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From flood control to flood adaptation: a case study on the Lower Green River Valley and the City of Kent in King County, Washington

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Abstract Despite massive investment in flood control infrastructure (FCI), neither cities nor rivers have been well served—flooding continues to challenge cities around the world, while riverine ecosystems are degraded by FCI. Although new flood hazard management concepts have shifted the focus away from FCI, many cities continue to count on FCI to prevent flood damage. It is assumed that existing built-up areas can only count on FCI, as large-scale retreat is often impossible. However, flood adaptation—retrofitting the built environment to prevent damage during flooding—as an option is often ignored. This paper argues against the continual use of FCI to prevent flood damage by reviewing FCI's established problems. The paper examines human–river interactions associated with FCI, focusing on the feedback mechanisms in the interactions, with a case study on the Lower Green River (LGR) valley in King County, Washington, USA. An urban ecology research model is employed to organize the case study, where interactions between floodplain urbanization, FCI, flow and sediment changes, flood risk, and riverine ecosystem are explored and two feedback mechanisms—river adjustment and flood risk perception—are explicitly addressed. The resulting complex dynamics, in terms of cross–scale interactions, emergence, nonlinearity, and surprises, are synthesized and limitations of FCI outlined. Flood adaptation is explored as a plausible alternative to flood control to nurture flood resilience. A management scenario of flood adaptation for the City of Kent—the largest municipality in the LGR valley—is developed to discuss the implications of flood adaptation on flood risk and river restoration.

Keywords City of Kent · Coupled human–natural systems · Built environment · Flood adaptation · Flood control infrastructure · Lower Green River · Urban flood management

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1 Introduction

With a faith in technology to solve water management problems (Bernhardt et al. 2006), cities in the industrialized world have responded to riverine flooding with flood control infrastructure (FCI), such as channelization, levees, and dams. While FCI can reduce flood frequency and stabilize the floodplain to allow urbanization and economic growth, its capacity is finite. Costly urban flood disasters are widespread (Zevenbergen and Gersonius 2007), indicating that cities dependent on FCI to prevent flood damage are poorly prepared for extreme floods. Meanwhile, as FCI dramatically alters natural flow regime and river morphology, it contributes to the ecological decline of urban rivers and limits the effect of ecological restoration (Nienhuis and Leuven 2001; Gurnell et al. 2007).

FCI as a dominant solution to prevent flood damage has been repeatedly criticized (e.g., White 1945; Mount 1995, Philippi 1996; Smits et al. 2006). Today, the non-structural solution of floodplain management championed by the late Gilbert F. White is widely practiced and the role of FCI in management de-emphasized. There has also been greater attention to other nonstructural measures such as flood insurance and flood warning system, and additional management concepts are exercised, such as flood risk management and integrated flood management (Smith and Ward 1998; Ashley et al. 2007). The focus away from FCI makes flood hazard mitigation and river restoration compatible—floodplain restoration has emerged as a measure to reduce downstream flood risk (Moss and Monstadt 2008), as demonstrated by the “Room for the River” and “Building with Nature” programs in the Netherlands and the “Making Space for Water” policy in England. It is also argued that agricultural land use can be compatible with periodic flooding (Opperman et al. 2009).

However, many cities continue to count on FCI to prevent flood damage (Montz and Tobin 2008), as exemplified by New Orleans’ recently upgraded FCI. It is often assumed that urbanized floodplains only have the option of either retreat or flood control to avoid flood damage (e.g., Allegata 2009). Government buyout programs do existed (Etkin 1999), and in the USA, there exist managed retreats involving multiple urban blocks, such as in Rapid City, SD (Rahn 1984); Tulsa, OK (Godschalk 2003); and Rahway, NJ (Obropta and Kellin 2007). Nevertheless, larger-scale retreats are politically difficult, socially disruptive, and thus rare, which seemingly leaves flood control as the only option. The idea that existing cities cannot live without FCI is seldom challenged, and flood adaptation—retrofitting the built environment to prevent damage during flooding—as an option is often ignored. Cities need to manage for extreme events that exceed FCI’s capacity, as flood risk is expected to increase with climate change (IPCC 2012). Cities also need to address barriers to urban river restoration, as the value of ecosystem goods and services associated with healthy rivers is increasingly recognized (Grimm et al. 2008). While the importance of non-structural measures is recognized, in practice, FCI often becomes exclusive because of its high cost (Castonguay 2007). It raises the question whether governments should continue to invest in maintaining and straightening FCI for long-term safety.

Since the continual use of FCI is a default in most cities, a critical review of various problems associated with FCI and an exploration of flood adaptation as an alternative are necessary for more informed decision-making. This paper does so with a case study on the Lower Green River (LGR) valley in King County, Washington, USA and on its largest municipality, the City of Kent (Fig. 1). With the Port of Seattle situated downstream of LGR at the mouth of Duwamish River, the LGR valley is part of a major warehouse and manufacturing center in the US. The valley epitomizes a conundrum shared by modern urban centers around the world—it is under elevated flood risk despite the extensive effort on flood control, which continues to limit river restoration in the Green/Duwamish basin (WRIA 9 Implementation Technical Committee 2012).

In the rest of the paper, I first introduce the analytical framework to examine FCI as a coupled human–natural system—where human and natural components interact reciprocally through complex feedback mechanisms (Liu et al. 2007). The human–river interaction associated with FCI in LGR valley is then examined, followed by a discussion of the complex dynamics arising from such coupling and a summery of the limitations of FCI. Building on the reviewed problems associated with FCI, flood adaptation is explored as a plausible alternative to flood control to nurture flood resilience. Lastly, I develop a management scenario of flood adaptation for Kent and discuss its implications on flood risk and river restoration.

2 The analytical framework

While exploring flood hazard management as an issue of human–river interaction is not new (e.g., Smith and Ward 1998; Parker 2000a; Wohl 2000a), the concept of coupled human–natural system provides further insights into the complex dynamics from FCI. The

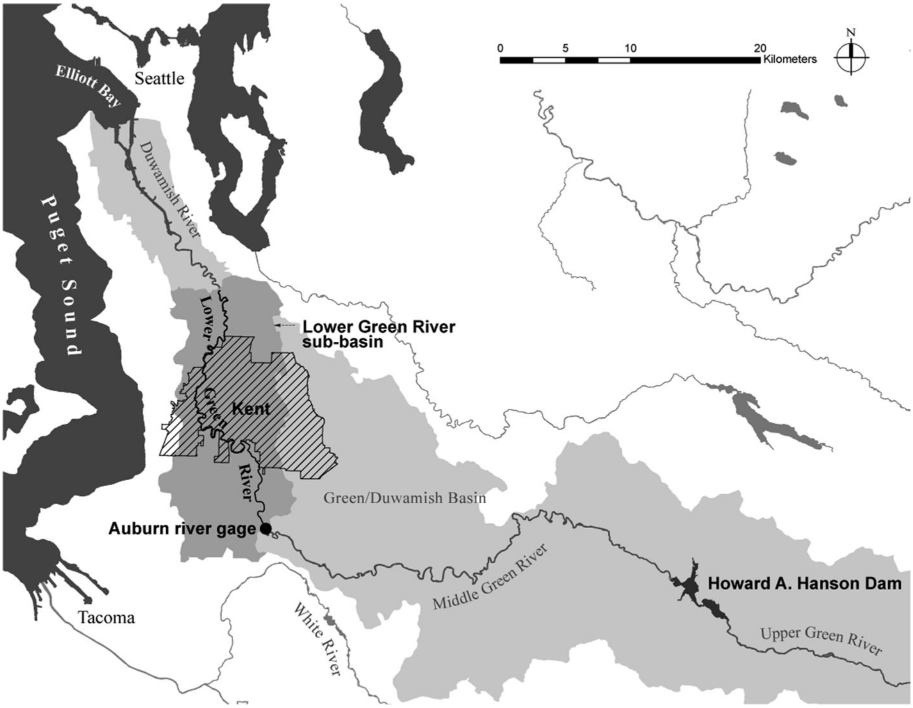

Fig. 1 The Lower Green River Valley refers to the flat terrain between the valley walls within the LGR sub-basin (*dark gray area*) of the Green/Duwamish River basin (*light gray area*). There are two dams in the Green/Duwamish River basin: the Howard A. Hanson Dam (HHD) and Tacoma Water Supply Diversion Dam (Tacoma Headworks) immediately down stream of HHD. HHD operates to prevent flows above 340 m^3/s at the USGS river gage in Auburn. The largest municipality in the valley is Kent (the *hatched area*), with a population of 92,411 in 2010. The LGR valley is also home to several other municipalities including Auburn, Renton, and Tukwila

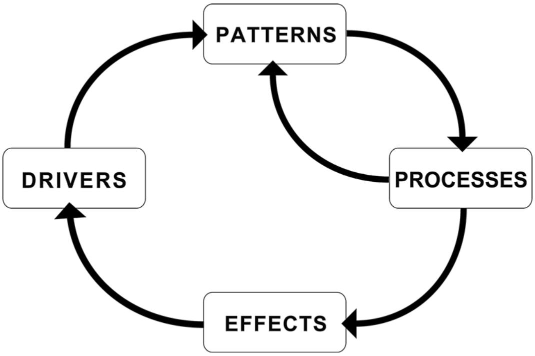

Fig. 2 Urban ecology research model developed by Alberti et al. (2003). The model is used to organize the case study because it emphasizes the linkage between patterns and processes and explicitly depicts the feedback loop. Its structural simplicity also allows easy inclusion of scale hierarchy. The model is developed 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, landuse 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

concept emphasizes the patterns and processes that link human and natural components; feedback mechanisms through which human actions both affect and are affected by natural components; and interactions across scales (Liu et al. 2007). To systematically address these aspects, an urban ecology research model developed by Alberti et al. (2003) is used as the analytical framework for the case study (Fig. 2). Recognizing that numerous factors are involved in the human–river interactions associated with FCI, this paper focuses on interactions between floodplain urbanization, FCI, flow and sediment changes, flood risk, and riverine ecosystems, with river adjustment and flood risk perception considered key feedback mechanisms in system dynamics (Fig. 3). Below I discuss these system components, and their interactions are summarized in Fig. 4.

2.1 System components

While floodplains have attracted settlers throughout history, the last two centuries have seen increasing floodplain urbanization due to population growth (Wohl 2000b). The notion that flooding is exception rather than norm justifies FCI, which is continuously in demand as a floodplain is progressively urbanized (Mount 1995; Tobin 1995). Here, FCI refers to engineering works to reduce overbank flooding. It does so most commonly through confining high flows within the channel with levees, conveying water downstream efficiently with channelization, and/or reducing high-flow discharge upstream with dams (Brookes 1988; Smith and Ward 1998). In so doing, FCI profoundly alters the natural flow and sediment regime (Petts 1984; Simon 1989; Mount 1995; Richter et al. 1996; Poff et al. 1997). It can also cause floodplain subsidence (Kroes and Hupp 2010).

The flow and sediment changes by FCI lead to hydrologic and geomorphic homogenization to severely degrade riverine ecosystems (Postel and Richter 2003). The river becomes dramatically different from its natural condition characterized by habitat

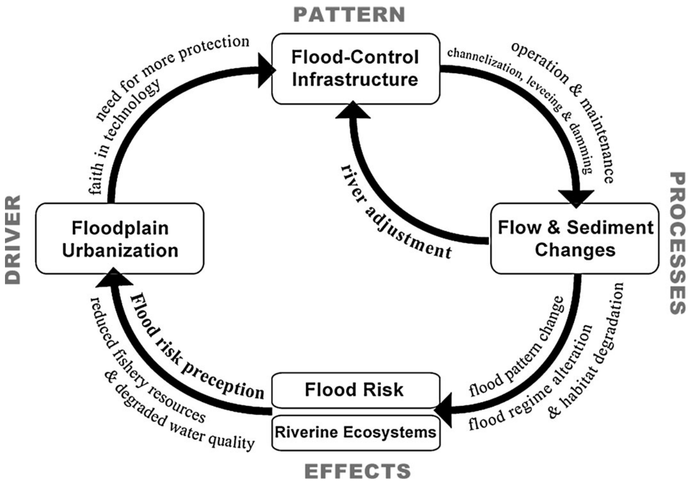

Fig. 3 The analytical framework of the case study

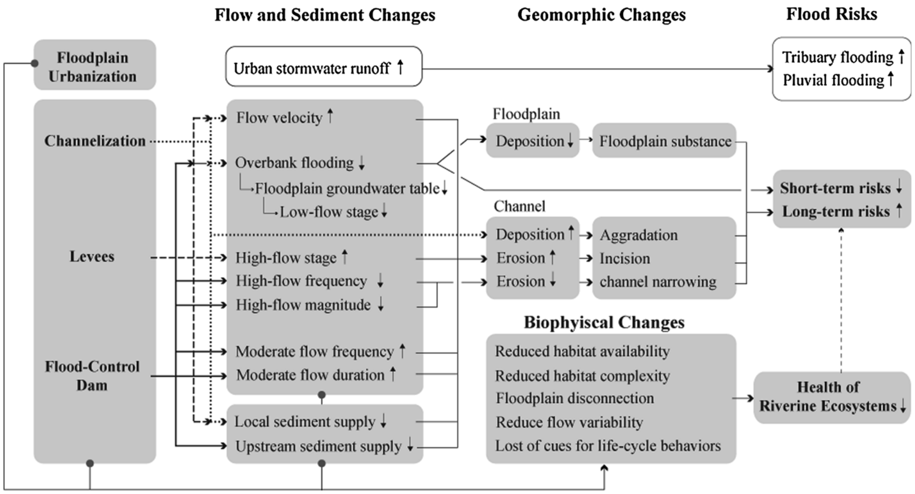

Fig. 4 A summary of the interactions between the system components in Fig. 3. The flow and sediment changes imposed by FCI (channelization, levees, and flood control dam) prompt river adjustment—further geomorphic changes—that eventually affects flood risk by changing FCI's structural integrity and capacity. Floodplain urbanization, FCI, as well as flow and sediment changes also cause direct biophysical changes to jeopardize the health of riverine ecosystems

complexity and flow variability (Tockner et al. 2008). Most destructive is the elimination of flooding—key to maintaining the ecological integrity of floodplain rivers (Ward and Standford 1995; Poff et al. 1997). In effect, FCI and floodplain urbanization create a novel environment, to which native species have little or no time to adapt (Bunn and Arthington 2002). Urban rivers are often species-poor, with degraded ecological functions to provide little ecosystem services (Grimm et al. 2008; Everard and Moggridge 2012). Degraded riverine ecosystems have socioeconomic consequences. For example, the reduced productivity of fluvial-dependent fish associated with FCI has hurt fisheries around the world

(Welcomme 2008); the natural water purification service is lost as floodplain wetlands are diminished and riparian zones degraded (Pinay et al. 2002).

2.2 Feedback mechanisms in system dynamics

As complex adaptive systems, rivers constantly adjust to changes (Lane 1955). Through river adjustment, the intended alterations by FCI inevitably cause unintended morphological changes, such as bed aggradation, bed incision, and channel narrowing (Schumm 2005). Aggradation and channel narrowing reduce channel capacity and necessitate dredging, which could be quickly offset by the adjusting river (Mount 1995). When aggradation and floodplain subsidence occur simultaneously, a small flood can trigger disproportionately large damage (Clark 1982). Incision undermines bank revetments, making them susceptible to erosion (Brookes 1988). During high flows, river adjustment is particularly intense and could bring a large amount of sediments to reduce channel capacity abruptly (Wohl 2000c; Griggs and Paris 1982); alternatively, levees could be breached and revetments destroyed, especially if the river was actively migrating before channelization (Brookes 1988). In the long term, through river adjustment, FCI can end up impacting itself and disturbing the very channel morphology it intends to maintain to affect flood risk.

Another feedback mechanism is flood risk perception. A misconception prevails that FCI eliminates flood risk, when in fact, the residual risk still exists (Hewitt and Burton 1971). Furthermore, although FCI decreases short-term flood risk, it could increase long-term flood risk because of the misconception. FCI is known to (and even built to) attract more development on the floodplain, leading to higher potential flood losses, the phenomenon of which is called levee effect or escalator effect (Parker 1995; Tobin 1995). It has been argued that increasing floodplain urbanization is most responsible for the increasing flood losses repeatedly reported over the years (Changnon 2003). Through promoting floodplain urbanization that leads to increased impervious surfaces, FCI could also indirectly increase the frequency and magnitude of tributary and pluvial flooding during localized storm events. The misconception of flood risk is essentially a false sense of security (Pielke 1999; Pinter 2005; Montz and Tobin 2008), which may be attributed to an entrenched faith in technology to control nature. As the river's high flows are mostly confined between levees or held behind the upstream dam, river dynamics are largely unnoticed and risk awareness diminished (Correia et al. 1998; Baan and Klign 2004; Siegrist and Gutscher 2008). When an extreme flood eventually overwhelms FCI, the reduced flood risk awareness could worsen the disaster.

3 The struggle for flood control and river restoration in the Lower Green River Valley

3.1 Floodplain urbanization and flood control infrastructure

Historically, LGR was the lower White River (Fig. 5) meandering through a broad, low-gradient, densely forested valley (Dunne and Dietrich 1979). The sediment-rich river made large deposition along the banks to form natural levees, making the banks 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-nineteenth century, European settlers turned floodplain forests and wetlands into farmlands, taking advantage of the rich alluvial soils while dealing with poor

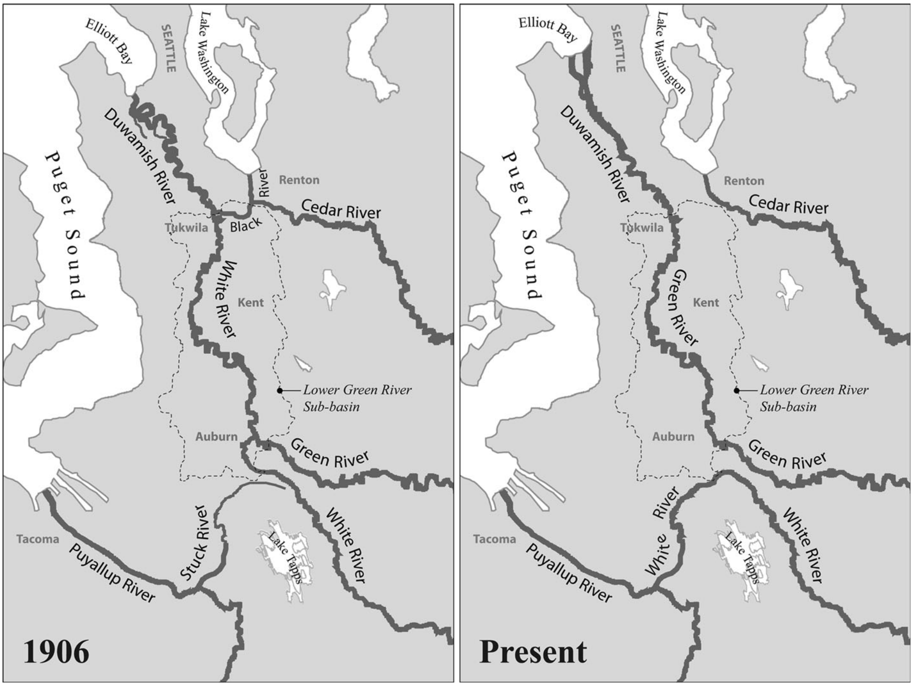

Fig. 5 LGR is the historic White River between two confluences. Near Auburn, the White River was joined by the Green River, before it was diverted during a flood in 1906. In Tukwila, the White River merged with the Black River to become the Duwamish River. Today, the Black River is only a fraction of 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 and Cedar/Black reduced the Green/Duwamish River Watershed to 30 % of its historic size (Kerwin and Nelson 2000). Adapted from Thomson et al. (2005)

drainage and flooding in localized fashions (Kerwin and Nelson 2000). A catastrophic flood in 1906 catalyzed large-scale flood control works in the twentieth century, 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 FCI protecting the valley includes virtually continuous levees and riprap revetments on both banks of LGR, as well as the Howard A. Hanson Dam (HHD) upstream (Fig. 1). 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 is expected to continue growing as it falls within the county's designated urban growth area. Between 2001 and 2005, the developed land increased from 52 to 68 % and is projected to reach 97 % in 2022 (Batker et al. 2005).

3.2 Flow and sediment changes

FCI profoundly reduces LGR's flow variability. The diversion of 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). While the river was still capable of reaching a discharge of 796 m^3/s (Dunne and Dietrich 1979), a cap of 340 m^3/s (the natural bankfull flow) has been placed at Auburn river gage (Fig. 1) since the operation of HHD. After that, only three times did the flow marginally exceed 340 m^3/s, while without HHD, it could have been 17–22 times with most flows larger than 566 m^3/s (NHC 2008; Tetra Tech 2010). Although HHD reduces flooding, it increases the frequency and duration of 340 m^3/s and other moderate flows, because following each major storm, HDD releases reservoir water at the rate of 340 m^3/s or smaller to prepare for the next storm (King County 2006). Being mainly a flood control dam, HHD also functions to augment summer low flows to mitigate the water diversions at the Tacoma Headworks (Fig. 1) to support fish spawning, using the water stored in the spring. By so doing, spring freshets are eliminated (Kerwin and Nelson 2000). FCI also reduced floodplain groundwater recharge, and the tributaries are rarely fed by the floodwater from LGR (Reinelt 2005).

Despite extensive FCI, LGR remains sinuous, unlike many other lowland urban rivers. Its overall low gradient (0.05 %), flow reduction after White River diversion, and artificial levees built upon natural levees together maintain the planform of 1906 (Reinelt 2005; Dunne and Dietrich 1979). However, LGR loses 75 % of its sediment supply after losing White River that drains the rapidly eroding volcanic terrain of Mt. Rainier (Mullineaux 1970). River adjustment is observed—the decreased input of fine sediment and gravel causes the channel to shrink by about 1/3 in width; it is further narrowed by HHD that reduces the channel-forming flow from 340 to 258 m^3/s (Dunne and Dietrich 1979). Today, the average bankfull width is 34 m, compared to 72 m in the mid-1860s (Collins and Sheikh 2005; Reinelt 2005). Meanwhile, erosion is enhanced by FCI, due to more intense stream power with the increased duration, velocity, and flow stage of moderate flows and due to reduced sediment input from upstream and from the banks (Dunne and Dietrich 1979; Kerwin and Nelson 2000). Enhanced erosion destabilizes the channel such that most reaches are subject to scour and incision, and the reaches with less bank armoring are prone to channel migration (King County 2006).

Ironically, the operation of HHD jeopardizes the levees along LGR, which were built upon old levees with questionable materials with steep slopes ranging from 1:1.5 to 1:1.75 (King County 2006). Channel scour and incision, to which HHD contributes, have undercut the steep levees and revetments during high flows. Furthermore, the rapid drawdown of water by HHD operation after a prolonged flow has resulted in levee slumping when the saturated levee experiences sudden suction of water. As such, the levee system constantly requires repair.

3.3 Heightened flood risk

Although FCI refrains LGR from overflowing, it exacerbates the interior drainage problem of the valley, frequently causing road closures in Kent (Satterstrom 1982; City of Kent 2004). Since LGR now runs bankfull more frequently and for longer periods, its tributaries back up more often to impede drainage of stormwater runoff. While there are numerous pump stations to address the problem, it remains challenging because growing urban development continues to generate more stormwater runoff. It is estimated that the increased stormwater runoff could increase the peak flows of small tributaries by over 2,000 % (Kerwin and Nelson 2000).

Rapid floodplain urbanization also leads to greater long-term risk. Today, the LGR valley sees the highest land and improvement values among King County's floodplains (King County 2006). Given that most of the valley lies below high-flow stages, if LGR were to overflow and breach levees, the damage would be unprecedented (Tetra Tech 2010). The response to this greater risk is focused on fixing the steep levees to ensure structural stability (King County 2006). A few levees were relocated landward to obtain gentler slopes; however, encroaching development prevented levee setback along most reaches, in which case, the levee toes are buttressed by rocks, but the levee is still intrinsically unstable (Tetra Tech 2010).

3.4 Degraded riverine ecosystems: declining salmonids

FCI and the urbanization of LGR valley contribute 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. HHD blocks the upstream migration of spawning salmonids (Kerwin and Nelson 2000). Juvenile salmonids are affected by the elimination of spring freshets, which serves as an important mechanism for initiating and facilitating downstream migration (Quinn 2005). 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 refugia during high flows (Pess et al. 2005). Today, these off-channel habitats are unavailable, since 87 % of the floodplain forest and 45 % of the wetlands are lost and the remaining 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 as FCI limits gravel recruitment from the floodplain. Sand and gravel bars largely disappeared and pools reduced. About 60 % of LGR’s banks 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 provides little cover and shade for fish, which is especially lethal during summer when a low flow combines with high solar loading to create intolerable water temperature (Coffin et al. 2011). It also means reduced input of organic matter and insects into the channel as food. With sparse trees, the riparian zone of LGR no longer provides instream large woods that can create pools and maintain habitat complexity (Abbe and Montgomery 1996).

Today, LGR is hostile for fish and wildlife. Juvenile Chinook move through it quickly, spending as little as several hours in winter and spring (Ruggerone and Weitkamp 2004). The ecological impacts of FCI go beyond LGR. 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). HHD also blocks upstream migration of spawning salmonids. It affects not only salmonid populations but also the entire upstream riverine ecosystem, since 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, due to the significantly reduced freshwater inflow associated with White River diversion and HHD operation (Kerwin and Nelson 2000).

3.5 A predicament

Tremendous efforts have been invested to restore salmonid populations, particularly Chinook salmon, in the Green/Duwamish basin. Sufficient off-channel habitats and healthy riparian zone along LGR are both considered necessary for the long-term viability of Chinook salmon (Reinelt 2005). The aforementioned levee setback projects have incorporated a narrow strip of low-velocity habitat on the mid-slope of the levee and large woods at the toe, and a few off-channel habitat restoration projects are underway. However, the scope of off-channel habitat restoration is limited by the requirement to protect urban land from flooding, and the maintenance of levees—involving periodic clearing of larger shrubs and trees—continues to compromise existing restoration efforts (WRIA 9 Implementation Technical Committee 2012).

Compromising salmon recovery, FCI nevertheless may not deliver long-term flood safety. The current focus on the levee system's structural stability is based on the premise that HHD will continue to regulate flows as designed (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 significant reduction in HHD's storage capacity to avoid a bigger disaster caused by structural failure. It implied that LGR could experience a flow >340 m^3/s (Tetra Tech 2010). The impaired HHD triggered a major crisis for the LGR valley. It is estimated that a 498 m^3/s flow combined with extensive levee failures could result in $3.75 billion of economic losses and 21,000 people displaced (FEMA 2009). The full capacity of HHD has been restored, but the crisis revealed the vulnerability of LGR valley that relies heavily on FCI to prevent flood damage.

4 Complex dynamics in human–river interactions

The case study of LGR valley illustrates that when the two feedback mechanisms—river adjustment and the misconception of flood risk—are at work, FCI leads to a vicious cycle that produces a greater disaster waiting to happen while compromising river health. Such a situation might not be universally shared, because river adjustment might not always work to jeopardize FCI and the levee effect might not exist. Furthermore, non-structural measures such as landuse regulation, building codes, buyout programs, and emergency training might exist to reduce flood damage. Nevertheless, the system dynamics, which are complex in nature documented in existing literature (Fig. 4) and seen in LGR valley, which are complex in nature still raise the question whether FCI-protected cities should continue to rely on FCI. In this section, I discuss the complex dynamics in the human–river interactions associated with FCI, in terms of emergence, cross–scale interactions, nonlinearity, and surprises, which are also characteristic to other coupled human–natural systems (Liu et al. 2007).

4.1 Emergence

Emergent properties are those not dictated by human or natural components separately but by their interactions (Liu et al. 2007). A prime example is FCI's performance against a flood. It is not determined by the design standard alone, as often expected, but by the interaction between FCI and geomorphic processes through river adjustment, which can be affected by other human and natural processes occurring in the past or elsewhere. That LGR valley suddenly faced a flood risk crisis in 2009 is a case in point. It reveals that HHD's protection is not dictated solely by engineering design but also by the storm that unexpectedly impaired the structure.

4.2 Cross–scale interactions

Although the benefits of FCI are primarily local for the city, it creates unintended consequences far beyond the city's geographic boundary (Fig. 6). Because FCI interacts not only with local but also basin-wide flow and sediment processes, it modifies flood risk elsewhere (Etkin 1999). Levees increase the flood stages both downstream and upstream (Mount 1995; Tobin 1995). The upstream flood control dam inundates the land otherwise not subject to flooding. It can also trap sediment that would otherwise help to maintain coastal wetlands and their ability to protect coastal communities against storm surge (Day et al. 2007). On the other hand, events and processes elsewhere can also affect FCI. Any change outside the city in the drainage basin, such as upstream 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, global climate change can exert impacts on any city's FCI through changing the river's flow regime.

Similarly, the social–ecological impacts of FCI go beyond the city. The upstream flood control dam affects a significant amount of terrestrial and riparian ecosystems by unusual inundation. Anadromous fish populations around the world are threatened with extinction as dams block their upstream migration (Nilsson and Berggren 2000), as also seen in the Green/Duwamish basin. Levees and the flood control dam can shrink estuary and coastal wetlands by reducing downstream sediment input (Day et al. 2007). FCI might have another far-reaching impact—today, many costal waters suffer from eutrophication and hypoxia due to increased nitrogen loadings to rivers and estuaries (Vitousek et al. 1997), and FCI might have played a role by facilitating this situation, as dams and levees are postulated to greatly reduce nutrient processing through limiting floodplain denitrification and nitrogen detention (Gergel et al. 2005).

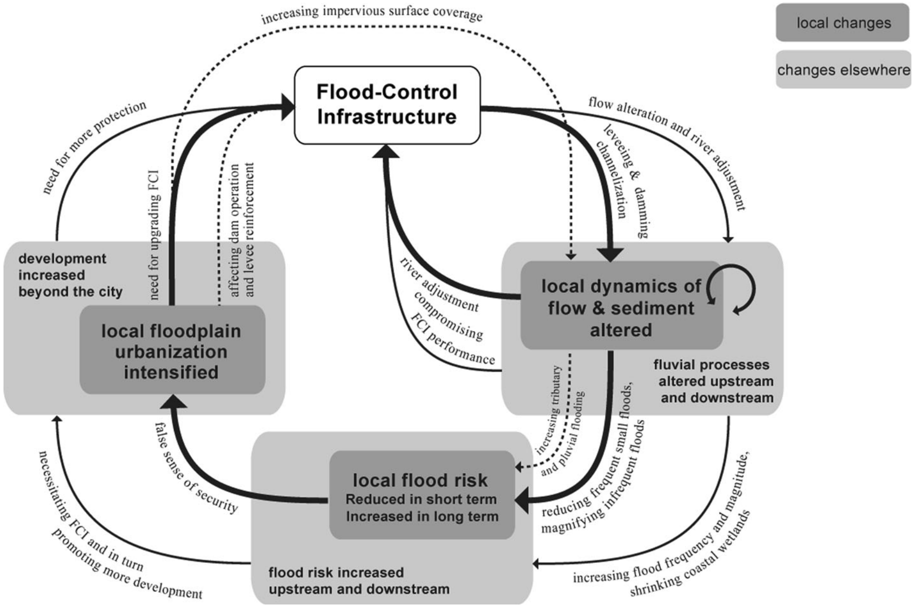

Fig. 6 Human–river interactions associated with FCI occur across space

The human–river interactions associated with FCI also occur across time, manifesting in legacy effect, i.e., what happened in the past impinges on current and future conditions (Liu et al. 2007). The legacy effect can be demonstrated by the heightened flood risk LGR valley is facing today, which is a legacy of a century's flood control endeavors. Temporal interactions also manifest in time lag. 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 delay responses (Brown 1996; Tockner et al. 2008). Time lags might also exist between ecological changes and noticeable declines on ecosystem services that impact human well-being (Palmer 2010).

4.3 Nonlinearity

Many of the relationships between the system components shown in Fig. 3 are nonlinear, and there may be thresholds—a common form of nonlinearity (Liu et al. 2007). 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 a form of nonlinearity. For example, the armored channel may appear stable for decades, giving an illusion that revetments have successfully controlled erosion; however, it might be because key hydraulic variables have not reached their thresholds (Church 2002). Storms often facilitate threshold crossing to reveal the nonlinearity. For example, despite LGR appears under control for most of the time, storms that force HHD to produce prolonged high flows combined with quick drawdown often lead to levee failures (King County 2006).

4.4 Surprises

Surprises arise when emergence, cross–scale interactions, and nonlinearity are unknown and unpredictable (Liu et al. 2007). Surprises are also products of society's overestimation of the predictability of technological–natural interactions. For example, some channelization projects are designed anticipating high flows to remove sediment accumulated in the channel, but it seldom materializes (Freitag et al. 2009). It is because the exact extent and long-term trajectory of river adjustment are often 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). Also impossible to predict is FCI's long-term ecological impacts, for ecological changes in the river are emergent phenomena that integrate many other human and natural processes, such as water pollution and climate change. Time lag may also produce ecological surprises in the future.

Research on human–natural interactions increasingly reveals that surprises are rather normal (Holling 1996; Berkes et al. 2003; Liu et al. 2007). However, when society fails to understand the complexity inherent to human–natural interactions, surprises are often mistaken as rare exceptions and received little attention in decision-making (Nelson et al. 2007). An example is the failure of FCI to prevent a flood not exceeding its design capacity due to unforeseen reasons. If FCI failure is more normal than unusual, it is dangerous to count on FCI to prevent flood damage in the first place.

5 Limitations of flood control infrastructure

The complex dynamics in human–river interactions suggest that rivers are not easily controlled. FCI is built on an invalid assumption of predictability and stationarity of river behaviors (Milly et al. 2008). It addresses only one part of flood hazard problem—the river—in isolation from other contributing and interacting factors. FCI exhibits at least the following limitations that need to be addressed by decision-makers before investing further in FCI.

First, FCI is designed with a specific capacity and is a centralized solution of large scope. Such nature makes it too rigid to quickly adjust to changing boundary conditions, such as local floodplain urbanization and upstream deforestation, which persistently make the protection level insufficient (Pahl-Wostl 2002; Jones et al. 2012). Adding to the challenge is climate change, which is expected to intensify storms whose exact nature is unpredictable (IPCC 2007).

Second, the efficacy of FCI depends heavily on unreliable factors. One example is the long-term commitment of periodic maintenance to counter undesirable river adjustment that compromises FCI's capacity and structural integrity. The cost of maintenance frequently exceeds initial estimate due to unexpected, emergent problems (Smits et al. 2006). Dredging, particularly, is often too expensive to be implemented as frequently as needed (Mount 1995). Another example of unreliable factor is the flawless operation that is required for a flood control dam to be effective—inappropriate operation would make a flood more disastrous (Williams 1998). Such a system design, which counts on system elements to perform perfectly, works poorly to deliver long-term flood safety.

Third, FCI produces social injustice by forcing its costs onto other communities (Smith and Ward 1998). The degradation of local riverine ecosystems attributed to FCI can have little impact on the associated city, since cities typically exploit biological productivity and freshwater elsewhere (Folke et al. 1997). However, rural communities upstream and downstream can be impacted if they depend heavily on the river for livelihoods. These communities can also suffer from increased flood risk transferred by FCI. In many cases, rural communities are often sacrificed during extreme basin-wide flood events, strategically flooded to avoid inundation of economically and politically more important cities. It was seen in 2011 in the floods of Mississippi River in the USA and Chao Phraya River in Thailand.

Fourth, even if the levee effect does not exist, FCI can still worsen long-term flood risk through structural failure when the capacity of FCI is eventually overwhelmed. Levee or dam breach would cause water and sediment to plunge onto the urbanized floodplain at high velocity to leave little or no evacuation time. Once it occurs, other intact levees would complicate drainage and prolong inundation to exacerbate the disaster (Colten and Sumpter 2009). Structural failure is less predictable and more damaging than naturally slow-rising floodwater, impacting more people in a single instance (Burton et al. 1993; Ashley and Ashley 2008).

Last but not least, FCI's very function—preventing periodic flooding—exerts significant ecological impacts. The idea that ecological impacts and flood safety are tradeoffs has justified the management practice that prioritizes flood control over ecological conservation and restoration. As the socioeconomic value of ecosystem services of urban rivers are increasingly recognized (Grimm et al. 2008), it is questionable whether sacrificing river health for only short-term protection is sensible. In wealthier cities, while the ecological decline associated FCI do not seem to limit urban development, the long-term socioeconomic impacts associated with the ecological decline remains to be seen. In low-income urban communities where the less privileged still depend on the river for fishery and water supply, the ecological impacts should be a serious concern. In both cases, society should recognize that flooding is not merely a hazard but also critical mechanism to maintain socioeconomically valuable ecosystem services (Postel and Richter 2003; Tockner et al. 2008).

6 Plausible alternative: flood adaptation for flood resilience

Coupling with ever-changing local, basin, and global conditions, rivers will continue to change by interacting human and natural processes to make flood control difficult. It is risky for cities to continue to count on FCI to prevent flood damage. Resilience—the capacity to cope with whatever the future brings—is the best policy to survive in a stochastic world (Gunderson and Holling 2002; Berkes 2007). Scholars increasingly advocate resilience to be the focus of flood hazard management (Adger et al. 2005; Freitag et al. 2009; Zevenbergen et al. 2011; Liao 2012).

6.1 Flood resilience

Resilience is defined as the ability of a system to maintain its essential functions, structures, feedbacks, and identity while undergoing changes (Walker et al. 2004). Resilience of a community to hazards is the capacity to absorb hazard impacts and to reorganize if disrupted (Adger et al. 2005; Berkes 2007). Resilience of a community to floods, referred as flood resilience here, can thus be interpreted as the capacity to tolerate flooding, and in the case where physical damage and socioeconomic disruption occur, the capacity to reorganize (Liao 2012). Flood resilience is not about flood prevention but concerns survival through flooding. Tolerance of flooding is thus important to prevent flood damage in the first place, and it depends on whether the city is adapted to floods.

The assertion that FCI is indispensible to cities is to assume that flooding equals disaster. It is not always valid. In tropical regions, there exist communities that live with floods, functioning normally through periodic flooding and even harnessing the ecological benefits of it (Cuny 1991; Laituri 2000). They exemplify flood resilience as they are adapted to floods. As an approach to flood safety, flood adaptation is fundamentally different from flood control—the former addresses the human community, and the later confronts the river.

In practice, flood control and flood adaptation can both be implemented to prevent flood damage, as Yokohama, Japan, has done (Nakao and Tanimoto 1997). However, flood control may compromise flood resilience (Holling and Meffe 1996; Liao 2012). Research on ecological and social–ecological systems indicates that artificially suppressing the inherent disturbance of the system erodes its resilience and leads to system collapse (Holling and Meffe 1996; Folke et al. 2002). It is because resilience to a disturbance is cultivated through learning from and adapting to that very same disturbance over time (Holling 1973; Gunderson and Holling 2002; Berkes et al. 2003; Gunderson 2010). This implies that resilience to infrequent, larger floods requires episodic learning from frequent, smaller ones; by preventing such learning, flood control compromises resilience (Liao 2012). While this theory needs to be substantiated by empirical studies, it agrees with the argument that FCI contributes to a lack of flood awareness and a false sense of security to increase long-term flood risk (Pielke 1999; Correia et al. 1998).

6.2 Environmental design strategies of flood adaptation

How the built environment—buildings, infrastructure, and open spaces—is designed determined whether a city would be damaged and disrupted in the first place during a flood. Here, I discuss plausible design strategies to adapt the urban built environment to floods.

6.2.1 Buildings

Architectural adaptation has existed for centuries, yet largely abandoned in modern society. Some traditional strategies are still kept in the modern concept of flood proofing (Parker 2000b). Flood proofing involves permanent or emergency techniques to prevent or minimize floodwater damage to the building (NHRAIC 1992). Techniques such as building on fills and flood barrier shields simply push floodwater elsewhere. Techniques allowing floodwater to enter the structure without damaging it are more socially responsible. These include building with pilotis or on buoyant foundation; using water-resistant building materials and water-tight seals to resist moisture and mold; and flexible uses of the lower floors (Guikema 2009; Zevenbergen et al. 2011). Piloti buildings have been promoted in Yokohama, Japan. Buoyant buildings or "amphibian houses"—which sit on dry land but can float vertically during flooding—have been built in Maasbommel, the Netherlands.

6.2.2 Infrastructure

There is no shortage of discussion on preventing infrastructure from failing by a flood; however, most focus on flood protection (e.g., Bosher 2009), as opposed to making it flood-tolerant. Modern infrastructure is often characterized by rigid structures and operational schemes that they cannot respond quickly to disturbances (Hallegatte 2009). One strategy of flood adaptation is to break the system into a collection of diverse functional elements with redundancy and flexible operation (Fiering 1982). Take the transportation system for example. Flooding would not disrupt mobility if the transportation system does not depend solely on roadways and vehicles. The transportation system could be "amphibious," incorporating both land-based and waterborne transportation modes that can be easily switched back and forth. Within a community, mobility could be maintained simply by putting up temporarily raised walkways, as is practiced in Venice, Italy. Flood adaptation of infrastructure may not require advanced technology but requires redesigning it at the system level.

6.2.3 Open spaces

While in the short term it is politically difficult to adapt buildings and infrastructure to floods, it should be relatively easy to do so with open spaces. It is increasingly common to direct excess floodwater/stormwater to green spaces to prevent buildings and infrastructure from flooding. In many urban communities in the USA and Europe, the sunken grassy areas between buildings also function for temporary stormwater retention. Some cities set aside large green areas to convey floodwater during emergency conditions, such as the 12-km Indian Bend Greenbelt in Scottsdale, Arizona, US, and the 324-ha Erchong Flood Spillway Park in Taipei, Taiwan. Such areas are called "green rivers" in Europe, emphasizing the multiple roles as a green space and a river (Vis et al. 2003). There are also urban parks designed as wetlands or floodplains to allow periodic flooding, such as the Yonging River Park in Taizhou, China, and the Bishan-Ang Mo Kio Park in Singapore. Responding to increasing urban flood risk, there is also an emerging trend to incorporate floodwater detention function into non-green open spaces. For example, in Rotterdam, the Netherlands, a climate adaptation project is underway to redesign several existing squares and playgrounds into sunken “water plazas” that would temporarily store floodwater to create playful and esthetically pleasing water features.

Designed creatively, urban open spaces can function for floodwater conveyance and storage while maintaining recreational and esthetic values. These open spaces could be interconnected through surface and underground trenches to become a network to hold a significant amount of floodwater to prevent buildings and infrastructure from flooding. A strategic rearrangement of different types of open spaces could maximize human access. More intensively used spaces such as sports fields, playgrounds, and parking lots can be assigned to higher ground that floods less frequent in the network, while passive recreation can take place at lower ground that floods more often.

6.3 Toward flood-resilient cities

Modern urban districts designed to adapt to floods have emerged, such as HafenCity in Hamburg. While a modern city dependent solely on flood adaptation to prevent flood damage is unknown to the author, the aforementioned design strategies point to the possibility of adaptation at the city scale. The transition from flood control to flood adaptation—from resistance to resilience—could be realized gradually. In the transition, some degree of flood control is still necessary. The method of “controlled flooding” (Klijn et al. 2004)—strategically rearranging levees to direct floodwater to areas fit for flooding—could be instrumental. The transition is a large-scale undertaking, implying great financial investment, but it is not impossible if the enormous resources allocated for FCI could be redirected to retrofitting the built environment.

Since FCI has many limitations and is not necessarily indispensible, decision-makers should assess the feasibility of flood adaptation as an alternative. Low-lying, high-risk urban areas such as Kent in LGR valley could especially benefit from such assessment. In fact, the USA is presented with an opportunity to make such a transition, as it currently faces a nation-wide crisis of aging and deteriorating infrastructure (Powell 2010). The same opportunity exists for Kent, as the steep levees along LGR are prone to failure and constantly under repair (King County 2006).

7 A management scenario of flood adaptation for Kent

In this section, I develop a management scenario of flood adaptation for Kent’s urbanized floodplain along LGR, which accounts for more than a third of the city’s total area (Fig. 7). Kent’s floodplain is home to the city’s downtown and an industrial park of regional importance, but is at risk if a flow overwhelms the levee system that can contain flows up to 362 m^3/s. A 498 m^3/s flow, for example, could cost the city $2.24 billion in building-related loss (FEMA 2009). Such a flow could cause widespread levee failures, whose more damaging effect is not included in the estimate. Seismic damage to HHD also poses a threat of catastrophic flash flooding to the city (City of Kent 2004).

Consider a scenario The levee system and HHD are dismantled and the built environment retrofitted such that it tolerates the 498 m^3/s flood. Most buildings are elevated, wet-proofed, or buoyant for at least 2 m above ground (Fig. 8), and all open spaces function for floodwater conveyance and storage (Fig. 9). Floodwater is directed first to the network of interconnected open spaces before reaching buildings and roads, such that while Kent is flooded frequently, flooding occurs mostly in open spaces. Public and private

Fig. 7 The highly urbanized floodplain area within Kent. In this paper, a floodplain is defined as the entire area between the valley walls (Anderson et al. 1996). Kent's floodplain boundary is delineated by the 21.3-m (70-feet) *contour line*. It has an area of 31.2 km^2, about 36 % of the total area of Kent

transportation systems are amphibious, and elevated pedestrian walkways are assembled quickly right before flooding. As an industrial city, there are numerous hazardous sites across the floodplain (Fig. 9). While many hazardous sites have undergone remediation, toxic substances might not be removed completely, and in some cases, contamination is simply capped (Ian Mooser, Washington State Department of Ecology, personal communication). There is thus a "flood control zone," where most hazardous sites are concentrated (Fig. 9), and floodwater from LGR is free to enter the floodplain except the zone. Outside the zone, sites still highly contaminated are protected by localized defense measures, such as flood barrier shields. Below I discuss the implications of the management scenario on flood risk and river restoration.

7.1 Implications on flood risk

Since floodwater damage to buildings and their contents is responsible for the majority of direct flood loss in cities (Scawthorn et al. 2006), architectural adaptation would help Kent prevent most flood damage. The aforementioned building-related loss of $2.24 billion from a 498 m^3/s flow would be spared.

Without levees (if not breached) to contain some flows, Kent would experience more frequent flooding and in some cases deeper floodwater; however, flooding is largely

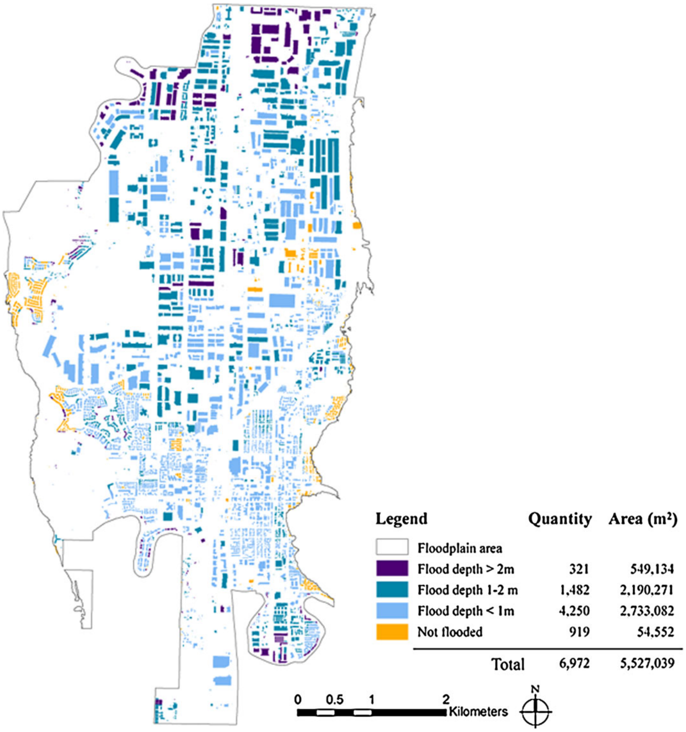

Fig. 8 Without levees, most areas on Kent's floodplain would be under <2 m of floodwater, given a 498-m^3/s flow at Auburn. This means most buildings would not be damaged if they were elevated, wet-proofed, or buoyant for more than 2 m above ground, although a few buildings would need to go higher. Flood depth is based on the simulated flood depth grids used in FEMA (2009)

benign. Furthermore, because flooding is tackled by accommodating it, flood adaptation would not transfer short-term flood risk elsewhere. Stormwater runoff is also accommodated, thereby also solving the interior drainage problem that has been plaguing Kent.

As for long-term flood risk, there would be no threat of catastrophic flash flooding triggered by levee or dam failures. Like FCI, flood adaptation cannot guarantee complete safety, but it could nurture resilience to extreme floods. Recent studies suggest that flood experience may increase risk awareness and promote preventive behavior (Siegrist and Gutscher 2008). Flood adaptation may have the same effect as it allows flooding to occur frequently; however, it requires further research to better understand the relationship between benign frequent floods and flood risk awareness. Flood adaptation may also promote episodic learning from periodic flooding. Each flood may bring something new (e.g., unexpected erosion or water level) to help the city better understand flood dynamics; if the city makes necessarily adjustment after each flood, it should be better prepared over time (Liao 2012).

7.2 Implications on river restoration

Flood adaptation could support salmon restoration in the Green/Duwamish river basin. Levee maintenance, which periodically disturbs the riparian zone, would no longer exist; moreover, the removal of levees provides an opportunity for riparian restoration. The reoccurrence of periodical flooding would give juvenile Chinook access to currently

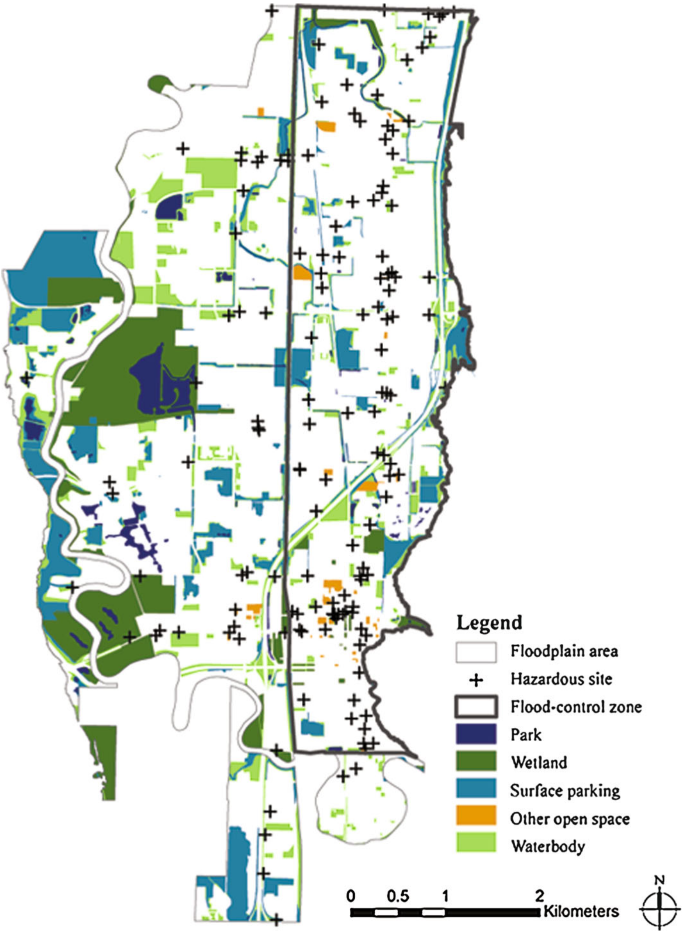

Fig. 9 Existing public and private open spaces and hazardous sites on Kent's floodplain. These open spaces account for 29 % of the floodplain area, including parks, wetlands, surface parking lots, as well as any other spaces that either are covered by vegetation or are underutilized bare grounds. In the scenario, all of these open spaces function for floodwater conveyance and storage. The Washington State Department of Ecology has identified numerous hazardous sites across the floodplain. Flooding of these sites could spread hazardous substance and thus should be prevented. In the management scenario, flood water from LGR can enter the floodplain except the "flood control zone," which is located in the eastern part of the floodplain where most existing hazardous sites are located

inaccessible floodplain wetlands and ponds. It could also enable an off-channel habitat restoration program of a much larger scale through floodplain restoration. To discuss the ecological implications of flood adaptation, below I explore two extreme cases that represent two ends of the spectrum of ecological benefits.

7.2.1 The case of large-scale floodplain restoration

Floodplain restoration refers to excavating channels and ponds, planting aquatic and terrestrial native vegetation, and placing cobbles, boulders, and large woods to resemble the natural floodplain landscape (Pess et al. 2005). Consider an ecologically preferable case, where floodplain restoration is carried out in all existing open spaces except in the flood control zone, such that they are either larger wetlands parks or smaller wetland gardens. Processes naturally accompanying flooding, such as spontaneous succession, erosion, sedimentation, and debris deposition, are allowed to occur to periodically rework the landscape. These processes are known to contribute to diverse topography, high species diversity, and intensified ecological processes in natural rivers (Naiman et al. 2005).

In this case of large-scale floodplain restoration, a significant amount of off-channel habitats can be recreated to support rearing of juvenile Chinook. During a 362-m^3/s flow—naturally occurring every 2–3 years without HHD (Kerwin and Nelson 2000)—at Auburn, a total area of 1,019 ha on the floodplain is made accessible to fish (Fig. 10). The 456 ha of inundated open spaces are high-quality rearing habitats that provide food, cover, and low-velocity refugia. The rest of the inundated area, although not designed for fish, may still have some habitat value. For example, the small amount of protected farmlands may not provide adequate cover and food but can serve as low-velocity refugia, thus are considered lower-quality habitats. Roads, buildings, and other paved areas, while ecologically hostile, could at least function temporarily as low-velocity refugia.

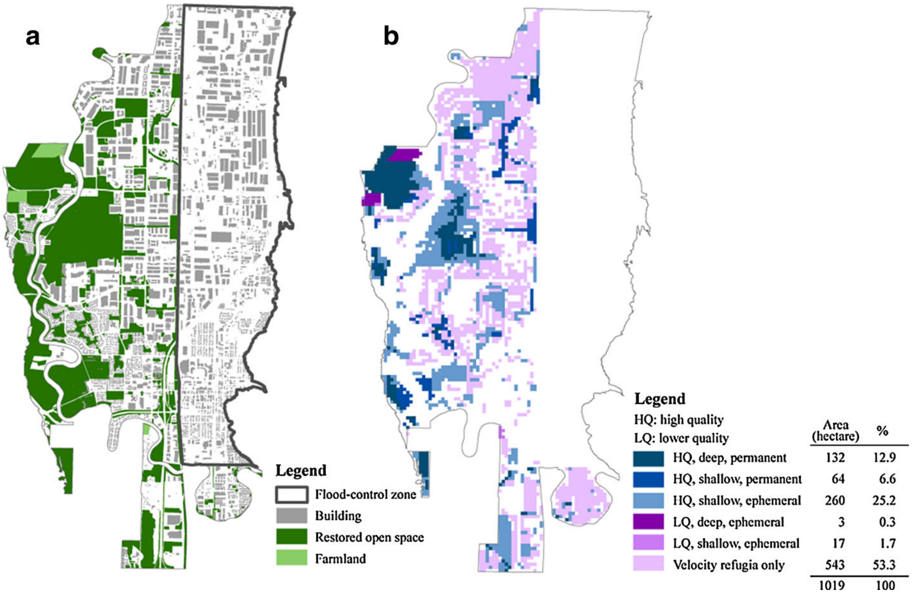

Fig. 10 **a** The case of large-scale floodplain restoration under the flood adaptation scenario. In this case, all existing open spaces—except those in the flood control zone—have undergone floodplain restoration. Including existing wetlands, these "ecologically restored open spaces" are designed as wetland parks or gardens. A small amount of farmlands still exist and are protected from development. **b** The distribution of off-channel habitats created during a flow of 362 m^3/s at Auburn. All inundated floodplain can serve for low-velocity refugia, but the ecologically 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 habitat distribution map is based on the flood depth simulation produced by the Northwest Hydraulic Consultants in 2009. It is assumed that floodplain restoration does not significantly change the existing topography. The flood depth information used here does not consider the flood control zone; therefore, the amount of off-channel habitats created could be underestimated.

Floodplain restoration could also benefit other wildlife such as amphibians, birds, and mammals (Swenson et al. 2003). The ecologically functioning floodplain and riparian zone could bring a host of ecosystem services to benefit the city directly, such as water purification through trapping sediments and processing diffuse nutrient pollutants brought by floods, stormwater runoff, and groundwater from upstream and upland areas (Pinay et al. 2002). Floodwater stored in the open spaces could restore the process of floodplain aquifer recharge to prevent subsidence. It would also ensure base flows during the dry season to help lessen the climate change impact because summer flows are expected to reduce and it could make fish passage increasingly difficult (Mantua et al. 2010).

7.2.2 The case of intensified development

While the case presented above is ecologically ideal, it may be practically unrealistic and politically difficult in Kent and most other cities. Consider an ecologically least favorable case, where no floodplain restoration occurs, and Kent's floodplain becomes more developed and impervious such that green spaces only exist within the landuse designation of Parks and Open Space; the remaining green spaces, except the existing wetlands, are designed to prioritize human activities, covered mostly by lawns and non-native plants. In this case of intensified development, the same 362-m^3/s flow would only provide 90 ha of high-quality rearing habitats that are existing wetlands, and 82 ha of lower-quality habitats on green spaces and protected farmlands (Fig. 11). Most of the inundated area serve merely as low-velocity refugia.

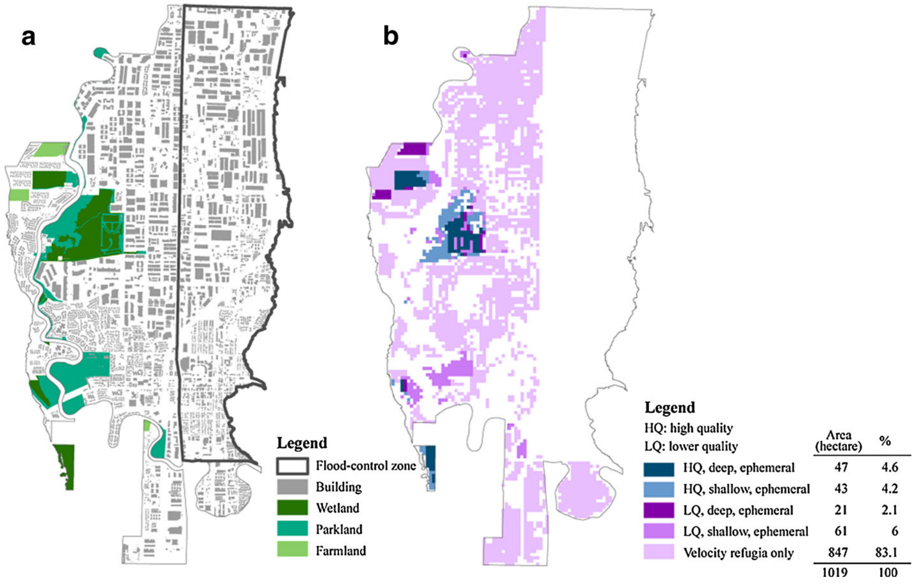

Fig. 11 **a** The case of intensified development under the flood adaptation scenario. In this case, the floodplain is more developed, and the green spaces are dramatically reduced and no restoration occurs. Except the remnant wetlands, the open spaces are all parklands, covered mostly by lawns with scattered trees. **b** The distribution of off-channel habitats created during a flow of 362 m^3/s at Auburn. This habitat distribution map is based on the flood depth simulation produced by the Northwest Hydraulic Consultants in 2009. It is assumed that existing topography remains unchanged

Although there is a much smaller amount of off-channel habitats in this case, flood adaptation would still have ecological benefits. First, it at least would open up the floodplain for juvenile Chinook as low-velocity refugia, which is significantly better than the existing condition. Second, it would improve the flow conditions of tributaries used by other salmonids, as floodwater from LGR would frequently feed the tributaries as it historically did before flood control (Collins and Sheikh 2005). Third, it would support the implementation of environmental flows, which has become an important restoration strategy for rivers regulated by dams for water supply, hydroelectricity, and other purposes (Poff et al. 2010). If Kent had room to allow floodwater and sediment to pass through the city safely, HHD could have released flows to create ecologically necessary floods to benefit the ecosystems of the more rural middle Green River (Christopher Konrad, USGS, personal communication).

8 Concluding remarks

Unprecedented amount of funding has been made available for reducing climate change impacts on the developing world; yet, most was spent on engineering interventions (Jones et al. 2012). In the developed world, although non-structural measures to flood hazard management are implemented, it is likely that FCI-protected cities will continue to invest in FCI to maintain the status quo, if not upgrading it. This paper questions the continual reliance on FCI to prevent flood damage in cities and propose a paradigm shift from flood control to flood adaptation, based on an understanding of the complex dynamics of human–river interactions arising from FCI. Because human–river interactions involve multiple factors across space and time, the decision-making in flood hazard mitigation should not based solely on simple cost-benefit analysis in isolation from other urban affairs. Social and ecological costs should be considered, and the socially and environmentally less destructive option of flood adaptation needs to be explored as an alternative. The analytical framework used in this paper (Fig. 3) can be modified to incorporate scale hierarchy to

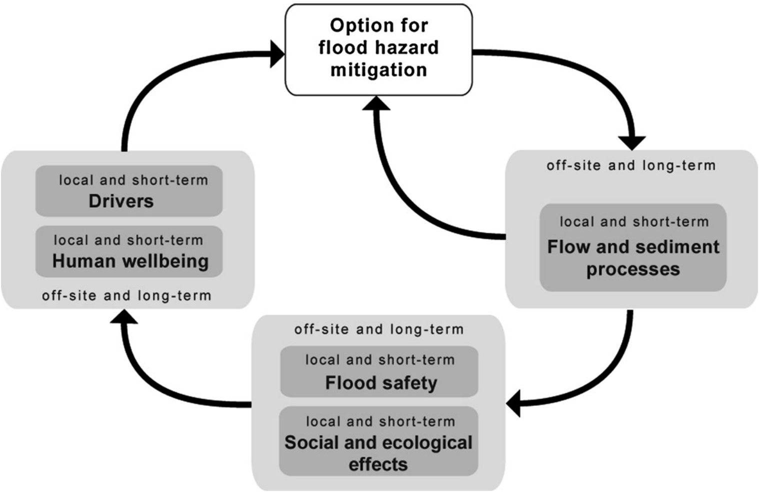

Fig. 12 An assessment framework for systematically investigating the effects of any option for flood hazard mitigation across space and time

serve as an assessment framework for evaluating effects of any option for flood hazard mitigation across space and time (Fig. 12).

This paper advocates for flood adaptation in place of flood control because of multiple problems associated with FCI. However, the theoretical argument that flood control compromises flood resilience needs further support from empirical research. And the links between flood adaptation, flood experience, flood risk awareness, learning, and resilience also need further exploration. Flood adaptation itself also requires further research. Although flood adaptation measures for modern cities receive increasing attention (e.g., Zevenbergen et al. 2011), the knowledge on flood adaptation is much less advanced compared to flood control. A topic that has not received enough attention is how to make infrastructure flood-tolerant at the system level.

Whether modern cities can live with floods to embrace both flood safety and river health is not a question of possibility but of choice. The paradigm shift from flood control to flood adaptation will meet a major social challenge—the current flood control regime is difficult to shake. The associated technologies, management practices, legal frameworks, and social perceptions have coevolved to stabilize one another (Pahl-Wostl 2006). Moreover, 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). In the short term, a wholesale change from the status quo seems unlikely. Nevertheless, deliberate transformational changes at smaller scales are possible (Folke et al. 2010), through implementing a few neighborhood-scale pilot projects of flood adaptation coupled with floodplain restoration. These pilot projects could be the catalyst to change, though initiating a social learning process (Pahl-Wostl 2006; Gunderson 2010), in which people observe up close the hydrologic, geomorphic, and ecologic dynamics of the river. The better appreciation of the river may eventually promote a perception toward floods not just as hazards but as social–ecological assets.

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