Effects of Detention for Flooding Mitigation under Climate Change Scenarios—Implication for Landscape Planning in the Charles River Watershed, Massachusetts, USA

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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, sea level rises, heat waves). Floods are omnipresent in almost every city in the United States and account for the most economic losses than any other single geophysical hazard (White and Haas 1975). Previous climate change studies have suggested promising trends of increasing 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 region. Flooding mitigation strategies have been focusing on structured engineering solutions such as dams and dikes along streams and rivers since the late 1910s. In recent decades, in lieu of conventionally engineered infrastructure, scholars have called for "soft" strategies such as green infrastructure (Thomas and Littlewood 2010) and land use planning (Burby 1998; Godschalk 2004) for comprehensive hazard mitigation and stormwater management integrated into planning and design interventions for flooding mitigation.

Stormwater detention is among the most prevalent stormwater management practices for flooding mitigation; however, the perceived benefits could be overestimated without empirical study (Beecham et al. 2005). In addition, planners are now facing challenges to cope with uncertainties from climate change impacts under a paradox between making room for water while managing growth in land use planning. For local planners and stakeholders to make adaptive land use decisions for climate change, this paper aims to answer two key questions: (1) to what degree and in what way does climate change have impacts on long-term flooding hazards? (2) how much detention area in the watershed would be needed for mitigating flooding hazards induced by climate change? And what do the results imply for innovations in landscape planning?

Climate Change and Urbanization Impacts on Flooding and Stormwater Management

Climate change is likely to increase intensity of precipitation pattern in its magnitude and duration and affects the global hydrologic cycle (Frederick and Major 1997; IPCC 2007). The effects of climate change intensify the intensity and frequency of storm events and therefore magnify the urban hydrological impacts (Wood, Lettenmaier, and Palmer 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 and drought events have significant impacts on populated urban regions where current water infrastructure is designed based on past climate trend and conventional knowledge. In addition, more frequent flooding and intensified storm events will cause more damage in populated urban regions. Therefore, alternative flooding mitigation and stormwater management are needed for accommodating climate change effects.

Man-made land cover changes derived from urbanization process contribute to climate change that has altered natural hydrological cycle and led to more frequent and intense floods. The increased impervious land cover is the leading cause for 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 remains 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 (IPCC 2007; Rock et al. 2001). Compounded by population growth in the Boston Metropolitan Area, more people are likely to be exposed to climate-induced disasters. As a result, landscape planning for enhancing capacity of absorbing urban flooding hazards has become a top national priority in cities (Godschalk, 2003; Beatley, 2009).

Green Infrastructure for Climate Change

Green infrastructure has been widely accepted as alternative stormwater management for restoring or enhancing ecological services. It is defined as a system that “uses natural systems—or engineered systems that mimic natural processes—to enhance overall environmental quality and provide utility services” by the United States Environmental Protection Agency (EPA). The enhanced ecological functions consequently help to increase resilience of ecosystems to absorb environmental impacts from climate change.

Green infrastructure includes both structural and non-structural stormwater best management practices (BMPs). 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 in mitigating impacts from urbanization and climate change impacts as well as an adaptive planning strategy for climate change adaptation strategy in spatial planning (Gill et al, 2007). Finally, adaptive green infrastructure planning and design serves as a critical path toward urban sustainability and resilience (Ahern, 2011; Wise, 2008)

Study Area

The Charles River watershed was one of the nine watersheds in the Boston Metropolitan Area. 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 minimum in this study. In addition, the watershed is comprised of 35 municipalities, including the City of Boston, and is the most densely populated. The watershed consists of the most environmental justice populations defined by the Massachusetts Office of Geographic Information (MassGIS)—implying potential higher social vulnerability to climate change impacts; therefore, research for climate change impacts in this watershed is particularly timely and critical for further social-economic impact studies.

Methods

Soil and Water Assessment Tool (SWAT) is a hydrological model for simulating baseflow and estimating hydrologic budgets in the watersheds (Arnold et al. 1998). It has been successfully employed for evaluating impacts of land use change on hydrology (Bormann et al., 2007), stormwater BMPs effectiveness on water quality improvement (Hunt et al. 2009) as well as climate change impacts on hydrology (Bekele and Knapp, 2010). Therefore, SWAT is suitable for evaluating stormwater BMPs under land use and climate change impacts in the urbanized watershed.

Key inputs for SWAT modeling were land use and weather data. The land use baseline was based on 2005 data from MassGIS. The temperature and precipitation used to build climate change scenarios were generated from weather program using historical data from 1990 to 2011. Climate change sensitivity assessment (Ficklin et al. 2009) from 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%)—resulting a total of 36 climate change scenarios, include the baseline climate (0,0,0). The SWAT run was based on a calibrated watershed model from the previous study (Cheng, in preparation). The output was stream outflow used for building long-term flooding Hazard Index (HI) (Figure 2). HI was defined as the probability of number of days in a study period of 45 years when the stream outflow (Q_i) would exceed the baseline bankfull discharge volume (Q_0) under baseline climate.

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

P: Probability
Q_i: Stream outflow (mm) under climate change scenario
Q_0: Baseline stream bankfull discharge volume (mm)

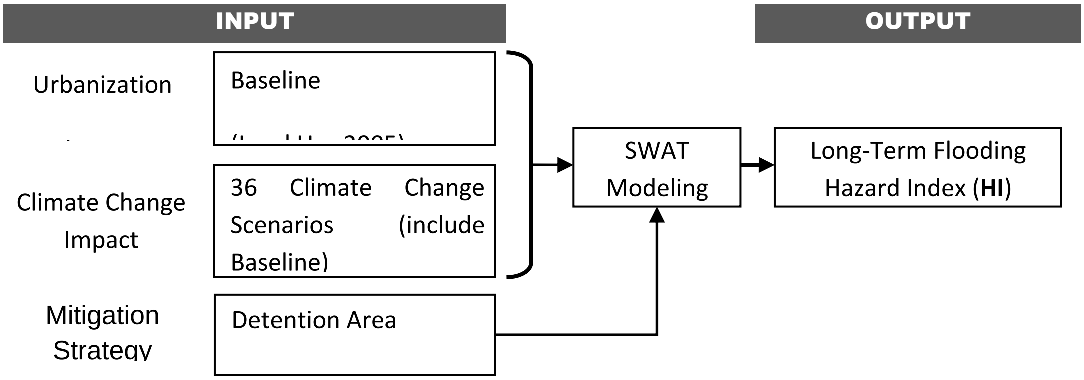

Figure 1. SWAT modeling inputs and outputs. Diagram by the first author.

Assessing detention area for flooding mitigation strategy was conducted an impoundment water routing function in SWAT for modeling water that was temporary stored for water supply or flooding control and mitigation. Besides reservoirs, wetlands, and ponds, which were controlled by land use in this study, the function of depressions/potholes was employed to simulate the function of stormwater detention areas. Potholes are closed depression areas in the watershed functioning as temporary water storage areas. Surfacewater and precipitation are the main source of the inflow and when storage exceeds the maximum volume assigned for each pothole, the excessive volume then becomes surfacewater and contributes to stream baseflow. In addition to water overflow, potholes loose water through evaporation and seepage during the day. In SWAT, only one pothole in each subbasin was created through assigning one hydrologic response unit (HRU). To optimize water storage function 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 long-term flooding hazard defined in this study, the maximum storage for each pothole was the volume of bankfull discharge volume in respective subbasin. Finally, linear regression method was employed for analyzing the relationship between the percentage of detention areas in the subbasin drainage areas and HI under each climate change condition. Two main independent variables were land use and detention areas in the drainage areas of the respective subbasins; dependent variable was HI under 36 climate change conditions; control variable was baseline land use.

$$Y = aX + b \tag{2}$$

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

Results

A total area of 3.2% of the Charles River watershed area was modeled as detention in this study. In average, each of the 54 drainage subbasins had 2.9% of detention area ranging from 0.9 to 8.7% with a standard deviation of 1.5%. The regression results indicated that detention area had significant effects—10 out of 36 climate change scenarios—reducing HI value at a range between 0.0006 and 0.0028 when 1% of detention area increases in the drainage basin, without consideration of land use impacts on the watershed.

In general, the effects of detention were most effective when precipitation variation was controlled at zero percent increase; somewhat effective when temperature were controlled at 1 or 2˚C increase or a 10% increase at precipitation mean; the least effective when mean temperature increased 3˚C or at any level of precipitation variation change (Table 1). In addition, increasing mean precipitation resulted in a trend with a greater slope; increasing mean temperature had a general trend of a smaller slope. When mean temperature increased 3˚C with no mean precipitation increase and precipitation variation increased 10% and 20%, the coefficient became positive.

In order to use the results sensibly for planning, two hazard mitigation policy goals for reducing HI to zero and baseline level were examined respectively by using regression models. The value of 0.01was the HI score for the entire Charles River watershed basin under baseline land use

(2005 data) with no climate change scenario. The results indicated a wide range between 12 to 79% of detention area would be needed for reaching zero long-term flooding hazards in the watershed; a range between 0 to 22% of detention areas would be needed for reaching baseline HI under all possible climate change scenarios (Table 1). However, examining from the selected ten climate change scenarios with significant coefficients, the results illustrated an average of 14% detention area for zero HI and an average of 5% detention area for mitigating HI to baseline level (Figure 2). Among selected climate change scenarios, a steeper slope tend to result in a smaller percentage for detention area to reach zero hazards; on the other hand, a larger detention area for reaching baseline level HI would be needed.

Table 1. Regression coefficients and projected percentage of detention area required for achieving HI=0 and HI=0.01 under climate change scenarios.

Climate Change Scenarios			Regression Coefficients		Detention Area Required	
Tmp (˚C)	Pmean	Pvar	a	b	HI=0	HI=0.01
1	20%	0	-0.2806*	0.0337**	12%	9%
1	20%	20%	-0.2467*	0.0312**	13%	9%
0	10%	0	-0.1620**	0.0205**	13%	7%
1	10%	0	-0.1457**	0.0180**	13%	6%
2	10%	10%	-0.1188*	0.0166**	14%	6%
2	10%	0	-0.1092*	0.0151**	14%	5%
0	0	0	-0.1014**	0.0132**	14%	4%
1	0	0	-0.0835**	0.0111**	14%	2%
3	10%	0	-0.0763*	0.0130**	18%	4%
2	0	0	-0.0573*	0.0091**	16%	-1%
0	20%	0	-0.2361	0.0363**	16%	12%
0	20%	10%	-0.2303	0.0373**	17%	12%
0	20%	20%	-0.2299	0.0385**	17%	13%
1	20%	10%	-0.1876	0.0322**	18%	12%
2	20%	0	-0.1577	0.0277**	18%	12%
2	20%	20%	-0.1509	0.0303**	21%	14%
2	20%	10%	-0.1466	0.0286**	20%	13%
0	10%	20%	-0.1248	0.0248**	20%	12%
0	10%	10%	-0.1216	0.0233**	20%	11%
1	10%	20%	-0.1138	0.0225**	20%	11%
1	10%	10%	-0.1087	0.0196**	19%	9%
3	20%	0	-0.0844	0.0242**	29%	17%
3	20%	10%	-0.0797	0.0255**	32%	20%
2	10%	20%	-0.0795	0.0201**	26%	13%
3	20%	20%	-0.0783	0.0268**	35%	22%
0	0	20%	-0.0640	0.0162**	26%	10%
0	0	10%	-0.0618	0.0147**	24%	8%
1	0	20%	-0.0506	0.0142**	29%	9%
1	0	10%	-0.0456	0.0127**	28%	6%
3	0	0	-0.0408	0.0080**	20%	-4%
3	10%	20%	-0.0353	0.0176**	50%	22%
3	10%	10%	-0.0287	0.0158**	56%	21%

2	0	20%	-0.0178	0.0125**	71%	14%
2	0	10%	-0.0139	0.0109**	79%	7%
3	0	10%	0.0071	0.0094**	-134%	7%
3	0	20%	0.0073	0.0108**	-149%	-132%

tmp: temperature mean; pcp: precipitation mean; pvar: precipitation variation; $*p<0.05$ $**p<0.01$

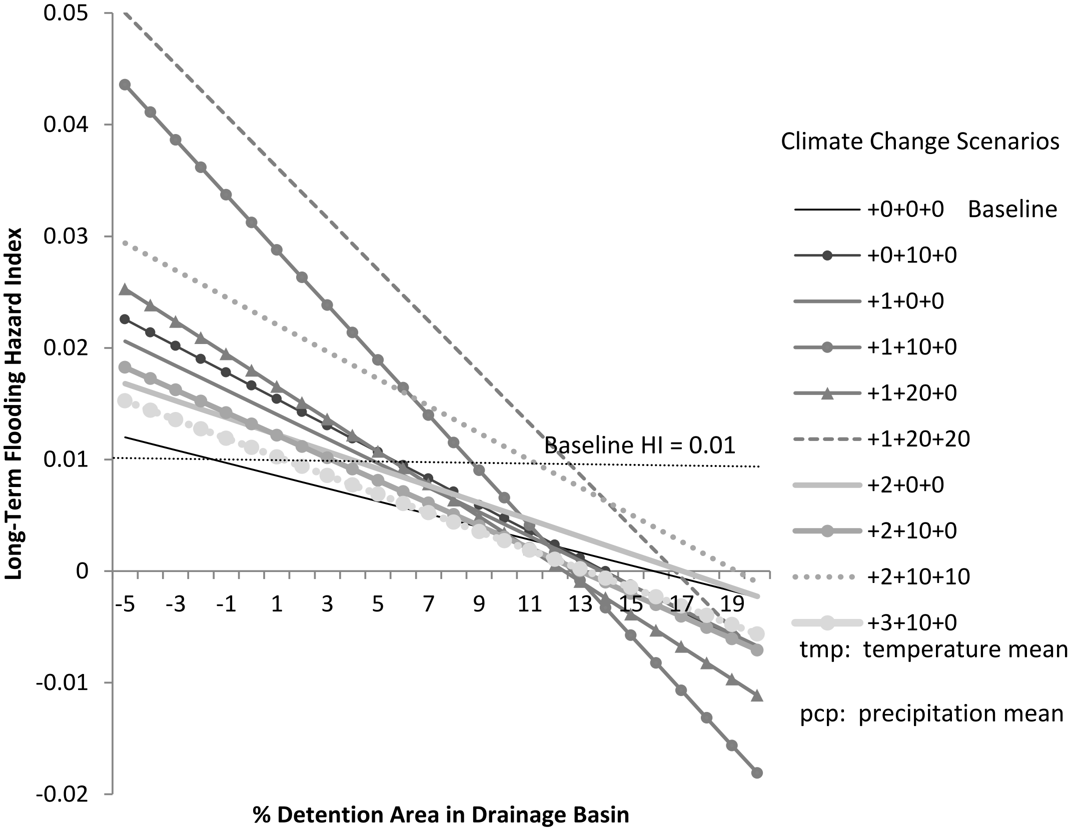

Figure 2. A range between 12 to 16 % of land area for detention function is required for mitigating long-term flooding Hazard Index to 0 under selected climate change scenarios. Comparing to current condition, a range of 2 to 9% of land area for detention function is needed to mitigate climate change impacts. Diagram by the first author.

Discussion

There was no clear threshold point for the effects of detention areas revealed under climate change scenarios due to the fact that climate change impacts on hydrology was complex and varied from watershed to watershed (Praskievicz and Chang 2009). From the results of the climate sensitivity assessment on HI under the baseline land use for the Charles River watershed, in overall, increasing temperature would result in lower HI due to higher evaporation; increasing precipitation in mean and variation would result in higher HI (Cheng et al. in preparation). Since higher temperature resulting in lower HI to begin with, it explained the insignificant effects of applying mitigation strategy. 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. In addition, it implied that evaporation played a greater role in reducing HI than applying detention area for mitigation strategy.

This study focused on detention stormwater management technique for flooding hazards mitigation. Detention area requires depressional land areas that can be inundated with water for a period of time. Applying this concept for landscape planning and design, those detention areas could possibly be applied on public recreational land use areas such as athletic fields and parks. Currently (based on land use 2005 data) Charles River watershed has 3.6% recreational land uses, including cemetery, golf courses, passive and active recreation, marina and beaches. Excluding privately owned golf courses and cemetery, only 1.7% land areas that are probable for using as detention areas, which is 2% to 7% short for reaching baseline level HI under selected climate change scenarios. Based on land use and land cover analysis, Charles River watershed has 43% of urban land uses (e.g., commercial, residential, utilities). Most of the impervious areas are derived from streets, building footprints, parking lots, and staging areas that are mainly under urban land uses and comprised 21% of total watershed area. With limited natural open space and recreational land use areas that could possibly allowed for detention area in urbanized watershed, in order to reach policy goals for reducing long-term flooding hazards, more innovative and aggressive land use planning and design would be necessary on both impervious and other pervious areas. For example, detention techniques could be implemented on residential lots for site scale detention. In addition, a recent project in Chicago has successfully implemented detention technique underneath impervious road surfaces. Therefore, retrofit BMPs to provide holistic green infrastructure network through urban systems (Ellis 2012) plays a critical role in mitigating climate-induced flooding hazards.

Conclusion

This study has demonstrated a range of potential climate change impacts on long-term flooding hazards and the effectiveness of using detention area for mitigating flooding hazards. Since climate change has implications in long-term environmental hazards associated with water resources and management, the findings were particularly timely for landscape planning for climate change. We examined two hazard mitigation policy goals for achieving zero and baseline level long-term flooding Hazard Index. Even though the zero percent chance of long-term flooding hazard was an extreme policy goal, it provides an upper boundary for developing policy frameworks with intermediate feasible goals. In addition, It is worth noting that detention area alone is limited for flooding mitigation and is no substitution for integrated land use and watershed management strategies such as open space and floodplain protection (Brody and Highfield 2013) as well as engaging the stakeholders and the public to “Make room for River” (Wolsink 2006) for both long-term and short term flooding hazards mitigation. Moreover, an innovation in planning and design to provide multiple-uses in recreation and public lands as well as detention and infiltration under impervious surfaces in urbanized areas plays a criticatl role in integrating stormwater management into green infrastructure system network for climate change adaptation.

References

Ahern, Jack. 2011. From fail-safe to safe-to-fail: Sustainability and resilience in the new urban world. *Landscape and Urban Planning* 100 (4):341-343.

Alexander, Douglas, Mark A. Benedict, and Edward T. Mc-Mahon. 2007. Green Infrastructure, Linking Landscapes and Communities. *Natural Areas Association Natural Areas Journal* 27 (3):282-283.

Arnold, J. G., R. Srinivasan, R. S. Muttiah, and J. R. Williams. 1998. Large Area Hydrologic Modeling and Assessment - Part I: Model Development. *Water resources bulletin.* 34 (1):73.

Beatley, Timothy. 2009. *Planning for Coastal Resilience: Best Practices for Calamitous Times*. Washington DC: Island Press.

Beecham, S., J. Kandasamy, M. Khiadani, and D. Trinh. 2005. Modelling on-site detention on a catchment-wide basis. *Urban Water Journal* 2 (1):23-32.

Bekele, E. G., and H. V. Knapp. 2010. Watershed Modeling to Assessing Impacts of Potential Climate Change on Water Supply Availability. *Water Resour. Manage. Water Resources Management* 24 (13):3299-3320.

Booth, D. B., and C. R. Jackson. 1997. Urbanization of aquatic systems: degradation thresholds, stormwater detection, and the limits of mitigation. *Journal of the American Water Resources Association* 33 (5):1077-1090.

Bormann, Helge, Lutz Breuer, Thomas Gräff, and Johan A. Huisman. 2007. Analysing the effects of soil properties changes associated with land use changes on the simulated water balance: A comparison of three hydrological catchment models for scenario analysis. *Ecological Modelling Ecological Modelling* 209 (1):29-40.

Brabec, Elizabeth, Stacey Schulte, and Paul L. Richards. 2002. Impervious Surfaces and Water Quality: A Review of Current Literature and Its Implications for Watershed Planning. *Journal of Planning Literature* 16 (4):499.

Brody, S. D., and W. E. Highfield. 2013. Open space protection and flood mitigation: A national study. *Land Use Policy* 32:89-95.

Burby, Raymond J. 1998. *Cooperating with nature : confronting natural hazards with land use planning for sustainable communities*, *Natural hazards and disasters*. Washington, D.C.: Joseph Henry Press.

Ellis, J. B. 2012. Sustainable surface water management and green infrastructure in UK urban catchment planning. *Journal of Environmental Planning and Management Journal of Environmental Planning and Management* (1):1-18.

Ellis, J. B., and J. Marsalek. 1996. Overview of urban drainage: Environmental impacts and concerns, means of mitigation and implementation policies. *Journal of Hydraulic Research* 34 (6):723-731.

Ficklin, D. L., Y. Luo, E. Luedeling, and M. Zhang. 2009. Climate change sensitivity assessment of a highly agricultural watershed using SWAT. *Journal of Hydrology* 374 (1-2):16-29.

Frederick, K. D., and D. C. Major. 1997. Climate change and water resources. *Climatic Change* 37 (1):7-23.

Gill, S. E., J. F. Handley, A. R. Ennos, and S. Pauleit. 2007. Adapting Cities for Climate Change: The Role of the Green Infrastructure. *Built environment.* 33 (1):115-132.

Godschalk, David R. 2003. Urban Hazard Mitigation: Creating Resilient Cities. *Natural Hazards Review* 4 (3):136.

———. 2004. Land use planning challenges - Coping with conflicts in visions of sustainable development and livable communities. *Journal of the American Planning Association* 70 (1):5-13.

Hunt, W. F., N. Kannan, J. Jeong, and P. W. Gassman. 2009. Stormwater best management practices: Review of current practices and potential incorporation in SWAT. *Int Agric Eng J International Agricultural Engineering Journal* 18 (1-2):73-89.

IPCC. 2007. Climate Change 2007: the IPCC Fourth Assessment Report. UNEP.

Praskievicz, Sarah, and Heejun Chang. 2009. A review of hydrological modelling of basin-scale climate change and urban development impacts. *Progress in Physical Geography* 33 (5):650-671.

Rock, Barrett N., Lynne Carter, Henry Walker, James Bradbury, S. Lawrence Dingman, and C. Anthony Federer. 2001. Climate impacts on regional water. In *The New England Regional Assessment*: University of New Hampshire.

Thomas, Kevin, and Steve Littlewood. 2010. From Green Belts to Green Infrastructure? The Evolution of a New Concept in the Emerging Soft Governance of Spatial Strategies. *Planning Practice & Research* 25 (2):203-222.

Urbonas, Ben. 1994. Assessment of stormwater BMPs and their technology. *Water Science and Technology* 29 (1-2):347-353.

White, Gilbert F., and J. Eugene Haas. 1975. *Assessment of research on natural hazards*. Cambridge, Mass.: MIT Press.

Wise, Steve. 2008. Green Infrastructure Rising. *Planning* 74 (8):14-19.

Wolsink, M. 2006. River basin approach and integrated water management: Governance pitfalls for the Dutch Space-Water-Adjustment Management Principle. *Geoforum* 37 (4):473-487.

Wood, Andrew W., Dennis P. Lettenmaier, and Richard N. Palmer. 1997. Assessing Climate Change Implications for Water Resources Planning. *Climatic Change* 37 (1):203-228.