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The Dynamics and Resilience of River Cities  
as Coupled Human-Natural Systems

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**Abstract**

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Around the world many river cities are challenged simultaneously by heightened flood risk and degraded river health. The prevailing approach to flood hazard mitigation—flood control, has been criticized to be ineffective for long-term flood safety. Flood control is also well-understood to be destructive to river-floodplain ecosystems through the homogenization of the biophysical environment and elimination of periodic flooding that maintains ecological functions. Despite these recognitions, it is still widely believed that flood control is indispensable in cities and that the associated ecological degradation is a necessary tradeoff for flood safety. This dissertation research challenges such conventional wisdom by understanding the dynamics of river cities as coupled human-natural systems whose system-level properties arise from the interactions of human and riverine processes, and by providing a theory for alternative urban flood hazard mitigation. This research is composed of three interrelated investigations that are presented as three independent chapters. The first chapter integrates disciplinary knowledge associated with flooding to provide an interdisciplinary account of the complex dynamics of human-nature couplings in cities dependent on flood-control infrastructure. Issues of flood control as a simple

solution to a complex problem are discussed. The second chapter develops a theory of ‘urban resilience to floods’ as a theoretic framework for alternative flood hazard management to better respond to the inherent dynamics and complexity of river cities. I explain why flood control is in fact dispensable and argue for a paradigm shift from flood control to flood adaptation to create resilient “floodable” cities. The last chapter then links flood safety to river health, exploring the practical solutions to and demonstrating the ecological benefits of floodable cities, where periodic floods are accommodated rather than resisted. Overall, this dissertation research provides a new way of approaching urban flood hazards. It serves as a point of departure for developing design and planning theories and practices that explicitly address the interactions of the urban built environment and inherent environmental dynamics.

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# INTRODUCTION

The environment we live in is dynamic. The land moves during earthquakes and landslides, and it floods where rivers flow through. Challenged by environmental dynamics, which is frequently considered hazardous, the industrialized world has been using engineering measures to artificially stabilize the environment to maximize population growth and economic development. However, such control-centered environmental management, of which flood control is a prime example, has limitation in reducing economic losses from natural hazards. Despite massive investment in flood engineering to bring rivers under control, researchers continue to report an upward trend of flood losses in the US and the world over (e.g., White 1945; Dune and Leopold 1978; Smith and Ward 1998; Changnon 2008). Flood-control infrastructure, such as levee and dams, by design cannot prevent infrequent large floods, and by providing a false sense of security it tends to attract more floodplain development, thereby exposing more people and properties in harm's way (Parker 1995; Tobin 1995). The recent years have seen many cities, albeit being protected by flood-control infrastructure, suffering from catastrophic flood losses, such as Bangkok, Thailand (2001-2012); Brisbane, Australia (2011); Guangdong, China (2007); New Orleans, USA (2005); Dresden, Germany (2002); and Taipei, Taiwan (2001). Unable to provide long-term flood safety, flood control also degrades the riverine ecosystems as the natural flow regime is forcefully changed and habitat complexity reduced. It affects the river's ecological functions and compromise its capacity to generate freshwater ecosystem goods and services, such as clean water, fisheries, and water purification (Postel and Richter 2003).

The determination to eliminate floods stems from the common perception that flooding is detrimental to society. But while it can be hazardous, flooding is also beneficial and even necessary. For example, some rural communities depend on flood recession agriculture, which takes advantage of periodic floods for irrigation and fertilization; livelihoods would be lost without flooding (Cuny 1991; Saarnak 2003). In the industrialized world where most agricultural practices do not depend on floods, it is still indispensable as a key component of the natural flow regime to sustain the ecological functioning of floodplain rivers, thus critical to the continual

provision of ecosystem services (Junk et al. 1989; Poff et al. 1997; Tockner et al. 2008). The prevention of periodic flooding for short-term flood safety is to eliminate a vital natural process and the benefits along with it. The solution to one problem ends up creating other problems.

### **Overarching Research Objective**

While the aforementioned problems of flood control have been well-recognized and non-structural measures to flood mitigation have existed, flood control continues to dominate flood hazard management. Particularly in cities where population is dense, land values high, and socioeconomic activities intense, it is widely believed that flood control is imperative and that the associated ecological degradation is a necessary tradeoff for flood safety. Such conventional wisdom is rarely challenged yet questionable from at least two perspectives. First, controlling floods is increasingly difficult in the era of climate change where storms can be increasingly intense and their exact nature and the consequential flood behavior are uncertain (IPCC 2007). It may be unrealistic to continue counting on flood control for flood safety. Second, because both flood safety and river health are critical for human development and welfare, to sacrifice river health for merely short-term flood safety is unwise. As urban population continues to grow and cities continue to expand in many regions in the world (UN-HABITAT 2008), balancing the two goals in urban development is an important sustainability issue at the local as well as at the global scale. This dissertation is motivated by the question whether flood control should continue to be the dominant management approach to flood safety.

The overarching research objective is to explore the relationship between cities and inherently dynamic environments. The subject is relevant not only to natural hazard management but also to ecosystem management. How a city chooses to interact with the dynamic river affects human communities as well as riverine ecosystems. I explore the city-river interactions through the issue of flood hazard management, focusing particularly on its underlying philosophy and mitigation approach. Flood hazard mitigation measures, of which flood control is the most common example, play a key role in mediating the interaction between the city and its river. I intend to better understand the dynamics and problems arising from the interaction mediated by flood control, in order to develop a theory as the basis for alternative mitigation measures that avoid ecological destructions and promote more sustainable outcomes.

## **Theoretical Construct**

Theories developed in the realm of ecology, particularly urban ecology and resilience theory, provide the theoretical underpinning and conceptual framework of the research. Both urban ecology and resilience theory are fundamentally grounded on complexity theory, which is an overarching term for a range of concepts, such as emergence, nonlinearity, and self-organization, that depict complex behaviors in systems that are open and far from equilibrium (Holling 2001; Alberti 2008). The phrase “the whole is greater than the sum of its parts” can best describe the nature of complex systems, where system-level properties cannot be found in system components alone but arise from their interactions (Simon 1962). Complexity theory thus radically departs from the traditional reductionist view that focuses on individual components, placing an emphasis instead on their interactions (Kauffman 1995; Capra 1996). Since system-level properties cannot be inferred solely from system components, complex systems are intrinsically unpredictable (Goldstein 1999). Many environmental problems humans face today can be fundamentally attributed to the ignorance of the complexity of the environmental systems. In flood hazard mitigation, rivers have been treated as simple hydraulic systems, and flood hazards are reduced to the problem of flows, addressed by the simple solution of flood control that aims to move the excess water around in time and space through drainage efficiency, levee confinement, upstream impoundment, and/or flow diversion (Brookes 1988). Flood hazards, however, are emergent phenomena arising from the interactions of multiple natural and human factors (Mitchell 2003). Addressing flows alone in isolation from other contributing factors is destined to fail and to create unexpected consequences (Holling and Meffe 1996). Moving away from the reductionist thinking, which often fails to solve but creates further problems, this research builds on a complex system perspective, i.e., flood hazard mitigation requires not only the understanding of all involving factors but also their interactions.

Specifically addressing interactions between humans and nature in cities, urban ecology researchers sees urban ecosystems as complex adaptive systems and ecological dynamics as emergent phenomena arising from the micro-scale interplay between socioeconomic and ecological processes (Grimm et al. 2000; Pickett et al. 2001; Alberti et al. 2003). Such a conceptual framework is adopted in this research for defining the system in question—cities located along the river, or river cities—to explore the dynamics arising from city-river

interactions with respect to riverine flooding. I conceptualize river cities as coupled human-natural systems—complex adaptive systems controlled by the interactions of both human and natural components that change constantly (Liu et al. 2007). In river cities, socioeconomic activities and riverine processes interact in nonlinear fashions, and feedbacks and reciprocal interactions across space and time are responsible for much of the system-level dynamics, including flood safety and river health.

Coupled human-natural systems such as cities are dynamic, and the system-level dynamics can be uncertain and unpredictable, with surprise being the norm as opposed to exception (Holling 1996; Liu et al. 2007). Managing such systems cannot rely on the conventional command-and-control approach, where the predictability of the system behavior is assumed and selected environmental variables controlled in order to maintain the system in a predetermined, idealized state. Such an approach, which aims to stabilize intrinsically dynamical systems, has been recognized to be unrealistic (Holling and Meffe 1996). Resilience theory suggests that instead of denying the unpredictability and variability of the system, a more realistic approach is to embrace them (Holling 1996). The term resilience is first used by Holling (1973) to describe the ecosystem's ability to absorb disturbances and still persist. Focusing on persistence instead of stability, the concept has been applied to integrated social-ecological systems (e.g., Berkes and Folke 1998; Berkes et al. 2003), and it is increasingly refined and has expanded to become a sophisticated theory addressing complex human-nature couplings. The resilience-based management moves away from trying to achieve certain fixed goals, e.g., biological productivity and water quantity, and builds on an understanding that neither natural nor human systems can be managed in isolation from the other (Walker et al. 2002; Anderies et al. 2006). It aims to maintain the system's capacity to deal with both sudden and gradual changes so as to retain the same desirable processes, structures, feedbacks, and identity (Walker et al. 2004). In this research, I build on resilience theory to develop a theory specifically for river cities as a basis for alternative flood hazard management.

### **Organization of the Dissertation**

This dissertation is composed of three chapters that are written as independent yet related papers. With a complex system perspective, Chapter 1 critically examines the problems associated with

the prevailing urban flood hazard mitigation—flood control. An urban ecology research model developed by Alberti et al. (2003) is used as an organizing framework to explore the complex dynamics of river cities as coupled human-natural systems. The chapter provides an account about how flood-control infrastructure interacts with riverine processes and other human factors to exert impacts on flood safety and river health within and beyond the city, demonstrating the inadequacy and even danger of the continual dependence on flood control. The lessons learned in Chapter 1 call for not only an alternative flood hazard mitigation approach but also a new underlying theory for urban flood hazard management that contrasts with the entrenched belief that humans are in control of nature.

Drawing on resilience theory, Chapter 2 presents a theory of ‘urban resilience to floods’ (URF) as a theoretical framework for more sustainable flood hazard management in cities. In the URF theory flood control does not contribute and is even counterproductive to resilience. Urban flood hazard management based on the URF theory focuses on how to make cities resilient—not resistant—to floods and on promoting cities’ capacity to tolerate—not resist—floods. I thus argue against the conventional wisdom, which holds that cities cannot live without flood control. The URF theory suggests that adaptation to floods can build resilience and is thus a more realistic mitigation approach to long-term flood safety. That flood control is not indispensable in cities challenges the notion that flood safety and river health are tradeoffs.

Building on the URF theory, Chapter 3 links urban flood safety to river health, exploring their reconciliation through replacing flood control with flood adaptation. I discuss existing and emerging solutions to adapting the built environment—including buildings, open spaces, and infrastructure—to floods. Without flood-control infrastructure, ecologically critical floods can enter the city periodically to reconnect the channel and the floodplain, providing an opportunity to restore floodplain habitats to rehabilitate ecological functions and improve the health of the urban river. A conclusion follows the three chapters to review the key arguments and discuss future research agendas.

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# CHAPTER 1

## RIVER CITIES AS COUPLED HUMAN-NATURAL SYSTEMS

### ABSTRACT

Despite massive investment in flood-control infrastructure (FCI) neither cities nor rivers have been well-served—flood hazards continue to challenge river cities around the world, while river health remains severely compromised by flood control. It reveals an ignorance of complex couplings between human decisions and natural dynamics. To better understand how FCI interacts with riverine and other human processes to affect the city it serves and the larger society, this paper examines river cities that depend on FCI as coupled human-natural systems. I use an urban ecology research model as the analytical framework to integrate disciplinary knowledge to provide an interdisciplinary account of FCI-induced dynamics. Interactions between floodplain development, FCI, flow and sediment changes, flood risk, and river health are examined and feedback mechanisms explicitly addressed. I articulate the complex properties of FCI-dependent cities, including cross-scale interactions, emergence, nonlinearity, and surprises. An urbanized floodplain, the Lower Green River valley in King County, Washington, USA, is examined as a case study. Facilitated by river adjustment and a false sense of security, a reinforcing feedback loop—a vicious cycle—is evident when the city relies on FCI for short-term flood safety. FCI breeds more floodplain development and more FCI while increasing flood risk and degrading river health. The account of FCI-dependent cities as coupled human-natural systems shows that flood control is an inappropriate, unrealistic approach in a complex, unpredictable context. It challenges the conventional wisdom that FCI is indispensable for cities.

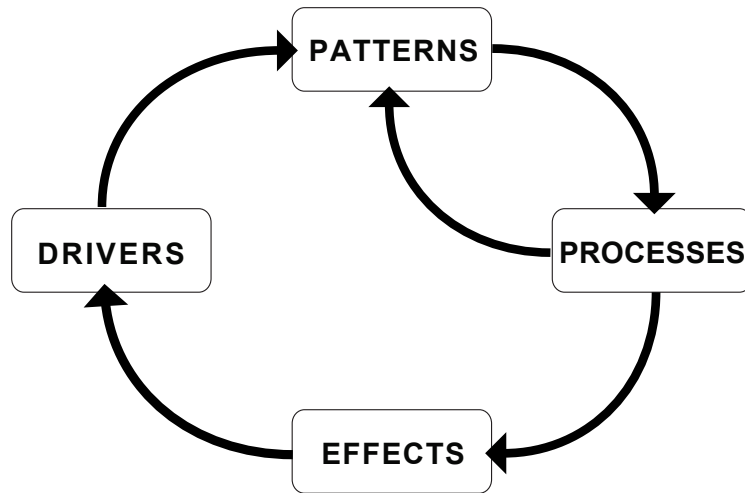
**Key words:** river cities; coupled human-natural systems; flood control; Lower Green River; research framework; flood hazard management.

## INTRODUCTION

Many cities co-evolve with rivers running through them. River cities are coupled human-natural systems, where human and natural components interact reciprocally through complex feedback mechanisms (Liu et al. 2007a, b). A prime example of such dynamics is flood hazards; yet they are often viewed as products of nature, and flooding rivers are deemed to require serious correction (Mount 1995; Park 2000). With a faith in technology to tame nature, flood-control infrastructure (FCI) has been the dominant solution to flood hazards (Petts 1990; Bernhardt et al. 2006). Despite its omnipresence in cities, urban flood disasters remain widespread and costly (Zevenbergen and Gersonius 2007). Currently, urban flood hazard mitigation typically relies on FCI. It not only fails to prevent disasters but also contributes to ecological declines of urban rivers, as it dramatically alters natural flow regime and river morphology (Gurnell et al. 2007). The fundamental problem lies in the ignorance of complex couplings between human decisions and natural dynamics. As urbanization and extreme storms are expected to increase worldwide (IPCC 2007; UN-HABITAT 2008), river cities will face greater challenges of flood safety and river health. It necessitates a critical reevaluation of the continual reliance on FCI, based on a better understanding of river cities as coupled human-natural systems. Such an interdisciplinary understanding is necessary to promote sustainable human communities and riverine ecosystems (Palmer 2010).

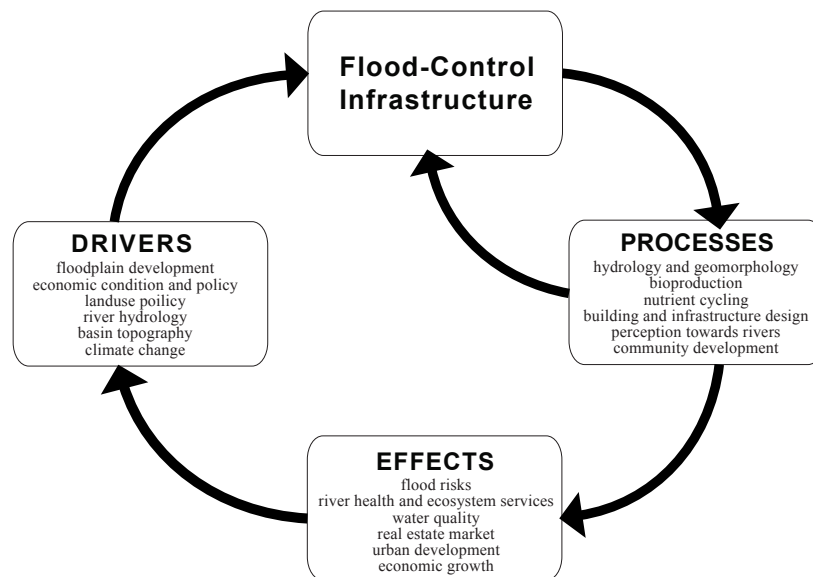
Although flood-related research abounds in engineering, sociology, and ecology, few integrate disciplinary knowledge to address interactions and feedback between associated human and riverine components. This paper provides an account of FCI-dependent cities as coupled human-natural systems, in the hope to inspire alternative approach to urban flood hazard mitigation. While interests on human-nature interactions are not new, the concept of coupled human-natural systems provides a fresh framework for understanding system dynamics by emphasizing the patterns and processes that link human and natural components; feedback mechanisms through which human decisions both affect and are affected by natural processes; and interactions across scales (Liu et al. 2007b). To incorporate these aspects, I employ an urban ecology research model developed by Alberti et al. (2003; Figure 1-1) for assessing social-ecological interactions in urban ecosystems. The model is selected over other same-purposed models (e.g., Grimm et al. 2000; Pickett et al. 2001) for the following reasons. It emphasizes the linkage between patterns

and processes and explicitly depicts the feedback loop. It does not distinguish between human and natural factors, thus better representing the indivisibility of urban environmental systems (Mugerauer 2010). Its loop structure captures the ever-evolving nature of human-nature couplings. While the model does not incorporate scale hierarchy, its structural simplicity allows easy inclusion of it.



**Figure 1-1.** The urban ecology research model developed by Alberti et al. (2003). The model is to help generate questions about how human and ecological processes interact over time and space. Drivers refer to forces that promote the existence and change of patterns and processes; examples include population growth, economic growth, land-use policy, infrastructure investments, topographic constraint, and climate change. Patterns refer to spatial or temporal distributions of elements, such as land use and land cover, transportation, artificial drainage, heat islands, and diseases. Processes refer to mechanisms, by which human or biophysical elements influence the effect of concern, such as erosion, nutrient cycles, movement of organisms, economic markets, and community development. Effects refer to changes in human or ecological conditions.

Using this model as the analytical framework, I unfold how FCI interacts with riverine and other human processes to affect the city it serves and the larger society. There could be various accounts for FCI-dependent cities as coupled human-natural systems because any pattern is driven by multiple factors (Alberti 2008; Figure 1-2). This paper provides only one account. In the remainder of the paper, a general depiction of FCI-dependent cities is first presented, followed by a specific case study on the Lower Green River valley, an urbanized floodplain in King County, Washington, USA. The complex dynamics in FCI-dependent cities are summarized to draw lessons for urban flood hazard management.



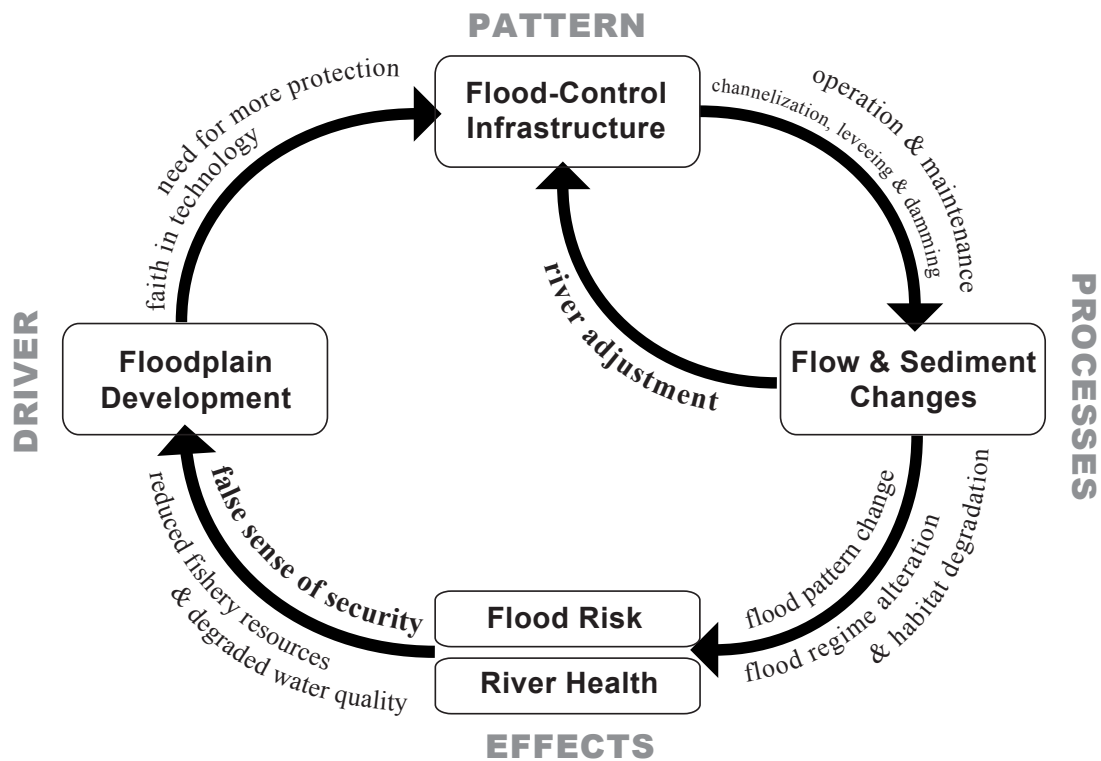
**Figure 1-2.** Flood-control infrastructure (FCI) affects and is affected by many different human and natural factors. As such, there exist multiple ways to define FCI-dependent cities and multiple accounts of FCI-dependent cities as coupled human-natural systems, depending on what factors are chosen as system components. For example, one account could be about how economic development of a city drives FCI, which changes the nutrient cycling of the river to affect water quality, which may eventually feedback to influence the city’s economic development.

## FCI-DEPENDENT CITIES AS COUPLED HUMAN-NATURAL SYSTEMS

Synthesizing existing literature, this section explores how floodplain development drives FCI, which interferences with the river’s flow and sediment processes to alter flood risk and river health (Figure 1-3). River adjustment and a false sense of security are addressed as key feedback mechanisms. The discussion focuses on medium to large rivers (bankfull width 30-150 m).

### Floodplain Development and FCI

Among many interacting human and natural factors that give rise to FCI, I consider floodplain development most fundamental, without which FCI is unnecessary. While floodplains have attracted settlers throughout history, the last two centuries have seen increasing floodplain development due to population growth (Wohl 2000). However, modern floodplain urbanization proceeds based on the perception that flooding is the exception rather than norm, which justifies flood control to prevent periodic flooding (Tobin 1995). As the floodplain is progressively developed, more FCI is continuously in demand.



**Figure 1-3.** Interacting humans and natural factors addressed in this paper as an account of FCI-dependent cities as coupled human-natural systems.

FCI here refers to engineering measures to control riverine flooding. The most common measures are levees, dams, and channelization, designed to improve the river's hydraulic efficiency and stability (Brookes 1988; Smith and Ward 1998). Levees are linear structures parallel to the channel to confine high flows. Channelization is the modification of hydraulic variables including width, depth, gradient, and edge roughness to maximize channel capacity and flow velocity. It often involves straightening, deepening, and/or widening, followed by installation of bank revetments, e.g., concrete or riprap armoring, to resist bank erosion. Riparian vegetation, snags, and logjams are often removed because they represent significant channel roughness that hinders hydraulic efficiency. Re-established trees and shrubs beyond certain sizes are pruned or eliminated. The flood-control dam, although physically outside the city, is still an element of its FCI to reduce high-flow discharge by intercepting water upstream.

## **Flow and Sediment Changes**

FCI essentially performs three tasks: confining high flows within the channel; conveying water downstream as quickly as possible; and/or reducing high-flow discharge (Dune and Leopold 1978). These manipulations of the river imply dramatic flow and sediment changes, yet also induce unintentional consequences.

The flood regime is most significantly changed, as flooding is virtually eliminated until FCI is overwhelmed. It leads to reduced groundwater recharge on the floodplain and lowered groundwater table, which could in turn cause floodplain subsidence and affect base flows in the dry season (Nilsson and Berggren 2000; Kroes and Hupp 2010). By impounding a significant portion of high-flow discharge and slowly releasing it later, the flood-control dam decreases high flows, increases low flows, extends durations of near-bankfull flows, and reduces flow variability between seasons (Richter et al. 1996). Levees decrease flood frequencies but increase high-flow stages because of flow confinement (Leopold 1994; Criss and Shock 2001). The flow velocity downstream of the urban reach increases because of more efficient drainage (Dunne and Leopold 1978). The flood stage also increases without upstream floodplain attenuation, and the floodwater rises faster because the lag time between the onset of heavy rainfall and flood peak is reduced (Mount 1995). The flood stage immediately upstream from the urban reach can also increase if the water backs up when flowing into the constriction (Mount 1995).

In terms of sediment changes, the supply often decreases because bank armoring prevents local input, and some dams can trap lots of sediments upstream that otherwise would move downstream (Petts 1984). This sediment deficit leads to increased erosion, which can be enhanced by channel straightening that increases gradient and stream power (Simon 1989). Alternatively, increased deposition is also possible when artificially enlarged cross section results in decreased unit stream power (Mount 1995).

## **Flood Risk**

FCI-induced flow and sediment changes affect flood risk. A misconception prevails that FCI eliminates flood risk (Etkin 1999). In effect FCI only transfers the risk elsewhere by increasing the flood stages downstream and upstream, inundating upstream uplands otherwise not subject to

flooding, and reducing downstream sediments to shrink storm-surge-attenuating wetlands for coastal communities (Tobin 1995; Day et al. 2007). FCI also transfers the risk through time. Even though FCI helps the city resist most floods, the residual risk still exists (Hewitt and Burton 1971). In the long term the flood risk is even higher than if there were no FCI, because FCI makes capacity-exceeding, structure-failing floods more harmful (Burton et al. 1993). Structural failure causes water and sediments to plunge onto the floodplain at high velocity and leave little or no evacuation time, thus more damaging than naturally slow-rising floodwater (Tobin 1995). Once it occurs, other intact levees complicate drainage and prolong inundation, further worsening the disaster (e.g., Colten and Sumpter 2009). Such a hazard impacts more people in a single instance and is less predictable (Ashley and Ashley 2008). The heightened long-term risk is worrisome, as infrequent but catastrophic floods are increasingly responsible for the mounting flood losses over the decades (Birkland et al. 2003; Changnon 2008).

### **River Health**

Besides transferring risks, it is well recognized that FCI degrades riverine ecosystems. Along with floodplain development, FCI produces hydrologically and morphologically homogenized rivers that are dramatically different from natural floodplain rivers characterized by habitat complexity and flow variability (Graf 2001; Tockner et al. 2008). Disconnecting the channel from the floodplain disrupts the movement and exchanges of organisms, sediments, and organic matter (Tockner et al. 2008). Riverine habitats shrink and become homogenized as floodplain wetlands, backwaters, and side-channels are filled and developed; instream islands, bars, pools, and riffles dredged; snags and logjams cleared; and riparian vegetation removed or simplified. Various habitats functioning as spawning grounds, nurseries, and refugia for aquatic species are largely gone (Ward et al. 2002). They also suffer from losing hydrologic cues of life-cycle behaviors after flow homogenization (Poff et al. 2007). Floodplain and riparian areas untouched by development are affected too—lacking periodic floods and with lowered groundwater table, they have become terrestrialized (Naiman et al. 2008).

In effect, FCI and floodplain development create a novel environment, to which native species have little or no time to adapt (Bunn and Arthington 2002). Consequentially, urban rivers are often species-poor, with degrading ecological functions (Grimm et al. 2008). Such unhealthy

rivers are socioeconomic problematic as they provide little ecosystem services (Postel and Richer 2003). For example, the reduced productivity of fluvial dependent fish associated with FCI has hurt fisheries around the world (Pess et al. 2005). The loss of floodplain wetlands and degradation of riparian zones is to forfeit the natural water purification service that traps sediments and processes diffuse nutrient pollutants brought by groundwater, stormwater runoff, and floods from upland and upstream areas (Pinay et al. 2002; Gergel et al. 2005).

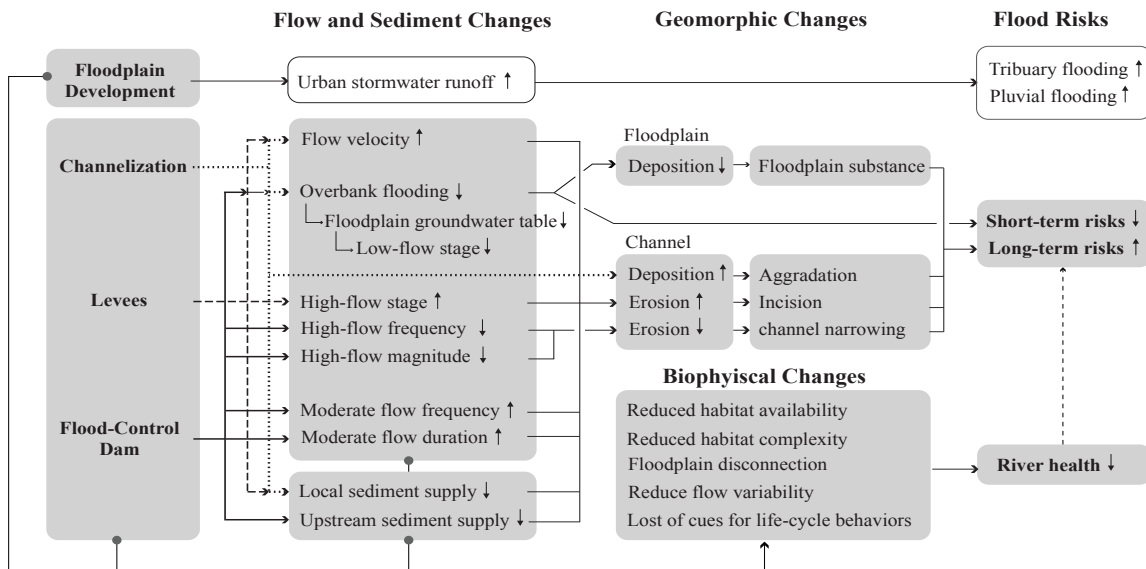
The social-ecological impacts of FCI of a city are not limited by its geographic boundary. Upstream, the flood-control dam affects a significant amount of terrestrial and riparian ecosystems by unusual inundation, and anadromous fish populations can be threatened with extinction as dams block their upstream migration (Nilsson and Berggren 2000). Downstream in estuary and coastal areas, besides shrinking wetlands, FCI also contributes to eutrophication and hypoxia through reducing nutrient processing (Vitousek et al. 1997). FCI's impacts could go far beyond the river basin if long-distance migratory species are affected.

### **River Adjustment as a Feedback Mechanism**

Rivers are complex adaptive systems, constantly adjusting to changes through river adjustment (Lane 1955). The intended flow and morphologic alterations imposed by FCI inevitably cause further unintended changes. The urban river may respond to FCI-imposed alterations by bed aggradation, bed incision, or channel narrowing. In low-relief environments, FCI preventing sediment from spilling onto the floodplain leads to aggradation, i.e., excessive deposition on the bed (Simon and Rinaldi 2006). Incision occurs when the gradient is artificially increased or flood-control dam decreases sediment input, because when banks are armored the river responds to increased stream power by eroding the bed (Ligon et al. 1995; Simon and Rinaldi 2006). Incision can propagate upstream, thus simultaneously causing aggradation downstream (Gregory 1985). When periodic high-flow scouring is absent because of the dam, it narrows the channel by allowing vegetation to establish on and stabilize bars and islands (Schumm 2005).

Aggradation and channel narrowing reduce channel capacity and necessitate dredging, which could be quickly offset by the adjusting river (Mount 1995). If aggradation and floodplain substance occur simultaneously, the riverbed becomes much higher than the floodplain, and a

small flood can trigger disproportionately large damage (Clark 1982). Incision undermines bank revetments, making them susceptible to erosion and threatening the integrity of other infrastructure such as bridges (Brookes 1988). River adjustment during high flows is particularly intense because of increased flow velocities and stages (Wohl 2000). High flows that deposit enormous sediments could abruptly reduce channel capacity (Griggs and Paris 1982). Alternatively, levees could be breached and revetments destroyed, especially if the river was actively migrating before channelization (Brookes 1988). FCI-induced river adjustment disturbs the very channel morphology FCI intends to maintain and thus affects flood risks (Figure 1-4). It is thus an important feedback mechanism in the dynamics of FCI-dependent cities.



**Figure 1-4.** A diagram showing the interactions among different human and natural factors in the FCI-dependent cities. The flow and sediment alterations imposed by FCI (channelization, levees, and flood-control dam) prompt river adjustment—further geomorphic changes—that eventually affects flood risks by changing FCI’s structural integrity and capacity. Floodplain development, FCI, as well as flow and sediment changes also cause direct biophysical changes to jeopardize river health. The degradation of river health could affect flood safety. While not directly increasing flood risk, a polluted river would worsen the damage once the city is flooded.

### The False Sense of Security as a Feedback Mechanism

As mentioned, FCI increases long-term flood risk by making large floods physically more powerful. It often enhances the risk further through encouraging floodplain development over

time to expose more people and properties in harm's way (White 1945; Parker 1995). This phenomenon is widely attributed to a false sense of security (e.g., White 1945; Pielke 1999), derived from an entrenched faith in technology to control nature. FCI is tangible and highly visual that confidence in FCI accumulates with each small flood prevented (Carolan 2007). As such, FCI-protected floodplains are no longer considered dangerous and continue to attract more development in cities without effective floodplain regulations (Pinter 2005). It has been argued that increasing floodplain development is most responsible for the upward trend of flood losses repeatedly reported over the years (Burton et al. 1993; Parker 2000; Changnon 2003). The false sense of security is thus another feedback mechanism in the system.

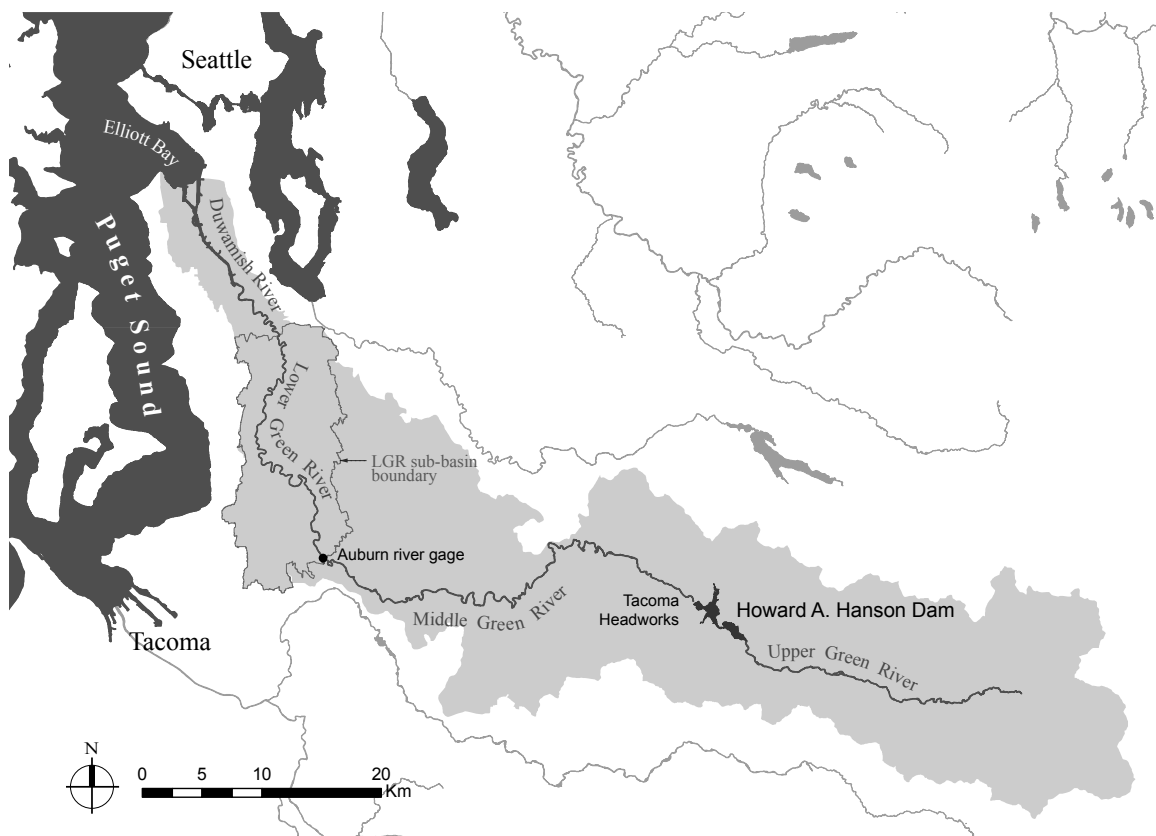
The confidence in technology and false sense of security also help perpetuate FCI, particularly levees. Erecting one risk-transferring levee prompts other new ones; each overtopped levee is replaced with a higher one (Tobin 1995). The river is thus progressively leveed, and levees are progressively larger and higher. Recurring flood disasters are rarely perceived as a message that flooding is not controllable; instead, they are attributed to insufficient control, only triggering more FCI (Tobin 1995). More FCI attracts more floodplain development and produces a more raging river to create ever-bigger flood disasters. This vicious cycle has long been recognized (e.g., Parker 1995; Tobin 1995; Zevenbergen and Gersonius 2007). However, reinforcing FCI is still the dominant solution to urban flood hazards.

### **Other Interactions**

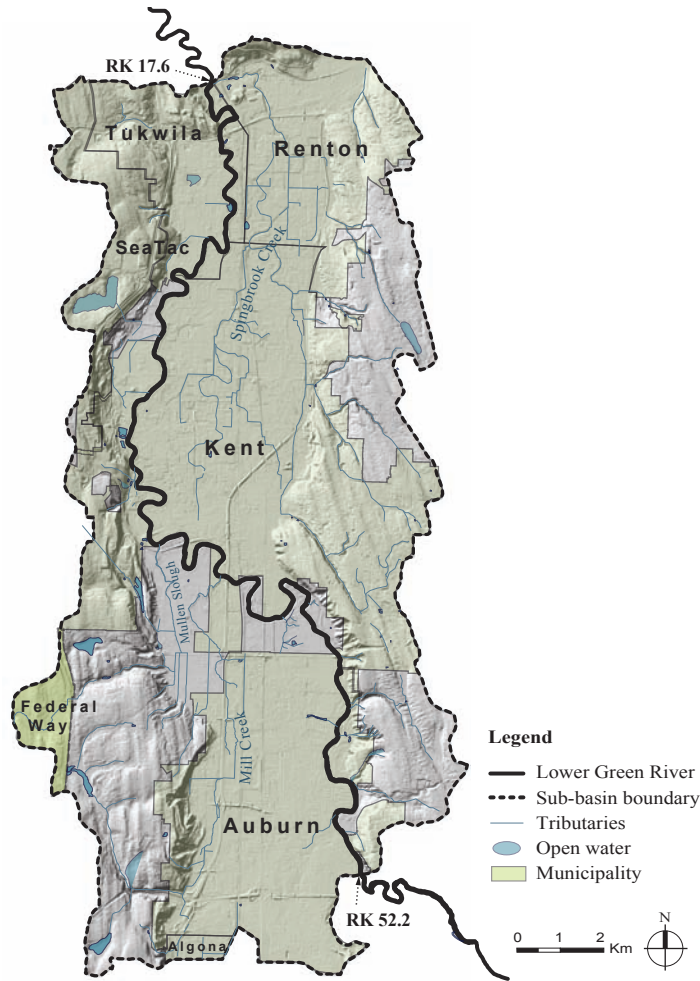
Besides the dynamics described above, other interactions exist between system components. For example, floodplain development brings about FCI but can also hinder its function. Development too close to the channel impedes the releasing operation of the flood-control dam and can eventually force undesirable release to cause catastrophic flooding (Williams 1998). It also prohibits levee enlargement, which may force the city to adopt less robust options, such as building floodwalls on top of the levees (Gordon and Little 2009). Furthermore, the progressively urbanized floodplain increases the frequency and magnitude of tributary and pluvial flooding, as more impervious surfaces increase stormwater runoff during localized storm events (Dunne and Leopold 1978).

## A CASE STUDY: THE LOWER GREEN RIVER VALLEY

The Lower Green River (LGR) valley in King County, Washington (Figure 1-5) demonstrates most of the dynamics depicted above. With the Port of Seattle situated downstream of LGR at the mouth of Duwamish River, the valley is part of a major warehouse and manufacturing center in the US and home to several municipalities (Figure 1-6).



**Figure 1-5.** The Lower Green River (LGR) valley is within the basin of the Green/Duwamish River (grey area), which originates in the Cascade Mountains and flows about 149 km before entering the Elliott Bay in Seattle and covers an area of 1,274 km<sup>2</sup>. The Duwamish River and LGR sub-basins are dominated by residential and industrial land uses, and the Middle Green River and Upper Green River sub-basins agricultural and commercial forestry land uses. There are two dams in the basin: the Howard A. Hanson Dam (HHD) and Tacoma Water Supply Diversion Dam (Tacoma Headworks). HHD operates to prevent flows above 340 m<sup>3</sup>/s at the USGS river gage in Auburn.



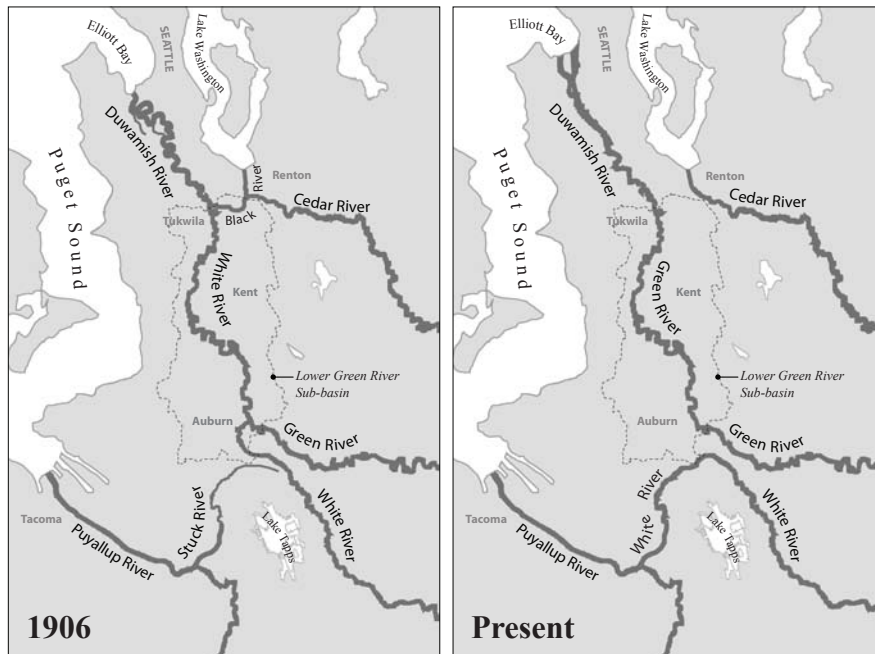
**Figure 1-6.** The LGR valley refers to the flat terrain between the valley walls within the LGR sub-basin. It is home to Cities of Auburn, Kent, Renton, and Tukwila. The LGR runs 33.6 km between river kilometer (RK) 17.6 and 52.2. Its tributaries include Springbrook Creek, Mill Creek, and Mullen Slough, besides numerous other smaller tributaries and pump stations (NHC 2008).

### **Floodplain Development and FCI**

Historically, LGR was the lower White River (Figure 1-7) meandering through a broad, low-gradient, densely forested valley (Dunne and Dietrich 1979). The sediment-rich river made large deposition along the bank to form natural levees, making the riverbanks 2-4 m higher than the floodplain, such that the entire valley bottom was easily flooded to create numerous wetlands (Collins and Sheikh 2005).

Arriving in the mid 19<sup>th</sup> century, European settlers turned floodplain forests and wetlands into farmlands, taking advantage of the rich alluvial soils while dealing with poor drainage and

flooding in localized fashions (Kerwin and Nelson 2000). A catastrophic flood in 1906 catalyzed large-scale flood-control works in the 20<sup>th</sup> century (Table 1-1), fueled by policies for economic development (Sato 1997). The upper White River was permanently diverted in 1911, and over the next decades numerous flood-control projects transformed LGR. Today, the valley's FCI includes extensive levees and riprap revetments on both banks of LGR, as well as the Howard A. Hanson Dam (HHD) upstream (Figure 1-5). While differences in channel characteristics exist among reaches, LGR is largely homogenized and tightly confined (Anchor Environmental 2004; Figure 1-8). Since the operation of HHD in 1962, valley-wide flooding has not occurred, providing a sense of security to fuel rapid urban development (Sato 1997). The valley will continue to grow as it falls within the county's designated Urban Growth Area. From 2001 to 2005 the developed land increased from 52% to 68% and is projected to reach 97% in 2022 (Batker et al. 2005).



**Figure 1-7.** LGR is the historic White River between two confluences. Near RK 50 the White River was joined by the Green River, before it was diverted during a flood in 1906. At RK 17.6 the White River merged with the Black River to become the Duwamish River. Today the Black River is only a fraction of its historic volume after it was cut off from Lake Washington when the Cedar River was diverted into the lake to facilitate navigation through the Ship Canal in 1916. The diversion of White River and Cedar/Black reduced the Green/Duwamish River basin to 30% of its historic size (Kerwin and Nelson 2000). Adapted from Thomson et al. (2005).

**Table 1-1.** A timeline of FCI development and major flood disasters of LGR in the 20<sup>th</sup> century<sup>1</sup>

Time	Flood-Control Activity or Flood Disaster
By 1900	<p><b>Construction of drainage channels and levees</b>            Drainage channels were constructed for agricultural development. Artificial levees were existent between the Black River confluence and Kent. Individual owners had built levees upstream of Kent. Levee-building continued for most of the 20<sup>th</sup> century as they were easily breached by small floods.</p>
1906	<p><b>Valley-wide flooding in November</b>            Overbank flows caused inundation of the entire valley from Auburn to the Black River. Some places were under over 3 m of water.<sup>2</sup></p>
1906/1911	<p><b>Diversion of the upper White River</b>            The White River was shifted back and forth between the Lower Green (White) valley and the Puyallup valley by settlers in both valleys to reduce flooding at the expense of the other, before a logjam formed during the 1906 flood forced the river to flow south through the Stuck River into the Puyallup River. As it was deemed a shorter route to the sea, compared to that through the Duwamish, the diversion of the White River was made permanent by a retaining wall in 1911.</p>
1933	<p><b>Valley-wide flooding</b>            The flow at Auburn reached 680 m<sup>3</sup>/s. Renton was under almost 3 m of water.</p>
1940s~1950s	<p><b>Channelization</b>            Numerous channelization projects were implement, involving building levees, widening the channel in some parts of the river, and systematically removing trees along the banks.</p>
1946	<p><b>Valley-wide flooding in December</b>            The flow at Auburn reached 623 m<sup>3</sup>/s. It took weeks before the water receded. Downtown Kent became a lake for a time.<sup>3</sup> Estimated damage was \$1.3 million.</p>
1959	<p><b>Valley-wide flooding in November</b>            The flow at Auburn reached 796 m<sup>3</sup>/s. The water took weeks to recede, and Federal assistance was requested. The estimated damage was \$1.6 million.</p>
1962	<p><b>Completion of the Howard A. Hanson Dam (HHD)</b>            A early as 1936 The US Army Corps of Engineers (USACOE) had begun the search of a site to build a flood control dam, but the effort was interrupted by World War II.<sup>4</sup> The 1946 flood helped resume the effort, and Congress adopted it as a federal project in 1950. The construction began in 1959 and completed in 1962.</p>
1960s~1970s	<p><b>Construction of levees</b>            Responding to the 1959 flood, King County voters approved two bond issues in 1960 and 1964 to create the River Management Program.<sup>5</sup> This led to extensive levee building throughout the 1960s and 1970s. The bond funds exhausted in the 1980s.</p>

**Table 1-1 (cont'd).**

Time	Flood-Control Activity or Flood Disaster
1965	<b>Flooding of the eastern valley in January</b> During a flow of 323 m <sup>3</sup> /s the right-bank levee near RK 35.2 failed, sending water to submerge the entire eastern portion of the valley. The water depth was around 1 m in the low-lying area in Renton.
1966	<b>Construction of drainage channels</b> Following the 1965 flood, Congress approved Soil Conservation Service (SCS) plans in 1966 to construct 55 miles of drainage channels to deal with interior flooding of the low-lying areas.
1972	<b>Installation of the Black River (P1) pumping station</b> To address backwater flooding, the Black River Pump Station was built. Over the following years, pump systems of similar or smaller capacities were built.
1990s ~2000s	<b>Interior flooding in 1990 1995, 1996, 2006, 2007</b> During these events levees and revetments were damaged.  <b>Levee repair and reconstruction</b> Between 1993 and 2005, more than \$9 million were spent on 30 projects for maintenance, repair, and reconstruction of damaged levees and revetments. A few overly-steepened levees were relocated landward to obtain stable slopes where sufficient easements were available, such as Desimone Levee (in Tukwila) and Boeing, Pipeline, and Narita Levees in Kent. Others were repaired in situ with biostabilization measures and buttressed with extensive rock toes. The 2006 King County Flood Hazard Management Plan proposes 13 levee-rehabilitating projects for 2007-2016.
2009	<b>Impairment of HHD</b> After a record-high water level in January 2009, two seepages emerged in the dam's right abutment. USACOE has since decided to limit HHD's storage capacity until the seepage is permanently fixed. Extensive flood fighting activities were subsequently carried out.

<sup>1</sup> After Dunne and Dietrich (1979); Satterstrom (1982); Sato (1997); Kerwin and Nelson (2000); King County (2006); Tetra Tech (2010).

<sup>2</sup> Stein AJ. 2001. Flood submerges South King County beginning on November 14, 1906. HistoryLink.org. [http://www.historylink.org/index.cfm?DisplayPage=output.cfm&file\\_id=3585](http://www.historylink.org/index.cfm?DisplayPage=output.cfm&file_id=3585).

<sup>3</sup> Stein AJ. 2001. Severe flood occurs in the Green River Valley beginning on December 11, 1946. 2001. HistoryLink.org. [http://www.historylink.org/index.cfm?DisplayPage=output.cfm&file\\_id=3574](http://www.historylink.org/index.cfm?DisplayPage=output.cfm&file_id=3574).

<sup>4</sup> Sprau D. 2003. Flooding, dams, and renamed rivers. White River Journal: A Newsletter of the White River Valley Museum. April 2003. [http://www.wrvmuseum.org/journal/journal\\_0403.htm](http://www.wrvmuseum.org/journal/journal_0403.htm).

<sup>5</sup> Stein AJ. 2001. Green River flood devastates valley around Kent beginning on November 24, 1959. HistoryLink.org. [http://www.historylink.org/index.cfm?DisplayPage=output.cfm&file\\_id=3575](http://www.historylink.org/index.cfm?DisplayPage=output.cfm&file_id=3575).



**Figure 1-8.** Most reaches of LGR are lined with overly-steepened levees and revetments that are covered predominately by Himalayan blackberry (*Rubus discolor*) and invasive knotweed (*Polygonum* spp.) (WRIA9 Implementation Technical Committee 2012). The photo shows a reach confined by a levee to the right and a revetment to the left.

### **Altered Fluvial Processes**

FCI profoundly reduced LGR's flow variability. Diverting the glacier-fed White River cut the drainage area of LGR in half, not only reducing flood flows but also removing 50% of summer low flows (Dunne and Dietrich 1979). Although the river was still capable of reaching a discharge of 796 m<sup>3</sup>/s (Dunne and Dietrich 1979), HHD later placed a cap of 340 m<sup>3</sup>/s (the natural bankfull flow) at Auburn (Figure 1-5; King County 2006). Since the operation of HHD only three times has the flow marginally exceeded 340 m<sup>3</sup>/s; while without HHD it could have been 17-22 times with most flows larger than 566 m<sup>3</sup>/s (NHC 2008; Tetra Tech 2010). Since flooding is prevented, floodplain groundwater recharge decreases, and tributaries are rarely fed by the mainstem floodwater (Reinelt 2005). Although HHD reduces flooding, levees and revetments increase flow velocities and can raise the flow stage as much as 6 m above the ordinary high water mark (King County 2006). HHD also increases the frequency and duration of 340 m<sup>3</sup>/s and moderate flows, because following each major storm HDD releases reservoir

water at a 340-m<sup>3</sup>/s or smaller rate in preparation for the next storm (King County 2006). Although HHD is mainly a flood-control dam, it also functions to augment summer low flows to mitigate the water diversion at the Tacoma Headworks (Figure 1-5) to support fish spawning, using the water stored in the spring. By so doing, spring freshets are eliminated (Kerwin and Nelson 2001).

Despite extensive FCI, LGR remains sinuous without substantial straightening, unlike many other lowland urban rivers. Low overall gradient of 0.05% (Reinelt 2005), flow reduction after White River diversion, and artificial levees built upon natural levees together have maintained the planform of 1906 (Dunne and Dietrich 1979). However, LGR lost 75% of its sediment supply after losing White River, which drained the rapidly eroding volcanic terrain of Mt. Rainier (Mullineaux 1970). It substantially decreased fine sediment and gravel, causing LGR's channel width to shrink by about 1/3, which was further narrowed by HHD as it reduced channel-forming flow from 340 m<sup>3</sup>/s to 258 m<sup>3</sup>/s (Dunne and Dietrich 1979). Today the average bankfull width is 34 m, comparing to 72 m in the mid-1860s (Collins and Sheikh 2005; Reinelt 2005). Meanwhile, erosion is enhanced by FCI. On one hand, the increased duration, velocity, and stage of moderate flows intensify the stream power; on the other, sediment input from upstream and from bank erosion is reduced (Dunne and Dietrich 1979; Kerwin and Nelson 2000). Enhanced erosion destabilizes the channel, subjecting most reaches to scour and incision, except for the downstream end of LGR where gradient is very low (0.02%). Where bank armoring is relatively less, the chance of channel migration is increased (King County 2006).

Ironically, HHD operations jeopardize the levees along LGR, which were built upon old levees with questionable materials and steep slopes ranging from 1:1.5 to 1:1.75 (King County 2006). Channel scour and incision, to which HHD contributes, have undercut many overly-steepened levees and revetments during high flows. HHD rapidly drawing down the water after prolonged flows has also resulted in many cases of slumping as saturated levees experience sudden suction of water. As such, the levee system is constantly under repair.

### **Increasing Flood Risk**

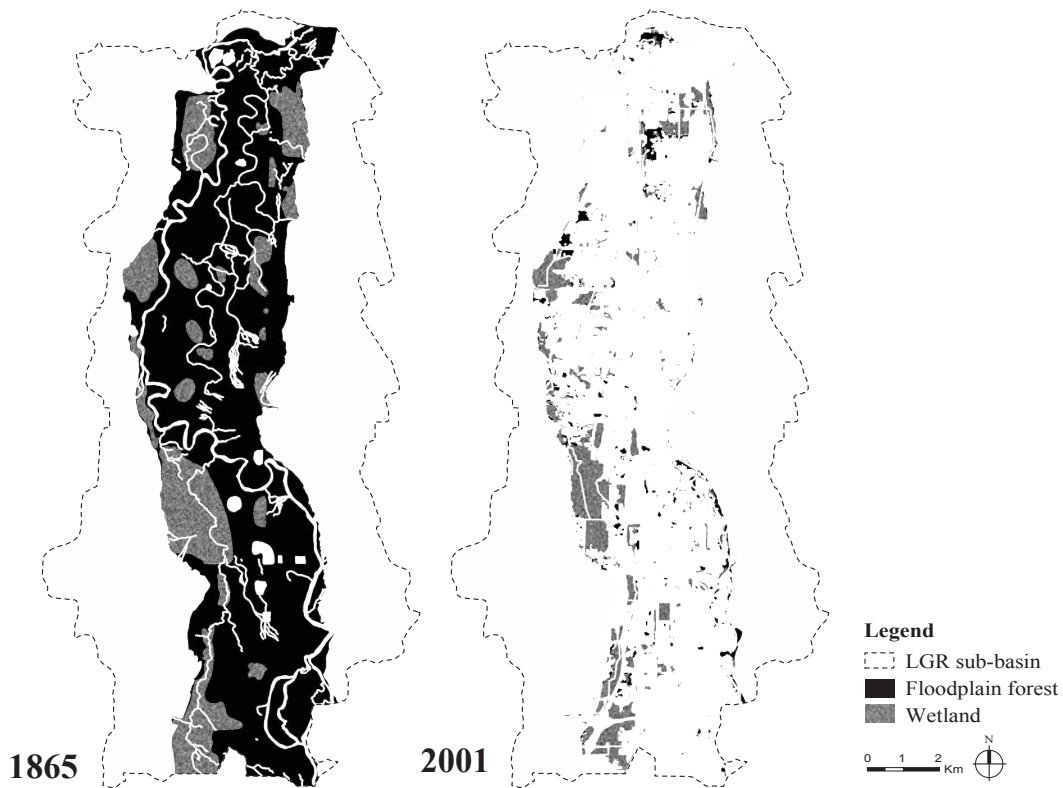
Although FCI have refrained LGR from overflowing, it exacerbates the interior drainage problem in low-lying areas (Satterstrom 1982). Since LGR now runs bankfull more frequently and longer, its tributaries back up more often. This prevents drainage of urban stormwater runoff and increases interior flooding. While numerous pump stations address this backwater problem, it remains challenging because growing floodplain development continues to generate more stormwater runoff, which is estimated to increase peak flows of small tributaries by over 2,000% (Kerwin and Nelson 2000).

Rapid floodplain development also brings about greater long-term risk. Today the LGR valley sees the highest land and improvement values in all of King County's floodplains (King County 2006). Given that most of the valley lands are at lower elevations than that of high-flow stages, if the river were to overflow and breach levees, the damage would be unprecedented (Tetra Tech 2010). While this greater risk is recognized, the response has focused on fixing the overly-steepened levees to ensure structural stability (King County 2006). A few levees were relocated landward to obtain gentler slopes, but along most reaches encroaching development prevents levee setback, in which cases levees are reinforced by rock toe buttressing, which is still intrinsically unstable (Tetra Tech 2010).

### **Declining Salmonids**

FCI and the urbanization of LGR valley have contributed greatly to the decline of Chinook salmon (*Oncorhynchus tshawytscha*) and bull trout (*Salvelinus confluentus*), both listed as threatened under the Endangered Species Act, as their habitats are substantially reduced and degraded (Kerwin and Nelson 2000). Downstream-migrating juvenile Chinook have evolved to venture into permanent or seasonally inundated water bodies on floodplains, e.g., side-channels, ponds, and wetlands, for rearing and refuge during high flows. Today these off-channel habitats are unavailable as 87% of the floodplain forest and 45% of wetlands no longer exist (Figure 1-9), and most of the remaining habitats are made inaccessible by FCI (Reinelt 2005). During high-velocity flows the lack of off-channel low-velocity refugia is especially lethal to juvenile Chinook as they can be flushed through LGR to enter the marine water prematurely (Ruggerone and Weitkamp 2004). The instream habitats are overall degraded and homogenized (Anchor

Environmental 2004). Gravel-bedded salmon spawning grounds can become silted as gravel replenishment is severely limited after White River diversion and FCI limits gravel recruitment from the floodplain. Sand and gravel bars have largely disappeared and pools reduced. Once dense and overhanging riparian vegetation is now limited on levees and revetments, consisting mostly of nonnative, invasive species to offer little shade and cover for fish and input less organic matter and insects into the channel. With sparse trees, the riparian zone no longer provides instream large woods that can create pools and maintain habitat complexity (Abbe and Montgomery 1996). Besides reduced habitat availability and suitability, also affecting salmonids is the elimination of spring freshets that serve as an important mechanism for initiating and facilitating the downstream migration of juvenile salmonids (Quinn 2005).



**Figure 1-9.** The reduction of floodplain habitats in the LGR valley. Most of the remaining habitats are inaccessible by fish. Adapted from Reinelt (2005).

Today LGR is a rather hostile environment for fish and wildlife. It has become primarily a migration corridor for salmonids—it is found that juvenile Chinook move through it quickly, spending as little as several hours in winter and spring (Ruggerone and Weitkamp 2004). FCI's impacts are far reaching. Upstream, HHD periodically floods wildlife habitats along 7.2 km of mainstem and 4.8 km of tributaries when the reservoir is full (Reinelt 2005). It also blocks upstream migration of spawning salmonids, affecting not just salmonid populations but the entire upstream riverine ecosystem because the oligotrophic system is no longer subsidized by marine-derived nutrients and organic matter borne by spawning salmonids (Naiman et al. 2009). Downstream, the transition zone between freshwater and saltwater in the Duwamish River has shrunk and moved upstream to affect the growth and survival of juvenile salmonids, because White River diversion and HHD significantly reduce the freshwater inflow (Kerwin and Nelson 2000).

### **The Predicaments**

Great resources have been invested to restore salmonid populations, particularly Chinook salmon, in the Green/Duwamish basin. Habitat restoration in LGR is identified as a critical requirement for the long-term viability of Chinook salmon (Reinelt et al. 2005). The aforementioned levee setback projects have incorporated a narrow strip of low-velocity habitat on the mid-slope of the levee and added large woods at the toe (King County 2006). However, the requirement of flood control prevents more aggressive restoration options (Tetra Tech 2010). It also limits salmon recovery, as the levee maintenance standard prohibits larger-sized trees that are critical to the quality of instream habitats (WRIA 9 Implementation Technical Committee 2012).

Compromising salmon recovery, FCI nevertheless fails to guarantee flood safety for the LGR valley. The current focus on the levee system's structural stability is based on the premise that HHD will continue to regulate flows as designed, i.e., the valley is safe as long as the levees can handle 340-m<sup>3</sup>/s flows (Tetra Tech 2010). However, this assumption became invalid in January 2009 when two seepages in HHD's right abutment were detected after a storm. It forced a significantly reduction of HHD's storage capacity in order to avoid a bigger disaster caused by structural failure (USACOE 2010). The reduced capacity implied the possibility of even longer duration of 340-m<sup>3</sup>/s flow and faster drawdowns—a combination that could fail the levees, and

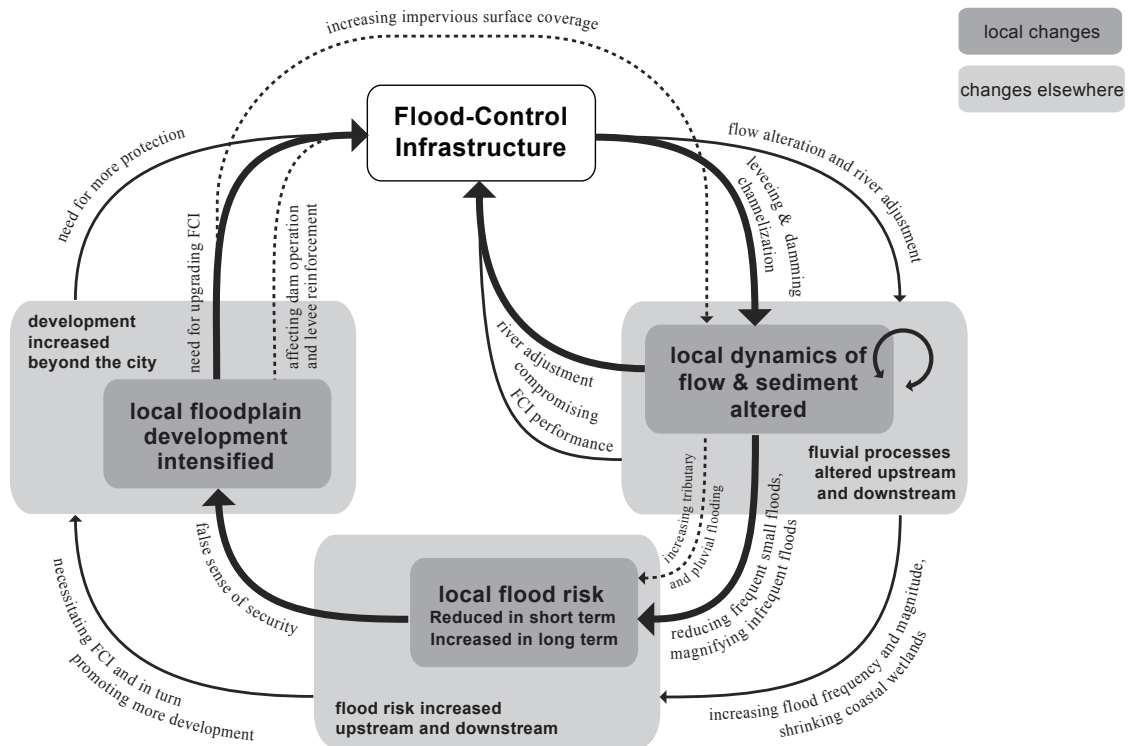
LGR could also experience greater flows the levee system cannot handle (Tetra Tech 2010). Emergency measures have been carried out to strengthen the defense. Hundreds of ecologically valuable trees on the levees were removed to increase drainage efficiency. Levees were temporarily raised by sandbags, prompting the concern that the additional weight on the already fragile levees could facilitate structural failure (Tetra Tech 2010). The impaired HHD triggered a major crisis for the economically highly valuable LGR valley—it is estimated that a 498 m<sup>3</sup>/s flow combined with extensive levee failures could result in \$3.75 billion of economic losses and 21,000 people displaced (FEMA 2009).

## **COMPLEX DYNAMICS OF HUMAN-RIVER COUPLINGS**

The human-river couplings in FCI-dependent cities illustrate a reinforcing feedback loop—a vicious cycle—where the human decision to control floods encourages more floodplain development, which breeds more FCI to increase flood risk and degrade river health (Figure 3). The system dynamics also exhibit complex properties characteristic to other coupled human-natural systems, such as cross-scale interactions, emergence, nonlinearity, and surprises (Liu et al. 2007a, b).

### **Cross-Scale Interactions**

Though primarily a localized purpose, a city's flood control nevertheless generates unintended consequences far beyond its spatial boundary (Figure 1-10). Because FCI interacts with not only local but also basin-wide hydrologic and geomorphic processes, it modifies the flood risk elsewhere and diffuses ecological impacts. FCI also engages in temporal interactions with other components, manifesting in legacy effect, i.e., what happened in the past impinges on current and future conditions (Liu et al. 2007b). For example, the heightened flood risk in the LGR valley is a legacy of a century's flood-control endeavors. Temporal interactions also imply time lags. For example, significant ecological decline responding to FCI may take years or even decades to unfold (Nilsson and Berggren 2000; Petts et al. 2006). This is because it takes time for ecological effects to travel through trophic levels in the ecosystem; moreover, the species' long life cycles and sensitivity thresholds can also delayed responses (Brown 1996; Tockner et al. 2008). Time lags may also exist between ecological changes and noticeable declines on ecosystem services that impact human well-being (Palmer 2010).



**Figure 1-10.** Changes generated by FCI within and beyond the city it serves.

Through cross-scale interactions, events and processes in the past and elsewhere can end up affecting FCI (Griggs and Paris 1982). Any change outside the city in the drainage basin, such as deforestation, would ultimately be reflected in river adjustment to create ever-changing morphology to challenge FCI’s stability (Lane and Richards 1997). At a much larger scale, even global climate change exerts impacts on any city’s FCI through changing the river’s hydrologic regime (IPCC 2007).

### Emergence

FCI-dependent cities exhibit emergent properties that are not dictated by humans or the river separately but by their couplings (Liu et al. 2007b). Flood safety is a prime example of emergence. FCI’s performance against a flood, which affects flood safety, is not determined by the design standard alone, as often expected. It is also governed by the interaction between FCI and geomorphic processes through river adjustment, which may be affected by other human and

natural processes occurring in the past or elsewhere. That the LGR valley is suddenly faced a flood safety crisis is a case in point. It shows that the protection HHD could offer is not dictated solely by humans but also by the storms that unexpectedly impaired the structure.

### **Nonlinearity**

Many relationships between system components in FCI-dependent cities are nonlinear, and there may be thresholds—a common form of nonlinearity (Liu et al. 2007a). Naturally, river adjustment proceeds nonlinearly and threshold-crossing shifts are common in the development (Simon 1989). Most ecological changes are also episodic rather than gradual (Holling 1996). When FCI interacts with such natural dynamics, the results are inevitably nonlinear. Time lag is an example of nonlinearity. For example, the armored channel may appear stable for decades, giving an illusion that revetments have successfully controlled the river; however, it may be because key hydraulic variables have not reached their thresholds (Church 2002). Storms often help cross thresholds and reveal the nonlinearity. For example, despite LGR appears under control for most of the time, storms that forced HHD to produce prolonged high flows combined with quick drawdown often led to levee failures (King County 2006).

### **Surprises**

When cross-scale interactions, emergence, and nonlinearity are unknown and unpredictable, surprises arise (Liu et al. 2007a). The failure of FCI to defend a flood it is supposed to resist is often unexpected by society lacking an understanding of these system properties. Surprises are also a product of society's overestimation of the predictability of technological-natural interactions. For example, channelization is often designed anticipating high flows to remove accumulated sediment in the channel, but it seldom happens (Freitag et al. 2009). The reality is that the exact extent and long-term trajectory of river adjustment are too stochastic to predict, due to its sensitivity to initial condition and accidents such as earthquakes and avalanches along the way (Phillips 1991; Schumm 2005). It is also impossible to predict the long-term ecological impacts due to flood control, for ecological changes are emergent phenomena that integrate many other human and natural processes, such as water pollution and climate change. Although many ecological effects associated with FCI and floodplain development have been observed, more surprises may unfold in the future due to time lags.

## **IMPLICATIONS FOR URBAN FLOOD HAZARD MANAGEMENT**

River cities have not been grasped as coupled human-natural systems in flood hazard management. Surprises arise from uncertain and unpredictable cross-scale interactions, emergence, and nonlinearity associated with FCI are mistaken as rare exceptions, often removed from discussion (Nelson et al. 2007). However, research on human-natural couplings increasingly reveals that surprises are rather normal (Holling 1996; Berkes et al. 2003; Liu et al. 2007a, b). It raises the question whether cities should continue to count on FCI for flood safety. FCI presumes predictability of human-river couplings (Milly et al. 2008), addressing only one part of the problem—the river—in isolation from other contributing and interacting factors (Mount 1995; Reid 2009). It also has several practical limitations.

### **Limitations of FCI**

First, as the socioeconomic importance of freshwater ecosystem services is increasingly clear, degrading river health by FCI in exchange with short-term safety is simply unwise. Second, the efficacy of FCI depends heavily on unreliable factors, such as a long-term commitment of periodic maintenance to counter undesirable river adjustment that compromises FCI's structural integrity and capacity. The cost of maintenance frequently exceeds initial estimate due to unexpected, emergent problems (Smits et al. 2006). Maintenance, particularly dredging, is often too expensive to be implemented as frequently as needed (Mount 1995). Another example is flawless dam operation—inappropriate operation makes floods more disastrous (Williams 1998). Such a system design that requires system elements to perform perfectly works poorly to deliver long-term safety. Third, designed with a specific capacity, FCI is too rigid to quickly adjust to changing boundary conditions that persistently make it inadequate (Pahl-Wostl 2002). FCI is a centralized solution of large-scope that its maintenance and reinforcement is difficult to keep up with the impacts from increasing local floodplain development and upstream deforestation. Adding to the challenge is global climate change, which is expected to intensify storms whose exact nature is unpredictable (IPCC 2007). Lastly, FCI produces social injustice by forcing its costs onto other communities (Smith and Ward 1998). FCI-induced ecological declines may not directly affect FCI-dependent cities because they typically exploit biological productivity and freshwater elsewhere (Folke et al. 1997). However, upstream and downstream rural communities dependent heavily on freshwater resources could suffer significantly. These communities may

also suffer from increased flood risks, transferred from cities by FCI. Moreover, they are often sacrificed during basin-wide extreme flood events, strategically flooded to avoid flooding of economically and politically more important cities, as seen in recent floods of the Mississippi River in USA and the Chao Phraya River in Thailand in 2011.

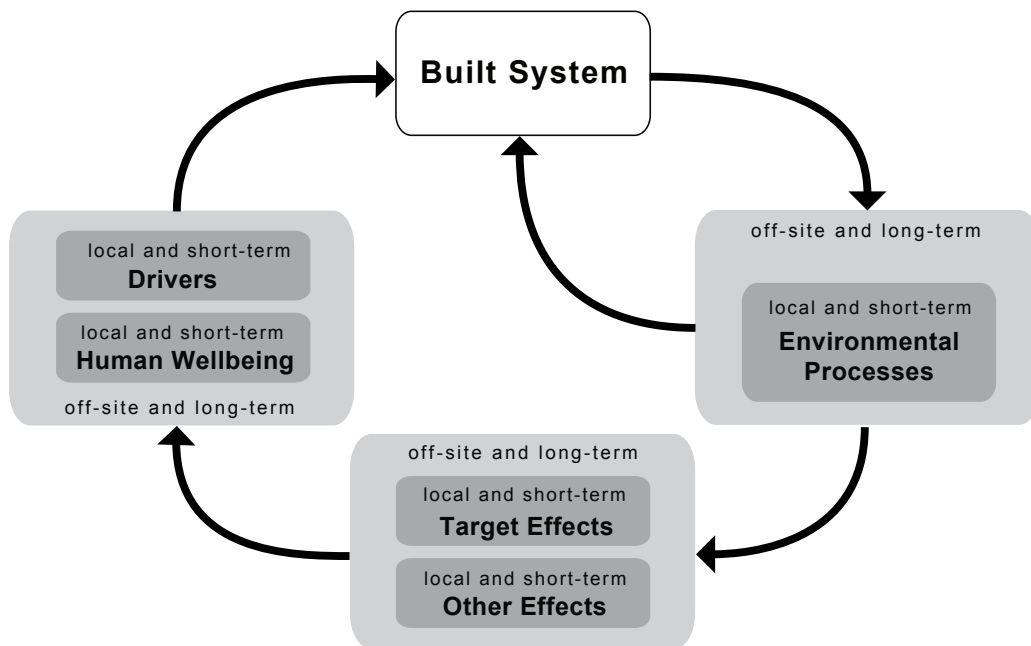
### **The Alternative to Flood Control**

Despite many well-recognized shortcomings, FCI is still largely considered indispensable for cities (e.g., Birkland et al. 2003). The vicious cycle, complex system properties, and limitations of FCI discussed here suggest that it is unrealistic and inappropriate for cities to continue relying on FCI for flood safety. Rivers are inherently dynamic. Coupling with ever-changing local, basin, and global conditions, urban rivers will continue to be altered in unexpected ways by both human and natural processes. Controlling the uncontrollable and unpredictable is destined to fail to incur severe socioeconomic and ecological repercussions (Holling and Meffe 1996). The best strategy is to live with natural dynamics and its uncertainty and unpredictability, striving for resilience of the city, not stability of the river (Gunderson and Holling 2002; Berkes et al. 2003). A more sustainable approach to flood safety is to make the city adapted to floods. It is also important to recognize that floods are not merely hazards but critical natural processes supporting socioeconomically valuable ecosystem services (Postel and Richter 2003; Tockner et al. 2008). Preserving and restoring the benefits of floods should be an agenda of urban flood hazard management.

### **An Assessment Framework**

In a globally connected world where human decisions are increasing powerful to dictate environmental dynamics at every scale, research on coupled human-natural systems has become ever important (Liu et al. 2007b). Built systems such as FCI play a major role mediating socioeconomic, biological, and geophysical processes in cities (Liu et al. 2007a). Although they are tightly coupled with natural processes, researchers are just beginning to address feedback explicitly (Alberti 2008). Using an urban ecology research model (Figure 1-1) as a framework to examine FCI-dependent cities as coupled human-natural systems, this paper demonstrates a method to explicitly address and illustrate the feedback loop when built systems interact with other human and natural factors. The model, slightly modified to incorporate scale hierarchy, can

also be used as a framework to assess both short-term and long-term environmental effects of existing built systems or to speculate potential effects of proposed projects to reduce surprises (Figure 1-11). Such a framework helps organize available literature and identify unknown relationships between system elements to generate useful research questions. For example, in FCI-independent cities examined here, the interaction between river health and floodplain development is unclear. What remains to be answered empirically is how declines of ecosystem services of the urban river, as a result of FCI, directly and indirectly affect the well-being of the FCI-dependent floodplain communities. The question is important because it has been asserted that flood control promotes human well-being which justifies the mitigation practice that prioritizes flood control over ecological conservation and restoration. Only when we understand the impacts of FCI more comprehensively can society more accurately evaluate the true costs of it.



**Figure 1-11.** An assessment framework for investigating environmental effects of an existing built system or speculating potential effects of a proposed built project, building on Figure 1-1. Using the framework that incorporates scale hierarchy, we can examine the interactions between a built system (e.g., a bridge across a river) and other human and natural components at four scales of space and time: local, off-site, short-term and long-term.

## **CONCLUDING REMARKS**

When society has an incomplete understanding of the cause of flood hazards, it narrowly defines the problem and prescribes solutions that are unsuccessful and even harmful measures (Mileti 1999; Park 2000). The vulnerability of FCI-dependent cities to floods and river health degradation associated with FCI fundamentally attribute to the perception that cities are decoupled from and in control of nature (Folke et al. 2002). The entrenched faith in human ability to control rivers with engineering technology essentially fuels the vicious cycle in FCI-dependent cities, in which FCI worsens the problem it is supposed to mitigate. A shift away from the illusion of human controllability over nature can stop this vicious cycle. It requires a transformation of the urban flood hazard management regime such that valuable resources are redirected from FCI to make the city adapted to floods. Or, the vicious cycle will ultimately break after several flood catastrophes eventually deprive the city of resources for FCI. This case would be far more costly.

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## CHAPTER 2

# A THEORY ON URBAN RESILIENCE TO FLOODS— THE BASIS FOR ALTERNATIVE PLANNING PRACTICES

### ABSTRACT

River cities require a flood hazard management approach based on resilience rather than resistance to floods. Resisting floods with flood-control infrastructure such as levees, dams, and channelization neglects inherent uncertainties arising from human-nature couplings and fails to address extreme events expected to increase with climate change, thereby not a reliable approach to long-term flood safety. Applying resilience theory to address system persistence through changes, I develop a theory on ‘urban resilience to floods’ (URF) as an alternative framework for urban flood hazard management. URF is defined as the capacity of the city to tolerate flooding and to reorganize should physical damage and socioeconomic disruption occur so as to maintain current socioeconomic identity. URF derives from living with periodic floods, treating them as learning opportunities to prepare the city to better cope with extreme ones. The URF theory argues against flood control, which erodes resilience. It challenges the conventional wisdom that cities cannot live without flood-control infrastructure. To operationalize the theory for planning practice, I propose a resilience surrogate measure—the Percent Floodable Area (PFA)—for quantifying the “floodability” of a city as a part of its resilience assessment. One way of building URF is to increase floodability of the city through adapting the built environment to flooding. Flood adaptation enables the inherent hydraulic and hydrologic functions of the floodplain and is a more reliable approach to flood hazard mitigation than flood control in the face of climate change. In order to build resilience for flood safety in cities, I argue for a management paradigm shift from flood control to flood adaptation.

**Key words:** adaptation; built environment; cities; extreme floods; flooding; floodplain functions; natural hazards; resilience surrogate; urban flood hazard management; urban resilience.

## INTRODUCTION

Flood hazards challenge river cities around the world. The 21<sup>st</sup> century has already seen large-scale flood disasters in Bangkok, Thailand (2011); Brisbane, Australia (2011); Guangdong, China (2007); New Orleans, USA (2005); Dresden, Germany (2002); Taipei, Taiwan (2001); among others. With dense populations, architectural agglomerations, and prosperous economies, river cities are vulnerable to flooding, despite extensive flood-control infrastructure such as levees, dams, and channelization.

In the industrialized world urban flood hazard management has centered on flood control. Dramatically altering the natural flow regime and fluvial geomorphology, flood-control infrastructure has been heavily criticized for harming riverine ecosystems and increasing long-term flood risk, among other things. Scholars have called for a change in such management (e.g., Mount 1995; Burby et al. 2000; Smits et al. 2006; Postel 2008). Alternative management concepts have emerged, emphasizing the integration of land and water management and of structural and non-structural measures (e.g., Schneidergruber et al. 2004; APFM 2009). While stressing the importance of non-structural measures, such as flood warning and landuse planning, over flood control, scholars continue to assume the indispensability of FCI for cities (e.g., Birkland et al. 2003; Godschalk 2003). This assertion reflects the entrenched belief in controlling nature, but demands a critical examination.

Like other water management system, flood-control infrastructure is designed and operated under an obsolete assumption that the pattern of flow variability remains unchanged over time (Milly et al. 2008). It suggests that flood control is not a reliable approach in the era of increasing uncertainties associated with climate change (Zevenbergen and Gersonius 2007). Cities that depends on flood-control infrastructure can resist floods only up to a certain magnitude, thereby are ill-prepared for capacity-exceeding extreme floods, which are expected to increase as climate change brings more intense storms whose exact natures are unpredictable (IPCC 2007). Extreme events and climate uncertainties have emerged as an urgent agenda for cities (Blanco and Alberti 2009). It calls for a new framework for urban flood hazard management, alternative to the current one that based on controlling nature.

This paper provides such a framework based on resilience. As a concept resilience has a long history in ecology and engineering, but its application to human communities in natural hazard management is relatively recent (Berkes 2007). Natural disasters were viewed predominately as products of nature, until it is recognized that the internal state of the community plays a critical role in the outcome of hazards (Parker 2000). It has been argued that a community's vulnerability to hazards is determined not only by exposure to them but also by its resilience (Turner et al. 2003; Füssel and Klein 2006). In other words, building resilience helps reduce vulnerability (Berkes 2007). Resilience receives increasing attention in field of flood hazard management, but what defines resilience to floods remains ambiguous.

In this paper I develop a theory on 'urban resilience to floods' (URF), particularly addressing the urban built environment and riverine flooding. Among the two major interpretations of resilience—engineering resilience and ecological resilience (Holling 1996)—that have been applied in the context of natural hazards, I show that the ecological resilience concept is more appropriate for defining URF to be a framework for urban flood management. A resilience surrogate measure that quantifies the “floodability” of the city is proposed for resilience assessment in order to operationalize URF theory for planning practices. The theory and the measure together suggest that flood adaptation should replace flood control as the approach to flood hazard mitigation in order to build resilience to achieve flood safety in the long term.

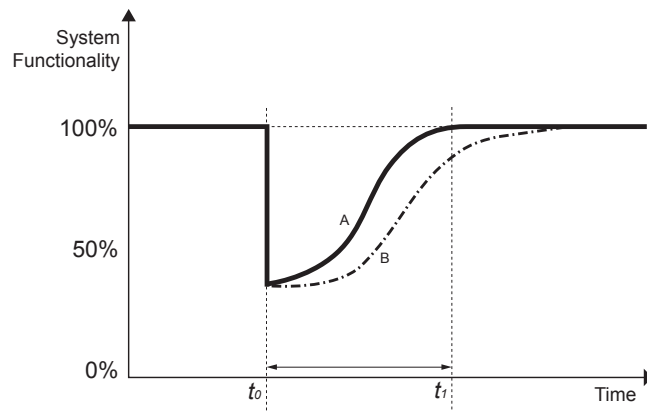
## **TWO INTERPRETATIONS OF RESILIENCE**

Engineering resilience and ecological resilience are two distinct interpretations of resilience (Holling 1996). Discerning their fundamental differences is important because the two concepts lead to divergent problem definitions, focuses, and approaches when applied to urban flood hazard management.

### **Engineering Resilience and Ecological Resilience**

In engineering, resilience is concerned with disturbances that threaten the functional stability of engineering systems. It is often linked with low probabilities of failures as well as quick recovery to normal levels of functionality in the case of failure (Wang and Blackmore 2009). It is argued that such resilience depends on four properties: robustness, the physical strength to withstand a

disturbance without functional degradation; redundancy, the extent to which system components are substitutable; resourcefulness, the capacity to identify problems and mobilize needed resources; and rapidity, the capacity to restore the system in a timely manner (Bruneau et al. 2003). This engineering resilience concept encompasses both resistance to and recovery from disturbances, although scholars have focus exclusively on recovery for its measurement (e.g., Hasimoto et al. 1982; Hollnagel et al. 2008). The faster the full functionality is restored, the greater the resilience (Figure 2-1). It indicates that engineering resilience focuses more on the ability to bounce back to the original condition when relaxed from stress (Wang and Blackmore 2009).



**Figure 2-1.** A conceptual representation of resilience of engineering systems, modified after Wang and Blackmore (2009). Resilience of a damaged system is measured by the time it takes ( $t_1-t_0$  for case A) to fully recover to 100% of its previous functionality. The longer it takes, the less resilient the system is (case B).

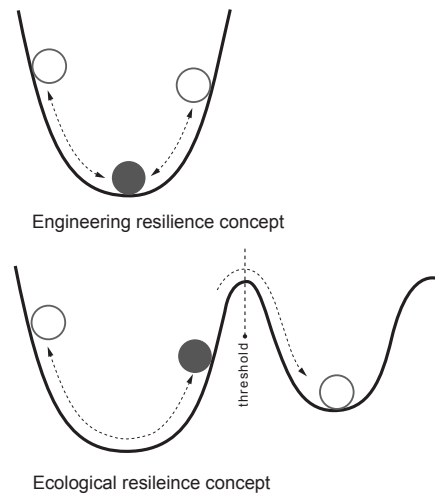
In ecology, Holling (1973) introduces a different meaning for the term resilience to describe observed ecosystem dynamics. It challenges the conventional ecological paradigm of equilibrium that assumes every ecosystem has a predetermined stable state, to which it eventually returns after every disturbance. Empirical studies have shown that some ecosystems never stabilize due to frequent disturbances. Multi-equilibria are also possible when the ecosystem stabilizes after a disturbance but in a different state, meaning the ecosystem is characterized by a different set of structures and processes. Returning to the previous ecosystem is extremely difficult if not impossible (Holling 1973; Scheffer et al. 2001). Building on an alternative paradigm of multi-equilibria/non-equilibrium, Holling (1973) defines resilience as the system's ability to absorb

disturbances and still persist. This ecological resilience concept focuses on persistence, or remaining within the same regime defined by the same ecological processes, structures, feedbacks, and identity (Walker et al. 2004). Because systems don't operate near equilibrium, resilience is associated with the change the system can tolerate and the ability to reorganize or renew (Carpenter et al. 2001). It is measured by the magnitude of disturbance the system can undergo before shifting to a different regime (Gunderson and Holling 2002).

Addressing different types of systems, several disparities exist between the concepts of engineering and ecological resilience (Table 2-1). They derived mainly from the fundamentally different assumptions of system dynamics regarding the number of possible regimes (Holling 1996; Figure 2-2). The assumption behind engineering resilience, which is about maintaining the optimal state of functionality, is congruent with the ecological paradigm of equilibrium, presuming only one regime with an idealized stable state as the norm. The paradigmatic divergence reflects different perceptions towards normalcy. In the engineering resilience concept any change from the optimal state is deviant, while in the ecological resilience concept any fluctuation within the regime is normal because systems are inherently dynamic (Holling 1973). In ecology, natural disturbances such as floods and wildfires are recognized as critical mechanisms for ecosystem maintenance, such that fluctuations in population numbers and rates of ecological functions are the norm instead of exception.

**Table 2-1.** Differences between engineering and ecological resilience

	<b>Engineering Resilience</b>	<b>Ecological Resilience</b>
Theoretic construct	Resilience = resistance + recovery	Resilience = tolerance + reorganization
Assumption	One equilibrium (one regime) Predictability	Multiple equilibria (multiple regimes) Unpredictability and uncertainty
Concerns	Deviation from the ideal level of system functionality or stable state	Regime shift
Focus	Stability/consistency—returning quickly to the equilibrium	Persistence—remaining within the current regime
Measurement	The speed of recovery to the previous stable state	The magnitude of disturbance the system can undergo before shifting to a different regime
Role of disturbances	Disturbances as threats	Disturbances as learning opportunities



**Figure 2-2.** The paradigmatic difference between engineering and ecological resilience can be illustrated by the ball-and-cup heuristic (Scheffer et al. 1993, Walker et al. 2004). The cup represents the region in the state space or ‘basin of attraction,’ in which the system tends to remain, and includes all possible values of system variables of interest. The ball represents the state of the system at any given time. The engineering resilience concept assumes only one regime, hence only one possible basin of attraction; and the very bottom of the basin represents the ideal stable state. The ecological resilience concept assumes multiple regimes, hence more than one basins of attraction. The system may move about within the basin, never settling at the bottom; it may also cross a threshold and settle in a new basin of attraction. Engineering resilience concerns remaining at the bottom of the basin, while ecological resilience concerns remaining within the current basin (Holling 1996).

Essentially, engineering resilience is the ability to maintain stability—remaining unchanged in system state or having minimum fluctuation; whereas ecological resilience is the ability to survive, regardless of the state. They are two different and even contradictory system properties. Systems with high engineering resilience may have low ecological resilience; low engineering resilience may introduce high ecological resilience (Holling 1973, 1996).

### **Community Resilience to Natural Hazards**

The aforementioned resilience concepts have received increasing attention in hybrid systems, such as social-ecological systems (e.g., Berkes and Folke 1998) and socio-technical systems (e.g., Hollnagel et al. 2008). In natural hazard management, which deals with the interaction between humans and environmental fluctuations (Mileti 1999), engineering resilience prevails in current definitions of community resilience. Few authors define it without implying an optimal reference

state, and it is frequently viewed as the capacity to withstand and recover quickly from disasters (Table 2-2). For example, Birkland and Waterman (2009) apply a resilience concept of infrastructural systems to propose three features of community resilience: damage prevention, speedy recovery, and preservation of community functionality, i.e., activities that characterized the community before the disaster. They argue that the more stresses the community can bear to preserve functionality, the faster the recovery is.

**Table 2-2.** Some existing definitions of community resilience to hazards

Definitions akin to engineering resilience	
Reference	Definition of Resilience
Tobin (1999:13)	Sustainable and resilient communities are defined as societies which are structurally organized to minimized the effects of disasters, and at the same time, have the ability to recovery quickly by restoring the socio-economic vitality of the community.
Buckle et al. (2000:13)	Resilience is the capacity to prevent or mitigate losses and then, if damage does occur to maintain normal living conditions as far as possible, and to manage recovery from the impact.
Godschalk (2003:136)	Resilient cities are capable of withstanding severe shock without either immediate chaos or permanent damage, as well as the ability to recover from the impacts of natural hazards.
Bosher (2008:13)	A resilient built environment should be designed, located, built, operated and maintained in a way that maximizes the ability of built assets, associated support systems (physical and institutional) and the people that reside or work within the built assets, to withstand, recover from, and mitigate for the impacts of extreme natural and human-induced hazards.
Lamond and Proverbs (2009:63)	The notion of resilience encompasses pre-disaster planning and warning systems, emergency handling procedures and post disaster reconstruction. Urban resilience encompasses the idea that towns and cities should be able to recover quickly from major and minor disasters.
Definitions without emphasizing recovery	
Reference	Definition of Resilience
Klein et al. (1998:263)	The resilience of the coast is its self-organizing capacity to preserve actual and potential functions under changing hydraulic and morphological conditions
Mileti (1999:32-33)	Resiliency is the ability to withstand an extreme natural event without suffering devastating losses, damage, diminished productivity, or quality of life and without a large amount of assistance from outside the community.
Pelling (2003:48)	Resilience is the ability of an actor to cope with or adapt to hazard stress. It is a product of the degree of planned preparation undertaken in the light of potential hazard, and of spontaneous or premeditated adjustments made in response to felt hazard, including relief and rescue.

**Table 2-2 (cont'd).**

Definitions without emphasizing recovery	
Reference	Definition of Resilience
Adger et al. (2005:1036)	Resilience is the capacity of linked social-ecological systems to absorb recurrent disturbances such as hurricanes or floods so as to retain essential structures, processes, and feedbacks.
Manyena (2006:446)	Disaster resilience could be viewed as the intrinsic capacity of a system, community or society predisposed to a shock or stress to adapt and survive by changing its non-essential attributes and rebuilding itself.
Berkes (2007:284)	Resilience is the capacity of a system to absorb disturbance and reorganize while undergoing change so as to still retain essentially the same function, structure, identity, and feedbacks.
López-Marrero and Tschakert (2011:230)	A resilient system is able to absorb hazard impacts without changing its fundamental functions; at the same time, it is able to renew, reorganize and adapt when hazard impacts are significant.

Discussions on community resilience place an overwhelming emphasis on recovery (e.g., Vale and Campanella 2005; Lamond and Proverbs 2009). In many cases, resilience is taken to mean exclusively the capacity to bounce back to the pre-disaster state, to differentiate from resistance, which means the ability to withstand a disturbance without disruption (e.g., Etkin 1999; Freitag et al. 2009). For example, in flood management resistance means flood prevention by FCI, while resilience is the rate of return from a flood-impacted state to the normal one, including the speed of floodwater recession (De Bruijn 2004).

## **ECOLOGICAL RESILIENCE AS THE THEORETIC FRAMEWORK**

Applying the engineering resilience concept to communities subject to natural hazards is fundamentally problematic because of the outdated equilibrium paradigm. While the focus on recovery is an acceptance that complete resistance to natural hazards is impossible (Parker 2000), recovery is often interpreted as returning to the pre-disaster conditions. It implies that a fixed, optimal reference state is assumed. However, the pre-disaster optimal state does not exist in coupled human-natural systems (Berkes 2007). Urbanized floodplains are such systems where climate, socioeconomic trends, built systems, and riverine processes interact across scales to affect flood hazards and disasters. They operate like evolving ecosystems rather than engineering systems and are characterized by complex behaviors associated with nonlinearity, emergence,

uncertainty, and surprise (Liu et al. 2007). Maintaining an optimal state is simply unachievable in such complex dynamical systems. To be sure, moving quickly from a chaotic state to an organized one after disasters is paramount, but it is unconstructive to restore the pre-disaster socioeconomic activities and built environment that are vulnerable in the first place (Klein et al. 2003). What remains unchallenged in this recovery notion is the strong tendency towards stability. Although generally perceived as positive, stability becomes problematic when forced at temporal and spatial scales at which the system is inherently dynamic (Cumming et al. 2006). The ecological resilience concept is a more appropriate framework for urban flood management, for it builds on a more realistic paradigm of multi-equilibria and focusing more pragmatically on persistence in a world of flux (Adger et al. 2005; Anderies et al. 2006).

### **Alternative Perspectives from Ecological Resilience**

Thanks to studies on integrated social-ecological systems (e.g., Berkes and Folke 1998; Berkes et al. 2003), the ecological resilience concept is increasingly refined to become a sophisticated resilience theory that focuses on complex human-nature couplings. Resilience theory builds on an understanding that neither natural nor human systems can be managed in isolation (Berkes 2007), thereby instrumental for addressing flood hazards that arise from the reciprocal interactions between riverine and urban dynamics. Challenging the prevailing control-centered management, it provides at least two alternative perspectives.

First, resilience arises from adapting to inherent variability, uncertainty, and surprise (Folke et al. 2003). Coupled human-natural systems lose resilience when the inherent variability is artificially suppressed to promote stability through command-and-control management (Holling and Meffe 1996; Holling et al. 2002). This suggests that forcing floodplains to be inundation-free and building socioeconomic functionality upon such forced hydrologic stability result in resilience erosion. Resilience theory challenges the bias in the control-centered management towards maintaining a dry floodplain and steady socioeconomic activities. Under such a resilience framework, urban flood management begins with accepting periodic flooding as a natural process and recognizes that socioeconomic activities on floodplains are inevitable affected by it. Neither flood resistance nor recovery to a previous state is relevant because flooding is accepted as normal.

Secondly, resilience theory holds that periods of gradual development and sudden changes complement each other (Folke 2006). As demonstrated in ecosystems subject to frequent disturbances, resilience is borne out of experiencing and learning from disturbances (Holling 1973; Gunderson and Holling 2002). Research into communities relying on natural resources also indicates that resilience to large, unpredictable disturbances derives from allowing smaller ones to enter the system (Berkes and Folke 1998; Berkes et al. 2003). It suggests that flooding itself is an agent for resilience because each flood creates a chance for cities to adjust the internal structures and processes and to build knowledge, leading to diverse coping strategies cumulated over time (Folke 2006; Smit and Wandel 2006). In other words, experiencing flooding triggers feedback to increase resilience through incremental adjustments. This contrasts with the attitude toward floods as threatening, idiosyncratic events that legitimizes FCI in the control-centered management. With FCI preventing most floods, cities only learn painfully from rare, catastrophic ones with high prices and little increase in resilience. Instead, the typical responses are attempts to increase resistance. Under the resilience framework, periodic floods are not only considered normal urban dynamics but also learning opportunities for cities to become better fit for extreme floods.

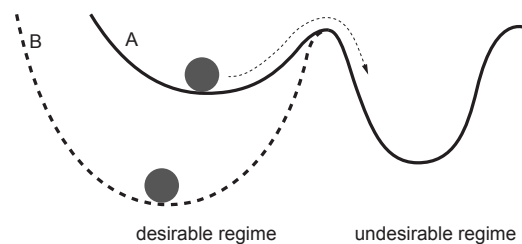
### **URBAN RESILIENCE TO FLOODS (URF)**

The URF theory is built on resilience theory, but two issues must first be confronted before applying a theory originating in the ecological science. The resilience of ecological systems is concerned with system collapse; yet such a concern for cities is almost irrelevant, as history shows that most cities that have experienced catastrophic destructions have persisted and even flourished (Vale and Campanella 2005). A city remaining as a city means little to those who have lost their lives and those forced into permanent hardship (Klein et al. 2003). Moreover, individual people matter in flood management, although individual creatures are irrelevant to ecological systems that build resilience through system-level adaptation where less fit individuals are continuously replaced (Gunderson 2010). Thus, URF encompasses dual concerns: the flood safety of individual citizens and the maintenance of the city's current identity.

## A Definition

The few available definitions of community resilience based explicitly on resilience theory stress the capacity to absorb recurrent hazard impacts and to reorganize while undergoing change so as to maintain fundamental structures, processes, identity, and feedbacks (Table 2-2). The word ‘change’ can be seen as the internal adjustment of the community responding to the environmental fluctuation. Following this interpretation, I define URF as *the capacity of the city to tolerate flooding and to reorganize should physical damage and socioeconomic disruption occur, so as to maintain current socioeconomic identity*. It can be conceptualized as the capacity to remain in the desirable regime while experiencing a flood. The desirable regime is defined by a set of variables reflecting aspects such as livelihood security, economic performance, and mobility that collectively represent the city’s socioeconomic identity (Adger 2000; Cumming et al. 2005, Gunderson 2010). URF is measured by the flood magnitude the city can undergo until it reaches a threshold and shifts to an undesirable regime. Such flood magnitude may be described by the amount of floodwater and sediments entering the floodplain.

Unlike that for biophysical systems, the regime is socially rather than scientifically defined. The desirable regime reflects the city’s collective tolerance of the range of socioeconomic state changes. This tolerable range matters to URF (Figure 2-3). A narrow range leads to a shallow basin of attraction that metaphorically represents the desirable regime, and a small flood could easily push the city out of the shallow basin (Carpenter et al. 2001; Walker et al. 2004). A wider range implies that the city considers a greater degree of socioeconomic fluctuations normal, hence a larger basin of attraction, out of which the city is harder to move.



**Figure 2-3.** The tolerable range of socioeconomic state change dictates the shape or size of the basin of attraction that represents the desirable regime. A narrow range means a smaller, shallow basin (case A), while a wider range leads to a bigger and deeper basin (case B).

A city is considered to have shifted to an undesirable regime when experiencing a flood disaster that causes widespread human, economic, and environmental changes that exceed the city's ability to cope using its own resources (UN/ISDR 2004). This regime is characterized by significantly reduced resources and assets, large-scale population displacement, livelihood disruption, and loss of security (Adger 2000; Berkes et al. 2003). Once in it, moving to a better regime or developing a socioeconomic identity similar to the previous one is impossible or costly.

Essentially, URF is the capacity to avoid flood disasters. It initially depends on how the built environment of the city would fare during a flood. Socioeconomic disruption would not occur if the built environment has the ability to remain intact or functional when it is flooded. I call this ability "floodability." However, floodability has its limit. When damage and disruption cannot be entirely prevented, remaining in the regime counts on reorganization, i.e., reestablishment of the socioeconomic order, which involves factors beyond those associated with the built environment. While the return to the pre-flood state is irrelevant, the speed of reorganization matters because prolonged socioeconomic disruption erodes the city's organizing capacity (Walker and Westley 2011), which can eventually push the city into an undesirable regime. Overall, URF is defined by floodability and reorganization, not flood resistance and recovery that engineering resilience would suggest.

### **Key Properties of URF**

Self-organization, adaptive capacity, and redundancy have been frequently associated with resilience (Carpenter et al. 2001; Low et al. 2003; Tompkins and Adger 2004). Self-organizing systems are resilient to disturbances because of the distributed character (Heylighen 2001). Adaptive capacity, the ability to adjust to changing internal demands and external conditions, is also that for increasing resilience over time, derived from the learning of the system (Gunderson 2000; Carpenter and Brock 2008). As for redundancy, it provides insurance against total system failure. These three concepts can be translated into the following key properties of URF.

The first property of URF is the localized flood-response capacity. Where each floodplain dweller and public manager could act immediately to avoid flood damages and reestablish order, cities are more agile in coping with flooding and thus more resilient than cities relying on a few

centralized mechanisms such as flood-control infrastructure. Such self-organizing cities can also quickly reorganize after flood disruption because of the internal ability to clean up and fix damages without waiting for external help from the central government or aid agencies, which don't always act soon enough.

The second property of URF is the adjusting capacity after every flood. URF can be increased over time by making timely behavioral, physical, and institutional adjustments to cope with future floods. Social learning from each flood experience is the adaptive capacity that increases URF. Every flood entails something new, e.g., debris deposition at unexpected locations. By understanding new phenomena and making necessary adjustments, the city increases floodability incrementally. It is a learning-by-doing process of adaptation, where novelty is involved to avoid repeating the previous configuration (Walker et al. 2004; Adger 2006; Berkes 2007).

The third property of URF is redundancy in every flood-related system. Redundancy is required in every urban system for URF, and it means more than duplication of the same element in an engineering sense, e.g., the freeboard added on top of the levee height required for confining the design flood. Redundancy entails diversity and functional replication across scales (Peterson et al. 1998; Adger et al. 2005). For example, a water supply network with redundancy would incorporate both regional and local systems and utilize a variety of sources including rainwater, groundwater, and surface water. A flood hazard management system with redundancy would incorporate a diversity of measures within every management aspect including mitigation, preparedness, response, and reorganization to buffer impacts should some of the measures fail. It would also ensure that the flood-response capacity is distributed across levels from individuals to communities to the municipality, so when the capacity of one level is overwhelmed, the city can still count on the capacity at other levels.

Fundamental to the aforementioned three properties are diversity and flexibility. Short-term adjustments and long-term adaptation are impossible without a diversity of options to choose from (Folke et al. 2002; Davidson-Hunt and Berkes 2003). Diversity is particularly key to resilience because it enables adaptation by providing seeds for new opportunities (Berkes 2007).

For example, a diverse economy or livelihood is known to facilitate reorganization after disasters (Berke and Campanella 2006). Flexibility is also paramount. It allows the self-organizing city to preserve overall functionality in the face of a flood by making immediate changes in the specifics at smaller, faster scales in its subsystems (Allen et al. 2005). Take the public transportation system for example, during flooding if the service mode could switch timely from land-based to waterborne, it would ensure mobility to keep the city functional. Flexibility also promotes adaptive capacity, for rigidity prevents timely behavioral, physical, and institutional adjustments before the next flood.

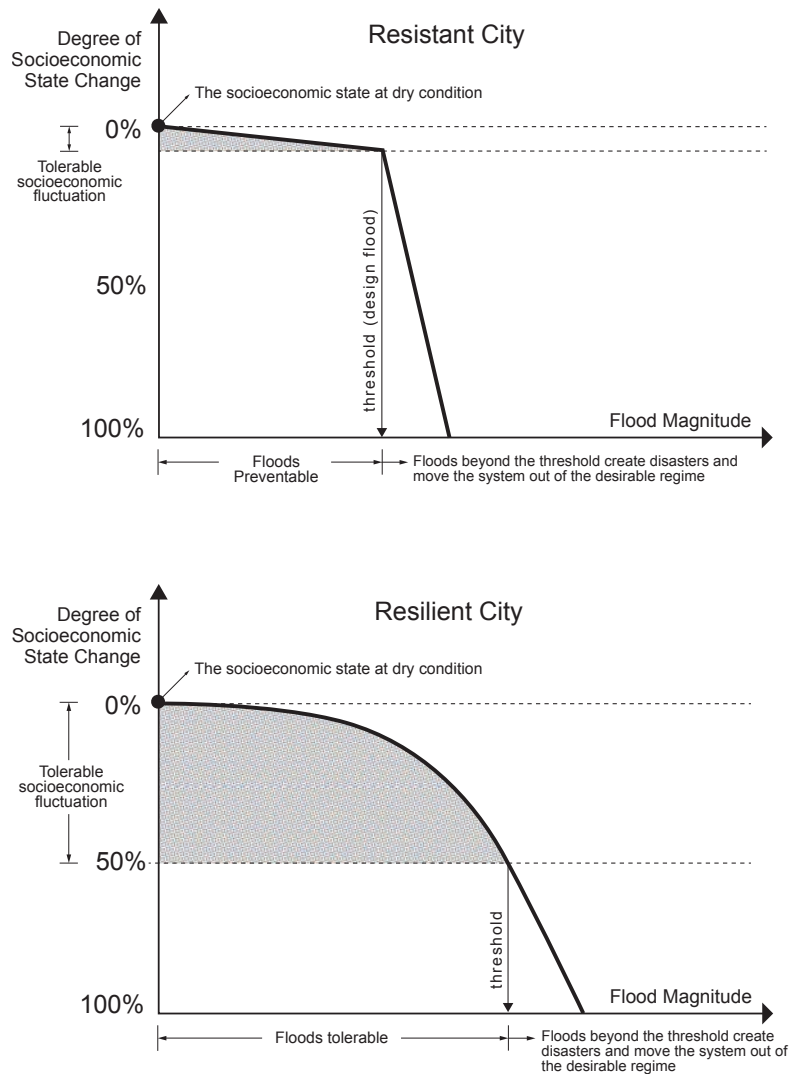
### **URF and the Resilience of the Urban River**

The resilience of ecological systems plays an important role in the human ability to cope with hazards. This is because it concerns the persistence of ecosystem services, the loss of which limits the options to adapt (Adger 2000; Berkes et al. 2003; Gunderson 2010). Ecosystem goods and services, such as fisheries and water supply, provided by rivers and other freshwater ecosystems are highly valuable (Constanza et al. 1997). While it is clear why ecosystem services are important to communities heavily dependent on local resources for livelihoods (Adger et al. 2005), it is not obvious how the resilience of the local urban river relates to URF in modern cities. With significantly altered hydrology, geomorphology, biochemistry, and species composition, many urban rivers today are arguably in socio-ecologically undesirable regimes already, too degraded to offer ecosystem services (Paul and Meyer 2001; Groffman et al. 2003). Although drawing on services generated elsewhere buffers the impact of local ecological declines, the degrading urban river still affects URF. Flooding of a polluted river increases flood damage and complicates reorganization. Moreover, if a flood disrupts the imports of goods and services, the city would have no access to critical resources, such as potable water. The resilience of the urban river matters to URF as the ultimate insurance against the most socioeconomically disruptive floods.

### **URF and Flood Resistance**

Conventional wisdom assumes an imperative of flood resistance in cities. However, resilience theory suggests that flood resistance erodes URF (Holling and Meffe 1996). In effect, the use of flood-control infrastructure puts the city in either contrasting condition: dry and stable; inundated and disastrous. With flood-control infrastructure in presence, flooding results exclusively from

its failure and is more hazardous than if there were no flood-control infrastructure (Tobin 1995). This results in the natural process of flooding becoming a synonym to disaster. Cities protected by flood-control infrastructure are of high resistance but low URF, as they have physically adapted to the artificially expanded dry-and-stable condition, thus becoming intolerant of wet conditions (Figure 2-4).



**Figure 2-4.** A comparison between the resistant and resilient city. The resistant city is dependent on flood-control infrastructure, functioning only in the dry condition and having little tolerance of socioeconomic state changes, i.e., narrow tolerable range. This leads to a small basin of attraction of the desirable regime, whose size is indicated by the shaded area; hence low URF. On the contrary, the resilient city tolerates flooding and much greater fluctuation in socioeconomic conditions, thus having a larger basin and consequentially greater URF.

In cities protected by flood-control infrastructure, the river's high flows are mostly confined between the levees or held behind the upstream dam. The flood frequency is dramatically reduced and river dynamics largely unnoticed. Each flood prevented is a loss of opportunity for learning (Klein et al. 1998; Colten and Sumpter 2009). With little experience of flooding, flood-risk awareness among the population is low (Correia et al. 1998). Most citizens are too accustomed to operating under the dry-and-stable condition, knowing little about how to cope with inundation once flood-control infrastructure fails. Furthermore, the structural rigidity and large scope of flood-control infrastructure leave little flexibility for making timely adjustments to respond to constantly changing boundary conditions (Pahl-Wostl 2002). Flood control also prevents the diversity of flood-coping measures in the management because it is too expensive to allow resources to be spent elsewhere (Castonguay 2007). Whereas flood-control infrastructure as a system may incorporate a diversity of engineering measures, each with structural redundancy, there is still little diversity and cross-scale redundancy with regards to flood hazard mitigation measures. In current flood hazard management, the emphasis is typically placed on the river but not the built environment. As a centralized measure flood-control infrastructure have created a false sense of security to preclude the need for localized flood-response capacity.

As flood control erodes URF over time, a flood could easily cause high casualties and severe damage, complicate reorganization that relies heavily on external forces, and push the city to an undesirable regime, as New Orleans has demonstrated after Hurricane Katrina in 2005 (Colten and Sumpter 2009). Flood control erodes URF also because it compromises the river's ability to provide ecosystem services (Tockner et al. 2008), which in turn limits the city's options to adapt. The periodic flooding prevented by flood-control infrastructure is a critical mechanism to maintain ecological functions and high biodiversity of floodplain rivers (Junk et al. 1989). The altered flood regime, with which native species are unfamiliar, affects the resilience of river ecosystems and contributes to system collapse (Poff et al. 1997; Folke 2003).

The argument that flood control erodes URF echoes the widely supported notion of risk transference in natural hazard management, which holds that resistance to natural hazards is simply postponing them, only to build up risks and worsen disasters later (Etkin 1999; Mileti 1999). Since flood control conflicts with URF, I argue that a city's persistence resulting from the

flood being resisted—in effect no flooding occurs—should not be mistaken and described as resilience.

## **OPERATIONALIZING URF THEORY**

Turning theory into practice requires developing tools to measure URF. The degree of resilience, however, is not known until the regime is shifted (Carpenter et al. 2001). The growing interest in managing for social-ecological resilience has prompted the research into methods for assessing potential resilience to future disturbances (e.g., Bennett et al. 2005; Cumming et al. 2005). Because resilience is not directly observable, it must be inferred from ‘resilience surrogates’—forward-looking proxies for future resilience, though recognizing that it is not possible to represent resilience with one surrogate alone (Carpenter et al. 2005).

### **Assessing URF**

Assessing URF requires surrogates that reflect the city’s floodability and the potential to quickly reorganize should physical damages and socioeconomic disruption occur. As an initial attempt to operationalize URF theory, here I explore a measure exclusively for floodability as one of the URF surrogates.

One way to find resilience surrogates for coupled human and natural systems is to look for the internal properties that alter resilience over time (Bennett et al. 2005). Slowly changing properties are often good candidates because they define the system’s underlying structure, thus controlling the shape of the basin of attraction, threshold location, and system’s position within the state space (Carpenter et al. 2001; Scheffer et al. 2001). For river cities, a property defining floodability would be one that reflects the hydraulic and hydrologic changes of the floodplain, over which human interests conflict with flood processes to give rise to flood disasters.

### **Hydraulic and Hydrologic Functions of Natural Floodplains**

Floodplains are essentially a part of rivers, naturally functioning to convey and store the share of high flows and sediments spilled overbank. During large floods the amount of floodplain conveyance and storage is significantly greater than that of the channel (Leopold 1994). Floodplain storage occurs when the water is disconnected from the main-channel flow and

slowly released after the peak has passed (Richards and Hughes 2008). Longer-term storage takes place on the surface of floodplain wetlands and through infiltration into the floodplain soils, which can store large amounts of water during wet periods (Keddy 2000). The floodwater stored on the floodplain is subject to evapotranspiration as well as biogeochemical changes due to sedimentation, nutrient uptake by the biota, and redox reactions (Hamilton et al. 2002).

Floodplain vegetation represents hydraulic roughness and exerts significant impacts on the flood process. For example, the overall patchiness increases the heterogeneity of flow patterns; dense vegetation dampens flood wave and traps sediments during minor floods; the floodplain forest delays the release of floodwater stored on the surface through frictional effect, further enhancing floodplain storage (Tabacchi et al. 2000; Richards and Hughes 2008). Because of floodplain conveyance and storage, floodplain rivers have lower flood peaks and velocities, and smaller flood discharges in downstream locations, compared to other types of rivers (Leopold 1994).

As a floodplain becomes urbanized, its hydraulic functions are often replaced by artificially enhanced channel capacity, drainage efficiency, and upstream impoundment. At the same time, the river sees higher peak flows with increased downstream discharges (Criss and Shock 2001). The flood risk is in effect heightened. Because there is less land functioning to convey and store floodwater and sediments, the urbanized floodplain becomes less tolerant of flooding.

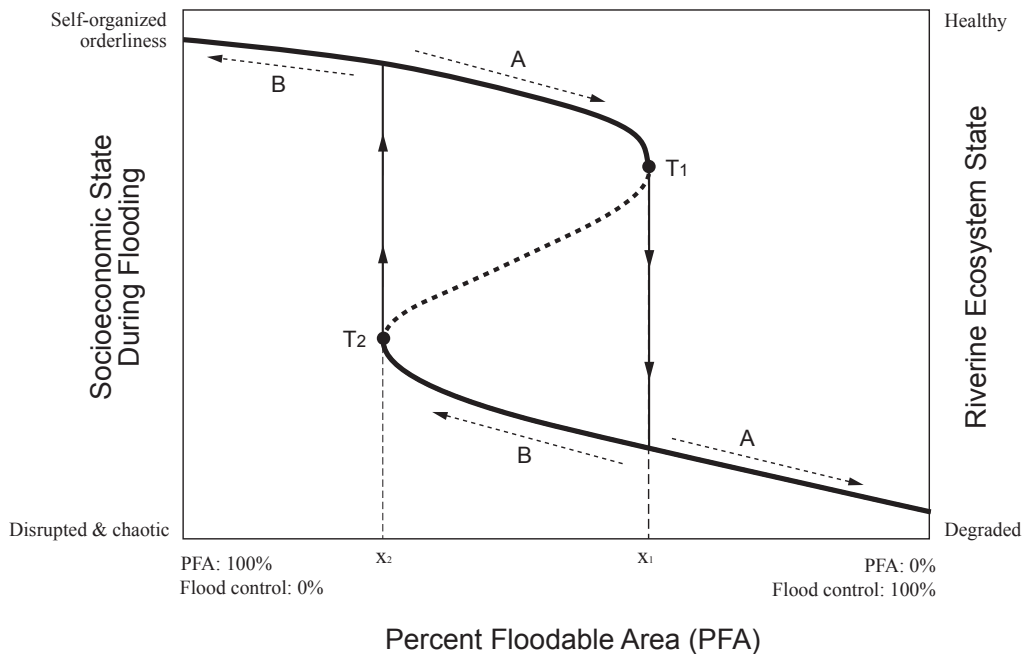
### **Floodable Lands and Percent Floodable Area**

To assess floodability, I propose a new concept—the floodable land, which is defined as a land that is capable of storing or conveying floodwater and sediments without incurring damage locally or elsewhere. Floodable lands do not exclusively refer to undeveloped or green areas such as wetlands. In fact, a green area subject to soil contaminated is not floodable because flooding of it would spread toxic substances. Floodable lands can be of any land use and land cover. For example, a residential lot with the building raised on poles is floodable. Floodable lands are important to URF in terms of flood tolerance, as a flood is benign and thus tolerable where it is floodable. Furthermore, if the combined area of floodable lands of a city is large enough, they can lower flood peaks and reduce the overall flood impact.

Identifying floodable lands on the floodplain of a city would be instrumental for assessing areas of vulnerability when comparing against simulated inundation scenarios. Theoretically, the more floodable lands the city has the more floodable it is. To quantify floodability of a city, I propose the metric ‘Percent Floodable Area’ (PFA)—the percentage of the total area of floodable lands within the floodplain area, which can be used as one of the URF surrogate measures for resilience assessment. The floodplain area refers to the entire valley floor between valley walls (Anderson et al. 1996). It is defined by any predetermined recurrence interval because resilience should not be limited to a flood of a specific return period, nor should it be based on an assumption of stationarity. PFA is a measure of physical fitness for flooding, although it is worth noting that a rare, extreme flood may still damage the city with a PFA of 100%, in which case reorganization plays a major role in URF. I hypothesize a positive but nonlinear relationship between PFA and floodability. At higher PFA, its marginal contribution to floodplain storage and conveyance should decrease significantly (Douglas et al. 2007).

The concept of floodability, along with its metric PFA, suggests a different thinking into flood safety, alternative to the notion of protection standard underpinning current flood hazard mitigation. It implies a different mitigation approach—increasing PFA to build resilience, as opposed to increasing the protection standard to improve resistance. I further hypothesize that besides nonlinearity, there may be hysteresis involved in the relationship between PFA and URF (Figure 2-5), as seen in other complex systems (Scheffer et al. 2001; Alberti and Marzluff 2004). The city may have to “go back further” in reestablishing floodplain functions in order to shift to a regime where the city is resilient, i.e., the city is able to remain in self-organized, orderly states during most floods, and the urban river is healthy to provide ecosystem services.

The aforementioned hypotheses are not readily verified with currently available empirical data but can be tested through modeling. They are to stimulate more research into the links between flood safety, built patterns, and floodplain functionality to facilitate the building of URF.



**Figure 2-5.** The hypothetical dynamic of Percent Floodable Area (PFA). During the process of floodplain urbanization (trajectory A), the city moves along the upper solid line and shifts dramatically at the threshold  $T_1$  ( $PFA = X_1$ ) to the lower solid line. Passing  $T_1$ , the floodplain has lost the natural functions to handle floodwater, and the city falls into a regime where flood safety is heavily relied on flood control and the river is degraded. Once a flood occurs, the socioeconomic dynamics become disrupted and chaotic. During the process of resilience-building through increasing PFA (trajectory B), the city moves along the lower solid line, but reaching  $X_1$  is not sufficient to restore the same degree of resilience before the shift ( $T_1$ ). The city needs to go further, passing  $T_2$  ( $PFA > X_2$ ) to move into a more resilient regime where the river health is largely restored and the city can self-organize to stay in socioeconomic order during most floods.

## RESILIENCE-BASED FLOOD HAZARD MANAGEMENT

Enhancing resistance to one disturbance in a complex adaptive system often creates vulnerabilities to others (Holling and Meffee 1996; Roberge 2002). Ignoring complexity and unpredictability, flood control has exacerbated flood risks and created ecological disasters. Today many cities—building on the hydrologic stability forced by flood-control infrastructure and tolerating little socioeconomic fluctuation—are not flood-safe (Figure 2-4). The control-based management must be abandoned (Folke 2003; Anderies et al. 2006). For long-term flood safety, cities need to switch to resilience-based flood hazard management.

## **Living with Floods**

Resilience derives from living with disturbances (Gunderson 2000; Walker et al. 2004). Studies have shown that long-enduring communities are those adapted, not resistant, to disturbances (Berkes et al. 2003). Building URF is essentially a process of adaptation—instead of fighting the river, cities live with periodic floods, allowing them to enter the city to learn from them, so as to become resilient to extreme ones. It is a paradigm shift from resistant to resilient cities with the management agenda redirected from ‘safety against floods’ to ‘safety at floods’ (Schielen and Roovers 2008). URF lies in a principle some scholars have advocated for decades—working with the river rather than against it (e.g., White 1945; Leopold 1977). It also echoes the ancient philosophy of ‘living with floods’ that is still practiced today in rural communities in developing countries such as Bangladesh, Cambodia, and Egypt (Laituri 2000; Berkes 2007). Distinguishing between benign frequent floods and disastrous rare ones, these communities adapt lifestyles and built environments to river dynamics, harnessing the post-flood productivity boosts in fisheries and agriculture (Cuny 1991).

The notion of living with floods is nothing new, and in rural areas the natural functions of floodplains are increasingly utilized for flood mitigation (Moss and Monstadt 2008; Opperman et al. 2009). However, it is dismissed in cities where lands are deemed culturally and economically too valuable to be inundated. There is an entrenched perception that cities and floods are simply incompatible, which is enhanced by the argument that the fundamental solution to flood hazards is to retreat from floodplains. Although logical, this prohibitionist discourse can close down options and prevent creative solutions (Antrobus 2010). Retreat is politically difficult especially for floodplains with large populations and long development histories; and with people intuitively assert that there is no space for flooding, cities have no choice but continuing to rely on flood control. This paper advocates an alternative view—cities are too valuable to reject the necessary paradigm shift.

## **Flood Adaptation**

The idea that cities and floods can’t coexist is a lack of imagination, resulting from being too accustomed to the kind of built environment not adapted to flooding. With a shift in perception and creative planning and design, cities can eventually phase out flood-control infrastructure and

live with floods by retrofitting the built environment and adding redundancy, diversity, and flexibility into every built system. Open spaces can become multifunctional to convey and store floodwater during wet seasons (Douglas et al. 2007). Infrastructure can be redesigned into a collection of diverse functional elements with flexible operation (Fiering 1982). Buildings can be remodeled to be elevated, floatable, or wet-proofed to allow the structure to become floodable (Guikema 2009). It implies a paradigm shift in city design as well, requiring architects, engineers, landscape architects, and urban planners to base design and operation on dynamism instead of presumed hydrologic stability.

Floodplains are constantly changing, rearranged not only by inundation but also by channel migration—land could become the site of flowing river and vice versa. Forgoing stability and perpetuity, building structures that are adaptive, movable, and temporary is the most realistic way to live in such a dynamic landscape. This challenges city design professionals to see urbanized floodplains as porous landscapes shared in time by the river and humans.

The resilience-based flood hazard management is itself adaptive. It is a process of learning by doing where specific objectives are open to adjustment after each flood. After all, it is the process of incorporating changes continuously that gives rise to resilience (Holling 1986). In a resilient city, its built environment is adaptive in two ways—it is designed to fit for known river dynamics based on historic patterns; it is also easily adjustable to changing boundary conditions, such as emerging weather patterns due to climate change. In other words, the resilient city is always a work in progress.

Replacing flood control with flood adaptation to mitigate flood hazards would correct several problems caused by flood-control infrastructure. First, it would avoid transferring the city's own problem elsewhere. It would not increase downstream flooding, as levees and channelization do by preventing floodplain conveyance and storage and by draining water quickly away from the city. Entailing local measures, it needs not submerge an upstream area and relocate people, as the flood-control dam does. Second, the tradeoffs between long-term and short-term flood safety would not exist, as there is no threat of structural failures, through which the damage by a rare, extreme flood would be more catastrophic than if there were no flood-control infrastructure

(Tobin 1995). Third, it would not conflict but could reconcile with the ecological preservation and restoration of urban rivers (Nienhuis and Leuven 2001). Because URF also depends on freshwater ecosystem services, management for URF would support river restoration to improve urban river health.

### **An Agenda of Multiple Scales**

Managing for resilience is an agenda of multiple scales, as it is controlled by dynamics at scales above and below the scale of the system in question (Walker et al. 2004; Anderies et al. 2006). The subsystems of the city affect URF by controlling the city's position in the basin of attraction. Take the flood hazard management system for example. The control-based management places the city very close to the threshold between desirable and undesirable regimes during flooding as it tolerates little inundation; contrarily, by accommodating floods the adaptation-based management places the city further away from the threshold. Other URF-affecting internal dynamics include economic status of households, crisis support network, institutional flexibility, design and operation of buildings and critical infrastructure, river health, etc.

These subsystems are simultaneously influenced by the economic, cultural, biophysical, and climatic dynamics at regional and even global scales, which change the shape of the basin of attraction in the state space to affect URF. Managing for URF thus requires attending to these cross-scale interactions, an example of which is the interaction between URF and socioeconomic activities. A city relies on flood control is not resilient not only because it places itself too close to the threshold but also because of a shallow basin of attraction that represents a rather narrow tolerable range of socioeconomic fluctuation (Figure 2-4). It results from only accepting uninterrupted intensity of socioeconomic activities as the norm, which builds on the assumed hydrologic stability. Increasing extreme floods and climate change uncertainties, however, will make the maintenance of hydrologic and socioeconomic stability increasingly costly and eventually unaffordable. The best approach to survival in a stochastic world is to have a large basin of attraction (Carpenter et al. 2001). Adjusting the form and intensity of socioeconomic functionality to the natural flood regime would greatly increased URF, but this would involve a worldview change away from obsessing with the idea of stability (Folke 2003).

## CONCLUDING REMARKS

Without a rigorous definition, resilience can be too vague a concept to be useful in hazard management (Manyena 2006). This paper presents a comprehensive URF theory that explicitly incorporates inherent dynamism and uncertainties. The theory provides unconventional perspectives for urban flood hazard management and addresses the issue of extreme floods and uncertainties, which cannot be neglected any longer. The theory challenges the current management paradigm that asserts the indispensability of FCI for cities, arguing that flood control compromises resilience and advocating for adaptation-based flood hazard management.

The URF theory is also an attempt to enrich the existing body of resilience theory through focusing on a specific type of system with a specific problem, i.e., river cities with flood hazards. Research on resilience associated with human-nature couplings is still in an explorative stage with few practical methods for real-world applications (Carpenter et al. 2005; Folke 2006). The URF theory, along with the surrogate measure of PFA for quantifying floodability, helps facilitate the application of field-based, interdisciplinary research.

To turn the URF theory into practice in the real world, the immediate challenge would not be how to maintain resilience, which most cities don't have, but how to catalyze the transformation from resistance to resilience. One daunting problem is that the current control-based management regime, with an entire industry built around it, is itself very resilient to change and locked into a paradigm of equilibrium. While disasters can be catalysts for social transformation (Pelling and Dill 2010), transforming by choice is much less costly. It requires transformability—the capacity to create a fundamentally new system, about which we know much less than what makes a system resilient (Walker et al. 2004; Pelling and Manuel-Navarrete 2011). It is a research frontier needed to move towards resilient cities.

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## CHAPTER 3

# LINKING URBAN FLOOD SAFETY TO RIVER HEALTH— TOWARDS FLOODABLE CITIES

### ABSTRACT

Flood safety and river health are both important elements of a sustainable city. Urban flood hazard mitigation typically relies heavily on flood control, which often jeopardizes river health and constrains the restoration of urban floodplain rivers, as many native species have evolved life cycles to adapt to periodic flooding that connects the channel and floodplain. This paper provides a theory of urban resilience to floods (URF) to link urban flood safety to river health. URF is defined by the floodability and reorganizational capacity of the city. This paper focuses solely on floodability, which I propose to be measured by the percentage of the floodable lands on an urbanized floodplain. I argue that improving floodability is a more reliable mitigation approach than flood control in the long term, as flood control compromises URF. The city can increase its floodability by retrofitting the existing open spaces, buildings, and infrastructure to adapt to floods. Adaptation techniques and real-world examples already exist to demonstrate the possibility of floodable cities. Replacing flood control with flood adaptation allows periodic floods to enter the city, providing opportunities for floodplain restoration to improve river health. Flood adaptation thus allows cities to simultaneously mitigate flood hazards and maintain river health. Promoting this more positive linkage between flood safety and river health also requires recognizing the complex and dynamic nature of river cities as coupled human-natural systems. Healthy urban floodplain rivers should support both ecosystem and socioeconomic functions, and sustainable floodplain urbanism should incorporate river dynamics. The City of Kent in King County, Washington, USA is used as a case for discussion throughout the paper.

**Key words:** adaptation; built environment; cities; flooding; flood hazard mitigation; floodplain restoration; flood safety; off-channel habitats; river health; urban resilience.

## INTRODUCTION

In the era of climate change, river cities face a major challenge to manage flood safety and river health simultaneously over the long term. Urbanized floodplains are under heightened flood risks as heavy-precipitation events are expected to increase in many areas around the world (IPCC 2007, 2012). The conventional mitigation strategy of flood control, which involves engineering measures such as levees, dams, and channelization, works only in the short term and neglects to address capacity-exceeding, extreme floods (Zevenbergen and Gersonius 2007). Meanwhile, growing attention has been paid to the health of urban rivers and the restoration of critical ecosystem goods and services such as clean water, fish, and water purification (Palmer et al. 2004; Grimm et al. 2008; Alberti 2010).

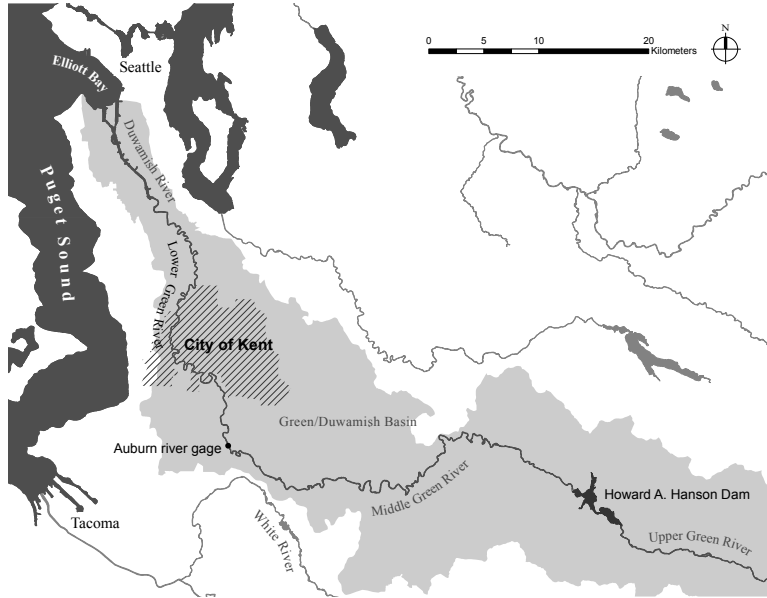
Flood safety and river health conflict when flood hazard mitigation relies on flood control (Pahl-Wostl 2006). Involving drastic modification of the river, flood control degrades and homogenizes aquatic and riparian habitats, damaging river fisheries and biodiversity (Graf 2001; Welcomme 2008). Most destructively, it disconnects the channel from the floodplain by preventing periodic flooding, to which native species adapt life cycles, thus terminating the very mechanism sustaining the functionality of floodplain rivers over the long term (Junk et al. 1989; Tockner et al. 2008). Numerous restoration projects have been implemented to reconstruct habitat complexity, such as placing large woods in the channel and re-planting riparian vegetation; however, it is widely agreed that the ecological effects would be limited without restoring the flooding process (Bayley 1995; Beechie et al. 2010).

Reintroducing ecologically critical flooding is possible under a new flood hazard mitigation concept, which recognizes the important role floodplains play in mitigation by retaining floodwater (Leopold 1994; Sparks 1995). Floodplain restoration, involving levee removal or setback to allow flooding on previously protected lands, has emerged as a solution to reducing downstream flooding (Moss and Monstadt 2008; Opperman et al. 2009). While such a practice is still relatively uncommon, at the basin scale flood safety and river health become less contradictory and even compatible (Bayley 1991; Nienhuis and Leuven 2001; Morris et al. 2004; Petts et al. 2006). Nevertheless, at the reach scale it is still unthinkable to permit flooding on economically more valuable urban lands. Although flood control is well recognized as

destructive to river health and ineffective for long-term flood safety, the flood-control imperative in cities is still asserted, and is frequently cited as a major socioeconomic constraint for urban river restoration (Nienhuis and Leuven 2001).

The trade-offs between flood safety and river health in cities are the result of a conceptualization of human and natural systems as separate. Cities are built to resist floods. It is increasingly becoming evident, however, that such conceptualization results in increased disasters and river degradation. As recurrent flood disasters have demonstrated the impossibility of complete control, it is increasingly argued that flood hazard management should focus on resilience instead of resistance to floods (e.g., Adger et al. 2005; Freitag et al. 2009). I argue that cities should not be an exception and that resilience-based flood hazard mitigation can support river restoration. This paper explores the re-conceptualization of urban flood safety by linking it to river health through shifting the mitigation strategy from flood control to flood adaptation (i.e., adapting the built environment to floods).

Throughout the paper, the City of Kent in King County, Washington (Figure 3-1) serves as a case for discussion. With a population of 92,411, Kent is situated by the Lower Green River that is confined by levees and revetments and regulated by the Howard A. Hanson Dam (HHD) upstream. Kent epitomizes a conundrum shared by modern river cities around the world. Despite the extensive flood-control infrastructure, the city is under elevated flood risk as more than a third of its territory is on the floodplain of the Lower Green River (Figure 3-2). At the same time, the flood-control infrastructure continues to limit river restoration in the Green/Duwamish basin (City of Kent 2004a; WRIA 9 Implementation Technical Committee 2012).



**Figure 3-1.** The City of Kent (the hatched area) is situated by the Lower Green River, which is part of the Green/Duamish River (the basin area in grey). The Howard A. Hanson Dam (HHD), primarily a flood-control dam, is located 51 km upstream from the city and operates to prevent flows above 340 m<sup>3</sup>/s at the river gage in Auburn. Upstream of the White River and 42 km upstream from Kent, there stands another flood-control dam—the Mud Mountain Dam. The White River used to join the Lower Green River but was permanently diverted to reduce flooding in 1911 (Kerwin and Nelson 2000).



**Figure 3-2.** The floodplain area within the City of Kent. In this paper a floodplain is defined as the entire area between the valley walls (Anderson et al. 1996). The boundary of Kent’s floodplain is delineated by the 21.3-m (70-foot) contour line. The floodplain has an area of 31.2 km<sup>2</sup>, about 36% of the total area of Kent.

In the remainder of the paper, I first introduce the concept of urban resilience to floods (URF) as a theoretical basis for alternative urban flood hazard management. I then focus on exploring an element of URF—floodability, and discuss the mitigation strategy of flood adaptation for increasing floodability as an alternative to flood control. The ecological implications of flood adaptation is examined, followed by a discussion of the re-conceptualization of river cities as coupled human-natural systems where flood safety is linked to river health.

## **URBAN RESILIENCE TO FLOODS (URF)**

Resilience is defined as the ability of a system to maintain its essential functions, structures, feedbacks, and identity while undergoing changes (Holling 1973; Walker et al. 2004). Its further application to coupled human-natural systems has emphasized the complexity and implications for scholarship and practice. In the context of natural hazard management, resilience implies the community's capacity to absorb hazard impacts and to reorganize if disrupted (Adger et al. 2005; Berkes 2007). Accordingly, I define urban resilience to floods (URF) as the capacity of the city to tolerate flooding and to reorganize should physical damage and socioeconomic disruption occur. A city is flood-tolerant if its everyday dynamic is undisrupted by flooding; it is capable of reorganizing if it reestablishes socioeconomic order quickly following disruption. The rest of the paper focuses only on flood tolerance, as it is the capacity that prevents physical damage and socioeconomic disruption in the first place.

### **Flood Control and Resilience**

According to the definition of URF, flood control is irrelevant to resilience because it does not make a city flood-tolerant, as demonstrated by Kent's high flood risk. Kent's floodplain is home to the city's downtown and an industrial center that is critical to the region's economic and employment base (City of Kent 2004b). The historically swampy floodplain is 2-4 m lower than the riverbanks (Collins and Sheikh 2005), and is protected by extensive flood-control infrastructure—virtually continuous levees and revetments along the Lower Green River and the Howard A. Hanson Dam (HHD) upstream. Since its operation in 1962 HHD has successfully prevented valley-wide flooding for Kent; however, seismic damage to either HHD or the Mud Mountain Dam on the White River (Figure 3-1) poses a threat of catastrophic flash flooding in the city (City of Kent 2004a). It is also recognized that a flow exceeding the capacity of HHD

and the levee system could also cause widespread damage (King County 2006). The flood risk was not a public concern until January 2009 when HHD's operational capacity was suddenly reduced due to an unexpected structural impairment, which drastically increased the likelihood of valley-wide flooding (USACE 2009). It triggered a major crisis involving possible economic losses of billions of dollars (FEMA 2009).

Regardless of the flood-control infrastructure and associated protection standard (e.g., protection against 100-year or 500-year flood), cities like Kent where flooding would cause damage are not resilient because they are intolerant of it. Flood control even compromises URF in the long term. Research indicates that artificially suppressing the inherent disturbance or natural variability of the system erodes resilience and leads to system collapse (Holling and Meffe 1996; Folke et al. 2002). A major reason is because resilience to a disturbance is nurtured through learning from and adapting to that very same disturbance over time (Holling 1973; Gunderson and Holling 2002; Berkes et al. 2003; Walker et al. 2004). The corollary is that resilience to larger floods requires episodic learning from numerous smaller ones (Gunderson 2010). Yet the very learning opportunities are eliminated by flood control, thereby compromising URF in the long term. In effect, levees and dams provide a false sense of security that floods will never occur (Pielke 1999). It results in the built environment and socioeconomic activities designed with little consideration of flooding. Consequentially, flooding is disastrous because cities are physically and behaviorally unprepared for it. Numerous flood catastrophes in cities protected by flood-control infrastructure, such as Brisbane, Australia (2011) and New Orleans, USA (2005), are cases in point.

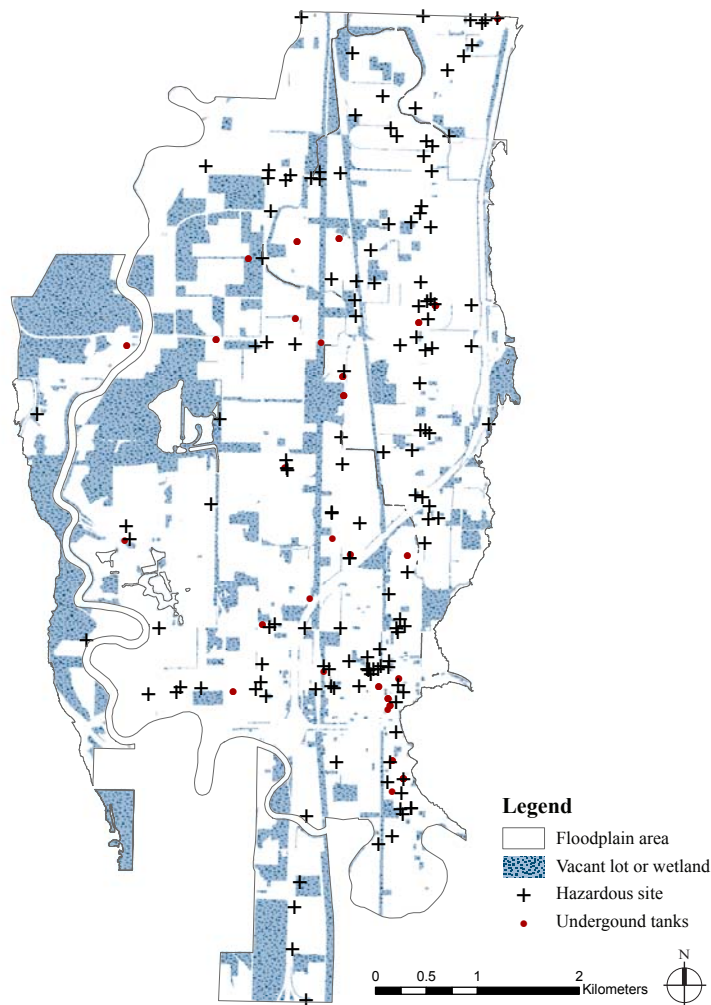
### **Measuring Flood Tolerance with Floodability**

The concept of URF provides a useful step in assessing resilience in practice. As defined, URF is associated with two capacities—flood tolerance and rapid reorganization, which should be assessed with separate measures since they are different system properties. Here I discuss how flood tolerance of the built environment can be assessed. Flood tolerance is considered here as the ability of the city to remain un-damaged and un-disrupted during a flood. Both tangible and intangible factors can contribute to it, but the built environment where urban activities take place plays a particularly important role—socioeconomic disruption would not occur if the built

environment remains intact or functional during a flood. Flooding is benign if it and associated processes such as sedimentation and channel migration do not cause physical damage and consequential socioeconomic disruption. In other words, the built environment tolerates a flood when it is “floodable.” Floodability—the ability of the built environment to be flooded without damage and disruption—can thus represent a city’s physical tolerance of flooding.

To quantify the floodability for resilience assessment I propose a measure—Percent Floodable Area, the percentage of the floodable lands within the floodplain. Determining the Percent Floodable Area for a place involves delineating its floodplain area and identifying all floodable lands. The floodplain area is not defined by any predetermined recurrence interval, e.g., FEMA’s 100-year floodplain, because resilience should not be limited to a flood of a specific return period nor should it be based on an assumption of stationarity. The floodplain area should include the entire valley floor between valley walls (Anderson et al. 1996), whose boundary can be delineated by elevation (Figure 3-2). Floodable lands are defined as areas that store or convey water and sediments during a flood without incurring damage locally or elsewhere and interrupting socioeconomic activities. Each piece of land would have different floodability criteria defined by water depth, quantity, or inundation period because of different elevations and land uses; and the floodability criteria would vary among different flood magnitudes.

In a city where floods mean disasters, existing floodable lands are largely limited to lands with no or few improvements to be damaged, such as vacant lots and wetlands. Take Kent’s floodplain for example, such lands account for 26%. However, not all of them are floodable because flooding could spread hazardous substance where the soil is contaminated. Across Kent’s floodplain there are numerous hazardous locations, as well as underground tanks, of which flooding could cause leaking (Figure 3-3). While the exact extent of existing and potential contamination of these sites is unknown and difficult to predict, they substantially affect Kent’s floodability that its Percent Floodable Area is estimated to be 16%. The methodology for calculating a city’s Percent Floodable Area and how Kent’s is estimated is detailed in Appendix A.



**Figure 3-3.** Vacant lots and wetlands accounts for 26% of Kent’s floodplain area; however, across the floodplain the Washington State Department of Ecology has identified numerous hazardous sites, as well as locations with underground tanks. Many of these hazardous or potentially hazardous locations are within or in the proximity to the vacant lots and wetlands.

Theoretically, a higher value of Percent Floodable Area implies higher floodability and thus higher safety, but the caveats of the metric should be noted. Floodability is scale dependent; for example, a community within a city may be low floodability while the city as a whole having high floodability. A corollary is that the bigger the city’s floodplain is, the less its Percent Floodable Area reflects local floodability conditions. In this case, resilience assessment should look further into the floodability of individual districts or communities. Another corollary is that it would be less informative to compare the Percent Floodable Area among cities dependent on

flood control because it is largely determined by the amount of natural or undeveloped open space and vacant lots, which does not necessarily affect how a city would fare during a flood as the socioeconomically more important components of the built environment, e.g., buildings and infrastructure, are largely non-floodable. Nevertheless, the metric is useful for assessing progress for a city as it proactively improves its floodability. It is also instrumental for comparison across cities in a future where more cities are working on increasing floodability instead of the protection standard of flood-control infrastructure. As floodability changes through time as the city undergoes physical alterations, the context (e.g., climate and population) also changes. This means that the same degree of floodability may not reflect the same degree of flood safety at a different time.

Overall, the floodability of a city can be seen as its physical fitness for a flood. It represents a different concept for addressing flood safety, shifting the focus from the river to the city itself. It can be an alternative to the protection standard of flood-control infrastructure that builds on the obsolete assumption of stationarity and predictability of flood behavior (Milly et al. 2008).

## **FLOODABLE CITIES FOR FLOOD SAFETY**

The concept of floodability is a response to the call for addressing not only the known but also the unexpected in natural hazard managements through nurturing resilience—the capacity to cope with whatever the future brings (Carpenter et al. 2001; Walker et al. 2002; Berkes 2007). This is especially important in the era of uncertain climate change. Mitigating flood hazards with flood control is to try to control the known, yet allowing little room for surprise (Birkland et al. 2003). Building resilience is a more reliable approach to flood safety, which should be re-interpreted as “safety at floods” instead of “safety against floods” (Schielen and Roovers 2008). A major challenge for cities is to increase floodability by increasing floodable lands.

Retreating from the floodplain is one solution. Government buyout programs have existed to encourage property owners to move out of harm’s way (Etkin 1999). There are also cases of managed retreat involving multiple city blocks, such as in Rapid City, South Dakota (Rahn 1984); Soldiers Grove, Wisconsin (Smith and Ward 1998); Rahway, New Jersey (Obropta and Kallin 2007); and Tulsa, Oklahoma (Godschalk 2003). However, such larger-scale retreats are

politically difficult and thus rare, since many urbanized floodplains contain high socioeconomic and cultural values. For example, not only is Kent's floodplain critical to the economies of the city and the region, its population and development will likely expand for the coming decades as it is within King County's Urban Growth Boundary, which is mandated to absorb a large proportion of the region's population growth (City of Kent 2004b). Nevertheless, it does not preclude the possibility to increase floodable lands. It can be done through retrofitting the existing built environment to adapt to flooding.

### **Retrofit Open Spaces**

Acknowledging the need for room to hold floodwater, several cities have made recreational open spaces multi-functional to serve for flood conveyance and storage during wet seasons. In Greater Manchester, UK, golf courses and nature reserves along River Mersey are also flood storage basins (Douglas et al. 2007). In Scottsdale, AZ a 12-km greenbelt composed of parks, golf courses, sports fields, and lakes along the lower Indian Bend is also a floodway capable of conveying a 850-m<sup>3</sup>/s flow through the city (Roach 2008). In Taipei, Taiwan a 324-hectare urban park is also a flood bypass for the Danshui River. Such floodable corridors are also called "green rivers" in Europe, emphasizing the role as both green space and river (Vis et al. 2003; Klijn et al. 2004).

Most such multi-functional spaces, however, are flooded only during emergency conditions at extreme flows. In order to prioritize human uses, periodic flooding is not allowed in these open spaces, which are really "sacrifice" spaces to prevent flooding in other areas. They would still be damaged by flooding, since they are not fit for inundation, erosion, sedimentation, and deposition of organic debris, thus requiring post-flood cleanups and repairs. To create truly floodable open spaces, an ideal solution is to turn them into naturalized landscapes such as wetlands. Designed creatively, these areas can accommodate periodic floods while remaining the city's recreational and aesthetic assets with little maintenance. An example is the Yongning River Park in Taizhou City, China, where the designers transformed a section of channelized river into a wetland park with elevated paths and platforms for human use. The more such floodable parks the city has, the easier it can deal with the large amount of sediment and woody debris frequently accompanying flooding.

Paved open spaces can become floodable lands too. Multi-level stacked parking system, which is widely used in densely-populated cities for space efficiency, can be a solution to floodable parking lots. In Rotterdam, the Netherlands, a climate adaptation project is underway to redesign several existing urban squares and playgrounds into sunken “water plazas” that temporarily store floodwater in ways that create playful and aesthetic water features (Boer 2010).

### **Retrofit Buildings**

Architectural adaptation to avoid flood damages has been practiced for centuries (Parker 2000), yet largely abandoned in modern society as flood control makes it seemly unnecessary. Still, some traditional adaptation measures are kept in the modern concept of flood proofing, typically implemented in areas without flood-control infrastructure (Parker 2000). Flood proofing involves permanent or emergency techniques to prevent or minimize floodwater damage to the building (NHRAIC1992). It should be noted that techniques preventing floodwater from entering the building, or dry proofing, such as building on fills and flood barrier shields, do not make it floodable but simply pushes floodwater elsewhere. Techniques that permit floodwater in the footprint area under the building make it floodable, such as the ancient solution of building on post foundation or the modern technology of buoyant foundation. Piloti buildings (i.e., buildings that are lifted above ground by pillars) have been promoted in the low-lying area along the Tsurumi River in the City of Yokohama, Japan (Nakao and Tanimoto 1997). Floatable buildings, or “amphibian houses”, that sit on dry land but can float vertically during flooding have been built in Maasbommel, the Netherlands along the banks of the Maas River (Figure 3-4), and are promoted in New Orleans after Hurricane Katrina. Wet-proofing the building can also make it floodable, such as using water-resistant building materials, water-tight seals to resist moisture and mold, and avoid using lower stores for living (Manojlovic and Pasche 2007; Guikema 2009; Lamond and Proverbs 2009).

Architectural adaptation is especially essential for URF for two reasons. First, it promotes resilience to larger floods by significantly reducing flood losses, as floodwater damage to buildings and their contents has been responsible for the majority of direct flood losses (Scawthorn et al. 2006). It may seem redundant if the city can allocate open spaces for flood retention to prevent buildings from inundation. Yet it is redundancy that promotes resilience (Low et al. 2003). The effect of flood retention decreases with flood magnitude, and during

extreme floods they may have little effect in mitigation (Douglas et al. 2007). Second, architectural adaptation directly involves the stakeholders of home owners to promote learning, since they own the problem instead of relying on a central or outside agency to solve it for them (Manojlovic and Pasche 2007).



**Figure 3-4.** Amphibious houses in Maasbommel, the Netherlands. They are built on dry land but capable of floating during flooding because of the concrete box foundation that gives the house buoyancy. Photo credit: Kuei-Hsien Liao.

### **Redesign Infrastructural Systems**

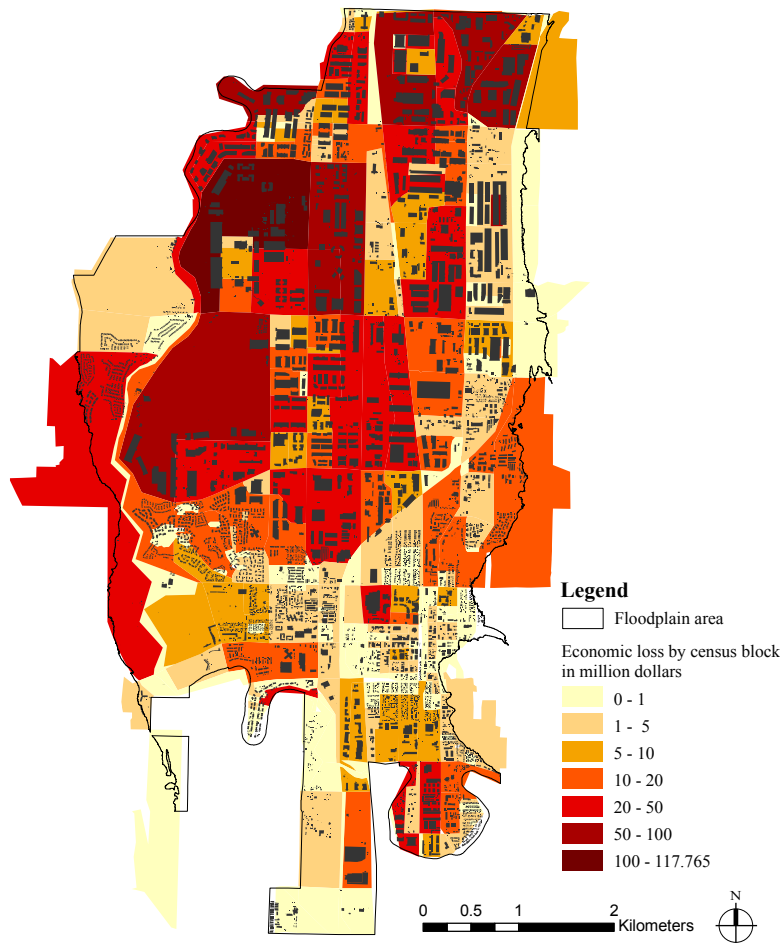
Achieving floodable cities ultimately requires redesigning infrastructure systems. Critically supporting socioeconomic functioning, systems and networks such as transportation, telecommunication, water and electricity supply, and waste removal and treatment need to be adaptive so as to continue operation during flooding (Bosher et al. 2007; Schielen and Roovers 2008). The structural and operational rigidities typical to modern infrastructure often prevent it from responding to quickly changing external conditions. For example, mobility in many cities becomes disrupted during flooding as it depends solely on roadways and vehicles. One solution is to break an infrastructural system into a collection of diverse functional elements with redundancy and flexible operation (Fiering 1982). Take the transportation system for example, if

it could include both land-based and waterborne transportation modes that can be easily switched back and forth, flooding would have little impact on mobility. For trips within walking distance, the solution can be as simple as temporarily constructing raised walkways, as Venice, Italy has been doing. A flood-adapted urban mobility system would allow roadways—accounting for a significant amount of the urban surfaces—to become floodable lands to significantly increase the city’s floodability. System-level infrastructural adaptation currently receives little attention but is a critical agenda demanding more research.

### **Flood Adaptation in Place of Flood Control**

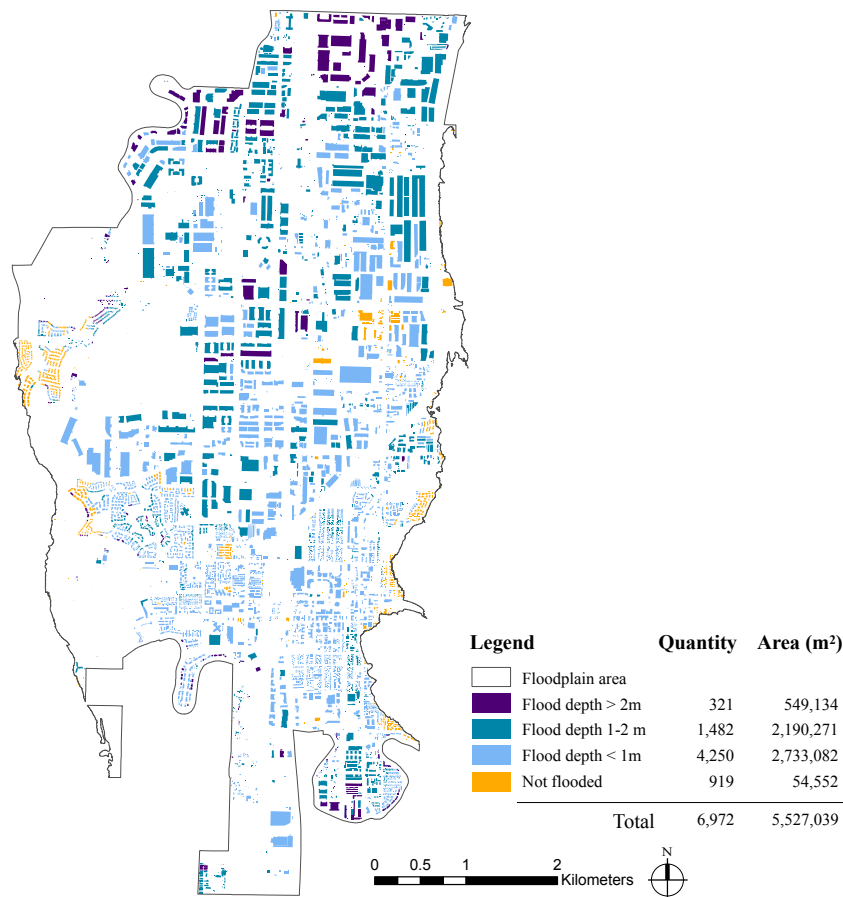
The aforementioned adaptation measures suggest the possibility for modern cities to coexist with floods, challenging the conventional wisdom that cities are too populated to be flooded. The Japanese city of Yokohama, which employs a variety of adaptation measures to mitigate flooding (Nakao and Tanimoto 1997), is a modern case closest to a floodable city, except that it still uses flood-control infrastructure. Modern cities have been allocating far greater resources to flood control to compromise URF than to flood adaptation to promote URF. In order to be resilient to extreme floods, for which many cities are ill-prepared, valuable resources need to be redirected to flood adaptation and eventually phasing out flood-control infrastructure. The US is presented with an opportunity to make such a transition, as it is currently facing a nation-wide crisis of aging and deteriorating infrastructure—the American Society of Civil Engineers gave a grade of D to both dams and levees on the 2009 Report Card for America’s Infrastructure (Powell 2010).

Kent is a quintessential example of a city that would benefit from a transformation from flood control to adaptation. Many levees along the Lower Green River are prone to failure as they were built in the 1970s with questionable materials and steep slopes (King County 2006); moreover, HHD’s unexpected structural impairment has proven the system unreliable. If Kent ignored this window of opportunity to become a floodable city, its economic loss from a capacity-exceeding flow would be unprecedented. According to an analysis conducted by FEMA (2009), a 498-m<sup>3</sup>/s (17,600 cfs) flow, coupled with widespread levee failures (the levee system can only contain flows up to 362 m<sup>3</sup>/s at the Auburn river gage), is projected to cost the city \$2.24 billion in building-related losses (Figure 3-5). The actual damage could be more severe because the estimate does not take into account the higher flow velocity associated with levee failure (FEMA 2009).



**Figure 3-5.** Kent’s economic loss by census block under a flood scenario of a 498-m<sup>3</sup>/s flow at Auburn with widespread levee failures. This is one of the three scenarios, under which FEMA (2009) estimates the economic loss of the entire Lowe Green River valley in the wake of HHD’s disrepair in 2009. This scenario generates the highest economic loss. In the flood scenario Kent would suffer an economic loss of \$2,239,474,000, which includes damages to building structures, contents, inventories, as well as consequential business interruption such as income, wage, rental income, and relocation.

Consider a management scenario of flood adaptation, where most levees are removed and the built environment retrofitted to at least fit for the 498-m<sup>3</sup>/s flood. That is, most buildings are elevated, wet-proofed, or floatable for at least 2 m above ground (Figure 3-6); all open spaces multifunctional; and public and private waterborne transportation systems and temporarily elevated pedestrian walkways available. By making itself floodable Kent could avoid billions of dollars of flood losses.



**Figure 3-6.** Without levees, most areas would be under less than 2 m of floodwater, given a 498-m<sup>3</sup>/s flow at Auburn. This means most buildings (5,732 out of 6,972 buildings on the floodplain) would not be damaged if they were elevated, wet-proofed, or floatable for more than 2 m above ground, although 321 buildings would need to go higher. The flood depth is based on the simulated flood depth grids used in FEMA (2009).

While floodable cities may experience more frequent flooding and in some cases deeper floodwater without a levee system to contain some flow if not breached, flooding is largely benign and flood depth no longer dictates the damage. Furthermore, the threat of flash floods triggered by levee and dam failures no longer exists. Flood adaptation can simultaneously address interior flooding, which is caused by local groundwater seepage, direct precipitation, and inflow of stormwater runoff generated upland (Mertes 2000). Such flooding, often aggravated by the corresponding high flow in the Lower Green River that prevents drainage, frequently causes road closures in Kent (City of Kent 2004a).

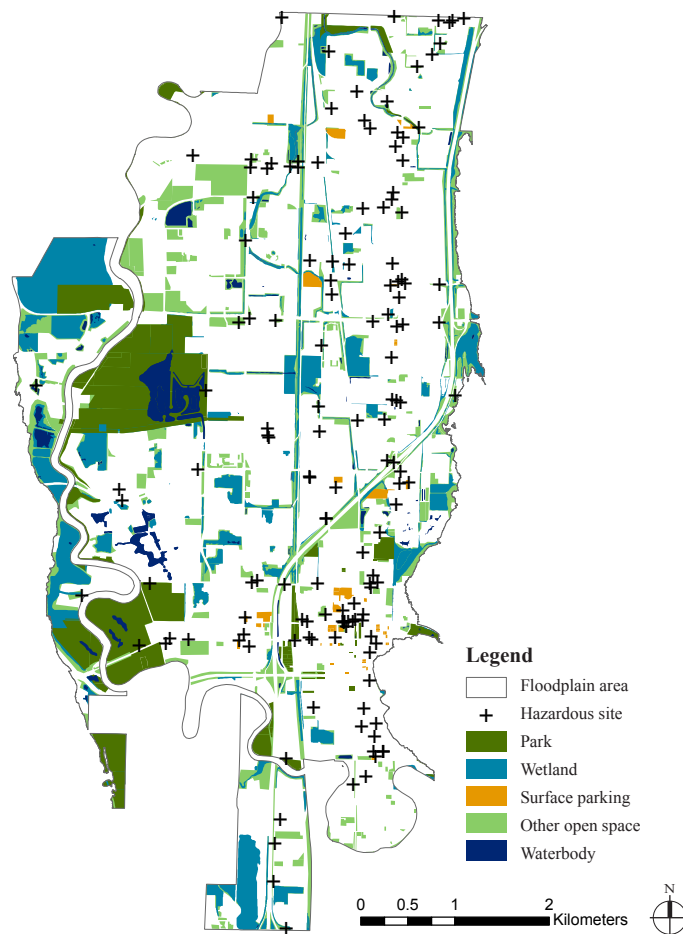
If Kent continues to rely on flood control, current and future economic risk will likely increase. More properties would be damaged, as the city is expected to add about 26,000 households and 35,000 jobs between 2006 and 2031, a portion of which is directed to the floodplain. In addition, climate change will increase flood risk in the Green/Duwamish River basin, as the increasingly higher average temperature implies more winter precipitation will come as rain rather than snow, which is projected to decrease by 57% in the 2020's and disappear by the 2080s (Elsner et al. 2010). While decreasing snowmelt will diminish peak flows during the spring, winter flood risk will intensify (Mantua et al. 2010). The uncertainty involving in climate projections will make flood control increasingly difficult.

While flood adaptation cannot guarantee complete safety either, it would better prepare the city for rare, larger floods by allowing the city to periodically experience smaller ones, because such experiences could foster a better understanding of river dynamics, thus promoting flood awareness. The transition from a resistant to resilient city takes time, during which some control is still necessary for flood safety. The interim control can be carried out by rearranging levees to direct floodwater to available floodable lands, i.e., controlled flooding, to prevent inundation in areas not yet floodable (Kijn et al. 2004). The controlled floods could be utilized as public educational events to learn about a different paradigm of flood hazard management and about the ecological importance of floods.

### **Inevitable Flood Control and Necessary Flood Retention**

In the long-term while adaptation is more reliable for flood safety, it may still be necessary to control flooding in some areas because of the legacy of past human activities that leave contamination, as demonstrated by the numerous hazardous sites on Kent's floodplain (Figure 3-3). Flooding needs to be prevented around hazardous sites because the remediation effort may not remove toxic substances completely, and in some cases contamination is simply capped (Ian Mooser, Washington State Department of Ecology, personal communication). Historic sites may also require flood protection if the retrofit for flood adaptation would undermine the cultural values. Infrastructure that needs to locate near the river and is difficult to coexist with flooding, such as wastewater treatment or power generation facilities, would need flood protection as well. The non-floodable sites can be protected by localized measures such as flood barrier shields.

If a significant share of the floodplain is permanently non-floodable, it is even more necessary to make the rest of the floodplain floodable to retain floodwater so as to reduce flooding in non-floodable areas. Fifty-six percent (56%) of Kent's floodplain area may currently be non-floodable, assuming an average contamination extent of 0.3 km<sup>2</sup> per hazardous site. These non-floodable areas can become safer against floods if the rest 44% is made floodable. Even if architectural and infrastructural adaptations fail to occur, retrofitting the open spaces alone could help Kent achieve a floodability of 18% (Figure 3-7).



**Figure 3-7.** Existing open spaces on Kent's floodplain. The open spaces identified here are both public and private, including parks, wetlands, surface parking lots, as well as any other spaces that either are covered by vegetation or are underutilized bare grounds. These open spaces account for 29% of the floodplain area. Taking into account the hazardous sites in the vicinity (assuming an average of contamination extent of 0.3 km<sup>2</sup> for each site), the remaining open spaces that can be made floodable account for 18% of the floodplain.

The floodable open spaces can be interconnected to form a network of temporary flood storage basins to retain a significant amount of floodwater. In the case of Kent, such a network would not be difficult to establish, as many existing wetlands are already connected by a network of ditches (ICF Interational 2010). A strategic rearrangement of different types of open spaces could maximize human access. That is, more intensively used spaces such as sports fields, playgrounds, and parking lots are placed on less flooded higher grounds, while lower grounds are reserved for passive recreation.

## **ECOLOGICAL IMPLICATIONS OF FLOOD ADAPTATION**

The resilience-based flood hazard mitigation depends on flood adaptation. Instead of drastically changing the river, it strives for flood safety by working with natural flood dynamics. Doing way from flood-control infrastructure, it would free the river from the channel maintenance works, such as dredging and clearing of riparian vegetation, that periodically disturb the aquatic and riparian ecosystems and compromise restoration efforts (Hupp et al. 2009). More importantly, allowing floods to enter the floodplain reconnects the channel and floodplain, providing an opportunity to promote ecologically critical processes such as sediment deposition, erosion, seed dispersal, delivery and processing of organic matter to restore habitats (Tockner et al. 1998; Konrad et al. 2008). It could lead to improved biodiversity and enhanced ecosystem services.

### **The Importance of Floodplain Habitats**

In the Green/Duwamish basin, tremendous efforts have been invested to restore the habitats for salmonid populations, particularly the federally-listed threatened Chinook salmon (*Oncorhynchus tshawytscha*). However, flood control continues to prevent more effective restoration options (WRIA 9 Implementation Technical Committee 2012). If Kent were to replace flood-control infrastructure with floodable built environment, it could support the restoration by significantly improving the rearing habitats along the Lower Green River for juvenile Chinook.

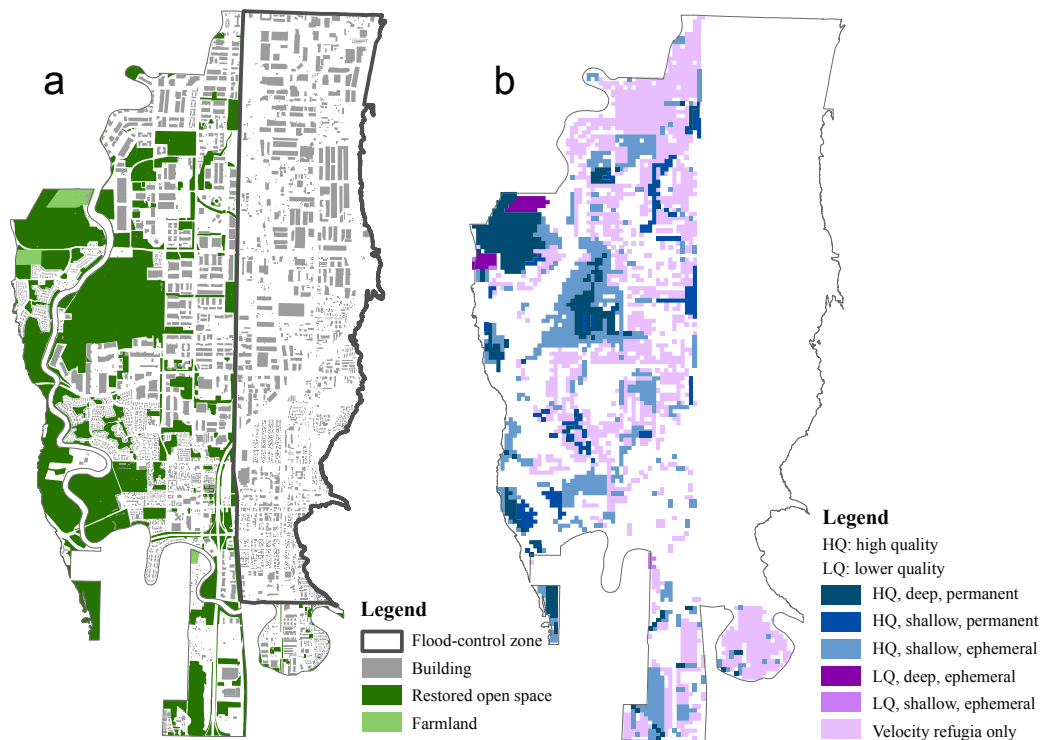
Permanent and ephemeral water bodies on floodplains such as side channels, oxbow lakes, backwater pools, and flooded wetlands are important off-channel rearing habitats for juvenile salmonids (Pess et al. 2005; Lestelle et al. 2005). They provide abundant invertebrate prey, more

stable temperature regime, shelter from predators, and low-velocity refugia from main-channel high flows (Sommer et al. 2004; Beechie et al. 2005; Morley et al. 2005; Moyle et al. 2007). During downstream migration, floodplain rearing helps juvenile Chinook grow into larger body size, which increases survivorship to adulthood after leaving freshwater (Sommer et al. 2001; Swenson et al. 2003; Jeffres et al. 2008). Flood control and floodplain development virtually prevent floodplain rearing along the freshwater Lower Green River before juvenile Chinook enter the freshwater-saltwater transition zone of the Duwamish River (Kerwin and Nelson 2000). Today juvenile Chinook spend only hours to days in the Lower Green River and may be flushed into marine water prematurely during high flows (Ruggerone and Weitkamp 2004). Restoring off-channel habitats along the Lower Green River has been identified as one of the necessary conditions for Chinook salmon recovery (Reinelt et al. 2005). Within Kent a few such projects will be implemented in the near future (Thomson et al. 2005). However, the extent of such restoration, which involves giving protected urban land back to the river, would be limited if Kent continue to depend on flood control, especially compared to the historic condition where frequent flooding created numerous wetlands and ponds throughout the floodplain (Collins and Sheikh 2005). Returning to the historic extent is impossible, but a floodable city would allow a much greater amount of off-channel habitats to exist.

### **An Adaptation Scenario with Floodplain Restoration**

Consider an adaptation scenario for Kent where the levee system and HHD are dismantled; flood safety is managed by retrofitting the built environment to fit for most floods, which enter the floodplain except the flood-control zone where most hazardous sites are concentrated (Figure 3-8a); floodwater is directed first to the interconnected open spaces before inundating buildings and roads, so while Kent is flooded frequently, flooding occurs mostly in open spaces. This means juvenile Chinook could gain access to existing wetlands and ponds. More off-channel habitats can be created within open spaces by excavating channels and ponds, planting aquatic and terrestrial native vegetation, and placing cobbles, boulders, and large woods to resemble the natural floodplain landscape (Jeanes and Hilgert 2001; Pess et al. 2005). More open entrances from the main channel can be dug out to facilitate fish access and adjustable weirs installed to enhance the hydro-period to reduce stranding when floodwater recedes (Henning et al. 2006; Ruggerone et al. 2006). These spaces would also allow spontaneous succession, erosion,

sedimentation, and debris deposition—processes accompanying flooding that periodically rework the landscape to contribute to diverse topography, high species diversity, and intensified ecological processes (Naiman et al. 2005; Geerling et al. 2006). To accommodate the structures and processes for floodplain restoration, larger open spaces can be wetlands parks or gardens and small ones vegetated swales.



**Figure 3-8.** (a) An adaptation scenario with floodplain restoration (the restoration scenario). The urbanized floodplain is retrofitted to become floodable except in the ‘flood-control zone’ in the eastern part of the floodplain where most existing hazardous sites are located, assuming that hazardous sites outside the zone would eventually be cleaned and floodable. All existing open spaces (22% of the total floodplain area) in the floodable area have undergone floodplain restoration. The ‘restored open spaces’ (including existing wetlands) are designed as wetland parks or gardens and vegetated swales. A small amount of farmlands still exist and are protected from development. (b) The distribution of off-channel habitats created by the restoration scenario during a flood of 362 m<sup>3</sup>/s. All inundated floodplain can serve for low-velocity refugia, but the restored open spaces also provide food and cover to be high-quality habitats ideal for juvenile rearing. Farmlands are not ideal but still more ecologically friendly than the area of buildings, roads, and other mostly paved area, thus are considered lower-quality habitats. Habitats with water depth lower than 2 m are regarded as shallow (Sommer et al. 2004). This map is produced based on the flood depth simulation released by the US Corps of Engineers in 2009. The inundated area and depth may be underestimated because the flood depth information used for the map does not consider the flood-control zone.

If every existing open space within the floodable zone is dedicated to floodplain restoration, along with existing wetlands it could re-create a significant amount of off-channel habitats to support juvenile rearing. Without changing the existing topography, during a frequent flood, for example, a 362 m<sup>3</sup>/s flow at Auburn gage that based on historic records would naturally occur every 2-3 years without HHD (Kerwin and Nelson 2000), 68% of these open spaces would be inundated (Figure 3-8b). Such a flood would create 456 hectares of high-quality rearing habitats, defined here as those capable of providing food and cover and functioning as low-velocity refugia (Table 3-1). The rest of the inundated floodplain, although not designed for fish, may still have some habitat value. For example, the small amount of protected farmlands may or may not provide adequate cover and food but can serve as low-velocity refugia, thus are considered lower-quality habitats. Roads, buildings, and other mostly paved areas under intense human uses, while ecologically hostile, could at least temporarily accommodate juvenile Chinook as low-velocity refugia. Given the plausible densities of juvenile Chinook in off-channel habitats, the relatively small flood of 362 m<sup>3</sup>/s could provide temporarily rearing for 462,000-2,536,440 juvenile Chinook in this ecologically ideal scenario of restoration. When the river does not flood, the 196 hectares of permanent habitats could still accommodate 196,000-1,076,040 juvenile Chinook to increase the river's rearing capacity. The methodology for estimating the rearing capacity is detailed in Appendix B.

**Table 3-1.** The temporarily increased rearing capacity for juvenile Chinook during a 362-m<sup>3</sup>/s flood in the restoration scenario.

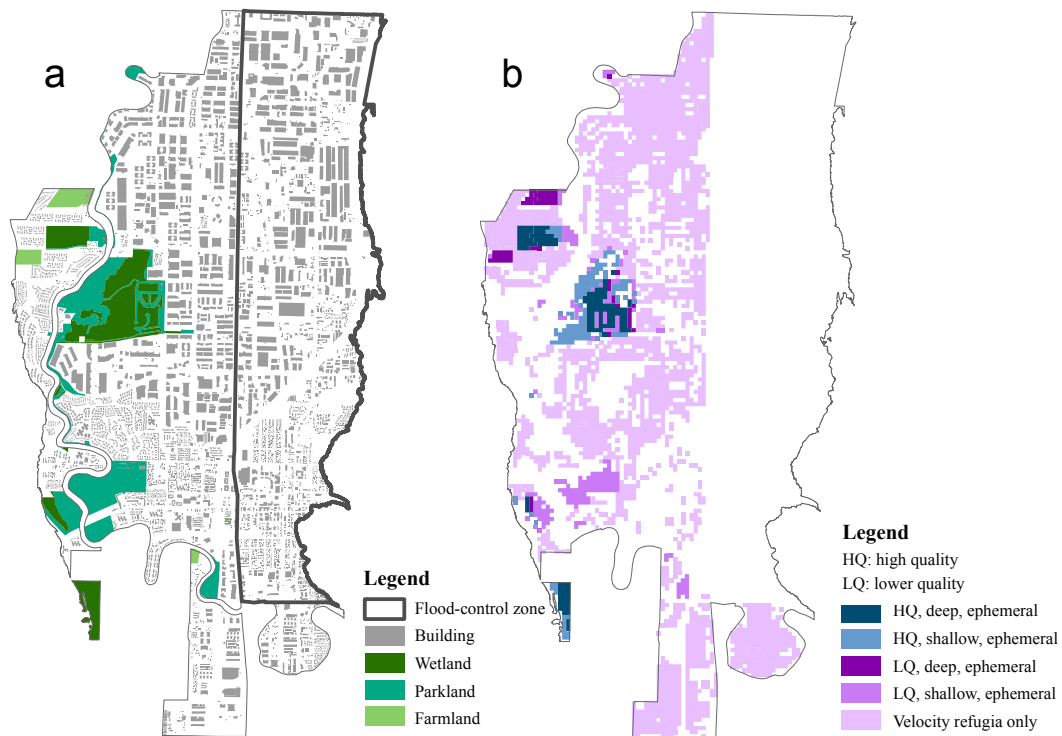
<b>Habitat Types</b>	<b>Area (hectares)</b>	<b>%</b>	<b>Chinook Density (fish/m<sup>2</sup>)</b>	<b>Rearing Capacity (number of fish)</b>
High quality				
shallow, permanent	64	56.3		
shallow, ephemeral	260	25.2	0.100 ~ 0.549	456,000 ~ 2,503,440
deep, permanent	132	12.9		
Subtotal	(456)	(44.7)		
Lower quality				
shallow, ephemeral	17	1.7	0.030 ~ 0.165	6,000 ~ 33,000
deep, ephemeral	3	0.3		
Subtotal	(20)	(2)		
Velocity refugia only	543	53.3	0	0
<b>Total</b>	<b>1019</b>	<b>100</b>		<b>462,000 ~ 2,536,440</b>

At least five life-history strategies of juvenile Chinook existed historically, only two of which (both short freshwater rearing) are common today (Ruggerone and Weitkamp 2004). The enhanced rearing capacity of the Lower Green River could potentially increase their residence time to restore the trajectories with longer freshwater rearing (Reinelt 2005). Floodplain access would also buffer against the climate change impact of more intense winter high flows by preventing juvenile Chinook from being flushed into the Duwamish estuary prematurely. Flood adaptation would also provide an opportunity to improve the riparian condition, which critically affects the quality of instream habitats (Naiman et al. 2005). About 60% of the banks of the Lower Green River—consisting of either levees or revetments—have no trees or shrubs or are covered by non-native, invasive species such as blackberry (*Rubus discolor*) and invasive knotweed (*Polygonum* spp.) (WRIA9 Implementation Technical Committee 2012). Such riparian condition means reduced food sources for juvenile Chinook as there is little input of organic matter and insects into the channel. Without trees and shrubs to shade the channel edge, it is especially lethal during summer when low flows combine with high solar loading to create intolerable water temperature (Coffin et al. 2011). Currently 67% of the levees within Kent are under such degraded condition. The removal of these levees, coupled with planting of native trees and shrubs along the banks, would address the riparian problem, which is identified as a limiting factor to salmon recovery of the Green/Duwamish River (Kerwin and Nelson 2000).

Besides Chinook salmon, the restoration scenario could also benefit other wildlife that has evolved to take advantage of floodplain habitats, such as amphibians, birds, and mammals (Swenson et al. 2003; Morris et al. 2004). Moreover, ecologically functioning floodplain and riparian systems could bring a host of ecosystem services to benefit the city directly. For example, the riparian zone and seasonally flooded wetlands would perform water purification by trapping sediments and processing diffuse nutrient pollutants brought by floods, stormwater runoff, and groundwater from upstream and upland areas (Pinay et al. 2002; Naiman et al. 2005). Floodwater stored on the pervious open spaces would recharge the floodplain aquifer. Without such a process the floodplain can undergo subsidence and the base flows of the river during the dry season would be reduced (Naiman et al. 1992; Kroes and Hupp 2010). For the Lower Green River, restoring such a process could also help lessen the climate change impact of reducing summer flows that will make fish passage increasingly difficult (Mantua et al. 2010).

### An Adaptation Scenario without Floodplain Restoration

While maximizing the area of open spaces for floodplain restoration is ecologically ideal, it would be politically difficult in cities prioritizing land development. Consider the same adaptation scenario depicted above but with a ecologically less favorable condition: Kent's floodplain becomes more developed and impervious that green open spaces only exist within the city's landuse designation of Parks and Open Space; no floodplain restoration occurs, and green spaces are designed to prioritize human activities, covered mostly by lawns and nonnative plants, except the remaining wetlands (Figure 3-9a).



**Figure 3-9.** (a) An adaptation scenario without floodplain restoration (the no-restoration scenario). Most assumptions are the same as in the restoration scenario (Figure 3-8a), except that the green open spaces are dramatically reduced and no restoration occurs. Except the remnant wetlands, the open spaces are parklands, which are landscapes covered mostly by lawns with scattered trees. (b) The distribution of off-channel habitats created by the no-restoration scenario during a flow of 362 m<sup>3</sup>/s. This map is produced based on the flood depth simulation released by the US Corps of Engineers in 2009. The inundated area and depth may be underestimated because the flood depth information used for the map does not consider the flood-control zone.

During the same flood of 362 m<sup>3</sup>/s, most inundated areas serve merely as low-velocity refugia for juvenile Chinook (Figure 3-9b). The remnant wetlands provide only 90 hectares of high-quality off-channel habitats, while the rest of the green spaces and the farmlands provide 100 hectares of lower-quality habitats (Table 3-2). In this no-restoration scenario the 362-m<sup>3</sup>/s flood could provide temporarily rearing for 114,600-629,400 juvenile Chinook. Without flooding, the 47 hectares of permanent habitats have a rearing capacity of 47,000- 258,030 juvenile Chinook.

**Table 3-2.** The temporarily increased rearing capacity for juvenile Chinook during a 362-m<sup>3</sup>/s flood in the no-restoration scenario.

<b>Habitat Types</b>	<b>Area (hectares)</b>	<b>%</b>	<b>Chinook Density (fish/m<sup>2</sup>)</b>	<b>Rearing Capacity (amount of fish)</b>
High quality				
shallow, ephemeral	43	4.2		
deep, permanent	47	4.6	0.100 ~ 0.549	90,000 ~ 494,100
Subtotal	(90)	(8.8)		
Lower quality				
shallow, ephemeral	61	6		
deep, ephemeral	21	2.1	0.030 ~ 0.165	24,600 ~ 135,300
Subtotal	(82)	(8.1)		
Velocity refugia only	847	83.1	0	0
<b>Total</b>	<b>1019</b>	<b>100</b>		<b>114,600 ~ 629,400</b>

Although the no-restoration scenario yields significantly less amount of habitats to support juvenile Chinook than the restoration scenario does, flood adaptation by itself still has ecological benefits. First, it at least opens up the floodplain as low-velocity refugia, which is significantly better for juvenile Chinook than the existing condition of almost no refugia. Second, it could improve the flow conditions of tributaries used by other salmonids, as the floodwater from the Lower Green River can frequently feed the tributaries as it historically did before flood control (Collins and Sheikh 2005). Third, it would support basin-scale river restoration by enabling the implementation of environmental flows that has become an increasingly important restoration strategy for rivers regulated by dams for water supply, hydroelectricity, and other purposes (Richter and Thomas 2007; Poff et al. 2010). If Kent had room to allow floodwater and sediment passing through the city safely, HHD could have released flows to create ecologically necessary

floods to benefit ecosystems of the more rural Middle Green River (Christopher Konrad, USGS, personal communication).

## **FLOODABLE CITIES AS COUPLED HUMAN-NATURAL SYSTEMS**

The societal attempt to control the river for flood safety has resulted in the human purpose to contradict to river health. The analysis in this paper suggests that replacing flood control with flood adaptation allows cities to reconcile flood safety with river health. The paradigm change in flood hazard mitigation would require a new understanding of the river cities as coupled human-natural systems (Liu et al. 2007). As opposed to separate systems that can be managed isolated from each other, urban rivers and floodplain urbanism are hybrid systems not controlled by nature or humans alone, and this fact need to be recognized in the management of flood safety and river health.

### **Urban Rivers as Novel Ecosystems**

Urban activities are frequently viewed as “constraints” for river restoration when a pre-development condition or more pristine river is explicitly or implicitly used as a reference. However, such a view fundamentally denies the reality that humans have been an integral part of many riverine ecosystems by shaping their forms and processes (Petts 1996). Since urban activities will continue to be a part of many rivers, a neutral attitude towards them would be more constructive than regarding them as constraining. Urban rivers should be thought of as novel ecosystems, defined as ecosystems with species compositions and relative abundances that have not occurred previously within a given biome (Hobbs et al. 2006).

As coupled human-natural systems, floodable cities are where wildlife becomes a part of the city and the built environment a part of the river during flooding. The river’s intermingling with urban activities gives rise to novel river-floodplain ecosystems. While ecologically more favorable, in the restoration scenario (Figure 3-8a) Kent’s floodplain is still heavily altered compared to the more pristine conditions, and in the foreseeable future the ecosystem of the Lower Green River will continue to lack the natural input of large woods, which is a key process that historically controlled the river dynamics (Collins et al. 2003; Collins and Sheikh 2005), since the idea of erodible forest communities would be politically unacceptable. These realities

suggests that the health of the novel river-floodplain ecosystems should not be judged against pristine conditions, including historical forms and species composition and relative abundance. Urban river health should be defined by whether the ecosystem can maintain ecosystem functions (e.g., productivity and nutrient cycling) to provide irreplaceable ecosystem goods and services (e.g., consumable fish and clean water) to support socioeconomic activities (Postel and Richter 2003; Palmer et al. 2004; Vugteveen et al. 2006).

A management implication is that healthy urban rivers can be biophysically different from their historic and rural counterparts (Graf 2001). Yet a related question remained to be answered: what criteria should be used to judge the health of novel river-floodplain ecosystems? A bottom line is that they should exhibit environmental variability rather than homogeneity and stability (Bernhardt and Palmer 2007). Since flow variability is the hallmark of the vitality of river systems, the naturalness of the flow regime should be one of the standards (Poff et al. 1997; Naiman et al. 2008). Indicators for effective river restoration exist for assessing improvement (e.g., Palmer et al. 2005); nevertheless, comprehensive criteria have yet to emerge for assessing the health of novel river-floodplain ecosystems. It will be an increasingly important agenda in the progressively urbanized world (Grimm et al. 2008).

### **River Cities as Novel Urbanism**

Viewing urban rivers as novel ecosystems of inevitable human influences is not an acceptance of all current ecosystem-degrading human activities. The concept is incomplete without a complimentary view that river cities, specifically the urbanized floodplains, are novel urbanism subject to inevitable influences of river dynamics.

The flip side of the reality that urban activities are an integral part of urban rivers is that river dynamics also participate in floodplain urbanism. It has been difficult for the public to conceive floodplains as in a state of flux because humans have dramatically altered them (Ward et al. 2002). The effectiveness of flood-control infrastructure to eliminate smaller floods gives an illusion that the floodplain is stabilized and large floods are aberrations. In reality, the protected floodplains are less stable than expected. Flooding occurs not only when the capacity of levees or dams is exceeded but also through other unexpected mechanisms, such as levee breach before

overtopping, levee seepage, and tributary backing up (Archer et al. 2006). Moreover, flooding affects the city not only by its depth but also velocity, inundation duration, and sediment content of floodwater (Zevenbergen et al. 2007). Some locations would also be affected by channel migration, which could erode lands abruptly and thereby completely change the environment.

Including flooding, river dynamics are the norm of urbanized floodplains, regardless of flood-control infrastructure that stabilizes the river in the short term. In fact, trying to suppress natural environmental dynamics often ends up with severe socioeconomic repercussions (Holling and Meffe 1996). For example, eliminating smaller floods with levees makes larger floods more disastrous through levee failures (Tobin 1995); stabilizing naturally eroding banks destabilizes the urban channel in the long term because bank erosion is a necessary process for river morphology to respond to incision and variable sediment loads to bring about channel stability (Chin 2006; Florsheim et al. 2008). This implies that floodplain urbanism cannot follow the same urban planning and design principles for environments not subject to riverine flooding. In order to be resilient, river cities need to operate differently to live with inundation, as well as gradual and sudden losses of land to the river, and it applies not only to the design and maintenance of the built environment but also to land policies and socioeconomic activities. For example, industries involving hazardous substances should not exist on the floodplain. Just like the ecologically functioning urban rivers, such resilient floodplain urbanism would be novel, the emergence of which requires pushing the boundary of current theories and practices of design and planning.

### **Barriers to Moving Towards Floodable Cities**

Moving toward floodable cities where flood safety and river health coexist will face major social challenges. First, the current flood hazard management regime that is centered on flood-control is difficult to shake, as technologies, management practices, legal frameworks, and social perceptions have coevolved to stabilize one another (Pahl-Wostl 2006). Mounting flood risk and recurrent flood catastrophes have acted to stimulate the call for stronger flood-control infrastructure; for example, Tokyo, Japan has already built earthquake-resistant “super levees” that also would not be breached. Because of the high cost and longevity of levees and dams, it would be complicated and expensive to substitute them with alternatives or to dismantle them

(Moss and Monstadt 2008). Although the control-centered flood hazard management is increasingly challenged, the associated policy communities and industries have controlled vast resources and political influence and often try to block attempts that threaten the regime (Moss and Monstadt 2008). The current flood hazard management system has fallen into a rigidity trap, where institutions are highly connected and self-reinforcing to become inflexible (Gunderson and Holling 2002).

Another challenge is to gain public support for urban floodplain restoration to improve river health. Many cities do not directly rely on local rivers for ecosystem goods and services, and levees segregating the river and the city put the river out of sight and out of mind. The lack of close interaction with the river leads to little public concern and a lack of feedback control to maintain river health (Folke 2006; Campbell and Butler 2010). Moreover, the entrenched perception towards wetlands as messy, mosquito-breeding grounds is likely to make large-scale floodplain restoration controversial.

In the short term a wholesale change from the status quo at the city scale is unlikely; nevertheless, deliberate transformational changes at smaller scales are possible (Folke et al. 2010), through implementing a number of neighborhood-scale pilot projects of flood adaptation coupled with floodplain restoration. To change the negative perception towards wetlands, restored open spaces can be designed with “cues to care,” such as neatly mowed edges, educational signage, and walkways, to satisfy the public preference for order and signify well-maintenance (Nassauer 1995; Minich 2011). These pilot projects could be the catalyst to change through initiating a social learning process (Pahl-Wostl 2006; Gunderson 2010), in which people have more opportunities to experience and observe up close the hydrologic, geomorphic, and ecologic dynamics of the river. The better appreciation of the river may eventually act as the feedback control to protect and restore the health of the entire urban river (Folke et al. 2010).

## **CONCLUDING REMARKS**

With flat terrain and easy access to the river’s ecosystem goods and services, floodplains have been attractive for human settlements throughout history. Today many urbanized floodplains are culturally, economically, and politically highly important. While it is wise to avoid further

development, urban activities will continue to exist on floodplains around the world. In the era of mounting urban populations and uncertain climate change, neither managed retreat nor flood control is a realistic solution to flood safety. The most pragmatic strategy is to be resilient to floods by adapting to them. After all, flooding is not disastrous if cities are fit for it. It also needs to be recognized that periodic floods are valuable learning opportunities for river cities to accumulate knowledge in order to cope with extreme floods and that they are also indispensable to healthy urban rivers. The benefits of a management paradigm shift from flood control to flood adaptation would be more than flood safety, and if combined with floodplain restoration, it could restore ecosystem services critical to human well-beings. Many practical and technical issues regarding the transition from flood control to flood adaptation are not explored in this paper, such as the cost of environmental retrofits and the process of dismantling levees and dams, and the research community probably will not address these issues any time soon. Nevertheless, the promise of the resilience-based flood hazard mitigation should not be dismissed. Whether modern cities can live with floods, embracing both flood safety and river health is not a question of possibility but that of choice.

## APPENDIX A: QUANTIFYING THE FLOODABILITY FOR A CITY

This appendix describes a method to quantify the floodability of the built environment of a city by measuring its Percent Floodable Area, using the City of Kent as an example. Percent Floodable Area (%FA) of a place is obtained using the following equation:

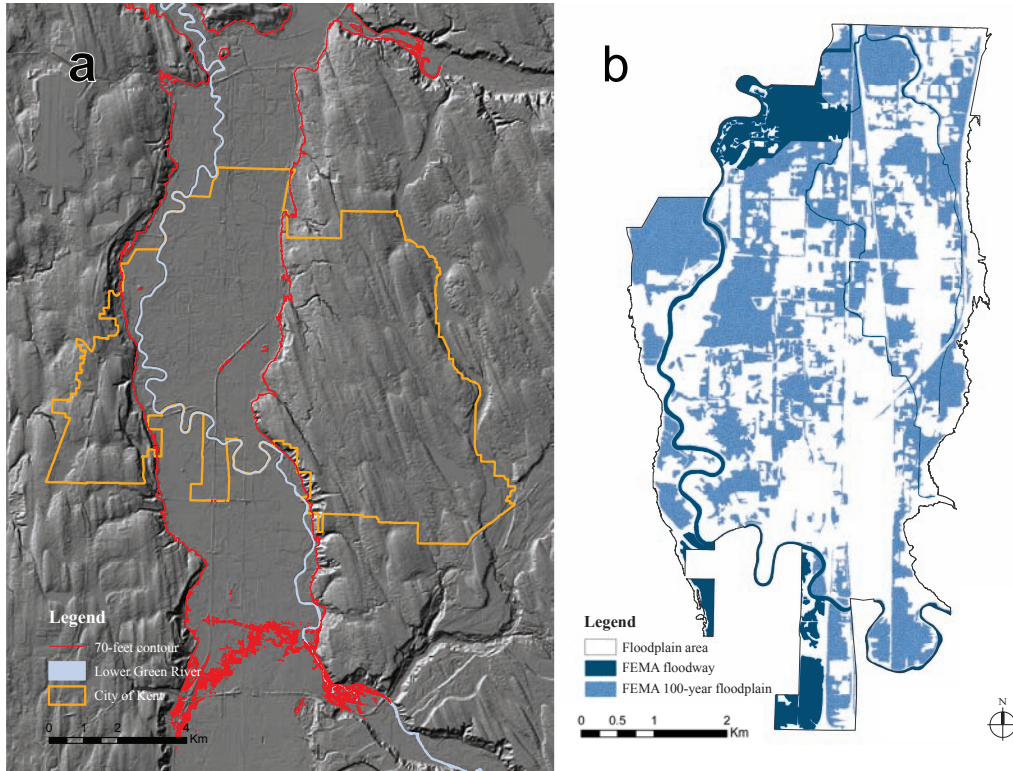
$$\%FA = \frac{\sum_{i=1}^n FL_i}{TFA}$$

$FL_i$  is the area of floodable land  $i$ .  $TFA$  is the total floodplain area. Below I explain how each element of the equation is determined.

### Total Floodplain Area

In this paper floodplain refers to the entire valley floor between valley walls (Anderson et al. 1996). The valley floor through which the Lower Green River flows is rather distinguishable. The contour line that most approximates the feet of both Kent's valley walls is used to delineate the boundary of Kent's floodplain (Figure 3A-1a). Because it encompasses the entire valley floor, the floodplain delineated here includes areas beyond the 100-year floodplain most recently defined by FEMA (Figure 3A-1b). In the calculation %FA, to account for only the land area within the floodplain boundary, major water bodies between the valley walls, including the Lower Green River between the top of the banks, major tributaries, and ponds, are excluded from the floodplain area. Kent's total floodplain area is 29.9 km<sup>2</sup>.

As other geomorphic systems, a floodplain does not have a clear-cut boundary. The floodplain area in Kent is relatively easy to determine because of the sharp change of the slope between the valley floor and the valley wall, but it may not be the case for other river cities without wall-like hill slopes. The choice of the specific contour line for defining a floodplain for a city is ultimately a judgment call of the researcher(s) that carry out the floodability assessment. It should be noted that it is not always necessary to decide on a contour line to define the floodplain. It may be possible that the entire city is clearly within a floodplain. In such cases, the total floodplain area would simply be the total area of the city.



**Figure 3A-1.** (a) Kent’s floodplain is delineated by the 21.34-m (70-foot) contour line in red. (b) The floodplain area encompasses areas beyond the 100-year floodplain defined by FEMA.

### Floodable Lands

Floodable lands are defined here as areas that store or convey water and sediments during a flood without incurring damages locally or elsewhere and interrupting socioeconomic activities. The criteria for determining whether a piece of land is floodable differ among different types of the built environments. A typical urban landscape can be simplified as composed of three major elements: (1) open spaces, including parks, civic plazas, parking lots, private yards, vacant lots, and other undeveloped or restored green spaces such as forests and wetlands; (2) roadways, including both vehicular and pedestrian; and (3) buildings.

Natural or undeveloped areas, such as wetlands, are most likely to be floodable, as flooding in these areas is harmless and even beneficial. In more intensively used urban parks and civic plazas, flooding would incur damage because the pavements, facilities, and vegetation are typically designed with little consideration of inundation, sedimentation, erosion, and debris

deposition. If an open space requires substantial resources for cleanup and repair after a flood, it is not floodable. It is worth noting that flood loss estimation, such as the HAZUS flood loss estimation model used by FEMA (Scawthorn et al. 2006), frequently ignores the damage to open spaces. It may be because the associated economic losses are relatively limited compared to those of buildings.

A roadway is floodable if the inundation of which does not impede necessary mobility that supports regular socioeconomic activities. For example, a flooded commuter thoroughfare would severely affect people's ability to go to work; however, if there are alternative routes or alternative transportation modes, such as boats or amphibious vehicles that allow traversing the flooded area, the commuter thoroughfare is considered floodable.

The land area a building sits on (i.e., the building footprint area) is considered floodable if the building is elevated, floatable, or wet-proofed because it allows for floodwater storage or conveyance without damaging the building structure and contents. Since building damage is commonly associated with flood depth (Kelman and Spence 2004), whether a building is floodable during a flood of certain magnitude depends on how high the building is elevated above the ground, how high it can float vertically, or how many floors it is wet-proofed. A threshold height is required to determine whether a building is floodable, and it would vary for buildings on different ground elevation. To avoid damage as much as possible, ideally the threshold height should exceed the highest flood depth in record or anticipated.

The floodability criteria described above suggest that most areas on the urbanized floodplains in most modern cities, such as Kent, are not floodable, as modern cities typically rely on modifying the river—as opposed to adapting the built environment—for flood safety, and frequently assume flooding as anomalous. I assume that none of the buildings on Kent's floodplain are adapted to floods, since the information on the first-floor height above grade and on flood proofing is unavailable. This assumption may not be entirely fair but not unreasonable, because according to the FEMA's (2009) HAZUS analysis for the entire Lower Green River valley, the economic losses associated with building damage in all flood scenarios are substantial. I also assume that none of the roadways can account for floodable lands, as an alternative urban

transportation system for mobility (and not for rescue and relief) during flooding is unheard of. Based on personal observations, it should also be reasonable to assume that none of the more intensively-used open spaces, including parks, sports fields, a golf course, parking lots, and residential yards, are floodable. Since most of the built environment on Kent's floodplain is not designed to be flood-tolerant, only two types of lands could be considered floodable—wetlands and vacant lots, both of which can be identified with the city's publically available GIS data.

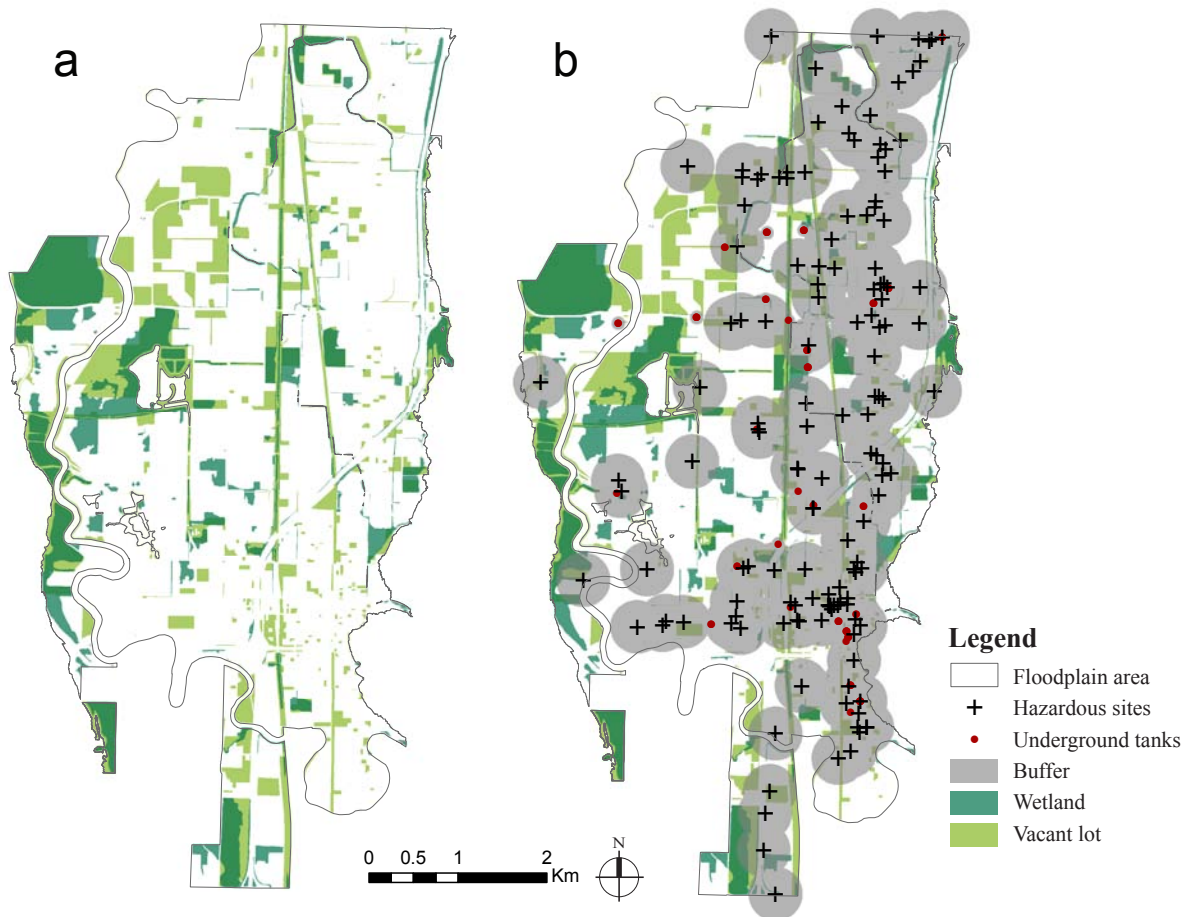
Despite intense urbanization, there are still numerous large and small remnant wetlands throughout Kent's floodplain. Vacant lots are floodable because the land has little to be damaged in the first place. They can be identified by parcels with zero improvement value, which include some wetlands. However, the zero improvement parcels also capture open spaces that are not floodable, including parks largely with manicured landscapes, parking lots, sports fields, and a golf course (the Riverbend Golf Complex). These parcels are excluded as floodable lands. Lands defined as vacant lots, wetlands, or both cover a total area of 7.78 km<sup>2</sup> to account for 26% of Kent's floodplain area (Figure 3A-2a). These lands, however, are only potentially floodable because some of them may be subject to soil contamination.

Because areas with soil contamination or underground tanks could release hazardous substance and cause groundwater pollution if flooded, they are not floodable. These areas need to be excluded from the potentially floodable lands in order to obtain the total area of floodable lands. GIS point data for the locations of hazardous sites and underground tanks on Kent's floodplain area is available from the Washington State Department of Ecology.<sup>1</sup> However, the exact geographic extents of the contamination of the hazardous sites are not mapped and in most cases difficult to know. The potentially impacted area of underground-tank leaking is also difficult to predict. The total extent of existing and potential contamination can only be roughly estimated. With an understanding that each hazardous site is unique in their nature of existing and potential contamination, I apply a buffer of 305 m (1000 feet) for each hazardous site and a buffer of 76 m (250 feet) for each underground tank site (Figure 3A-2b). The buffers are used simply for

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<sup>1</sup> Here, hazardous sites refer to those with confirmed and suspected contamination, as well as those that have been "cleaned." The "cleaned" sites are included because the toxic substances might not be removed but simply capped, and there remains a possibility that flooding could damage the engineered containment (Ian Mooser, Washington State Department of Ecology, personal communication).

estimating the total area of the existing or potential contamination associated with the hazardous sites and underground tanks on Kent's floodplain. They do not represent the actual and predicted geographic extent of contamination.



**Figure 3A-2.** (a) The potentially floodable lands consist of vacant lots and wetlands. (b) The buffers of the hazardous sites and underground tanks are used to estimate the total area of existing and potential contamination.

After subtracting the buffers from the total area of potentially floodable lands, the total area of actually floodable lands is 4.79 km<sup>2</sup>, which result in Kent's Percent Floodable Area being 16%. The number can serve as a benchmark for improving the city's floodability in the future.

## **Caveats**

It should be emphasized that the Percent Floodable Lands for any city is only a rough estimation, because there are uncertainties involved in identifying floodable land. Soil contamination, which is common in urban areas, presents a particular challenge, as shown in the case of Kent. Due to financial constraint or technical difficulty, a city may never be able to find out the existence and extent of the soil contamination on the floodplain, and the “cleanness” of a cleaned-up site can also be uncertain. Another uncertainty concerns the availability of data on the use of the land that may affect its floodability. For example, a residential parcel may be defined as floodable because the building is elevated on poles; however, it may actually be non-floodable because the owner piles rubbish or stores toxic materials on the ground. This kind of landuse information would be difficult to obtain especially for bigger cities.

It is my hope that the proposed metric of Percent Floodable Lands would inspire further discussion on the concept of floodability. The methodology presented here is a first attempt to quantify floodability—the physical fitness of the city to flooding. Kent as an example here only represents one of the many different floodplain typologies and socioeconomic conditions. It would require further analysis on various geomorphic and socioeconomic contexts of urbanized floodplains to make the methodology of floodability assessment more sophisticated and more applicable to different cities.

## **APPENDIX B: ESTIMATING FLOODPLAIN REARING CAPACITY**

The appendix describes how the floodplain rearing capacities in the two adaptation scenarios are estimated. Juvenile salmonid abundance is affected by the quantity and quality of habitats and it can be reasonably predicted by coupling the total area of habitat with habitat specific densities (Beechie et al. 1994; Roni et al. 2010). This logic is adopted here to estimate the floodplain's holding capacity of juvenile Chinook rearing in abundance. Following I explain the density information used in Table 3-1 and 3-2.

### **Ocean-type Chinook in the Green/Duwamish River basin**

Before discussing the density of juvenile Chinook, the dramatic changes of the Green/Duwamish River basin should be mentioned because it had substantially compromised the diversity the life history strategies of Chinook salmon. Historically the basin had a much larger geographic extent, encompassing the White River and Lake Washington/Cedar River, before they were diverted in 1906 and 1916 respectively (Kerwin and Nelson 2000). The basin used to support two types of Chinook—ocean-type and stream-type (Ruggerone and Weitkamp 2004). Juveniles of the former migrate to the marine water soon after emerging from the gravel, while those of the later rear in freshwater for at least a year before migrating to marine water. Today, only the ocean-type Chinook is still naturally produced (i.e., not by hatcheries) in the river (Ruggerone and Weitkamp 2004). The diversion of the rivers, particular the White River and the construction of the Tacoma Headworks and HHD (Figure 3-1), coupled with flood control, have eliminated a significant amount of the headwater and off-channel habitats typically used by the stream-type Chinook that it is believed that the naturally produced stream-type Chinook have been extirpated from the river (Grette and Salo 1986; Ruggerone and Weitkamp 2004). I assume that only naturally produced subyearling Chinook (i.e., juveniles less than one year old) would be present in the off-channel habitats on Kent' floodplain in the adaptation scenarios for two reasons. First, it is unlikely for the White River to rejoin the Lower Green River in the near future. Second, while a fish passage system has been planned in the HHD to increase Chinook habitats, it has been postulated that it would not lead to a significant increase in freshwater rearing of the juveniles (Ruggerone and Weitkamp 2004). This implies that the fish densities of off-channel habitats used here should be limited to those for subyearling Chinook.

### Applicable Density Information

Few, if any, off-channel habitats exist along the Lower Green River (Anchor Environmental 2004), and historical density data is unavailable. I thus searched for published density data from other rivers that meets the following criteria: for off-channel habitats, on freshwater floodplains, located within the Puget Sound area, and of subyearling Chinook. Such data is sparse, only two sets of which are available (Table 3B-1).

**Table 3B-1.** Applicable subyearling Chinook densities in off-channel habitats

<b>River</b>	<b>Habitat type</b>	<b>Density (fish/m<sup>2</sup>)</b>	<b>Reference</b>
Duwamish	Side-channel (re-created)	0.535	Ruggerone et al. 2006
Skagit	Backwater	0.563	Beechie et al. 2005
<b>Average</b>		<b>0.549</b>	

The density information of the Duwamish River is from the Codiga Cove at river kilometers 13.6, which is a side-channel constructed by the US Army Corps of Engineers in 2004 to provide shallow fish habitat protected from the mainstem current and is in an urban setting. The density information is converted from the data of catch per river seine that includes both natural and hatchery Chinook based on the weekly fish sampling from February 3 to July 12, 2005 (Ruggerone et al. 2006). During the time of sampling, the Codiga Cove was characterized by steep riprap banks and low-gradient bottom with some emergent vegetation and large woods (Ruggerone et al. 2006). The density of rearing juvenile Chinook vary greatly among sampled weeks because density is influenced by the different habitat needs of different life stages and are also affected by the release of hatchery Chinook (Ruggerone et al. 2006). The highest observed density—0.535 fish per square meter—is used to represent the rearing capacity of the Codiga Cove.

Chinook salmon in the Skagit River exhibit predominantly ocean-type life history. The density information of the Skagit River is the mean from 18 natural backwater sites between river kilometer 13.7 near Mount Vernon and river kilometer 137 near Marblemount (Beechie et al. 2005). Backwaters are described as partially enclosed, low-velocity areas separated from the main river channel, containing aquatic plants and wood cover (Beechie et al. 2005). Fish

sampling occurred between 1995 and 1998 from February through June and in September and October during the peaks of downstream migration of juvenile salmonids. As the data is presented in the format of relative density in Beechie et al. (2005), the mean density 0.563 fish per square meter for the backwater sites was acquired through personal communication with Tim Beechie of NOAA Fisheries.

**Plausible Densities for Kent’s Floodplain Habitats**

While the existing density information is limited, it provides a point of reference for assigning the plausible densities that Kent’s floodplain habitats might be able to support (Table 3B-2). Shown in Figure 3-8b and 3-9b, the high-quality habitats are assumed to function like natural habitats, capable of providing sufficient food and cover and can serve as low-velocity refugia. The average of the two documented densities—0.549 fish per square meter is used as the highest average density and 0.1 the lowest for the high-quality habitats (Robert J. Naiman, University of Washington, personal communication). Lower-quality habitats refer to sites that are either farmlands or parklands covered mostly by lawns and nonnative plants. These sites would provide substantially less flood and cover than high-quality habitats would, and thus are assumed to support only 30% of the densities of the high-quality habitats. ‘Velocity refugia only’ are sites that are roads, buildings, and other mostly paved areas under intense human uses, and when flooded they are generally ecologically hostile environments with little food and cover. I assume that juvenile Chinook would not voluntarily venture into these sites and stay for rearing.

**Table 3B-2.** Plausible densities for Kent’s floodplain habitats

<b>Habitats by quality</b>	<b>Plausible Density (fish/m<sup>2</sup>)</b>
High quality	0.100 ~ 0.549
Lower quality	0.030 ~ 0.165
Velocity refugia only	0

It should be noted that the estimation of the rearing capacities under the flood adaptation scenarios is crude. It does not factor in other habitat conditions, such as surface connectivity to and distance from the main channel, length of the hydro-period, dissolved oxygen, and temperature, that would affect the likelihood of juvenile use (Henning et al. 2006).

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## CONCLUSION

The built environment of the river cities, including buildings, open spaces, and infrastructure, directly mediates the interaction between humans and the river. Having chosen to construct flood-control infrastructure to eliminate periodic floods and to build the living environment without taking floodplain dynamics into account, modern cities have been having clashing relationships with their rivers. Preoccupied by the fear of the river as a source of hazards, modern cities ignore the fact that the river also represents socioeconomically valuable ecosystem goods and services (Postel and Carpenter 1997). As the problem of flood hazards is defined in isolation from other factors, the major solution—flood control—is problematic and even disastrous (Mount 1995; Tobin 1995). Flood control has made rivers more raging and cities more fragile (Zevenbergen and Gersonius 2007; Freitag et al. 2009). Because cities only know how to deal with the expected, the unexpected easily creates calamities (Colten and Sumpter 2009). As cities' suffering from floods become more catastrophic, the riverine ecosystems are afflicted by the hydrologic and geomorphic changes imposed by flood control.

To mend the violent interaction between rivers and cities, flood hazard mitigation must be approached from a complex system perspective, recognizing that river cities are coupled human-natural systems whose system-level dynamics cannot be reduced to the sum of their components, and explicitly acknowledging the dynamism and unpredictability intrinsic to such systems. The fundamental agenda lies beyond the question of how flood hazards should be dealt with, but more broadly in how cities should interact with inherently dynamic and uncertain environments in ways that promote sustainability. This research responds to this agenda with three key arguments that are re-emphasized here.

### **Key Arguments**

Building on resilience theory, the first key argument made in this research is that cities should replace flood control with flood adaptation, learning to live with the river's natural dynamics instead of trying to change them. Research into climate change suggests that the world will

become even more dynamic and uncertain (IPCC 2012). The answer to flood hazards is not adding more tools to the management toolbox, in addition to the engineering measures. It requires a fundamentally different management philosophy or theoretical underpinning that is based on a more realistic worldview that recognizes the inherent unpredictability and thus uncontrollability of nature. Chapter 2 introduces a new concept of floodability that describes a city's physical fitness for flooding. The purpose is to transform the meaning of flood safety from 'safety against floods' to 'safety at floods' and to concretize the philosophy of living with floods in cities. In modern society that has been accustomed to the management paradigm of controlling nature and comfortable with the status quo, the idea of cities living with floods seems idealistic and naïve. However, viewing from a complex system perspective it is actually conservative and pragmatic. With emergence, self-organization, nonlinearity, and unpredictability at work, any factor in a coupled human-natural system is linked with many other known and unknown ones. Through reinforcing feedback loops small changes in the system could be amplified and could generate surprising consequences, as demonstrated in Chapter 1. In the complex, uncertain world, what is idealistic and naïve is the belief in human controllability to solve problems that are in fact complex. It is rather risky to rely on flood control that subject society to flood risks that are considered negligible and thus "acceptable" because however low the risk is it still exists. It has been argued that environmental decision-making should base on assessing alternatives as opposed to acceptable risks associated with a specific solution (O'Brien 2000). An alternative for flood hazard mitigation does exist. It is to be conservative—to adapt to floodplain dynamics and changing the river as little as possible. This research thus advocates the abandonment of flood control—a paradigm shift in flood hazard management from flood control to flood adaptation.

The second key argument made in this research is that there are ways for cities to live with floods. In other words, not only is the paradigm shift theoretically necessary, it is also technically possible. To be sure, flood hazard management has been an evolving concept—new terminologies have replaced old ones to reflect new thinking. Today the term 'flood risk management' is preferred over 'flood protection' or 'flood defense' (Johnson et al. 2007). Flood defense involves using flood-control infrastructure to prevent floods up to a certain magnitude by providing a certain protection level; while flood risk management further considers the possible consequences once the flood exceeds the protection level. Flood risk management thus involves

reducing community vulnerability, on top of flood control (Meyer et al. 2009). This updated concept is more comprehensive but nevertheless still anchors to the paradigm of control, where nonstructural measures such as insurance, landuse regulation, and warning systems, albeit received more attention, are supplementary to flood control. That flood control continues to be considered imperative can be fundamentally attributed to the difficulty of the modern society to envisage how it can coexist with periodic floods. Even more challenging is to imagine how it could happen in cities when few, if any, examples exist, especially given the architectural agglomeration and complicated networks of infrastructure, on top of which prosperous economies build. Nevertheless, a paradigm shift completely away from flood control is possible. As demonstrated in Chapter 3, existing and emerging design and planning solutions for buildings, open spaces, and infrastructural systems collectively point to the plausibility of a large-scale flood adaptation of the built environment to move towards floodable cities.

The third key argument made in this research is that flood safety and river health are not tradeoffs, contrary to what is generally assumed. A solution to flood safety, the concept of floodable cities has implications to river health as well. As emphasized throughout the chapters, periodic flooding is an important natural process that sustains the functioning of river-floodplain systems, and it is not only ecologically critical but also socioeconomically meaningful (Junk et al. 1989; Tockner et al. 2008). This beneficial aspect of flooding should be acknowledged in urban policies and practices that relate to or may exert impacts on the river, particularly in flood hazard mitigation. Under the paradigm of control, the engineering measures stabilize and homogenize the biophysical environment of the riverine ecosystems, which contradicts the natural tendency of the river—variability (Huges et al. 2005; Naiman et al. 2008). To recover river health, natural variability, particular the natural flow regime that is key to ecological vitality, need to be restored (Poff et al. 2010). In cities it requires confronting flood control instead of passively considering it as a given constraint because flood-control-induced ecological degradation should not be justified. Under the paradigm of flood adaptation, the phenomenon of flooding does not necessarily mean flood damage. Chapter 3 shows that if integrated with floodplain restoration, flood adaptation has the potential to significantly improve the habitat conditions of the urban river, which in turn could restore native species as well as the ecological functions associated with ecosystem goods and services.

A corollary of the plausible reconciliation of flood safety and river health is that ecologists should not give up on urban rivers. Where most cities are located, lowland floodplains and deltas have undergone dramatic landscape changes leading to severe river degradation; yet, restoration actions often take place on headwaters and small tributaries (Pess et al. 2002; Bernhardt et al. 2005; Beechie et al. 2010). Many urban rivers are highly polluted and segregated from the everyday urban life by levees and floodwalls. Unattractive, unapproachable, and out of sight, they are often ignored, which promotes a vicious cycle—the longer the river is ignored, the more acceptable it is to be sacrificed for short-term human benefits and less possible it is to gain public support for restoration. While it is unlikely for urban rivers to be restored to the pre-urbanization conditions, without flood control it is possible to approximate natural flow regime to increase river-floodplain connectivity, geomorphic complexity, and habitat heterogeneity, which could in turn improve its biodiversity and societal value (Bernhardt and Palmer 2007; Waples et al. 2009). Flood adaptation and floodplain restoration could initiate a reinforcing feedback loop where improved appearance, access, and visibility of the river increase the public awareness of its socioeconomic benefits. This could lead to support for more restoration and prompts collective actions to counteract shortsighted human actions that degrade the river.

### **Agendas for Future Research**

Building on resilience theory and urban ecology, this research contributes to enrich the two fields by working out the application of theories that are general to specific systems—in this case, cities that are challenged by flood hazards and ecological degradation. It also contributes to advance flood hazard management by critically examining the conventional wisdom that cities cannot survive without flood control and by providing a resilience-based framework to approach flood safety. Exploring an alternative management paradigm of adaptation, this research provides an unconventional vision for floodplain urbanism. It serves as a point of departure for developing design and planning theories and practices that explicitly address the interaction between the built environment and dynamic environmental systems. Here I point out several unexplored subjects and unexamined assumptions in the three chapters for future research.

Urban resilience to floods (URF), as introduced in Chapter 2, is attributed to two capacities—flood tolerance and rapid reorganization following disruption. Because this research focuses on physical design and planning, it only explores flood tolerance of the built environment, which is linked to the concept of floodability and can be quantified by the metric of Percent Floodable Area. The URF theory would become more complete by developing the surrogate measure for another component of URF—reorganizational capacity, thereby allowing the city to assess URF more comprehensively. Developing the surrogate measure requires probing what constitutes and contributes to reorganizational capacity, which would also help advance the understanding of the relationship between floodability and reorganizational capacity. It may help answer the following important questions: does living in a floodable setting and periodically experiencing benign flooding nurture the individual and collective reorganizational capacity? How does relying on centralized flood-control infrastructure affect reorganizational capacity? The URF theory postulates that cities with localized flood-response capacity can better self-organize and thus can quickly regain order after flood disruption. Relative to flood control, flood adaptation of the built environment, particularly that of buildings at the individual lot level, distributes the flood-response capacity; therefore, the way the built environment is designed should affect reorganizational capacity, but this assumption and the involving mechanisms requires further investigation.

The argument that flood adaptation should replace flood control builds on the following line of reasoning. Flood adaptation could prevent flood damage and eliminate the threat of catastrophic structural failures that comes with flood control. Moreover, by letting periodic floods enter the city it provides opportunities for the city to learn, thereby helping build resilience. The later argument needs further research because it is only an assumption. It implicitly assumes adaptive capacity as a given—people always learn, drawing on historic experiences and making necessary adjustments in preparation for future events. Whether cities can really learn from the past is nevertheless unclear. It is argued that the human ability to learn and make adjustments distinguishes human systems from nonhuman ones (Adger 2000; Tuner et al. 2003). However, a study examining whether lessons after the 1965 Hurricane Betsy were incorporated into the preparation for Hurricane Katrina in New Orleans in 2005 finds that hazard planners seriously neglected the historical record (Colten and Sumpter 2009). The study suggests that learning from

the past is not always assured. Nevertheless, it does not imply that learning does not exist for some cities. Learning may be related to time scale, controlled by duration for which social memory is preserved (Colten and Sumpter 2009). It is thus worth addressing the question whether a city can learn better if it experiences flooding much more frequently. Answering this question can help better understand the link between flood adaptation and learning.

While this research provides both theoretical and practical supports to argue for a shift from the management paradigm of control to that of adaptation, making it politically acceptable inevitably requires a cost-benefit analysis that compares flood adaptation with flood control. The analysis should not be carried out in the conventional manner, where the cost of flood control is narrowly defined as the spending on construction, operation, and maintenance of the physical structures, ignoring all other direct and indirect costs, such as the losses of ecosystem goods and services and costs occurring elsewhere for dealing with the increased flood risks transferred by flood-control infrastructure. Similarly, the benefits of flood adaptation should not be limited to flood damage prevention and should include socioeconomic benefits, particularly that of ecosystem goods and services that are restored or preserved.

Even if the cost-benefit analysis turns out to favor flood adaptation, the paradigm shift would still not be easy. As illustrated in Chapter 1, cities dependent on flood control have put themselves into a reinforcing feedback loop—a vicious cycle, where flood control induces more floodplain development, which increases flood risk and consequentially prompts more demand for flood-control infrastructure. As the floodplain is progressively built out and the artificially-stabilized environment considered the norm, it is harder for people to imagine any other way to live safely on the floodplain but flood control. The modern society is essentially “addicted” to flood control, and it is extremely difficult to quite. This can be exemplified by the Yuba County of California, which allowed additional flood-prone development to occur in order to generate the funding for strengthening the flood-control infrastructure for existing floodplain development (Montz and Tobin 2008). The vicious cycle is well recognized today, but how to break this cycle remains a major challenge. It requires fundamentally altering the nature of the management system—a transformation (Walker et al. 2004; Gallopín 2006; Nelson et al. 2007). After decades of research into resilience, researchers now realize that navigating transformation, i.e., shifting to another regime, is as important as maintaining resilience, i.e., remaining in a regime (Folke et al.

2010). From a management standpoint, resilience is not always desirable (Walker et al. 2004). A system can be very resilient to change in an undesirable regime, such as a lake being in the degraded condition of eutrophication (Carpenter et al. 2001). The urban flood hazard management system is currently in an undesirable regime, in which flood control dominates the system, and the system is very resilient to change that it is difficult to transform and shift into a regime of adaptation. While future catastrophes may eventually force the transformation, it would be much more costly than a deliberate transformation by planning (Folke et al. 2010; Pelling and Dill 2010). However, currently we know much less about transformation than resilience (Walker et al. 2006; Pelling and Manuel-Navarrete 2011). It would be fruitful to inquire into transformability—the capacity to combine sources of experience and knowledge to navigate transition from one regime to another and develop new development trajectory to become a new system (Folke et al. 2010).

### **The Tradeoff between Instability and Stability**

Both instability and stability are important to coupled human-natural systems, which changes frequently but nevertheless persistent (Gunderson and Holling 2002). The two properties can reside simultaneously in the system, only at different scales—instability at the smaller subsystem scale helps foster overall stability at the larger system scale (Folke et al. 2010). In other words, changes through adaptation and transformation promote overall persistence of the system. Resilience is the tendency of a system to continuously change and adapt yet remain within critical thresholds to maintain identity (Walker et al. 2004; Folke et al. 2010). URF theory is thus about changeability and adaptability of the built environment, socioeconomic activities, and institutions, as much as about the city's overall persistence. This is why flood control does not contribute to resilience because it provides the city with short-term persistence, not as the city undergoes changes (being flooded) but as the city remains unchanged (floods being prevented).

The key to developing a better relationship between urbanism and the inherently dynamic environments lies in understanding the interplay and tradeoffs between instability and stability with a scale dimension. The metaphor of the sand pile in the theory of self-organized criticality can serve as a heuristic for grasping the issue. Observing a sand pile with additional sand continuously and steadily dripping onto it, Bak (1996) noticed that the same dripping action

produces both small and large avalanches, whose frequencies and magnitudes follow a power-law distribution, and he termed such a phenomenon self-organized criticality. The same distribution pattern has been observed in a range of self-organizing systems with various types of events, such as earthquakes and traffic jams, leading Bak (1996) to postulate that self-organized criticality is the underlying control of nature. While the theory is criticized as incomplete and simplistic as an all-encompassing paradigm (e.g., Levin 1999; Wu & David 2002), it nevertheless provides a different lens to understand environmental dynamics. The sand pile is particularly an insightful metaphor, if viewed from a different perspective—in the face of continuously dripping of sand as disturbances, it maintains the overall configuration by feeding off the avalanches (Levin 1999). In other words, the system maintains overall stability through minor instability, although low-frequency catastrophic events happen unavoidably.

If self-organized criticality is really at work regulating nature, it means cities must accept that both minor and major environmental fluctuations are inevitable no matter how much control human impose on nature (Bak 1996). More importantly, cities should be aware that suppressing minor instabilities can trigger major catastrophes, examples of which abound—suppressing periodic floods, localized bank failures, and small forest fires have all led to larger-scale disturbances (Holling and Meffe 1996; Fonstad and Marcus 2003). The tradeoff between minor instability and overall stability is the reality cities must face. Most modern cities have chosen to force and enjoy the short-term stability for now and to worry about the long-term consequences later, but they need to be aware of an alternative—learning to live with short-term instabilities now and never need to worry about the long-term.

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