GREEN INFRASTRUCTURE RESILIENCE PLANNING FOR CLIMATE CHANGE: STORMWATER BMPS AND SOCIAL VULNERABILITY FOR CLIMATE-INDUCED FLOODING RISK ASSESSMENT FRAMEWORK

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Abstract

Climate change and urbanization affect hydrological cycle and lead to more frequent and intense human-influenced climate-induced floods that subsequently have significant environmental, economic, social, and cultural impacts on the society. Under increasing urbanization trends worldwide, more people are likely to be exposed to flooding hazards that threaten their livelihood; particularly for those who are socially vulnerable with low coping capacity. Green infrastructure, including both structural and non-structural stormwater best management practices, has been widely accepted in polices for stormwater management and an emerging strategy for climate change adaptation in spatial planning. There is a need in planning for integrating risk assessment and using green infrastructure as an adaptive planning strategy for resilience planning. The goal of this research is to provide a resilience planning framework to unpack risk assessment methodology and a tool for investigating the role of green infrastructure for climate change adaptation using the Charles River watershed in the Boston Metropolitan Area as a case study.

The overarching research questions are: (1) to what degree does the climate change become sensitive to long-term flooding hazards? (2) what are the key indicators for evaluating urban resilience and social vulnerability to long-term climate-induced flooding risks in the Boston Metropolitan Area? (3) to what degree can green infrastructure mitigate long-term climate-induced flooding risks of the Boston Metropolitan Area? (4) what is the role of green infrastructure in integrating social vulnerability and climate-induced flooding risks for climate change adaptation in landscape and urban planning?

Risk assessment is synthesized and spatially correlated through hazard, exposure and vulnerability studies. The long-term flooding hazard is defined by the probability of daily flow rate higher than the bankfull discharge. Exposure refers to the population who live in the flooding hazard zones. Vulnerability is reflected upon social-economic indicators related to flooding hazards coping capacity. Hydrological modeling for stream flow is conducted using the Soil and Water Assessment Tool

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(SWAT). In addition, six green infrastructure land cover patterns varying in development density with a combination of various stormwater BMPs (porous paving, bioswales, and green roofs) based on the concept of transect planning are identified for Hydrologic Response Units (HRU) in SWAT. Climate change sensitivity approach through combinations of temperature and precipitation scenarios (+1, +2, +3, +4 ºC with an increment of 10% daily precipitations) are used to assess climate-induced long-term flooding hazards and mitigation threshold capacity from stormwater BMPs.

The expected results will demonstrate the effectiveness of applying a full range of probable stormwater BMPs in rural to urban transect planning for reducing climate-induced long-term flooding risks. The limitation of structural BMPs indicates that non-structural BMPs and comprehensive land use and watershed management policies for green infrastructure planning is needed for climate change adaptation. More over, an integrated hydrological risk assessment including social vulnerability is essential for resilience planning. Finally, this paper proposed a comprehensive green infrastructure resilience planning framework and methodologies that can be applied in practice to cope with climate change and enhance resilience in the Boston Metropolitan Area and other urbanized watersheds.

1. Introduction

"*Man takes a calculated risk when he builds his towns, cities, and other installations on the floodplain of a river. He, thus, is responsible for flood damages, if not for the floods that cause them.*" (Savini and Kammerer, 1961, pp.1591-A)

Not only is man responsible for the human-induced floods as a result of urbanization but also for the environment and the society that man created for socially vulnerable groups to be more susceptible to flooding hazards. Our built environment is multifaceted that involves limited natural resources and diverse cultures under local, regional, and global political and socio-economic context. The complexity between natural and human systems is intertwined and intangible. The world population grows exponentially since industrial revolution changed the face of civilization. The consequence of urbanization development has caused significant and irreversible environmental, economic, social, and cultural impacts that are not sustainable for our future generations (Bruntland 1987). One of the pressing issues is the climate change, which is a result of green house gas emission largely derived from urbanization and anthropogenic changes to the atmosphere (Karl, Melillo, and Peterson, 2009; IPCC, 2007).

Climate change and urbanization affect hydrological cycle and lead to more frequent and intense human-influenced climate-induced floods that subsequently have significant environmental, economic, social, and cultural impacts on the society. One of the major impacts from urbanization is the increased impervious land cover that alters hydrological cycles resulting in excessive runoff, lack of infiltration, and insufficient aquifer recharge (Booth and Jackson, 1997; Brabec, Schulte, and

Richards, 2002). Consequently, human-induced flooding at various scales is a problem in urbanized areas. Under climate change impacts, climate-induced flooding as a result of increased intensity and duration of storm events are likely to affect the New England region (Rock et al., 2001). Compounded by population growth in urbanized areas, more people are likely to be exposed to climate-induced disasters. The under-served population would be particularly more vulnerable due to a lack of available resources for risk mitigation, preparedness, response, and recovery (Hardoy and Pandiella, 2009; Bartlett, 2008; Douglas et al., 2008; Maantay and Maroko, 2009). Hardest hit are often the socially vulnerable groups, such as the elderly, those of low socio-economic status, and minority communities. Finally, top-down regulatory planning over past decades tends to dismiss local knowledge that traditionally passes down to generations in coping with Nature. The alteration and eroding of local culture therefore increases community's vulnerability to climate change (Umemoto and Suryanata, 2006).

1.1 Green Infrastructure and Stormwater BMPs

Green infrastructure, including both structural and non-structural stormwater best management practices (BMPs), has been widely accepted as alternative stormwater management for restoring or enhancing ecological services. In lieu of grey infrastructure, green infrastructure is defined by the United States Environmental Protection Agency (EPA) as a system that "uses natural systems – or engineered systems that mimic natural processes – to enhance overall environmental quality and provide utility services." Applying what ecosystem services can provide to achieve the same functions that are designed to serve urban infrastructure purposes; green infrastructure incorporates alternative BMPs to better improve environmental quality. The enhanced ecological functions consequently help to increase resilience of ecosystems to absorb environmental impacts from climate change.

Structural BMPs emphasize ecological engineering design such as bioswales or rain gardens, porous pavements, and green roofs. Non-structural BMPs emphasize policy and regulations that help to alleviate the root of the problem – urbanization – and engage the public (Urbonas, 1994). Non-structural BMPs include a wide range of strategies, including but not limited to land use planning, natural resources management, streams and wetlands restoration (Ellis and Marsalek, 1996), and smart growth. Recent research suggests that the integrated structural and non-structural approach in green infrastructure plays an important role as an adaptive planning strategy for mitigating flooding risks and serves as a climate change adaptation strategy in spatial planning (Gill et al., 2007).

1.2 Planning for Climate Change

Planners have been given the challenge for decades in resolving conflicts between environmental protection, economic development, and social equity for sustainability (Campbell, 1996). Under the climate change impacts with increased risks to human-influenced and climate-induced natural disasters, planners have a greater mission in planning for resilience and facilitating resources distribution to achieve multiple mutual benefits for the environment, economy, equity, as well as diverse cultures.

Planning for resilience in enhancing capacity of adaptability to climate change impacts is a top national priority in cities (Godschalk, 2003; Beatley, 2009) and a top agenda in the world climate change summit. Planning strategies in the new urban world require robustness and adaptability with multiple objectives in order to be resilient to climate change variations and uncertainty (Ahern, 2011). The theory and application of resilience in planning application remain an open discussion in that what a resilient urban form is like (Hamin and Gurran, 2009), how the governance structure can be more resilient (Lynch, 2008), or in what planning process can achieve resilience (Hebbert, 2009; Lessard, 1998). This research is intended to fill the gap of resilience research in green infrastructure planning.

1.3 Research Goals

The goal of this research is to provide a resilience planning framework to unpack risk assessment methodology and a tool for investigating the role of green infrastructure for climate change adaptation using the Charles River watershed in the Boston Metropolitan Area as a case study. The overarching research questions are: (1) to what degree does the climate change become sensitive to long-term flooding hazards? (2) what are the key indicators for evaluating urban resilience and social vulnerability to long-term climate-induced flooding risks in the Boston Metropolitan Area? (3) to what degree can green infrastructure mitigate long-term climate-induced flooding risks of the Boston Metropolitan Area? (4) what is the role of green infrastructure in integrating social vulnerability and climate-induced flooding risks for climate change adaptation in landscape and urban planning? This paper will address those questions from theoretical and methodological framework and provide implications of using the green infrastructure planning framework into practices for climate change planning.

2. Theoretical Framework

2.1 Resilience Theory

Resilience is defined as a capacity in a system to absorb shocks from disturbances that change the system’s ability to return to the state of the same structure and functions (Holling, 1973; Walker and Salt, 2006). Resilience thinking can be applied to society as a “capacity to anticipate, prepare for, respond to, and recover from significant threats with minimum damage to social well-being, the economy, and the environment” (NRC, 2010). It provides system thinking in dealing with complex issues such as climate change in the coupled natural and human systems (Liu et al., 2007). The resilience framework should be robust rather searching for optimal control in the social-ecological systems and this framework is intended to inform adaptive planning (Anderies, Walker, and Kinzig, 2006).

2.2 Vulnerability Theory

Vulnerability is a sign for the erosion in the elements of social-ecological resilience (Adger, 2006). When communities have insufficient coping capacity for the shocks and disturbances in the coupled natural and human systems, they are more vulnerable to the adverse effects of uncertainty and extreme variation which climate change has promised. Vulnerability for climate change is closely associated with social resources in terms of an individual as well collective adaptive capacity to mitigate, prepare for, respond to, and recover from environmental hazards (Birkmann, 2006). Under the context of complexity in politics and economics in the urbanization process, a “risk society” is often created with socially vulnerable groups who are more susceptible to environmental hazards (Colten, 2006; Blaikie, 1994).

Social vulnerability is therefore intertwined with environmental, economic, social, and cultural dimensions. Environmental vulnerability refers to the physical environment that is susceptible to natural or manmade hazards. For example, the low land and floodplain areas are prone to flooding hazards or the built environment with massive impervious areas increasing the risk of flash floods. Economic vulnerability is intertwined with the economic systems at global, national, regional, local, and individual levels. Depends on the scale of vulnerability assessment, the economic vulnerability can be specified at appropriate scale. For example, poverty is the key indicator for economic vulnerability and its measurement is often to be gross domestic product (GDP) at the global or national scale and median household income at the regional or local scale. Social equity vulnerability refers to whether the society created inequitable environment in which the policies and resources distribution are limited for marginal groups of society thus making those people who tend to get more exposure to hazards and are susceptible to damage and causality caused by disasters. Socially vulnerable groups include low income, disabled, women, children, aged groups, minorities, and immigrants (Pelling, 1997; Laukkonen et al., 2009). Cultural vulnerability is the inverse of cultural sustainability that aims to preserve tangible or intangible cultural heritage. It is related to individual as well as collective attitudes and behaviors toward actions in climate change mitigation and adaption to achieve the culture sustainability. All vulnerability factors among four dimensions are interrelated and have impacts and feedbacks on one another.

3. Green Infrastructure Resilience Planning Framework

Climate change and urbanization have impacts on hydrological cycle, land cover change, and people’s livelihood. Landscape and urban planning is essential for an integration of coupled natural and human systems to reduce environmental hazards and social vulnerability while in the mean time achieve climate change mitigation and adaptation. Risk assessment encompasses three components: hazards, exposure, and vulnerability. Hazards are spatially defined in the physical environment; exposure refers to population who are located in the hazard zones. Social vulnerability indicates coping capability of a community to mitigate, respond to, recover from, and adapt to the exposed hazards (Birkmann, 2006; De Wrachien, Mambretti, and Sole, 2008). When exposure is highly spatially correlated with social vulnerability, it implies an equity issue in which people who have least resources to cope with disasters live in the highest environmental hazard areas. This research focuses on climate-induced long-term flooding risk assessment.

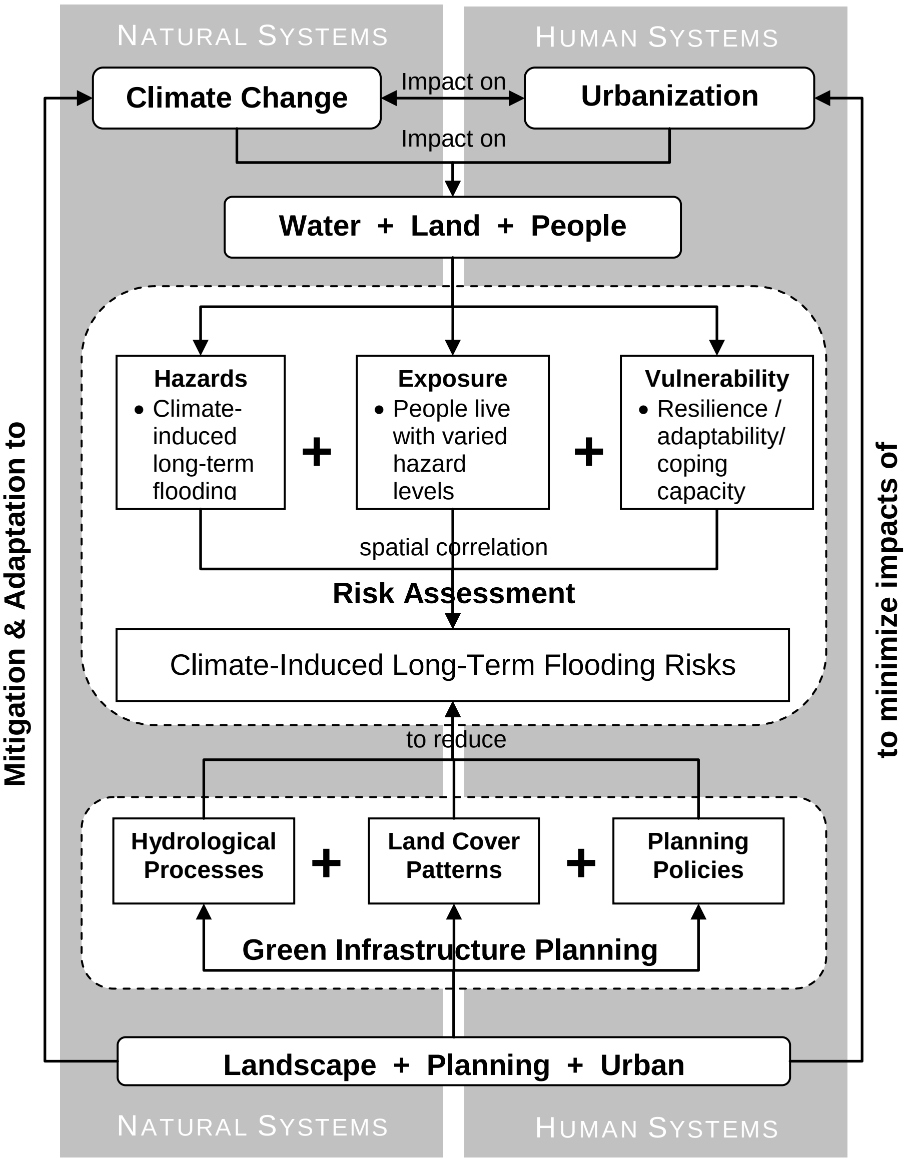

Figure 1. Green infrastructure resilience planning framework integrating climate-induced flooding risk assessment for climate change adaptation in the coupled natural and human systems

A comprehensive green infrastructure planning addresses hydrological processes, land cover patterns, and planning policies for reducing climate-induced long-term flooding risks. Effective integration of structural and non-structural BMPs can reduce impervious land cover and restore hydrological function in urbanized areas for stormwater management and long-term flooding hazards mitigation. Planning policies influence the location and implementation of green infrastructure practices that are closely linked to land cover patterns and hydrological processes. Finally, green infrastructure has multiple benefits that can subsequently mitigate urbanization and climate change impacts such as reducing carbon emissions, minimizing impervious surfaces, reducing urban heat island effects, and improving environmental quality (Figure 1).

4. Methodologies

4.1 Study Area

The study area includes 24 municipalities in the 770 square kilometers of the Charles River watershed. As population growth continues in urbanized areas under current development patterns, more impacts from urbanization and interactions with climate change will impose more potential risks for society. Aside from the potential climate-induced sea level rise impacts on the coastal communities, this study focuses on inland climate-induced long-term flooding risks. Charles River watershed has over 3 millions population and is the most populated watershed in the Boston Metropolitan Area, including the City of Boston. Charles River watershed encompasses the most environmental justice populations defined by the Massachusetts Office of Geographic Information, including neighborhoods with high minority, non-English speaking, low-income, and foreign-born populations.

4.2 Risk Assessment

Risk assessment is highly spatially correlated in the coupled natural and human systems through a comprehensive synthesis of three major analyses: hazards, exposure and vulnerability. Long-term flooding hazard is defined as a probability of daily stream flow higher than the bankfull discharge:

$$P(Q > Q_{bankfull}) = \frac{days\ when\ Q > Q_{bankfull}}{365}$$

Stream flow can be simulated through hydrological models. Soil and Water Assessment Tool (SWAT) is a long term hydrological model that operates on a daily time step (Arnold et al., 1998). Key elements used to simulate hydrological balance in a subbasin level include digital elevation model (DEM), temperature, precipitation, land use, soil, and slopes. The hazards index will be built upon 20 years of data from 1992 to 2011, in addition to 2-year warm up period 1990-1991. Assuming the maximum long-term flooding hazard reaches the probability of stream flow surpasses bankfull discharge everyday in the raining season; the long-term flooding hazard index can be scaled from 0 to 1 for each subbasin in the watershed. Climate-induced long-term flooding hazards are calculated through climate sensitivity study using a combination of incremental temperature (+1, +2, +3, and +4 ºC in daily temperature) and precipitation (an increment of 10% in daily precipitation) change until the long-term flooding hazard index reaches 1. The climate sensitivity study reflects a range of probable climate change scenarios at the local scale.

Exposure index is illustrated by the ratio of percentage population of total in the US census 2010 at the unit of block groups in GIS. Based upon hazard index in each subbasin, population at the census block groups can be spatially overlaid to determine the total affected population in the watershed as well as affected population in each subbasin. Exposure index can then be calculated based on the ratio of affected population in each census block groups over the total affected population in the watershed.

Social Vulnerability Index is built upon a US nation-wide study conducted by Cutter (Cutter, Boruff, and Shirley, 2003). Key social-economic indicators related to the Boston Metropolitan Area will be identified to reflect regional characters for climate-induced long-term flooding risks. Vulnerability index will then be constructed at a scale from 0 to 1 based on key indicators in each unit of the census block group.

4.3 Stormwater BMPs Assessment

Structural stormwater BMPs for mitigating climate-induced long-term flooding risks are assessed through land cover patterns change on the hydrological processes under the assumption that on-site stormwater management can help to mitigate a range of long-term flooding hazards under climate scenarios. Three commonly used stormwater BMPs are tested: bioswales or raingardens, porous paving, and green roofs. Six stormwater modeling typologies (SMT) are developed based on the concept of rural-urban transect planning (Dunay and Talen, 2002) as hydrologic response unit inputs for SWAT hydrological modeling. Land cover patterns vary in close association with development density that is largely defined by six land use categories: forest, rural residential density or agriculture, low density residential, medium density residential, high density residential and other intensely built areas such as commercial, industrial, transportation, and institutional land uses. Each type of development patterns implies different potential for stormwater BMPs applications. For example, bioswales or raingardens can be applied at a greater scale in the low density than those in the high density residential areas. In addition, porous paving and green roofs are more likely to be implemented in the high density and intensely built areas than those in the rural and low density residential areas. As a result, six stormwater modeling typologies with a full range of probable stormwater BMPs are developed. Then determine parameters in the SWAT model to reflect the stormwater BMPs in each stormwater modeling typology for completing the risk assessment described above.

4.4 GIS Spatial Analyses

Risk assessment and stormwater BMPs assessment designed in this research are highly spatially correlated and rely heavily on GIS spatial analyses. The expected results will indicate the low, medium, and high risks levels for long-term flooding under low, moderate, and high climate change scenarios. In addition, socially vulnerable index can be spatially correlated with exposure index to examine to what extent the vulnerable populations are also spatially distributed in the high hazard zones. Moreover, the stormwater BMPs assessment will indicate a range of threshold capacity under various climate change scenarios. Finally, risk assessment at the census block group level in the watershed scale can reflect the variance of sensitivity and vulnerability to climate change scenarios between municipalities and between upstream and downstream communities.

5. Conclusions

Planning essentially is a science of resolving people's problems over time addressing long-term sustainability. As climate change emerges as a top global as well as local agenda, its impact on the coupled natural and human systems needs to be addressed in resilience planning. This paper explores the link between climate change, risk assessment, and green infrastructure planning through the lens of climate-induced long-term flooding risks, social vulnerability, and stormwater BMPs. Climate Change is likely to impose long-term hydrological impacts on the urbanized watershed. As a result, more people, particularly socially vulnerable groups, will be exposed to climate-induced long-term flooding hazards. Structural stormwater BMPs have threshold capacity and are not sufficient in mitigating climate-induced flooding risks. Therefore, it is critical for green infrastructure planning to incorporate risk management and non-structural BMPs across watershed scale for climate change adaptation. The proposed comprehensive green infrastructure resilience planning framework and methodologies can be applied in practice to cope with climate change and enhance resilience in the Boston Metropolitan Area and other urbanized watersheds.

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