RETHINKING STORMWATER MANAGEMENT IN A CHANGING WORLD: EFFECTS OF DETENTION FOR FLOODING HAZARD MITIGATION UNDER CLIMATE CHANGE SCENARIOS IN THE CHARLES RIVER WATERSHED

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1 ABSTRACT

Climate change is projected to have impacts on increased temperature as well as frequent and intense rainfalls in the northeast region of the United States. Integrated green infrastructure planning with both structural and non-structural stormwater management practices has emerged as a critical climate change adaptation strategy. Under the uncertainty of climate change impacts on long-term flooding hazards, this paper employed SWAT hydrological modeling for an empirical study examining the effectiveness of using detention area for the mitigation of a 45-year period riparian flooding hazard under 36 climate change conditions. Statistical results illustrated a weak yet positive effect of using detention for flooding hazard mitigation. A range of from 12 to 18% and 0 to 8% of the drainage area would be required for on-site detention in order to achieve policy goals for zero flooding hazard indices and to the level of current climate conditions respectively. Under the constraints of limited adaptive uses of lands or the availability of large land areas for natural detention in the urbanized watershed, this paper suggested that innovations in employing on-site detention techniques in impervious and non-natural pervious areas play an important role in mitigating climate change-induced flooding hazards. Integrating on-site detention functions (wet and dry detentions) as part of the green infrastructure network in urban stormwater management systems is therefore crucial in landscape architecture planning and design practices for climate change adaptation.

1.1 Keywords

detention, climate change, flooding hazard mitigation, green infrastructure

2 INTRODUCTION

Climate change has posed increased risks to environmental hazards (e.g., flooding, droughts, hurricanes) in addition to new challenges under climate change impacts (e.g., early snow melt, rising sea levels, heat waves) (IPCC, 2007). Floods are omnipresent in almost every city in the United States and account for more economic losses than any other single geophysical hazard (White and Haas, 1975; Gall et al., 2011). Previous climate change studies have suggested trends of increased temperature and changing precipitation patterns as well as increased intensity and duration of storm events that are likely to result in more flooding events in the Northeast (IPCC, 2007; Rock et al., 2001). Since the early 1900's, flooding hazard mitigation strategies in the United States have focused on structural engineering solutions such as dams and dikes along streams and rivers (Godschalk, 1999). In recent decades, scholars have called for biological and non-structural strategies such as green infrastructure (Thomas and Littlewood, 2010) and land use planning (Burby, 1998; Godschalk, 2004) to be integrated into planning and design interventions for comprehensive hazard mitigation and stormwater management.

Detention and retention are among the most prevalent stormwater management practices for flooding hazard mitigation; however, without an empirical study, the perceived benefits of these approaches could be overestimated (Beecham et al., 2005). If growth development trends continue to increase impervious surfaces and consume more floodplains, wetlands, forest and agricultural lands, fewer open lands would be available for natural on-site detention and retention (i.e., depressional land areas designated for temporary surface water runoff or flood storage). Landscape architecture plays a critical role in implementing stormwater detention and retention that can serve as a climate change adaptation strategy for mitigating climate change-induced flooding. This paper aims to use empirical studies to support the hypothesis of using green infrastructure design for climate change adapation by answering the question: To what degree does on-site detention and retention mitigate riparian flooding hazards induced by climate change?

3 BACKGROUND

3.1 Climate Change Impacts on Stormwater Management

Climate change is likely to increase the intensity, magnitude and duration of precipitation patterns affecting the hydrologic cycle (Frederick and Major, 1997; IPCC, 2007) and therefore magnify urban hydrological impacts (Wood, Lettenmaier, and Palmer, 1997; Frederick, Major, and Stakhiv, 1997). More frequent and intense storm events are likely to occur in some areas such as the New England region (Rock et al., 2001). The consequences of irregular and intensified flooding events have significant impacts on populated urban regions where current water infrastructure is designed based on past climate trends and conventional knowledge (Ashley et al., 2005; Means, West, and Patrick, 2005). In addition, alternative structural stormwater design may be needed for accommodating climate change effects (Semadeni-Davies et al., 2008). Consequently, increased capital investment in upgrading necessary drainage infrastructure (Muller, 2007; Arisz and Burrell, 2006) would impose additional socio-economic impacts in society. As a result, enhancing stormwater management and flooding absorption capacity for building capacity of communities in coping with climate change-induced flooding hazards is an emerging priority for resilient cities (Beatley, 2009).

3.2 Urbanization Impacts on Flooding

Increased impervious surfaces derived from the urbanization process are the leading cause for excessive runoff, lack of infiltration, and insufficient aquifer recharge (Leopold, 1968; Booth and Jackson, 1997; Schueler, 1994; Brabec, Schulte, and Richards, 2002; Brabec, 2009). For example, compared to natural ground cover, which has 10% runoff and 50% infiltration, urbanized areas that have surfaces over 75% impervious result in less than 15% infiltration and contribute to more than 55% of runoff (NRCS, 1998). In addition, impervious surfaces have been highly associated with shorter lag times between the fall of precipitation and runoff mass that instigates the increase of *flashy* variation of streamflow or a peak discharge in a short period of time (Simmons and Reynolds, 1982). In completely impervious basins, the lag time can be as little as one eighth of that in the natural state (Anderson, 1970), resulting in significant increases in stormwater runoff and flash floods in urban areas (Hosseinzadeh, 2005; Sala, 2003).

As for the impacts of urbanization on riparian flooding, Leopold (1968) found a positive relationship between the ratio of the number of overbank flooding events and urbanization effects. When the watershed was 50% sewered, the overbank flooding events were nearly four times more than those in the natural state (Leopold, 1968). Numerous studies have supported the correlation between increased stormwater runoff associated with imperviousness and the increased magnitude and frequency of flood events (Ng and Marsalek, 1989; Allen et al., 1979; Huang et al., 2008; Moscrip and Montgomery, 1997). Nevertheless, the effect of impervious areas decreases with the increase of flood recurrence intervals (Hollis, 1975) and eventually becomes negligible (e.g., a study showed a threshold of 50 year intervals in metropolitan Charlotte, North Carolina (Martens, 1968)).

Urbanization increases the frequency of small and regular flooding events many times more than the rare and extreme flooding events (Hollis, 1975). Moreover, critique has focused on the understudied impacts of urbanization impacts on baseflow (Price, 2011; Hollis, 1975). In the natural state of the stream, baseflow is largely sustained by groundwater. Correlation of urbanization with decreased baseflow can be found as a result of increased evapotranspiration and decreased infiltration (Price, 2011). Since increased impervious surfaces are associated with decreased baseflow (Shuster et al., 2005), urbanization could contribute to negative effects on riparian flooding while flash floods remain dominant in cities (Lasda et al., 2010).

In addition, it is critical to make the distinction between the total impervious areas (TIA) (i.e., all roads, roofs, building footprints that are impervious) and effective impervious areas (EIA) (i.e., hydrologically connected impervious areas). Effective impervious areas are hydrologically connected through curbs, gutters and pipes; by contrast, non-effective impervious areas drain to pervious areas, such as disconnected downspouts from roof areas to adjacent lawns (Alley and Veenhuis, 1983). Most studies have used total impervious area that conflate both effective and non-effective impervious areas (Brabec, Schulte, and Richards, 2002) and therefore overlook the accuracy and effectiveness of using impervious area as an indicator for stormwater management (Brabec, 2009). Further studies are needed to understand the true effects of urbanization, incorporating multiple indicators in addition to effective impervious areas on streamflow, particularly the baseflow. This analysis can then be used to develop appropriate corresponding watershed planning and stormwater management practices for mitigating urbanization impacts on the hydrological function of the watershed.

3.3 Green Infrastructure and Stormwater Mitigation

Green infrastructure, in lieu of grey infrastructure, is a system that "uses natural systems—or engineered systems that mimic natural processes—to enhance overall environmental quality and provide utility services" (EPA, 2012). The concept of preserving natural areas and using ecological design for protecting, enhancing, and restoring ecosystem services in order to improve environmental quality and provide hazard mitigation is fundamental in the concept of green infrastructure (Fabos, 1995; Benedict and McMahon, 2006; McDonald et al., 2005; Ahern, 2007). Its origin lies in the paradigm of "design with nature", which integrates natural resources and hazard assessment in order to design sensibly and responsibly with the environment (McHarg, 1969).

Stormwater best management practices (BMPs) embrace both structural and non-structural strategies to manage stormwater runoff (Urbonas, 1994). Structural BMPs emphasize ecological engineering design including detention basins, infiltration trenches and wells, vegetated swales and rain gardens, vegetated buffer strips, porous pavements, constructed wetlands and greenroofs. Non-structural BMPs emphasize policy and regulations that help to alleviate the root of the problem—urbanization—and to engage the public. These include, but are not limited to, land use planning, natural resources management, streams and wetlands restoration, management of household chemicals, on-site programs of runoff management and flood insurance (Ellis and Marsalek, 1996; Ellis, 2012).

In summary, urbanization alters the natural hydrological cycle, which is further impacted by climate change. The changing water cycle, particularly in urbanized watersheds, affects the ability of stormwater management programs to restore watersheds to their pre-development states. Therefore, it is critical to explore innovations in stormwater management practices in order to maximize their ability to mitigate urbanization impacts while in the mean time serving as cliamte change adaptation strategy for communities (Figure 1).

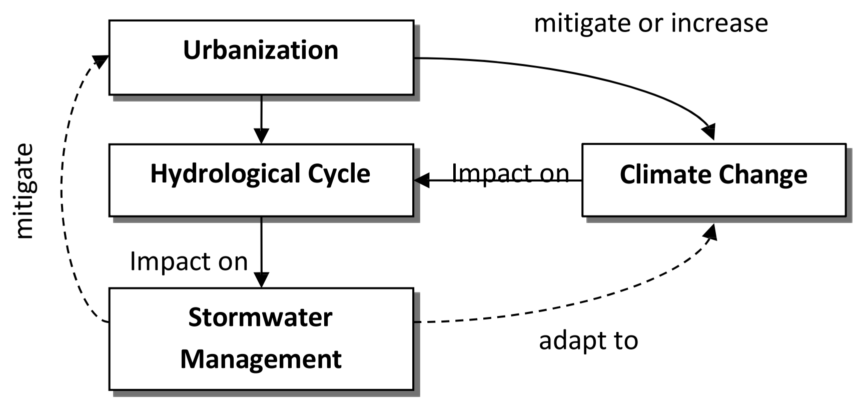

Figure 1. Relationships between urbanization, climate change and stormwater management (direct impacts shown in solid arrows; indirect impacts shown in dashed arrows)

4 STUDY AREA CONTEXT

The Boston Metropolitan Area has a population of 3 million with an estimated increase of 11 per cent (181,000 people) in 2030, according to the Metropolitan Area Planning Council (MAPC, 2009). As population growth continues, it is likely that more vulnerable populations will be exposed to flooding hazards in the region. Recent vulnerability research has been conducted in central Massachusetts for droughts hazards (Polsky, Neff, and Yarnal, 2007; Yarnal, Polsky, and O'Brien, 2009) and for impacts from projected sea level rise in Massachusetts coastal communities (Kirshen, Knee, and Ruth, 2008). However, recent significant flooding events in 2010 and 2011 were mainly non-coastal floods, suggesting further research on inland flooding is needed. Moreover, further vulnerability research is needed as Massachusetts urged that "the need to perform risk and vulnerability assessments was widely recognized across all sectors" in its *Climate Change Adaptation Report* (Cash, 2011, p.3). Finally, the State further identified green infrastructure as "ecosystem-based adaptation" strategy for climate change planning (Cash, 2011, p.29).

The Charles River watershed was chosen out of nine watersheds in the Boston Metropolitan Area for several reasons. First, the entire 778 km^2 watershed is predominately within the Boston Metropolitan Area with minimal coastal lines so that the influence from costal flooding was minimal in this study. In addition, the watershed is comprised of 35 municipalities, including the City of Boston, and is the most densely populated in the state. Finally, it consists of the most socially at-risk populations in the state, defined as *Environmental Justice* populations considering minoriry, low-income, and english-isolation groups by the Massachusetts Office of Geographic Information (MassGIS)—implying potential higher social vulnerability to climate change impacts. Given these factors, research for climate change impacts in this watershed is particularly timely and critical for further social-economic impact studies.

The Charles River watershed consists of rural-urban gradient in land use and land cover composition (Figure 2). The natural areas cover half of the watershed—36% of forests, 11% of wetlands, 3% of water bodies. The other half of the watershed is heavily influenced by human acativities—44% of urbanized areas (i.e., commercial, industrial, residential, transportation, institutional, junkyard, utilities), 3% of agriculture lands, 3% recreational lands. Within the urbanized areas, 21% of the watershed area are covered by impervious surfaces (e.g., building footprints, streets, parking areas) while the remaining 23% of the watershed area consists of non-natural pervious areas (e.g., lawns, planting beds).

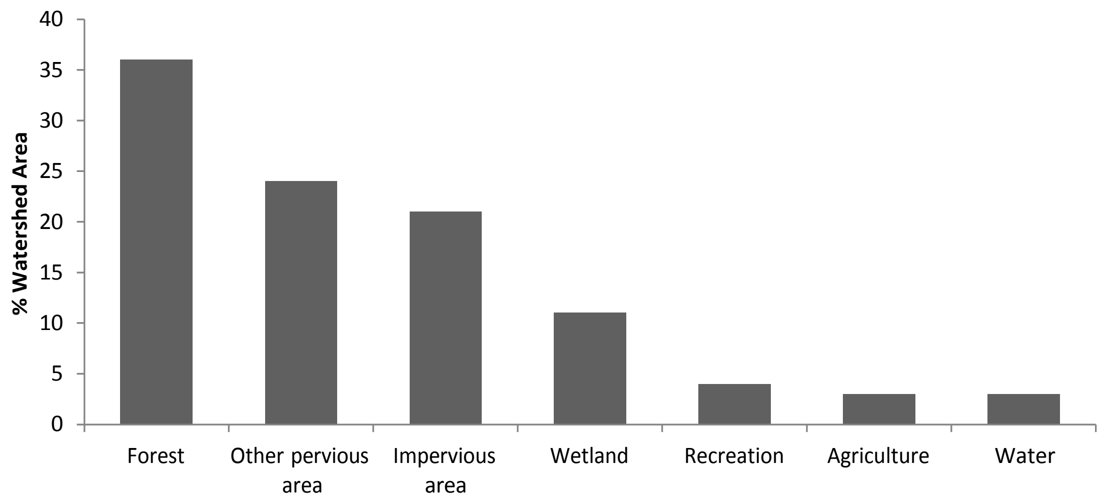

Figure 2. Current land cover types in percentages of the Charles River watershed area

5 METHODS

5.1 SWAT Modeling and Data Source

To achieve the goals of this study, the capacity of incorporating climate change data and detention functions into stream flow impact simulation is critical. The Soil and Water Assessment Tool (SWAT) (Arnold and Allen, 1996; TAMU, 2011) has been successfully used to study climate sensitivity and impacts on hydrology at a regional watershed scale (Wu, 2007). In addition, multiple General Circulation Models (GCMs) and IPCC climate change scenarios have been incorporated in SWAT for studying hydrologic cycles, stream flows and water availability (Takle et al., 2005; Bekele and Knapp, 2010). Combined with GIS compatibility, SWAT can simulate the temporal and spatial variability of the hydrological processes at the subbasin level defined in the model (Santhi, 2008).

Originally developed for rural environments (Arnold and Allen, 1996), SWAT has progressed in modeling urbanized watersheds with rural-urban gradient similar to the Charles River watershed (e.g., stream flow simulation in an area of 127 km^2 and 38% urbanized watershed in Korea (Lee et al., 2012), a water supply modeling in an area of 33 km^2 watershed with the river flowing from rural to urban areas in Mexico City (Jujnovsky et al., 2012)). In a case study of the Neponset watershed that consists of southern portion of the City of Boston and is due south of the Charles River watershed, Tian et al. (2012) found SWAT is capable simulating streamflow well in growing seasons yet less effectively simulating snow melt in areas with large impervious areas for modeling dissolved organic carbon in stream flow. In addition to the capacity of modeling climate change impacts and detention functions, SWAT is chosen in this study for the purpose of simulating stream flows in a rural-urban watershed for riparian flooding that primarily occurs in the growing seasons.

The 30 m grid-based Digital Elevation Model (DEM) generated by the USGS National Elevation Dataset (NED) was used for the initial delineation of watershed and subbasin boundaries. In order to better match the size of census tracts to integrate a *Social Vulnerability Index* in the flooding risk assessment (Cheng et al., 2012), additional outflow points were manually added to the main channel. The median size of census tracts in the watershed, 1 km^2, was used as the minimum size for additional subbasins. As a result, a total of 54 subbasins were delineated, ranging from 0.5 to 35 km^2 with a mean size of 14 $km^{2.}$

Within each subbasin, the water balance is simulated for each of the Hydrologic Response Units (HRUs). Each stream channel outflow volume is the sum of the water balance in all HRUs within the respective subbasin. The HRU was determined based on land uses and hydric soil types. Four major urban land use categories (UCOM, URHD, URMD, URLD) and four non-urban SWAT land use categories (AGRL, FRST, WETL, WATR) were derived from a 2005 state-wide land use dataset and based on the similarity of development intensity and characteristics of urban (e.g., commercial, industrial, residential) and non-urban (e.g., agriculture, forest, wetlands, water) land use categories. Considering that the combined agricultural and recreational land areas comprised only 6% of the watershed area, the land cover was assumed to have similar grassy characteristics for the purpose of modeling the streamflow in this study.

Soil data was derived from the United States Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS). The SSURGO-certified soil datasets have met all standards and requirements approved by the NRCS and possess the most detailed information developed by the National Cooperative Soil Survey. The hydric soil groups used for delineating HRUs included hydric soil group A (35% of watershed area), group B (30% of water shed area), group C (24% of water shed area), and group D (11% of water shed area). A total of 1470 HRUs were then identified with a combination of SWAT land use type and hydric soil group properties.

Daily observed weather data between 1990 and 2011 was obtained from the National Climatic Data Center (NCDC) at three stations—Walpole 2 (USC00198757), East Milton Blue Hill Observatory (USW00014753), and Boston Logan International Airport (USW00014739). The three variables used to calibrate the watershed were maximum temperature, minimum temperature, and total precipitation. The completeness of daily records poses the greatest constraint for gathering observed weather data. The weather stations were chosen because the complete historical daily records in addition to their locations were immediately due south and in close proximity to the upper, middle and lower basins respectively.

Calibration is the process of adjusting model parameters to minimize the difference between simulated output and observed values (NRC, 2009). Validation is the process of using part of the dataset as an input in the calibrated model in order to compare the calibrated model results with the observed values. The observed daily streamflow data between 1990 and 2011 was obtained from the United States Geological Survey (USGS) database at stream gage number 01104500 located in Waltham, Massachusetts, at the lower basin along the Charles River main stream. This study used a 2-year warm-up period (1990 to 1991), a 14-year calibration period (1992 to 2005) and a 6-year validation period (2006 to 2011). The results of the Nash-Sutcliffe model efficiency coefficient (NSE) (Nash and Sutcliffe, 1970) were 0.81 for the calibration period and 0.93 for the validation period, which represented a high level of confidence in the simulated model in its resemblance to the basin properties. A NSE value of 1 represents a perfect match and 0.6 is considered a good model fit (Moriasi et al., 2007).

5.2 Climate Sensitivity Tests

In the climate change impact assessment using climate sensitivity tests (Ficklin et al., 2009), a combination of three weather variables were examined—mean temperature (0,+1,+2,+3˚C), mean precipitation (0,+10,+20%), and variation of precipitation(0,+10,+20%). A total of 36 climate change conditions including the current climate conditions (0,0,0) were applied to the calibrated SWAT model (Figure 3).

5.3 Flooding Hazard Index (HI)

The output of stream outflow was used to compute flooding Hazard Index (HI) along with climate change impact assessment (Figure 3). HI was defined as the probability of number of days in a study period of 45 years when the stream outflow (Q_i) in respective climate change conditions would exceed the bankfull discharge volume (Q_0) in current climate conditions.

$$HI = P(Q_i > Q_0) = \frac{\text{Days when } Q_i > Q_0}{\text{365 days a year * 45 years}} \tag{1}$$

P: Probability

Q_i: Stream outflow in climate change conditions

Q_0: Stream bankfull discharge in current climate conditions

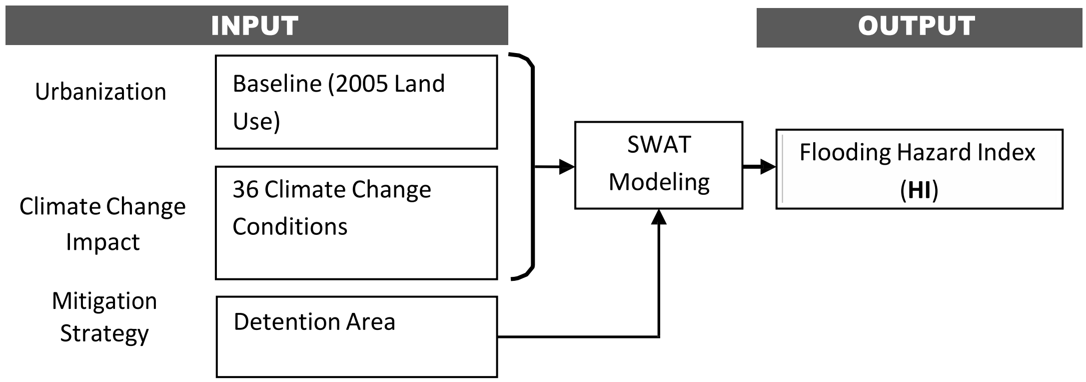

Figure 3. Research design using SWAT modeling for testing effects of detention for mitigating flooding hazards in climate change conditions

5.4 Detention Tests and Analyses

To assess the detention functions for the flooding hazard mitigation strategy, SWAT has an impoundment water routing function for modeling water that is temporarily stored and hydrologically connected in the watershed. Besides reservoirs, wetlands, and ponds, which were controlled by land use in this study, the function of potholes was employed to simulate the function of stormwater wet detention (i.e., retention). Potholes are closed depressions in the watershed functioning as temporary water storage areas and in this model function most similarly to wet detention ponds. For the remainder of this paper, we will refer to these as detention functions.

Surfacewater and precipitation are the main source of the inflow to the potholes and when storage exceeds the maximum volume assigned for each pothole, the excessive volume then joins the surfacewater system. Potholes contribute to stream baseflow through infiltration, and will impact total stream flow when capacity is reached. In addition, potholes loose water through evaporation. In the SWAT model, only one pothole in each subbasin was created by assigning one hydrologic response unit (HRU). To optimize water storage functions in the model, HRUs with the largest AGRL SWAT land use category (i.e., agricultural and recreational land uses) were selected as potholes. In addition, 100% of the selected HRU area was assigned as the drainage area for each respective pothole (POT_FR=1). Furthermore, for the consistency of the flooding hazard defined in this study, the maximum storage for each pothole was the volume of bankfull discharge volume in the respective subbasin. Finally, a linear regression was employed for analyzing the relationship between the percentage of detention areas in the subbasin drainage areas and HI under each climate change condition.

$$Y = aX + b \qquad (2)$$

Y: HI of each drainage subbasin area under given climate change scenario
X: Fraction of detention functions (pothole/wet detention) area in the drainage subbasin area
a: X variable coefficient
b: Intercept constant

6 RESULTS

A total area of 3.2% of the Charles River watershed area was modeled as detention functions in this study. Among 32 climate sensitivity tests, only 10 present weak yet significant effects between the flooding hazard indices (HI) and the presence of wet detention (Pr ranges from -.27 to -.39; R^2 ranges from 0.07 to 0.15, $p<0.001$) (Table 1).

Considering the parameters of climate change and flooding hazards for landscape planning, two hazard mitigation policy goals were examined: (1) reduce flooding hazard indices (HI) to zero, and (2) mitigate flooding impacts to the level in *Current Climate Conditions* (HI=0.013, which is the intercept of the regression equation) (Table 2). The results illustrated that an average of 14% with a range of 13 to 18% of detention area in a sub-watershed would be needed for reaching the first goal, while an average of 5% and up to 8% of the wet detention area would be needed for reaching the second goal.

Table 1. Summary of mean and standard deviation of the flooding hazard index (HI) and Pearson's correlation coefficient between HI and the fraction of wet detention area in drainage subbasin area under climate change conditions (combination of climate variables of temperature & precipitation).

Climate Change Conditions			HI S		Correlation	
Temp mean (+˚C)	Precip mean (+%)	Precip var (+%)	Mean	Std. Dev.	Pea rson's r (Pr)	Relatic to dete
0	0	0	1.0%	0.4%	-.390**	Signific Mode to W
1	0	0	0.9%	0.4%	-.366**	
0	10	0	1.6%	0.7%	-.359**	
1	10	0	1.4%	0.6%	-.358**	
1	20	0	2.6%	1.2%	-.346*	
1	20	20	2.4%	1.1%	-.344*	
2	10	10	1.3%	0.5%	-.341*	
2	10	0	1.2%	0.5%	-.329*	
2	0	0	0.7%	0.3%	-.304*	
3	10	0	1.1%	0.4%	-.272*	
0	20	0	2.9%	1.4%	-.263	No Signific We
0	20	10	3.1%	1.4%	-.255	
3	0	0	0.7%	0.2%	-.255	
0	20	20	3.2%	1.4%	-.255	
1	20	10	2.7%	1.2%	-.242	
0	10	10	2.0%	0.8%	-.234	
0	10	20	2.1%	0.8%	-.233	
1	10	10	1.6%	0.7%	-.233	
1	10	20	1.9%	0.8%	-.233	
2	20	0	2.3%	1.1%	-.228	
2	20	20	2.6%	1.1%	-.215	
2	20	10	2.4%	1.1%	-.213	
0	0	10	1.3%	0.4%	-.212	
0	0	20	1.4%	0.5%	-.204	
2	10	20	1.8%	0.6%	-.188	No Signific Very V
1	0	20	1.3%	0.4%	-.180	
1	0	10	1.1%	0.4%	-.174	
3	20	0	2.2%	0.9%	-.140	
3	20	10	2.3%	0.9%	-.129	
3	20	20	2.5%	1.0%	-.126	
3	10	20	1.7%	0.6%	-.098	Negli
3	10	10	1.5%	0.5%	-.085	
2	0	20	1.2%	0.4%	-.073	
2	0	10	1.0%	0.3%	-.061	
3	0	10	1.1%	0.3%	.035	
3	0	20	1.0%	0.3%	.036	

*p<0.05 **p<0.001 temp: temperature; precip: precipitation; var: variation

A steeper slope represents a greater effect from applying detention functions in respective climate change combinations. Increasing the mean precipitation resulted in a trend with a steep slope, while increasing the mean temperature resulted in a trend with a gentle slope (Figure 4). For example, when the temperature increases 1°C in combination with a mean precipitation increase of 20%, every 1% increase in detention area could decrease the HI between 0.25% to 0.28%. However, no detention was needed to mitigate climate change-induced flooding hazards to current climate conditions when only temperature increased with no precipitation change. It is worth noting that a general trend of climate change impact assessment in this study reveals that increasing temperature reduces flooding hazard indices, possibly due to the increased evapotranspiration in this particular watershed. As a result, detentions appear to be less effective when temperature increases to 3°C (Table 1).

Table 2. Results of regression coefficients and percent detention area required for reaching flooding hazard mitigation goals for zero hazards (HI=0) and to the level of current climate conditions (HI=0.013).

Climate change variables						**Min.% detention area to reach**
Temp mean (+˚C)	Precip mean (+%)	Precip var (+%)	X variable a	Intercept b	R Square	HI=0
0	0	0	-0.101**	0.013**	0.152	13
1	0	0	-0.084**	0.011**	0.134	14
0	10	0	-0.162**	0.021**	0.129	13
1	10	0	-0.146**	0.018**	0.128	13
1	20	0	-0.281*	0.034**	0.120	13
1	20	20	-0.247*	0.031**	0.119	13
2	10	10	-0.119*	0.017**	0.116	15
2	10	0	-0.109*	0.015**	0.108	14
2	0	0	-0.057*	0.009**	0.092	16
3	10	0	-0.076*	0.013**	0.074	18

*p<0.05 **p<0.001 temp: temperature; precip: precipitation; var: variation

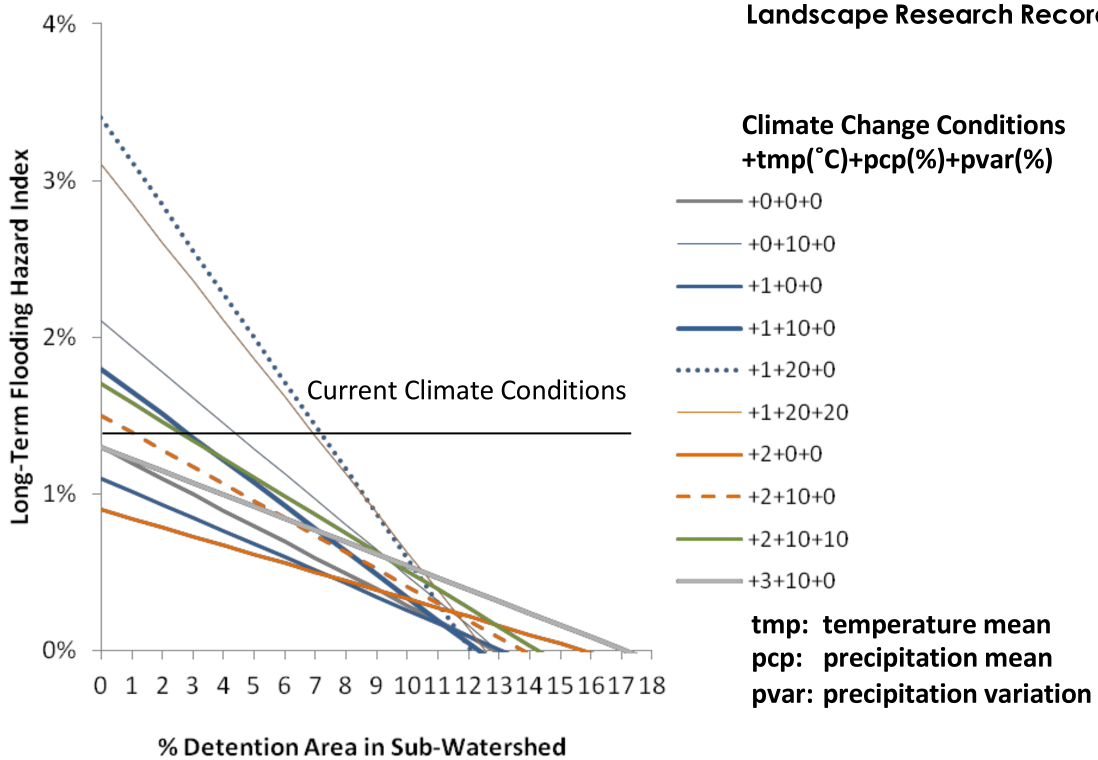

Figure 4. The effects of detention in mitigating flooding hazards in 10 climate change conditions in relation to percent of detention area in respective drainage subbasin.

7 DISCUSSION

7.1 Effects of Detention on Flooding Hazard Mitigation

Climate change impacts on hydrology are complex and varied from watershed to watershed (Praskievicz and Chang, 2009). The climate sensitivity assessment of the long-term flooding hazard index (HI) illustrated increasing temperature would result in lower HI due to higher evapotranspiration, while increasing both mean and variation in precipitation would result in a higher HI (detailed assessment methods and results can be found in Cheng, in press). For example, detention coefficient became positive values and detention requirement became negative when the mean temperature increased 3˚C indicating that the HI was already lower than the baseline HI. There was no clear threshold point for the effects of detention areas revealed under climate change impact assessment due to the fact that climate change impacts on hydrology was complex and varied from watershed to watershed (Praskievicz and Chang, 2009). In addition, there is a positive yet a weak correlation between the increased amount of detention area and reduced HI, which implies that wet detention alone is not the most effective strategy. Moreover, SWAT has limitation in modeling additional dry detention functions with infiltration enhancement, which could be a more effective flooding hazard mitigation strategy for capturing, storing, and infiltrating stormwater.

7.2 Innovations in Green Infrastructure for Climate Change Adaptation

Green infrastructure has multiple functions in landscapes. In addition to providing ecological services such as stormwater management and flooding hazard mitigation, it is integrated into landscape planning and design to provide recreation as well as aesthetic values for communities (Echols and Pennypacker, 2008). In response to climate change impacts (IPCC, 2007), recent research has investigated the role of green infrastructure for mitigation and adaptation to climate change. For example, planting design combined with aesthetics and ecological resilience functions (e.g., structural diversity, redundency, biodiversity) can mitigate effects from increasing temparature as well as enhance adaptive capacity of the landscape in responding to climate change uncertainty (Hunter 2011). In addition, Gill et al.

(2007) found increasing vetegated land cover in the Greater Manchester metropolitacn areas can help to reduce increased stormwater runoff and temperature, which are induced by climate change.

Built upon previous studies on the role of using green infrastructure for climate change adaptation, this study focused on using detention functions as one of the stormwater BMPs for flooding hazard mitigation. Detention functions require depressional land areas that can be inundated with water for a period of time. Applying this concept to landscape planning and design, those detention areas could possibly be applied on public recreational lands such as athletic fields and parks. Currently, 3.6% of the Charles River watershed is for recreational uses, including cemeteries, golf courses, passive and active recreation, marinas and beaches. Excluding privately owned golf courses and cemeteries, only 1.7% of the land area could potentially be used as detention functions, which is up to 6% short of reaching the current climate conditions level of the HI and 10% to 15% short of reaching the zero hazard (HI) goal.

Rainfall is the major source of stormwater runoff and flooding. On-site storage and rainwater harvest is therefore the key for managing urban stormwater (Tjallingii, 2012; Beeham, 2005). With limited natural open space and recreational land use areas that could possibly allow for wet detention areas in an urbanized watershed, achieving policy goals for reducing flooding hazards will require more innovative and aggressive land use planning and design in both minimizing impervious surface and maximizing the availability and use of pervious areas. For example, on-site detention functions could be implemented on residential lots. In addition, projects in Chicago and other areas of the country have successfully implemented detention functions beneath impervious road, parking and other impervious surfaces (e.g., Streetscape and Sustainable Design Program at www.cityofchicago.org/Transportation). As a result, innovations in green infrastructure design such as greenroofs, cisterns, rainbarrels, and underground storage underneath pavement or buildings can function as detention. Thus, a network of green infrastructure in landscape planning and design can help to mitigate climate change impacts and in turn to enhance adaptive capacity of communities for climate change (Gill et al., 2007).

8 CONCLUSION

This study has demonstrated a range of potential climate change impacts on riparian flooding hazards and the effectiveness of using detention functions (wet detentions) for their mitigation. Since climate change has implications for long-term environmental hazards associated with water resources and management, the findings are particularly timely.

We examined two hazard mitigation policy goals, for achieving a zero flooding hazard index (HI) and maintaining the hazard index associated with current climate conditions. Even though the zero percent chance of flooding hazard is an ambitious policy goal, it provides an upper boundary for developing policy frameworks with feasible intermediate goals. In addition, it is worth noting that wet detention alone has limited potential for flooding hazard mitigation and is no substitute for integrated green infrastructure network, land use and watershed management strategies such as open space and floodplain protection and wetlands restoration (Brody and Highfield, 2013) as well as engaging the stakeholders and the public to “Make room for the River” (Wolsink, 2006) for comprehensive flooding hazard mitigation.

Stormwater management has evolved to look beyond the effect of imperviousness and structural BMPs in order to examine their balance with pervious surfaces and non-structural BMPs (Brabec, 2009). Urbanization associated with unsustainable development patterns and living styles is the root cause of climate change and urban flooding. There is no single solution to resolving the effects of climate change. As climate change is an integral factor of anthropogenic influence in the hydrologic cycles in this changing world, this is a critical time for rethinking green infrastructure for mitigating climate change impacts and serving as strategies for climate change adaptation. Landscape architecture planning and design thus play an important role in achieving innovations in integrated green infrastructure network systems, particularly in urbanizaed areas, for coping with climate change.

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