharge volume (Q_O) in simulated baseline climate conditions (i.e., zero temperature and zero precipitation change). The bankfull discharge volume—the water volume that represents the maximum holding capacity of the river channel—was determined by the 2-year return period (Reed, Johnson, & Sweeney, 2002).

$$\text{FHI} = P\,(Q_i > Q_O) = (\text{Days when } Q_i > Q_O)/(45 \text{ years} = 16425 \text{ days})$$

P: ProbabilityQ_i: Stream outflow in climate change conditionsQ_0: Stream bankfull discharge in baseline climate conditions

3.4. Climate sensitivity tests

To overcome the uncertainty from downscaling issue mentioned in the introduction, we applied a weather generator developed by Steinschneider and Brown (2013) to generate current and future climate forcing based on the historical data from local weather stations. The weather generator was tested and evaluated to perform climate stress tests that demonstrated the robustness of a system to internal climate variability (Steinschneider & Brown, 2013, p. 7217). We drove our model with this generated climate forcing, constructed climate response surfaces with modeling results and then superimposed available GCM information on top of the climate response surface to inform the probability of future climate. This method is called *decision scaling* (Brown et al., 2012), which resembles a ‘bottom-up’ approach.

SWAT has been applied to assess the effects of green infrastructure at the watershed scale to mitigate increased peak stream flows under different changing precipitation and temperature. For example, Dakhlalla and Parajuli (2016) adjusted precipitation change of ± 10% and ± 20% and temperature change of +1 °C, +2 °C, and +4 °C in reflection projections to the 21st century across the North America from IPCC 2013 report. In this study, systematic climate sensitivity tests were applied to understand to what degree the watershed's hydrology responds to temperature and precipitation change reflecting on FHI.

A total of 150 combinations of climate change conditions with three

Table 1
MassGIS 2005 land use categories were simplified and reclassified into SWAT land use inputs.

SWAT Land Use	Descriptions	MassGIS Land Use 2005	Total Area (acres/ha)	% Watershed Area
AGRL	Agricultural; Non-forest open space; Grassy land cover	Agriculture –Orchard –Nursery –Cropland –Pasture Recreational –Participation Recreation –Spectator Recreation –Golf Course –Cemetery	11,943/4,833	6.3
FRST	Forest	Forest –Forest –Bushland/Successional	68,271/27,628	35.8
WETL	Wetlands	Wetlands and Water –Non-Forested Wetland –Saltwater Wetland –Cranberry Bog –Forested Wetland	20,437/8,271	10.8
UCOM	Commercial	Commercial –Commercial –Industrial –Transitional –Junkyard –Open Land Urban Public/Institutional Transportation Utilities –Mining –Waste Disposal –Powerline/Utility	24,501/9,915	12.9
URHD	Residential-High Density	Residential –Multi-Family –High Density	22,816/9,233	12.0
URMD	Residential-Medium Density	Residential –Medium Density	16,652/6,739	8.7
URLD	Residential-Low Density	Residential –Low Density –Very Low Density	20,234/8,189	10.6
WATR	Water	Water	5,634/2,280	3.0

weather variables—six mean temperature (0, +1, +2, +3, +4, +5° C), five mean precipitation (0, ± 10, ± 20%), and five variation of precipitation (0, ± 10, ± 20%) conditions—were applied as SWAT precipitation (*.pcp) and temperature (*.tmp) inputs and thereafter the respective FHI were constructed. Simulated 50-year weather data was used as climate inputs in SWAT modeling, including a 5-year warm-up period and a 45-year study period, which is equivalent to 16425 days. The results of the tests were used to create climate response surface of FHI to be overlaid with GCM projections (Fig. 4).

The results from climate response surface demonstrated a general trend: when controlling for precipitation change, increases in temperature would reduce FHI; when controlling for temperature, increases in mean precipitation and precipitation variation both would increase FHI (Fig. 4). The model revealed that increasing temperature alone would increase evaporation and evapotranspiration and therefore reduce available water in the streamflow. On the other hand, increasing precipitation alone contributes to increased water inputs to the streamflow. Since we were interested in the climate change conditions that are likely to result in increased flooding hazards under global warming projections (i.e., climate change-induced flooding), 36 combinations of four increased mean temperature (0, +1, +2, +3° C), three mean precipitation (0, +10, +20%), and three variation of precipitation (0, +10, +20%) conditions were selected for further assessment.

3.5. Stormwater detention modeling

Detention is a common stormwater management practice that temporarily stores water during storm events and releases excessive water through overflow devices. SWAT has been regularly used to assess water quantity and flood regulation ecosystem services (Francesconi, Srinivasan, Pérez-Miñana, Willcock, & Quintero, 2016) and has been identified as one of the effective hydrological models for simulating geographically isolated wetlands, which function similarly as detention ponds in that runoff could be temporarily stored (Golden et al., 2014). Specifically, the method of delineating potholes in each HRU in the SWAT modeling has been successfully used to model aggregated effects of geographically isolated wetlands on downstream hydrology (Evenson, Golden, Lane, & D'Amico, 2015), which is a compelling case to this study focusing on aggregated effects of detention in overall watershed performance. Other studies used 'ponds' in SWAT modeling to simulate wet detention ponds that are maintained at a regular water level (Dakhlalla & Parajuli, 2016). We used 'potholes' to resemble stormwater detention areas that are regularly in dry conditions.

Potholes are closed depression areas in sub-basins and function as temporary water storage areas that are hydrologically connected in the watershed through impoundment water routing systems (TAMU, 2011). Potholes receive water through precipitation and surface water within its responsive drainage area and lose water through evaporation and seepage. When storage exceeds the maximum volume assigned for each pothole, the excessive volume then joins the surface runoff water in the drainage area and contributes to stream flow in respective sub-watersheds. A HRU could be defined as a pothole and its water balance described in SWAT as:

Table 2
Calibration parameters and calibrated values in SWAT processes.

Process	Parameter	Description	Value
Surface runoff	CN2	Curve number	−20%
	Soil_AWC	Available soil water capacity	
		Hydric soil A	0.195
		Hydric soil B	0.27
		Hydric soil C	0.18
		Hydric soil D	0.12
	SOL_K	Saturated hydraulic conductivity (mm/hr)	
		Hydric soil A	250
		Hydric soil B	250
		Hydric soil C	250
		Hydric soil D	250
	ESCO	Soil evaporation compensation factor	
		HRU parameter (.hru)	0.95
		Basin parameter (.bsn)	0.9
	SURLAG	Surface runoff lag coefficient (day)	0.1
Baseflow	Alpha_BF	Baseflow recession constant	0.16
	Alpha_BNK	Baseflow alpha factor for bank storage	0.95
	CH_K(1)	Effective hydraulic conductivity (mm/h) in subbasin (.sub)	170
	CH_K(2)	Effective hydraulic conductivity (mm/h) in main channel alluvium (.rte)	170
	GW_Delay	Groundwater delay (day)	35
	GWQMN	Threshold depth of water in the shallow aquifer required for return flow to occur (mm)	80
	GW_REVAP	Groundwater re-evaporation coefficient	0.1
	RCHRG_DP	Deep aquifer percolation fraction	0.1
	REVAPMN	Threshold depth of water in the shallow aquifer required for re-evaporation to occur (mm)	0.02
	TRNSRCH	Fraction of transmission losses partitioned to the deep aquifer	0.01
Plants	CANMX	Maximum amount of water trapped by fully developed canopy (mmH2O)	3
	EPCO	Plant uptake compensation factor	
		HRU parameter (.hru)	0.95
		Basin parameter (.bsn)	0.95

$$V = V_{stored} + V_{flowin} - V_{flowout} + V_{pcp} - V_{evap} - V_{seep}$$

where V is the volume of water in the impoundment at the end of the day (m^3H_2O), V_{stored} is the volume of water stored in the water body at the beginning of the day (m^3H_2O), V_{flowin} is the volume of water entering the water body during the day (m^3H_2O), $V_{flowout}$ is the volume of water flowing out of the water body during the day (m^3H_2O), V_{pcp} is the precipitation falling on the water body during the day (m^3H_2O), V_{evap} is the volume of water removed from water body through evaporation during the day (m^3H_2O), V_{seep} is the volume of water lost from water body by seepage during the day (m^3H_2O). The water balance of potholes matches the hydrological model of detention ponds using SWAT interface in a previous study (Kannan et al., 2014).

This study's assumption was to maintain urban commercial, urban residential and natural land uses and allow agricultural or recreational land areas to be adapted for stormwater detention. One pothole in each sub-basin was then created by assigning the largest AGRL SWAT land use as potholes. The potholes were selected based on the necessary size for the detention since the focus of the study was on aggregated effects as a whole in the watershed rather than optimizing effects of detention within each sub-basin or between sub-basins (i.e., upstream-downstream effects). Therefore, the low point was not part of the selection criteria. In average, each sub-watershed consisted of 2.9% of land delineated as potholes with a range between 0.9% to 8.7% and a standard deviation of 1.5%, resulting in a total of 3.2% of the watershed area that was modeled as stormwater detention. Their respective HRU were assigned as responsive drainage areas (POT_FR = 1). The maximum storage for each pothole was assumed to be the bankfull discharge volume used to calculate FHI.

Descriptive statistics and paired-samples *t*-test in SPSS Statistics 2.1 were used to test the effects of detention treatment. Finally, a linear regression method was applied where the fraction of detention area in its respective sub-watershed area was the independent variable and FHI under 36 climate change conditions was the dependent variable using the following formula:$Y = aX + bY$: FHI of each sub-basin under a given climate change condition$X$: Fraction of stormwater detention (pothole) area in its respective sub-watershed area$a$: X variable coefficient$b$: Intercept constant

4. Results

4.1. Climate change assessment

The climate sensitivity study in the watershed was illustrated through climate response surfaces in 36 climate conditions before and after detention treatment (Fig. 4). Each color band indicates a 0.5% interval in FHI. A dashed line represents the baseline (FHI = 1.1%) condition with no detention treatment indicating a probability of 167 flooding days over 45 years (an average of 3.7 days per year). For every 0.5% increase in FHI represents an extra 82 flooding days over 45 years (an average increase of 1.8 days per year). The watershed responded to climate change following a general trend in climate sensitive tests (section 3.3): FHI increases when mean and variation of precipitation increase; FHI decreases when mean temperature increases.

This study compared the results from climate sensitive tests to both IPCC's Fourth Assessment Report (AR4) (IPCC, 2007) and Fifth Assessment Report (AR5) (IPCC, 2014) scenarios since current Massachusetts climate change adaptation plans were based on AR4 scenarios yet we anticipate the updated plans hereafter would employ AR5 scenarios. IPCC gathers and reviews global climate models in assessment reports and named the ensemble of the models the *Climate Model Intercomparison Project* (CMIP). CMIP3 in AR4 was based on four main storylines (A1, A2, B1, B2) and six greenhouse gas (GHG) emission scenarios (A1F1, A1T, A1B, A2, B1, B2) derived from the Special Report on Emission Scenarios (IPCC, 2000). Each scenario storyline has various policy goals in different sectors (e.g., energy, industry) and sustainable development goals (e.g., economy, social equity, environment). The A1 and A2 storylines lead to higher GHG emissions than B1 and B2 scenarios. CMIP5 in AR5 was based on a new direction of climate change scenarios considering social and ecological vulnerability based on various policy goals. The climate change scenarios were illustrated via GHG emission volumes along each pathway, known as Representative Concentration Pathways (RCP). Four scenarios were delineated in AR5–RCP2.6, RCP4.5, RCP6.0, and RCP8.0–with the higher number representing higher GHG emission scenario.

To reflect the global climate trends in the Northeast region in the next five decades, Fig. 4 summarized average temperature and precipitation change in low GHG emission scenarios of B1 and RCP2.6, moderate GHG emission scenarios of A1B, RCP4.5 and RCP6.0, and high GHG emission scenarios of A2 and RCP8.0 (Joyce et al., 2011; Yang, 2016). Subsequently, the projected temperature and precipitation change in IPCC scenarios were compared to the climate response surfaces. In general, the IPCC scenarios are within a range of FHI between 0.5% and 1.5% before detention treatment. Based on changes in mean temperature (°C), mean precipitation (+%) and precipitation variation (+%), five climate conditions represent seven IPCC scenarios—1 °C + 10% + 0% (RCP 2.6), 2 °C + 10% + 0% (RCP 6.0), 2 °C + 10% + 10% (B1 and RCP 4.5), 3 °C + 0% + 0% (A1B), 3 °C + 10% + 0% (A2 and RCP 8.0)—in addition to the baseline (i.e., zero change in temperature and precipitation) were identified for this study.

4.2. Stormwater detention assessment

Comparing among 54 sub-basins paired samples before and after

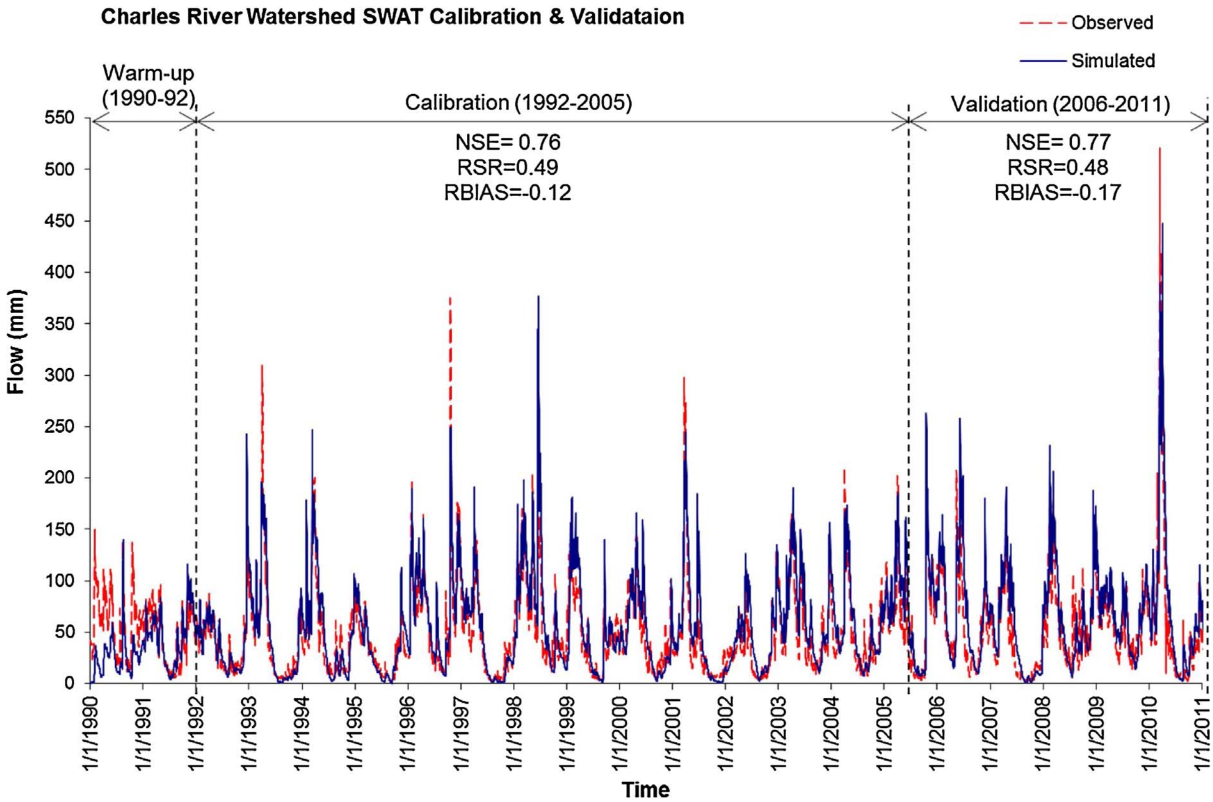


Fig. 3. SWAT modeling hydrograph in the Charles River watershed in daily time step shown by years in warm-up (1990-92), calibration (1992-2005), and validation (2006-2011) periods. Three calibration and validation metrics indicated satisfactory model performance: Nash-Sutcliffe model efficiency coefficient (NSE), the ratio of the root mean square error to the observation standard deviation (RSR), and percent bias (PBIAS).

Note: NSE ≥ 0.50, RSR ≤ 0.70, and PBIAS within ± 0.25 considered as satisfactory model performance (Moriasi et al., 2007)

detention treatment, the mean FHI decreased between 0.06% and 0.13% (Table 3). The results of *t*-tests revealed significance in mean difference represent positive effects for mitigating climate change-induced flooding hazards in all selected climate change scenarios. Under the low to moderate GHG emission scenarios of RCP2.6, B1 or RCP4.5, and RCP6.0, when the temperature increases 1 °C to 2 °C with 10% increase in mean or variation precipitation change, the distribution of FHI is in a wider range and the reduction in mean FHI is greater than 0.1% (Fig. 5). When the temperature raised to 3 °C, the mean FHI overall decreases and thus the effect of detention is smaller than 0.1%.

4.3. Climate change-induced flooding hazard mitigation goals assessment

In assessing the adaptive capacity of the watershed in terms of percent of watershed area required in mitigating climate change-induced flooding, two policy goals were examined: 1) mitigate flooding hazards to maintain baseline level (FHI = 1.1%); 2) achieve hypothetic zero flooding hazards (FHI = 0). The results of regression analysis revealed significant positive ($p < 0.001$) yet weak (R^2 ranges from 0.047 to 0.152) relationship between percent of detention area in the watershed and FHI (Table 4). Detention is more efficient in reducing flooding hazards in low and moderate emission scenarios (e.g., B1, RCP2.6, RCP4.0 shown as steeper slopes) than those at high emission scenarios (e.g., A1B, A2, RCP6.0, RCP8.5 shown as more gentle slopes) (Fig. 6). For example, every 1% watershed area increase for detention would decrease the probabilities of flooding hazard by 0.041% in high emission scenarios A2 and RCP8.5 comparing to a higher reduction of 0.146% in low emission scenario RCP2.6 over the next five decades.

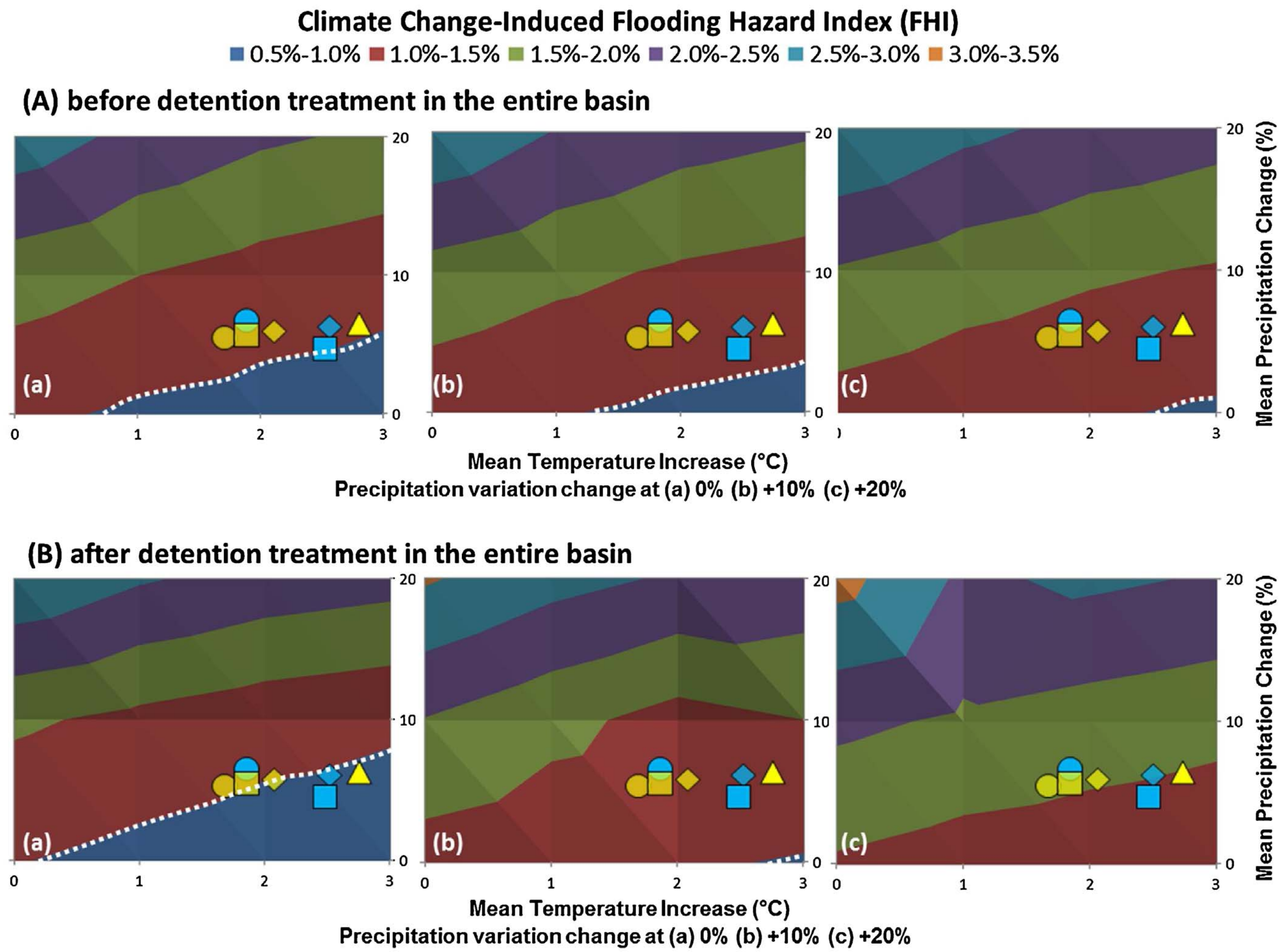
In order to reach the first policy goal of net zero climate change impacts from the baseline, it will require up to 5% of watershed area under RCP2.6, RCP4.5, and B1scenarios. Nevertheless, much more land between 13% and 20% watershed area would be needed to achieve the second goal of hypothetic zero flooding hazard. Considering a 3% of watershed area has been modeled, an additional spatial demand of 2% land area to reach net zero climate change impacts or up to 17% of the watershed's land area to reach zero flooding hazards in the Charles River watershed.

5. Discussion

5.1. Flooding mitigation capacity between detention and infiltration

This study revealed two variables with major impacts on the effects of detention in mitigating flooding hazards in the Charles River watershed: climate change and land cover change associated with detention. In general, after detention treatment, the FHI is reduced. However, FHI appears to be particularly sensitive to precipitation variation. To better understand the implication in stormwater management and watershed planning, we examined the modeling principles and intermediate results below.

The stormwater detention was modeled as potholes in SWAT for temporary stormwater detention and allows only a negligible amount of seepage to be recharged into the reservoir, which functions similar to retention ponds. When the pothole exceeds its holding capacity, then it contributes to surface runoff, which in turn increases probability of flooding hazards. When the additional recreational or agricultural land areas were delineated as detention treatment in this study, the change of land use and land cover properties in turn altered the water balance. Table 5 illustrates the difference of mean daily surface runoff and groundwater volumes before and after detention treatment. The results showed an increase in surface water runoff and decrease in groundwater after detention treatment in all scenarios. The same trends applied to decreased volumes in both percolation and soil water content after detention treatment. The model then exemplified a trade-off



IPCC Scenarios	Legend (projection year)	Annual Temperature Change (°C)	Annual Precipitation Change (%)	Climate Sensitivity Conditions: mean temperature (+°C) – mean precipitation (+%) – precipitation variation (+%)
CMIP3[1]	2040-2069			
B1	●	1.85	5.88	2-10-10
A1B	◆	2.58	5.18	3-0-0
A2	■	2.54	2.82	3-10-0
CMIP5[2]	2041-2070			
RCP2.6	●	1.65	4.00	1-10-0
RCP4.5	◆	2.09	4.70	2-10-10
RCP6.0	■	1.85	4.30	2-10-0
RCP8.5	▲	2.84	5.50	3-10-0

Fig. 4. Climate response surface illustrates the results of climate sensitivity tests on climate change-induced flooding hazard index (FHI) (A) before and (B) after detention treatment for the entire Charles River watershed basin comparing to the baseline condition (white dashed line) and corresponding IPCC climate change scenarios derived from CMIP 3 ([1]Joyce et al., 2011) and CMIP 5 ([2]Yang et al., 2016).

between the groundwater flow and surface water runoff. The groundwater flow is associated with percolation rate and soil water contents related to infiltration capacity; the surface water runoff is associated with detention capacity that mimics ponds.

The results implied that when land use areas with high infiltration rate were converted to detention pond with less holding capacity than infiltration, then it is likely to increase surface water runoff and contribute to higher flooding hazards. Therefore, enhancing flooding mitigation capacity requires a thorough landscape assessment on infiltration and detention capacity for stormwater management and watershed planning before land use designation and land development in the watershed. Land cover areas with high infiltration capacity are recommended to be undisturbed or the impacts from soil compaction and impervious surfaces should be minimized in order to maximize the

Table 3
Paired sample statistics and t-test results of climate change-induced flooding hazard index (FHI) under climate change scenarios before and after detention treatment for the entire basin.

Paired Samples Statistics, N = 54								**Paired Samples T-Test**				
IPCC Scenarios	temp +°C	prec +%	pvar +%	ID[1]	Mean	SD	Std. Error Mean	Paired Difference Mean	SD	Std. Error Mean	t	sig.[2]
Baseline	0	0	0	B000	1.10%	0.46%	0.06%	0.07%	0.09%	0.01%	6.001	**
				A000	1.02%	0.40%	0.05%					
RCP2.6	1	10	0	B110	1.50%	0.71%	0.10%	0.13%	0.12%	0.02%	7.798	**
				A110	1.38%	0.63%	0.09%					
RCP6.0	2	10	0	B210	1.31%	0.60%	0.08%	0.11%	0.11%	0.02%	7.396	**
				A210	1.20%	0.51%	0.07%					
B1/RCP4.5	2	10	10	B211	1.43%	0.62%	0.08%	0.12%	0.12%	0.02%	7.353	**
				A211	1.32%	0.54%	0.07%					
A1B	3	0	0	B300	0.74%	0.30%	0.04%	0.06%	0.08%	0.01%	4.981	**
				A300	0.68%	0.25%	0.03%					
A2/RCP8.5	3	10	0	B310	1.17%	0.50%	0.07%	0.09%	0.10%	0.01%	6.753	**
				A310	1.08%	0.43%	0.06%					

temp: mean temperature; prec: mean precipitation; pvar: precipitation variation; +: increased value.
[1] Identification in Fig. 5: B-before detention treatment; A-after detention treatment.
[2] sig.: ** Significance of two-tailed $p < 0.001$.

infiltration capacity. These areas could be designed as dry detention or bioswales, and protected from converting to wet detention ponds with impervious lining beneath. Consequently, siting effective detention areas combined with soil conservation is a critical flooding mitigation strategy for climate change adaptation using green infrastructure.

5.2. Making more space for water

The Boston Metropolitan Area includes 101 municipalities with a total population of three million in 2000 and is projected to grow 11 percent in population in 2030 (MAPC, 2009). It was estimated that additional 1% of watershed area of open space would be converted to residential development (Cheng et al., 2013). As this study showed that up to additional 2% and 17% of watershed land areas would be needed for mitigating climate change-induced flooding hazards to the level of baseline or zero FHI respectively, the findings reveal a challenge in accommodating land demands for both population growth and green infrastructure development in the next decades.

The positive yet weak correlation between the increased amount of detention area and reduced FHI shows that detention alone is not sufficient in mitigating floods and is no substitution for integrated land use and watershed management strategies such as open space and floodplain protection and wetlands restoration (Brody & Highfield, 2013). Essentially, our cities need to make more space for water to decelerate, bypass, retain, infiltrate, and discharge since climate change increases the frequency and intensity of future storm events. In particular, efforts should be made to convert large impervious surfaces in transportation, industrial, and commercial land use areas into multi-functional

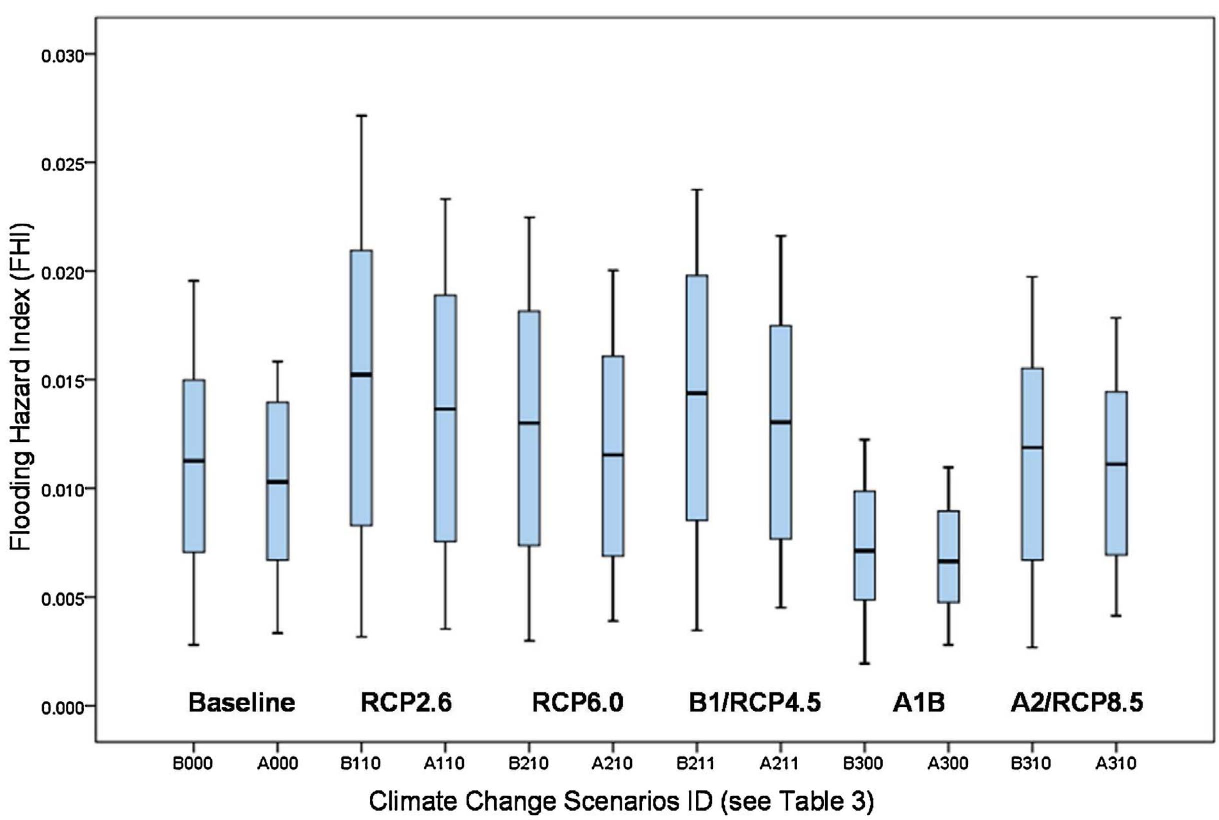


Fig. 5. Box plots of paired sample statistics of flooding hazard index (FHI) before and after detention treatment under selected climate change scenarios.

Table 4
Climate change adaptation goals assessment in percentage of watershed area needed for detention (X variable) in relation to reaching baseline level or zero flooding hazard index (FHI in %) under climate change scenarios.

IPCC Scenarios	Climate Change Variables			Regression Coefficients			Total% watershed area for detention[1]	
	temp (+°C)	prec (+%)	pvar (+%)	X variable a	Intercept b	Adjusted R^2	Goal 1: Baseline FHI = 1.1%	Goal 2: Zero FHI = 0%
Baseline	0	0	0	−0.101**	0.013**	0.152	2	13
RCP2.6	1	10	0	−0.146**	0.018**	0.128	5	12
RCP6.0	2	10	0	−0.109*	0.015**	0.108	4	14
B1/RCP4.5	2	10	10	−0.119*	0.017**	0.116	5	14
A1B	3	0	0	−0.041	0.008**	0.047	−7	20
A2/RCP8.5	3	10	0	−0.076*	0.013**	0.056	3	17

temp: mean temperature; prec: mean precipitation; pvar: precipitation variation; +: increased value. *$p < 0.05$; **$p < 0.001$.
[1] Total% watershed area for detention required to achieve policy Goal 1 of reaching FHI at baseline level and Goal 2 of zero FHI includes 3% modeled as detention treatment in the study.

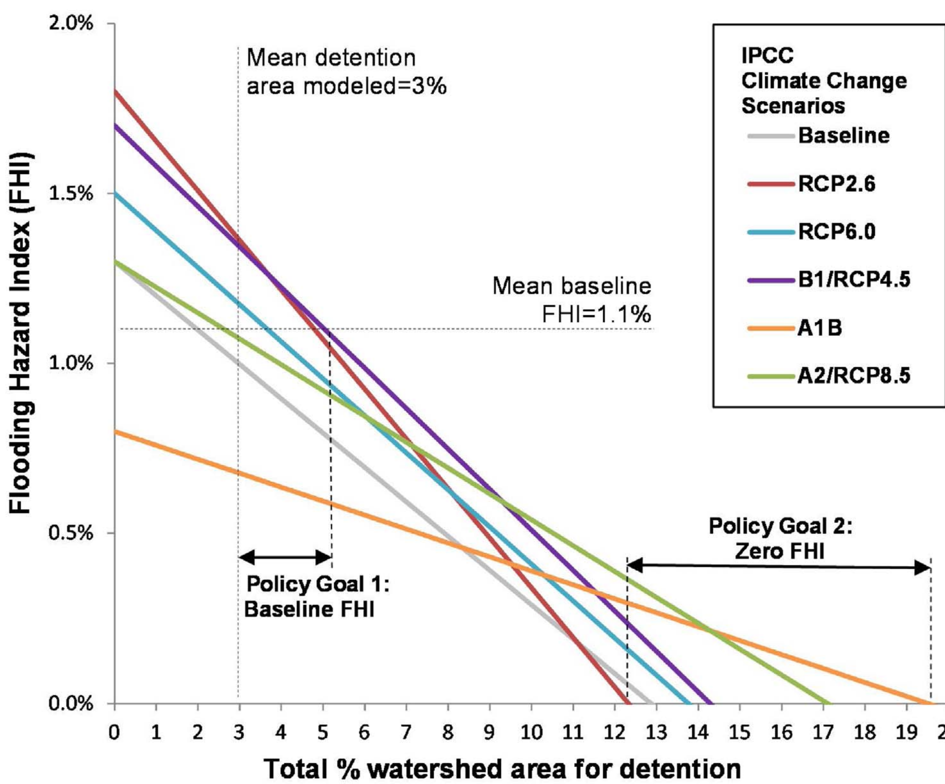


Fig. 6. Regression results of baseline and climate change scenarios between the total percentage of watershed area for detention and its effects on mitigating climate change-induced flooding hazards for Goal 1–mitigate to baseline FHI condition; and Goal 2–mitigate to zero FHI.

landscapes with new infiltration and detention opportunities.

Several landscape and urban planning practices such as on-site stormwater management and adaptive land use planning have been developed to allow temporary flood storage and waterways in multi-functional and adaptive landscapes (Pahl-Wostl, 2007; Ellis, 2012). For example, agricultural lands may consider rotating and cultivating flood-tolerant crops according to flooding seasons (e.g., OECD, 2016). Public open space such as urban parks, plazas and golf courses may temporarily store stormwater and serve as adaption measures (Matos Silva & Costa, 2016). Urban dwellings can be adapted to floods by elevating living spaces and allowing the ground floor to be waterway zones (Liao, 2014). In addition, in dense urban areas, large impervious areas such as buildings, parking lots, and plazas, could build in underground detention capacity structures to help mitigate floods and to serve as water storage and water reuse facilities for water conservation (Lai & Mah, 2012). To date, many existing developed areas in the watershed pre-date current stormwater regulations that require on-site stormwater management. Thus, there is a lack of detention facilities, particularly in urbanized areas. Complying with stormwater regulations will require retrofits of existing sites along with collaborative efforts beyond property lines and political boundaries to implement these new detention needs.

Table 5
Surface runoff and groundwater volume after detention treatment from baseline condition among climate change scenarios.

IPCC Scenarios	temp (+° C)	prec (+%)	pvar (+%)	surq (mm)	gw (mm)
Baseline	0	0	0	0.024	−0.024
RCP2.6	1	10	0	0.076	−0.031
RCP6.0	2	10	0	0.079	−0.032
B1/RCP4.5	2	10	10	0.032	−0.032
A1B	3	0	0	0.071	−0.025
A2/RCP8.0	3	10	0	0.033	−0.032

+: increased value; temp: mean temperature; prec: mean precipitation; pvar: precipitation variation. surq: Surface runoff contribution to streamflow during time step. gw: Groundwater contribution to streamflow.

5.3. Implications for integrating climate science in planning

Many cities and watershed organizations in the United States are incorporating climate change into their planning as climate trends suggesting increased flooding risk in the Northeast, Midwest and Southwest (Melillo, Richmond, & Yohe, 2014). This study demonstrated the integration of climate science into a hydrological modeling method and a transdisciplinary planning framework for providing empirical evidence and simulations that inform planning policies at a watershed scale (Fig. 1). This framework is applicable to other flood-prone regions in the United States and around the world. In addition, this study illustrated the merits of using both 'bottom-up' and 'top-down' approaches in watershed planning and place-based assessment that helped to overcome uncertainty of using downscaled global climatic models (Brown et al., 2012; Corney et al., 2013; Mullan et al., 2012). The novelty of this study is that it integrates climate science and provides a range of possible scenarios and outcomes for decision-making under uncertain futures while anticipating the impacts from climate change. For example, even though planning for a zero percent chance of long-term flooding hazard is an extreme policy goal and counter to natural hydrologic cycle, it provides an upper boundary for developing policy frameworks with feasible intermediate goals. The science provides a planning framework for decision-makers to develop climate change adaptation strategies in various scenarios, including extreme cases.

This study points the way for other urban watershed planners worldwide to integrate these range of climate predictions into more adaptive planning studies. In addition, an integration of transdisciplinary approach and climate sciences in water research can assist spatial adaptation planning (Krueger et al., 2016; Wolsink, 2006). For example, applying climate change scenarios in flood risk assessment through demonstration of a range of simulated climate change impacts on the rise of water level and potential infrastructure failure combined with social vulnerability help to illustrate 'tipping points' for spatial planning and flood risk management policies Klijn, de Bruijn, Knoop, & Kwadijk, 2012). As urban watersheds are dynamic inter-linked social-ecological systems, it is critical to integrate climate science into green infrastructure planning for mitigating climate change impacts and developing innovative strategies for adaptation and climate justice (Cheng, 2016).

5.4. Limitations and further research

Due to uncertainty and limitation in climatic and hydrological modeling, the results from this study are watershed-specific and planning oriented that are best used to inform watershed-based decision-making but not for detailed engineering design purposes.

Using SWAT has its advantage of modeling watershed hydrology yet has limitation in integrating urban drainage systems and green infrastructure strategies for on-site stormwater best management practices (e.g., bioswales, greenroofs, porous paving). Combining alternative stormwater modeling such as Storm Water Management Model (SWMM) (USEPA, 2016) in urban areas can increase the understanding of the effects of other types of green and grey infrastructure in addition to climate change impacts for policy-making (e.g., Chang et al., 2013). Further studies could include the upstream-downstream effect in order to identify the most effective locations for installing green infrastructure strategies that benefit a community's adaptive capacity and address climate justice (Cheng, 2016). Moreover, a comprehensive suitability study could be conducted to include multi-criteria selection for siting detention areas, such as low point of each sub-basin, well-drained soil type, property ownership for feasibility of land use adaptation, and habitats that are flood-resilient. Finally, when data become available, sub-daily scale model could be applied for studying a shorter period of time frame.

Qualitative research such as surveys, interviews, and focused groups is critical to gain insights about the motivations and obstacles to implementing green infrastructure and for understanding a community's resilience and adaptive capacity (Matthews et al., 2015). The next steps could include bringing the findings to stakeholders and community members to discuss to what level of flooding hazards are acceptable to the community and to what level of climate change adaptation capacity that the community plans to achieve (Brown et al., 2012). Policy-makers could then plan for multiple green infrastructure and stormwater management strategies based on a range of climate change impacts along with short-term and long-term goals in mitigating climate change-induced flooding hazards.

6. Conclusion

Integrating climate science in place-based assessment allows a comprehensive and unique understanding of the extent to which the hydrological dynamics in a particular watershed respond to changes in climatic conditions. This study aims to apply currently available modeling tools in assisting landscape and urban planners to integrate climate science for climate change planning. As knowledge accumulates and methodology advances, the transdisciplinary planning framework combined with the hybrid of "top-down" and "bottom-up" decision-scaling model remains a valuable approach for planners to assess the sensitivity of their communities and investigate a range of possible futures and strategies in coping with climate change. Climate sensitivity study plays an important role in framing watershed-based stormwater management as the impacts from climate change on flooding vary within a watershed by geophysical characteristics (e.g., slopes, soil, land use and land cover, and water features) as well as vary between watersheds (Praskievicz & Chang, 2009). In addition, integrating climate science into place-based green infrastructure assessment enhances understanding of bio-physical capacity of landscape performance under conditions of climate change. Planners could demonstrate a range of potential climate change impacts and the effectiveness of using green infrastructure in the transdisciplinary process of developing climate change adaptation plans with their communities. Communities would then be more informed by climate science and in the planning process to increase their institutional capacity (Matthews et al., 2015) to better prepare for climate change and enhance their resiliency.

Acknowledgement

This research is based upon work supported by the National Institute of Food and Agriculture, the U.S. Department of Agriculture,the Massachusetts Agricultural Experiment Station, the Department of Environmental Conservation under Project No. MAS009584 and MAS00971, and the National Science Foundation under Grant No. BCS-0948984. In addition, this work is funded by the Water Resources Research Center (grant award year 2012–2013) at the University of Massachusetts Amherst

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