Changes in fluvial habitat conditions across a disturbance continuum: Implications for salmon restoration

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A dissertation
submitted in partial fulfillment of the
requirements for the degree of

Doctor of Philosophy

University of Washington
2013

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Abstract

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A spatially explicit watershed and riparian habitat model was developed for quantifying site characteristics of riparian habitats of the lower Cedar River, Washington. The spatial complexity and distribution of combined habitat and anthropogenic landscape features were used to define habitat “indices“ of the relative quality of riparian habitats. Patches of contiguous grid cells were measured in terms of their locations, sizes, and relative degree of fragmentation to estimate riparian restoration opportunities in the watershed. One key area was impacted by a channel-damming landslide on February 28, 2001 when a magnitude 6.8 earthquake hit the region, causing the river to occupy an existing floodplain side channel. The channel and floodplain ecosystem responded rapidly until the channel’s geomorphology settled into a short-term dynamic equilibrium according to LeChatelier’s General Law. Large trees recruited to the channel facilitated lateral channel expansion as well as bed topographic variability. One year of pre-disturbance data was compared with three years of post-disturbance data in a spatially explicit analysis of the complexity of channel form and bed surface elevations. The landslide disturbance changed reach-scale habitat conditions and distributions of sockeye salmon (*Oncorhynchus nerka*). Annual changes in river habitat conditions and spawning distributions before and after the disturbance were evaluated with an exhaustive CHAID (chi-squared automatic interaction detection model. Before the landslide, the spatial and temporal patterns of sockeye distributions were heavily influenced by spawning locations of parental generations. Sockeye densities were highest in the upper-most river reaches where anthropogenic influences were least apparent. After the landslide, habitat complexity and fish densities increased in the lower river reaches that were directly affected by the landslide disturbance. The CHAID model analyses indicate fluvial habitat complexity, river discharge characteristics, and the fish density of respective parent generations were significant ($P < 0.001$), and explained spawning distributions by reach. Analyses of how changes in habitat complexity influence salmon populations at the reach-scale, inform questions of the magnitude and intensity of disturbance necessary to restore habitat functions of river landscapes that are vital to restoring imperiled salmon populations.

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Acknowledgements

This work was funded by EPA – STAR program, Grant #R827149-01-0, the H. Mason Keeler Endowment for Excellence, and the Galen and Helen Maxfield Fisheries Scholarship. Special and profound thanks go to my major professor, Robert C. Wissmar and the rest of my dissertation committee: David A. Beauchamp, Thomas A. Leschine, Miles G. Logsdon, and David R. Montgomery. Thank you for your patience and encouragement. You all influenced my thinking during this process more than you will ever know. This work was improved greatly by rich interactions both in the lab and the field with Julie Crittenden, Michele Kohler, Josh Latterell, and many other peers and friends in the School of Aquatic and Fishery Sciences. In addition, data were provided and ideas gardened with Steve Foley (deceased) of the Washington Department of Fish and Wildlife, Hans Berge and Terry Butler of King County Department Natural Resources and Parks. Thanks also to Mason Bryant, and Jonathan Frodge who reviewed multiple versions of this dissertation and were perennial sources of encouragement. Lastly, there are those that support you and those that carry you. My mother-in-law, Bonnie Rattner is included in the latter category. Thank you Bon! This could not have happened without you.

Dedication

I lovingly and gratefully dedicate this work to my parents, Raymond Sr. and Marcia for encouraging me to wonder and for always tolerating my muddy boots and wet jeans. To my wife Laura, I know you know, there are no words equal to the task of thanking you. To my daughter Maddie, thank you for your unwavering love and patiently accepting “soon sweetie” as an answer. There is nothing beyond your grasp if you try hard enough. To the rest of my family for accepting and supporting my compunction to undertake this effort. Finally, in memory of Rickie, my stalwart field companion.

Chapter 1

Overall Introduction:

Providing for economic progress and environmental quality is the ultimate challenge of watershed management (NRC 1999). Land development is one of the most prevalent threats to freshwater biodiversity, and is among the most controllable (Vorosmarty et al., 2010). Conversion of watershed land cover and modifications to river ecosystems by flow control, levees and otherwise armored river banks, interrupts the natural dynamics of local sediment erosion and storage that result from channel-floodplain interactions and are critical habitat forming processes (Beechie et al., 2010).

In the Pacific Northwest, these types of changes in fluvial ecosystem function are implicated in the severe depletion or complete loss of salmon runs (Lackey et al., 2006). In Puget Sound, the first salmonid listings under the Endangered Species Act (ESA) occurred in 1999 (Federal Register, 2005). The listings affected the entire evolutionarily significant unit (ESU) of fall-run Chinook salmon in Puget Sound, including the run in the Cedar River. In part, these protections were implemented in response to more than a century of economic development of the land and water resources in the State of Washington that resulted in substantial loss of natural resource function (Lombard, 2006). Uncertainty over how the ESA listing would affect watershed management issues in the Cedar River, including the interplay between salmon recovery efforts and human safety and economic concerns, led to a study funded by the Environmental Protection Agency (EPA) intended to inform salmon recovery efforts throughout the region (Wissmar et al., 1998).

This dissertation grew out of a portion of that EPA-funded study. It is an interdisciplinary effort that draws from landscape ecology, fluvial geomorphology, and fisheries ecology to address the question of how the disturbance regime in the Lower Cedar River—both natural and anthropogenic—affected the spatial and temporal distribution of spawning sockeye (*Oncorhynchus nerka*) from 1952 through 2005. To answer this question, first I address the relative condition of watershed and riparian habitat quality. This analysis quantifies the composition and configuration of land cover, and summarizes it in relative quality ratings to determine restoration opportunities in the watershed. I then examine the reach-scale fluvial geomorphic response to a channel-damming landslide that occurred in one of the reaches identified as high quality riparian habitat. Lastly, I relate the spatial and temporal distributions of spawning sockeye salmon to fluvial habitat conditions, discharge characteristics, and densities of parental spawners using a multivariate tree model. This analysis is performed on pre- and post-landslide spawner distributions in four reaches of the river.

Chapter two is a geographic analysis of watershed and riparian conditions as determined by the spatial coincidence of “ecologically functional” and “socio-economic” land cover datasets. These data were used to evaluate restoration and preservation opportunities in the watershed. High quality riparian conditions were identified in the model as highest priority for preservation while those with some anthropogenic impacts were suggested locations of restoration actions. Locations in the watershed with lowest habitat values occurred in highly urbanized portions of the watershed and were generally not targeted for restoration actions. The Elliott reach was identified in the model exhibiting high riparian habitat quality. Because of the high quality habitat, this channel reach was included in channel characterization measurements that became the “pre-“ dataset used to compare the channel-floodplain geomorphic response to the landslide. This reach also happened to be the location of the landslide disturbance discussed in chapters 2 and 3.

The third chapter is an evaluation of the fluvial geomorphic consequences of the channel-damming landslide disturbance on the channel and floodplain study reach that was directly impacted by the disturbance. As a direct result of the landslide, the entire discharge of the lower Cedar River was diverted into an existing floodplain side channel. The side channel was substantially overfit and expanded laterally more than 200% to accommodate the flows. In the process, large trees were recruited to the channel, creating turbulent flow and more lateral erosion until the channel conveyance capacity was matched to the river discharge. Physical surveys were performed to measure changes in the channel geomorphology. Annual point measurements of the channel, before and after the landslide, were used to spatially interpolate estimates of sediment storage and export, physical habitat complexity, and conveyance capacity. Interannual estimates of sediment volumes were derived by subtracting serial digital elevation models (DEM) from each other. Complexity of fluvial bedforms were estimated by calculating the fractal dimension of yearly channel configurations. Fractal analyses of fluvial habitat patch types were computed by regressing the log of patch area against the log of patch perimeter (McGarigal and Marks, 1994). Significance of differences between years was determined by comparing the slopes of these regression lines using analysis of covariance (ANCOVA; Zar, 1999).

The fourth chapter is an investigation into the ways in which disturbances (natural and anthropogenic) have shaped the spatial and temporal use of four river reaches by the population of sockeye salmon that inhabits the river. Included in the analyses were spawning timing and reach selection in the lower Cedar River from 1952 – 2005. In the pre-landslide period, (1952-2000), anthropogenic impacts to channel and floodplain systems decreased habitat complexity progressively from upstream to downstream. Because the best spawning habitat existed in the upper reaches of the river, highest numbers of sockeye spawned in the upper portions of the river. On February 28, 2001, a landslide dammed the channel approximately 6km above the mouth at Lake Washington, and caused dramatic changes in habitat complexity and spawning fish distributions during the 2001-2005 period of study. Channel complexity was calculated using an area-weighted edge density estimator (McGarigal and Marks, 1994). Multivariate analyses were conducted using an exhaustive chi-squared automatic interaction detection (CHAID) tree model. Tree models iterate through input variables to find the most significant relationships with the dependent variable and results are presented in hierarchical trees (PASW, 2009). They are capable of handling unbalanced, nonparametric data and are robust to many of the problems that plague parametric statistical approaches. This makes them ideal for analyzing interactions in ecological datasets, especially those that span long time periods (Urban, 2002). The weekly total of spawning fish was summarized by reach and then related to the area weighted edge density of six fluvial habitat patch types, discharge characteristics, and the size of the parent generation in each reach.

Together the three chapters are integrated to answer the questions: (chapter 2) Are there any good places left in the watershed? Where are they? And what makes them good?; (chapter 3) What happens when channel and floodplain habitats are reconnected by removing anthropogenic constraints on the ecosystem? ; and (chapter 4), How do fluvial geomorphic responses to a relatively large natural disturbance affect fish use of the river ecosystem? By addressing these questions, this work advances understanding of process-based watershed restoration with direct implications for restoring salmon populations. Watershed conditions inform where habitat quality is favorable for riparian and fluvial restoration actions. In turn, the magnitude of the restored processes that resulted from the landslide disturbance was sufficient to affect spawning fish use of the river system. When coupled together, the three chapters presented here provide a comprehensive watershed approach to salmon restoration. Each chapter is either published or submitted for publication in the peer reviewed literature as follows:

Timm, R.K., R.C. Wissmar, J.W. Small, T.M. Leschine, and G. Lucchetti. 2004. A screening procedure for prioritizing riparian management. Environmental Management 33(1): 151-161.

Timm, R.K., and R.C. Wissmar. 2013. Response to disturbance in a highly managed alluvial river: Does it conform to LeChatlier's General Law?. Geomorphology 182: 116-124.

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Chapter 2: A Screening Procedure for Prioritizing Riparian Management

Raymond K. Timm, Robert C. Wissmar, John W. Small, Thomas M. Leschine, Gino Lucchetti

Abstract

A spatially explicit linear additive model was developed for quantifying site characteristics of riparian areas of the lower Cedar River, Washington. The spatial complexity and distribution of combined habitat and anthropogenic landscape features were used to define habitat "indices" that indicate the relative quality of riparian habitats. Patches of contiguous grid cells were measured in terms of their locations, sizes, and relative degree of fragmentation. Additionally, intra-patch heterogeneity was measured to identify unique combinations of habitat and anthropogenic factors for individual grid cells within patches. Model verification indicated that existing floodplain riparian habitats received positive indices more than 90% of the time. Mean patch sizes and fragmentation indices were similar for all positive indices throughout the reaches in the valley floor. Among all reaches, reach 7 had the highest number of positive patches due to a higher degree of meandering in this reach. This procedure and model outputs provide unique screening opportunities for prioritizing management of riparian areas (e.g., conservation, restoration and enhancement).

KEY WORDS: Riparian management; Quantitative spatial assessment; Natural and anthropogenic factors; Landscape ecology metrics.

Introduction

Riparian systems along streams and rivers can be viewed as corridors of plant communities that interact with terrestrial and aquatic ecosystems (National Research Council 1992, Schaefer and Brown 1992). Riparian systems are dynamic transition areas with high variability. Natural riparian areas can extend across different spatial scales of drainage landscapes (Frissell, et al., 1986) and vary in structure and function depending on the degree of habitat connectivity and the extent that physical and biotic processes interact with adjoining ecosystems (Wissmar, et al.,, 2003). However, along rivers within suburban and urban development, riparian corridors are often fragmented ranging from intact natural habitats with native species assemblages to highly altered areas exhibiting land use modifications and pervasive non-native biotic communities. Riparian systems altered by human developments commonly experience long-lasting impacts caused by increases in impervious surfaces and physical constraints caused by flood control levees, roads and other facilities (Denysius and Nilsson 1994; Wissmar, et al., 2000, May and Horner 2000).

In many biogeographical regions (e.g., high rainfall and semiarid) of the United States, recognition of the ecological and societal value of healthy ecosystems has caused government agencies, resource managers, landowners and other interest groups to require watershed assessments and management guidelines that identify impaired conditions and restoration needs (Collins and Pess 1997, Kondolf 1995, Wissmar and Beschta 1998). However, these provisions are generally not designed to prioritize habitat sites for diverse management purposes (e.g., conservation, restoration and enhancement). The lack of quantitative, repeatable methods for identifying and prioritizing riparian areas is evident in the frequency of uncertain policy decisions, poor implementation and questionable success of management projects. Such shortcomings often lead to the arbitrary selection of sites that do not adequately consider the presence of important habitat factors (e.g., relic channels and wetlands) and limitations imposed by anthropogenic constraints (e.g., levees and roads). In addition, the failure to recognize the spatial interplay among these factors can further confound management actions.

This paper presents a spatially explicit linear additive model that prioritizes site characteristics of riparian areas. The objective is to provide a procedure for identifying the most favorable sites for different management actions based on land cover, data availability and quality. Our approach considered “natural and modified” land covers that can influence land and water quality and uses in the riparian corridor along the lower Cedar River near Seattle, Washington. We applied the procedure to riparian–floodplain areas of eight river reaches.

Methods

Study Area

The lower Cedar River drainage (165 km^2) drains from the Cascade Mountains into Lake Washington near Seattle, Washington. The drainage is dominated by glacio-fluvial landforms where the river has incised down through various types of deposits (Booth 1984). Within the drainage, there is continuing land development and fragmentation of natural habitats, particularly along the urban-rural interface (King County 1993, Wissmar, et al., 2000) (Figure 2-1). Population growth has increased during the past three decades, fragmenting and degrading riparian and stream habitats (King County 1993, Wissmar and Beschta 1998). County, city, state and federal governments are challenged by conflicts between land-use and habitat quality issues (King County 1998).

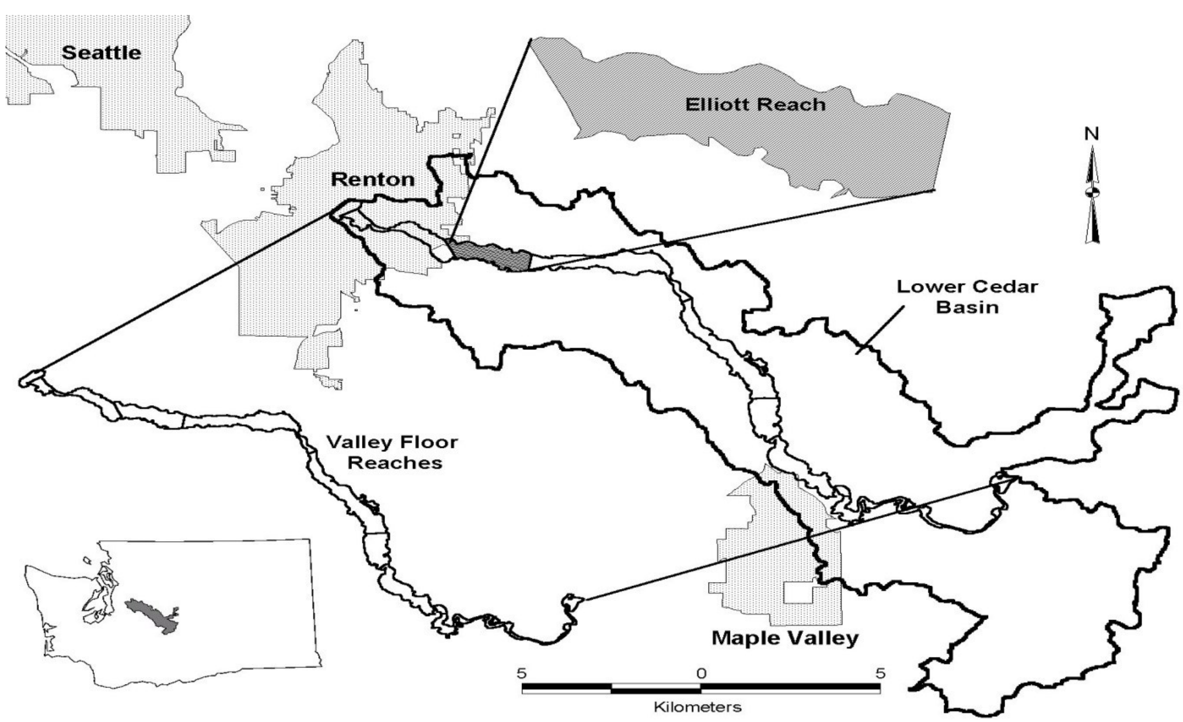

Figure 2-1. Lower Cedar River basin near Seattle, Washington. The drainage covers 165 km^2 from the Cascade Mountains to Puget Sound. Valley floor reaches occupy a changing landcover matrix

from dense urban to rural. The Elliott reach is partially located within the City of Renton on the urban-rural gradient.

Land-use and habitat issues have been evident in recent policy and management actions. For example, the Washington State Growth Management Act (GMA) required implementation of King County's Urban Growth Boundary (UGB). The federal Endangered Species Act (ESA) and recent listings of salmon stocks in the Puget Sound region along with riparian provisions of Habitat Conservation Plans (HCP), and numerous watershed recovery guidelines (e.g., county, state and federal) have required various agencies and local governments to develop plans for protecting and restoring riparian and stream habitats and open spaces.

An example of a coordinated local government effort aimed at ESA-listed salmon recovery is the Tri-County Coalition for Puget Sound counties (Tri-County 2002). A key Tri-County recommendation is a system of riparian management zones around all salmonid-bearing streams. This plan strives to protect ecological functions of riparian habitats while providing for differing levels of human activity. A major challenge for managers across the region is identifying and prioritizing the most opportune sites for different management purposes. This need is the primary reason for the development and application of our procedure.

Procedure

Our procedure was designed to incorporate different ecological and anthropogenic conditions into the prioritization process. First, salmonid-bearing streams in the drainage were identified and buffered following the TriCounty (2002) recommendation for riparian management zones. These management zones were used to spatially limit the analysis to the riparian zones of salmonid-bearing streams. Next, we assumed that a discrete set of habitat and anthropogenic factors were representative of conditions contributing to the overall character of riparian zones in the drainage. "Habitat" factors were considered to represent relatively "intact habitat areas" (e.g., wetlands) with important ecological functions, while "anthropogenic" factors represented managed uses that could limit ecological functions of riparian and channel habitats.

We developed indices of habitat potential by examining the spatial coincidence of habitat and anthropogenic factors (Figure 2- 2). Our analysis applies the Tri-County riparian management zones to riparian corridors in the eight channel-floodplain reaches of the lower

Cedar River. High-resolution (5 m) grid cells ensured that all factors were spatially represented in index calculations. For example, small features like roads and armored banks that might be obscured in larger grid cells were accounted for by the model. Clusters of grid cells with the same indices

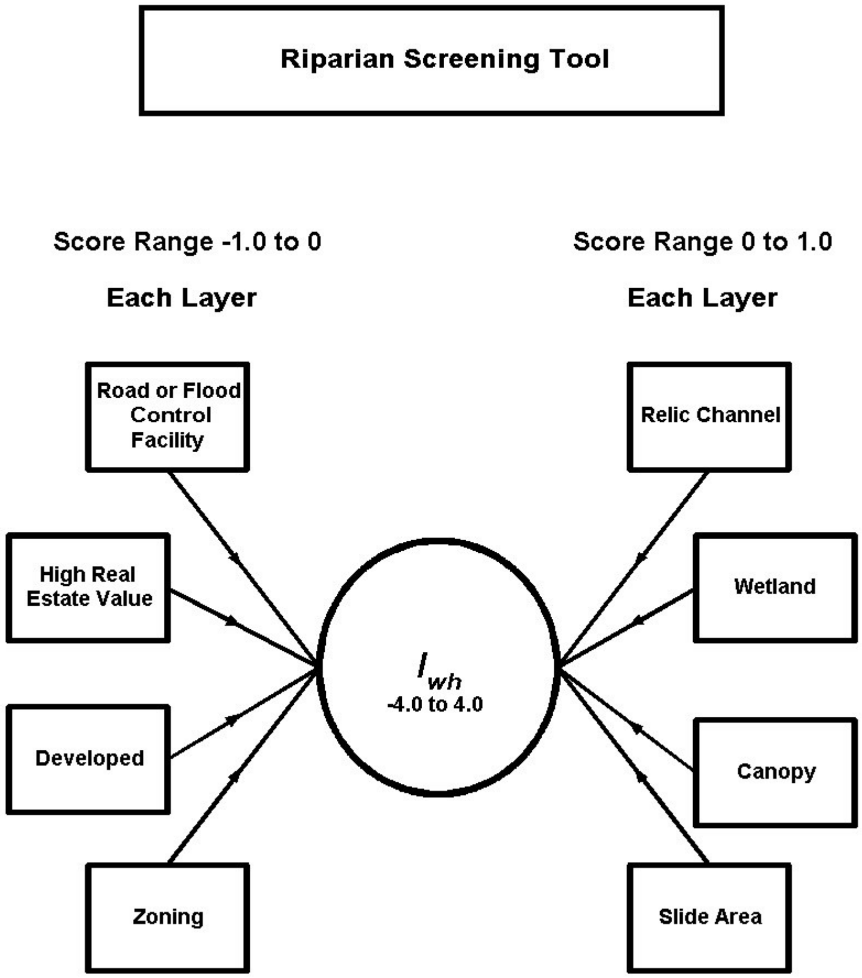

Figure 2-2. Habitat potential index model. Indices are calculated by adding all grids (layers) together and multiplying by a spatially corrected weighting factor. Indices range from –4 to 4. High positive indices indicate dominance of habitat factors with few or no anthropogenic factors. Low negative indices indicate dominance of anthropogenic factors with few or no spatially coincident habitat factors.

were treated as contiguous patches. Additional analyses identified independent grid cell characteristics within habitat patches and were used to spatially filter anthropogenic factors to reveal the most “intact habitats”.

Analysis

Riparian conditions within the lower Cedar River drainage can be affected by changes that occur along the urban-rural gradient. To allow for comparisons among areas, the floodplain was subdivided into reaches using changes in channel gradient to determine the reach breaks following Perkins (1994) (Figure 2-1). Reach areas were determined by extending the reach breaks out to the valley walls perpendicular to the channel. For all reaches the spatial characteristics of habitat and anthropogenic factors were determined by combining groups of grid cells with the same indices into patches. These patches were analyzed in terms of their composition and configuration with the *FRAGSTATS* extension to *ArcView* (McGarigal and Marks 1995). Patches were then considered in terms of mean patch size (MPS), total numbers of patches (NP), and fragmentation index (FI).

Habitat and Anthropogenic Factors

Land cover grids of "habitat factors" and "anthropogenic factors" (Table 2-1) were analyzed in a grid stack consisting of eight grids (four habitat and four anthropogenic) to determine the

Table 2-1. Habitat (H) and Anthopogenic (A) factors used to calculate a relative index of habitat potential.

Analysis Factors	Factor Type	Criteria	Source
Mature Canopy	H	Mature Coniferous, Deciduous, and Mixed Canopy	Wissmar, et al., (2000)
Relic Channels	H	1865 River Channel Configuration	Perkins (1994)
Wetlands	H	Existing GIS data layer	King County GIS Derived from National Wetlands Inventory
Slide Prone Areas	H	Existing GIS data layer	King County GIS
Developed	A	> 10% impervious	Wissmar, et al., (2000)
Zoning	A	High Density Residential, Neighborhood Business, Regional Business Office, Commercial, Industrial, and Mineral	King County GIS
High Real Estate Value	A	> Median Real Estate Value for the basin (Land + Improved value = >$105/ m^2)	King County GIS
Channel Constraints	A	Levees, Revetments, Roads, and Railroads	King County GIS

spatial overlap among all grids (Figure 2-2). These factors met several criteria. First, supporting data were available from existing GIS coverages. Data sources included King County, the University of Washington Libraries, the University of Washington Puget Sound Regional Synthesis Model (PRISM), and data collected for previous studies by Wissmar, et al., (2000). Second, the data had to be of sufficient quality, in terms of the spatial accuracy and precision of the datasets (Mowrer 1999). Finally, the data needed to be functionally relevant to the biophysical condition of the site.

Habitat factors were assumed to represent beneficial attributes that contributed to habitat potential within the study area and included “canopy” (C), “relic channels” (RC), “wetlands” (W), and “slide-prone areas” (SA). Canopy consisted of mature coniferous, deciduous and mixed riparian forests (Wissmar, et al., 2000), which can moderate stream temperatures through shading and contribute to instream habitat complexity when large wood recruits to the system (Murphy, et al., 1986, Bisson, et al., 1987). Relic channels occur in alluvial floodplains and were considered to be active and potential zones of interaction between surface and sub-surface waters (Ward and Stanford 1995). The major benefits of wetlands were assumed to be water storage and habitat functions (Wissmar and Beschta 1998). Slide-prone areas were assumed to indicate potential gravel source areas, which are critical for spawning fish. Within the Cedar River drainage, many gravel source areas lie behind levees and revetments (Perkins 1994), resulting in a loss of normal sediment storage and recruitment dynamics between the channel and floodplain (King County 1993).

The anthropogenic factors used in the analysis included “developed” (D), “zoning” (Z), “high real estate value” (HR), and “channel constraints” (CC). Developed grid cells represented areas with greater than 10% impervious area (Wissmar, et al.,, 2000). Zoning included classes that encourage development (e.g. high density residential, commercial, etc.). High real estate value consisted of areas that exceeded the median land plus improvement value of the drainage. Channel constraints consisted of physical barriers to channel migration including roads, railroads, levees and revetments.

Index Models and Patch Characteristics

The *Spatial Analyst* extension in *ArcView GIS 3.2* (ESRI 1999) was used to apply a linear, additive model to the grid stack (Figure 2-2, Equation 2-1). Each habitat and anthropogenic grid was comprised of grid cells with values that represented the absence of the respective feature (0) or the presence of the respective feature. Areas defined by habitat factors (i.e. C, W, RC, SA) were characterized by grid cells assigned values of positive one (+1). Conversely, grid cells representing the anthropogenic factors received values of negative one (-1). The high spatial resolution of the grids allowed for the assumption that factors present within grid cells spatially dominated that cell. The grid stack was then added together to yield an unweighted index of habitat potential (*I*, Equation 2-1).

$$I = \left(\sum_{g=1}^{4} A_{g,i,j} + \sum_{g=5}^{8} H_{g,i,j} \right) \qquad (2\text{-}1)$$

I was calculated by adding grid cells from all anthropogenic factor grids (*A*), and habitat factor grids (*H*), in all rows (*i*), and columns (*j*), across all grids (*g*). The output illustrated the spatial coincidence of factors across all grids yielding different indices for habitat potential.

In order to spatially apply *I* to appropriate management criteria, we used the Tri-County riparian guidelines (Tri-County 2002) for "Inner and Outer Management Zones" (IMZ and OMZ, respectively). The IMZ was defined by the 45-meter buffer adjacent to salmonid-bearing streams; a zone intended to exclude human activity. The OMZ represented an additional 21-meters with limited-allowable human activity (Tri-County 2002). The scaling was accomplished by weighting the *I* index by $W_{i,j}$. $W_{i,j}$, a decay function, was defined by the reciprocal of the distance of any grid cell in row (*i*) and column (*j*) from the outer edge of the IMZ boundary. Grid cells considered in this analysis were located between the outer edge of the IMZ, and the hydrologic boundary that defined the river drainage network. A weighted index (I_w) was estimated by multiplying each grid cell's *I* index by ($W_{i,j}$). I_w represented a spatially weighted habitat potential index in the riparian zone (Equation 2-2).

$$I_W = (W_{i,j})(I) \qquad (2\text{-}2)$$

We verified equation 2 by comparing model estimates of habitat potential to existing riparian habitats and field-verified restoration opportunities in the lower Cedar River floodplain as identified by King County (1998). These habitats were compared to predict I_w indices for each reach to evaluate the relative performance of equation 2-2.

The next phase spatially filtered anthropogenic factors through independent identification of grid cell characteristics within all habitat patches (I_{wh}, equation 2-3).

$$I_{wh} = W_{i,j}\left(\sum_{g=1}^{4} A_{g,i,j} + (1/(n+1)) * (\sum_{g=5}^{8} H_{g,i,j})\right) \qquad \text{for all } I_w > 0 \qquad (2\text{-}3)$$

Filtering anthropogenic factors was an important step in identifying areas with minimal human influences. Individual grid cell characteristics within patches were examined to distinguish which unique combinations of factors were contributing to patches of I_w indices. For example, a grid cell within a patch of I_w index of 3 could be comprised of any 3 habitat factors with no spatially coincident anthropogenic factors, or it could consist of 4 habitat factors with 1 anthropogenic factor. This was accomplished through a combinatorial process (ESRI 2001) whereby the grid cell attributes from all 8 grids (four habitat and four anthropogenic) were combined prior to filtering. The filtering process adapted from the concept of a binary mask (Lillesand and Kiefer 1994) involved applying a multiplier (1/*n*+1) to habitat factors where *n* was the number of anthropogenic factors measured in any given grid cell with an I_w value greater than zero. I_{wh} indices represented riparian areas with the most intact habitats. I_{wh} analysis emphasized the grid cells (and patches) that were least affected by anthropogenic factors.

The output from equation 1-3 revealed patterns of grid cells characterized by common indices. These contiguous groups of grid cells (patches) were further analyzed in terms of their composition and configuration with the *FRAGSTATS* extension to *ArcView* (McGarigal and Marks 1995). Composition was defined by the indices that characterized the analysis area (i.e. which indices and how many patches of each). We defined configuration in terms of a fragmentation index as the number of patches of each index divided by the mean patch size for each reach. High numbers of patches and small total area indicated high fragmentation (i.e. lots of small patches). This definition recognizes that there are numerous measures of patch configuration, many with considerable redundancy because of strong correlation between metrics (Turner, et al., 2001, McGarigal and Marks 1995).

Results

Index Comparisons

Our analysis identified relative riparian conditions with a focus on the floodplain of the mainstem reaches in the river. I_w indices for the floodplain show wide ranging results for percent of total area (TA), percent of total numbers of patches (NP), mean patch size (MPS), and fragmentation index (Table 2-2). High numbers of patches and relatively small mean patch size indicated fragmentation of habitats. Throughout the drainage, patches of positive I_w indices had larger mean patch size (range 0.13 to 0.35 ha) than patches of negative I_w indices (range 0.02 to 0.06 ha). In addition, the fragmentation index (number of patches divided by mean patch size)

indicated substantially less fragmentation of habitats with I_w indices of 3 and 4 than for all other indices.

Table 2-2. Valley Floor / w indices in terms of percent of the total valley floor area, as a percent of the total number of patches, by mean patch size (MPS), and by fragmentation index.

Iw Index	Total % Area	Total % Patches	MPS (ha)	Frag Index
4	0.70	0.63	0.19	74.47
3	8.54	5.35	0.27	12.62
2	49.73	23.61	0.35	3.78
1	31.55	39.96	0.13	0.84
-1	7.47	21.84	0.06	0.72
-2	1.67	7.09	0.04	0.46
-3	0.33	1.44	0.04	1.39
-4	0.01	0.08	0.02	4.27

The procedure's capability to identify optimal areas for habitat management was improved when equation 2-3 was applied to all floodplain reaches. Relative to the I_w results, I_{wh} indices in the floodplain showed increases in fragmentation for indices 1, 2, & 3. However, fragmentation of I_{wh} index 4 remained constant with I_w index 4 because there were no anthropogenic factors in patches of I_w index 4 (Table 2-3). I_{wh} indices 3 and 4 exhibited the largest MPS (0.20 and 0.19 ha respectively) as well as the lowest fragmentation index (0.28 and 0.01 respectively). I_{wh} indices had smaller MPS (0.07 and 0.03 ha respectively) and higher fragmentation indices (0.94 and 3.12 respectively). Areas characterized by high positive indices and low fragmentation were identified as the most favorable for management actions including active restoration or preservation.

Table 2-3. Valley Floor / wh indices in terms of percent of the total valley floor area, as a percent of the total number of patches, by mean patch size (MPS), and by fragmentation index (Frag Index).

I_{wh} Index	Total Area (ha)	Total % Patches	MPS (ha)	Frag Index
4	39.13	1	0.19	0.01
3	123.12	25	0.20	0.28
2	49.92	29	0.07	0.94
1	33.99	44	0.03	3.12

Reach-Scale Analysis

Among the 8 reaches in the lower Cedar River, reaches 1 and 2 lie entirely within the City of Renton, Washington, reach 3 is completely within the urban growth boundary, and the remaining reaches exhibit differing degrees of development (Wissmar, et al., 2000). Reach 1 exhibited the lowest I_{wh} indices, fewest number of patches (NP), smallest mean patch size (MPS), and highest fragmentation (FI)index among all reaches (Table 2-4). Reaches 2 through 6, and reach 8, had I_{wh} indices ranging from 17% to 21% of the total area, MPS ranging from 0.11 ha to 0.17 ha, and FI of 0.03 and 0.02 in respective reaches. Reach 7 had similar MPS and FI, but I_{wh} indices occupied almost 34% of the total reach area. The higher percentage of total reach area is due to a higher degree of meandering in this reach.

Table 2-4. Positive /wh indices by reach. Iwh indicates are represented in terms of total area (ha)* the percent of total reach area, number of patches (NP) and the mean patch size (MPS) for all /wh indices within each reach.

Reach	Total Area I_{wh} (ha)	Total % of Reach	Total I_{wh} NP	MPS (ha)	Frag Index
1	1.34	4.1	44	0.03	0.11
2	23.66	18.0	268	0.11	0.03
3	28.96	19.7	286	0.12	0.03
4	47.12	19.8	584	0.16	0.02
5	44.02	18.6	458	0.13	0.03
6	18.84	16.8	190	0.13	0.03
7	50.25	33.7	263	0.16	0.02
8	31.97	21.3	232	0.17	0.02

Sub-reach analysis identified localized areas with high I_{wh} indices and relatively low fragmentation. An example is the Elliott section of reach 3 that is characterized by high values for mean patch size and total area, and relatively low numbers of patches (Figure 2-3). However, Elliott lies within the City of Renton and some patches within the reach were characterized by I_w of indices -1 and –2 that pointed to the presence of dominant anthropogenic factors that could affect management options (Figure 2-3a). This reach, while confined by steep cliffs on the north side of the valley, had more extensive floodplain areas on the south side. Within the Elliott reach floodplain areas, spatial distributions for I_w indices showed areas of the mid-reach contained relatively high positive I_w indices. In contrast, areas upstream and downstream and along tributaries exhibited negative indices (Figure 2-3a). The number of patches, total area and mean patch size frequencies (range 5% to 31%) for indices -1 and –2 indicated the presence of some anthropogenic factors. Nevertheless, similar number of patches, total area and mean patch size frequencies (range 2% to 39%) for positive I_w indices of 3 and 4 indicated the presence of high quality habitats within the floodplains of the Elliott reach (Figure 2-3a).

In the Elliott area, I_{wh} indices provided greater focus on the presence of priority habitats (Figure 2-3b). Comparison of number of patches, total area and mean patch size areas (ha) for (unfiltered, I_w) and (filtered, I_{wh}) for index 4 indicated the same number of patches (6), total area (0.6 ha) and mean patch size (0.1 ha) for both unfiltered and filtered estimates (Table 2-5). The pattern was the same for index 3, number of patches (15), total area (4 ha) and mean patch size (0.3 ha). These estimates indicate that the filtering process provided the same level of resolution for habitat identification as unfiltered values for indices 3 and 4.

Comparisons of estimates for indices 1 and 2 showed a variety of filtering effects. The filtering process identified distinct portions of the unfiltered areas that could be high priority habitats. Filtered and unfiltered estimates for index 2 (I_{wh} and I_w respectively) identified the same number of patches. However, total area and mean patch size were 80 and 120% of unfiltered areas, respectively (Table 2-5). For I_{wh} index 1, all filtered values were less than unfiltered areas, number of patches (70%), total area (70%) and mean patch size (90%) relative to respective I_w values.

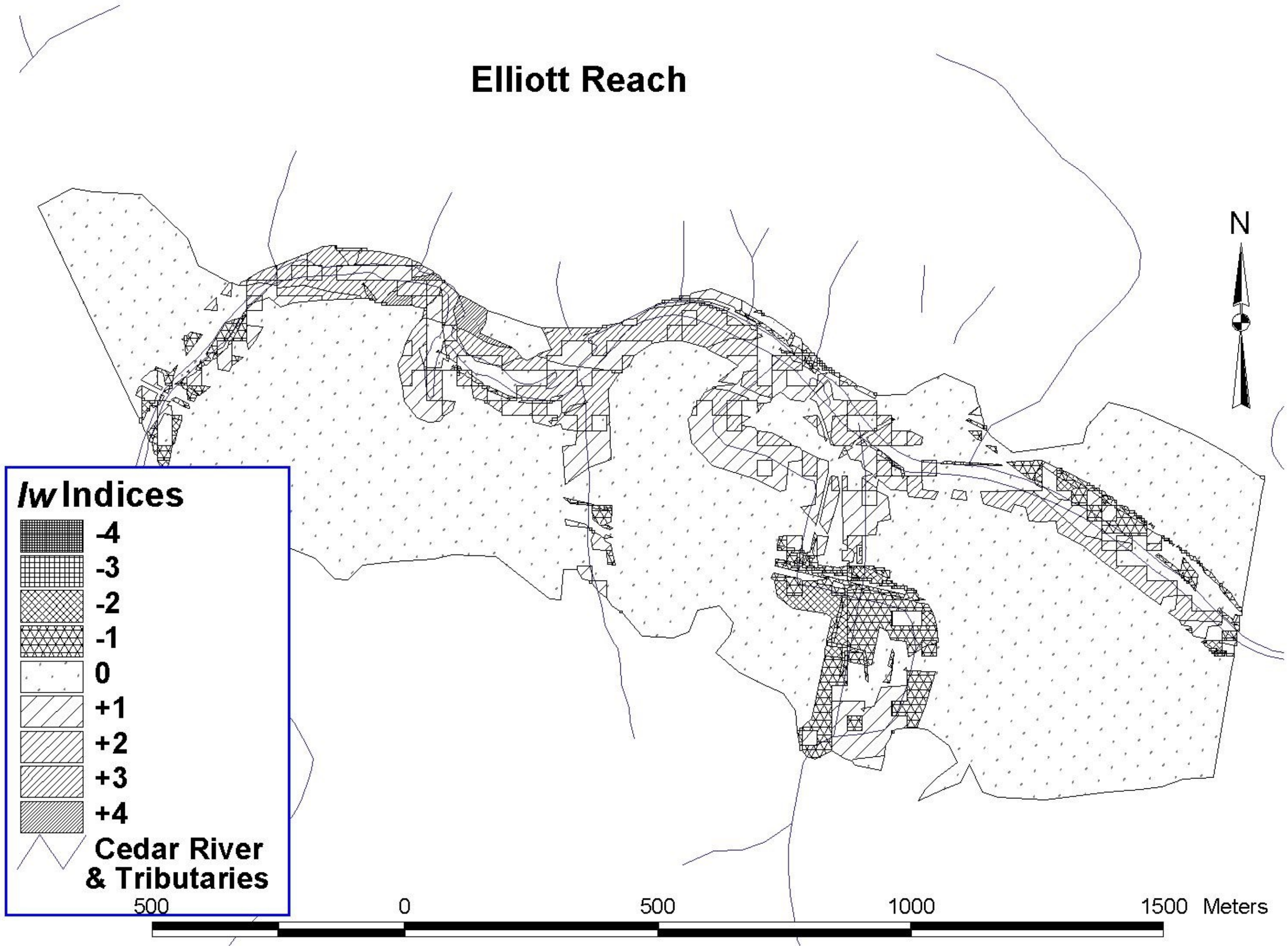

Figure 2-3A. Spatially explicit model output of Iw indices in the Elliott Reach. Patches of indices along the mainstem of the river in the central part of the reach are dominated by positive indices. Patches near the ends of the reach, as well as along the dominant tributary are characterized by relatively negative indices.

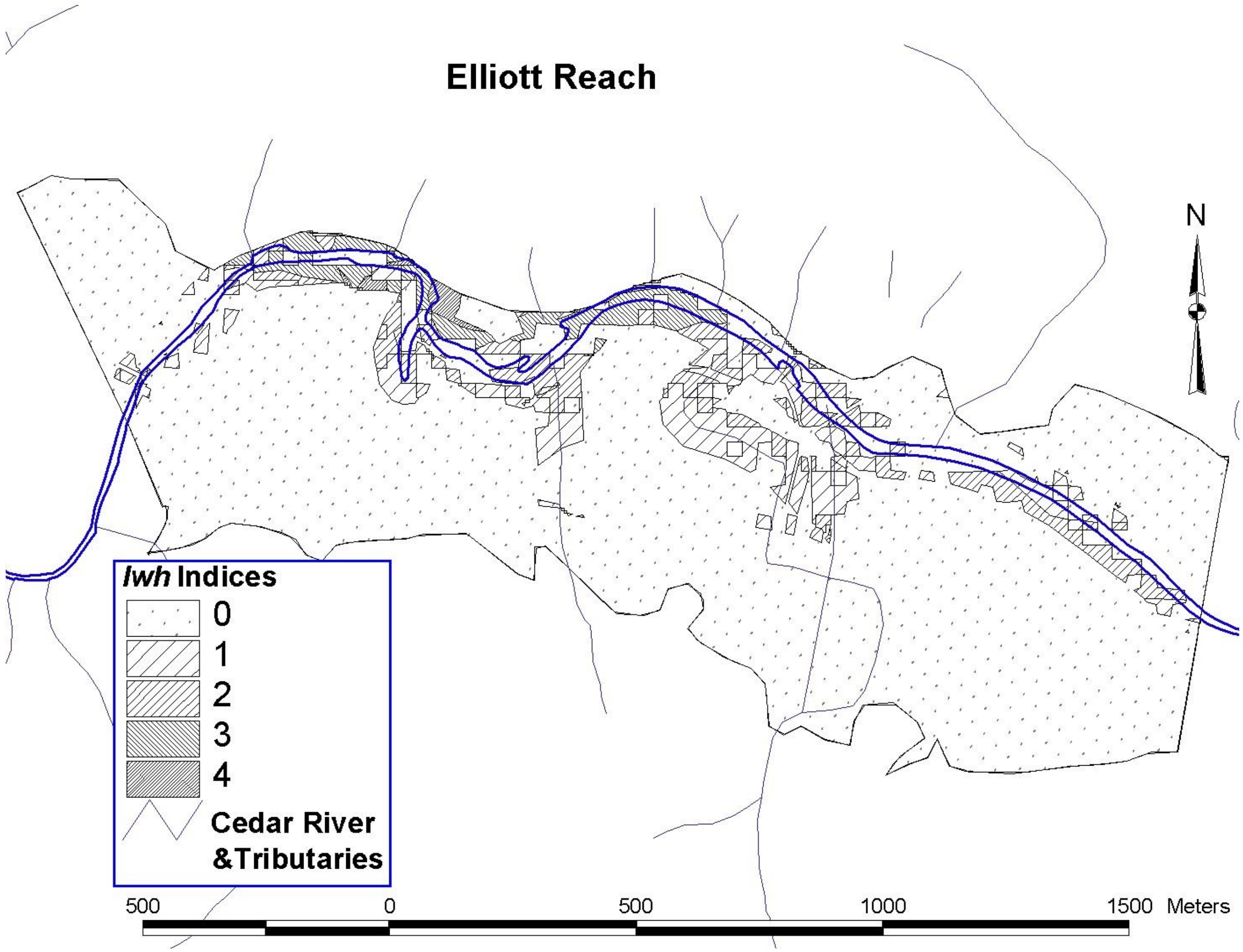

Figure 2-3B. Spatially explicit model output of lwh indices in the Elliott Reach. Application of Equation 2-3 highlighted the areas least affected by anthropogenic factors. Highest indices remain in the middle sections of the reach with little change in composition or configuration. Total area (TA) was dramatically reduced for indices 1 and 2. Number of patches (NP) and mean patch size (MPS) showed increases for index 2, while both decreased for index 1.

Table 2-5. Comparison of spatial characteristics for unfiltered (Iw) and filtered (Iwh) indices within the Elliott section of reach 3. Filtering decreased Iw indices relative to the influence of anthropogenic factors within patches of grid cells (equation 2-3). TA indicates the total area, NP is the number of patches, and MPS is the mean patch size in hectares of each index class.

	Unfiltered	Filtered	Unfiltered	Filtered	Unfiltered	Filtered
Index Class	TA	TA	NP	NP	MPS	MPS
	--(ha)--		--(No.)--		--(ha)--	
4	0.60	0.60	6	6	0.10	0.10
3	4.06	4.08	15	15	0.27	0.27
2	7.70	7.54	78	65	0.10	0.12
1	12.82	8.97	110	82	0.12	0.11

The analysis of patch composition of I_{wh} scores for the Elliott Reach was generated in a combinatorial grid (Table 2-6). At Elliott, 15 combinations of factors were observed. Approximately 99% of grid cells were characterized by a combination of habitat factors with no spatially coincident anthropogenic factors. The proportion of habitat factors included, 25% slide-prone areas (SA), 65% mature tree canopy (C), 9% wetlands (W), and 87% relic channels (RC). Only 1% of all grid cells had spatial co-occurrence of anthropogenic factors.

Table 2-6. Combination of habitat and anthropogenic factors contributing to each /wh factor within the Elliott Reach. Total patch area (TA) and grid cell counts are for habitat (positive scores) and anthropogenic (negative scores) factors within each I_{wh} class

I_{wh} Class	*CC	*Z	*D	*HR	**SA	**C	**W	**RC	TA (ha)
4	0	0	0	0	1	1	1	1	0.63
3	0	0	0	0	1	1	0	1	3.06
3	0	0	0	0	1	1	1	0	0.53
3	0	0	0	0	1	0	1	1	0.16
3	0	0	0	0	0	1	1	1	0.35
2	0	0	0	0	1	1	0	0	0.18
2	0	0	0	0	1	0	1	0	0.02
2	0	0	0	0	1	0	0	1	0.34
2	0	0	-1	0	1	0	1	1	0.19
2	0	0	0	0	0	1	0	1	7.11
2	0	-1	0	0	1	1	0	1	0.06
2	-1	0	0	0	1	1	0	1	0.03
1	0	0	0	0	1	0	0	0	0.09
1	0	0	0	0	0	0	0	1	6.70
1	0	0	0	0	0	1	0	0	2.04

*CC = channel constraints, Z = zoning, D = developed, HR = high real estate value,
**SA = slide prone areas, C = mature canopy, W = wetlands, RC = relic channels

Ground-truth Validation

Extensive field investigations were performed by King County in the floodplains of the lower Cedar River to evaluate habitat extent and condition. In addition, based on these surveys, potential restoration sites were identified and mapped (King County 1998; Wissmar, et al., 2003). We applied our procedure to these data to test the performance against known riparian habitats as well as locations that were identified as possible restoration sites. Analyses included reaches 3 through 8 because reaches 1 and 2, which are the most urban in the basin, had no field-verified floodplain habitat areas. For all reaches, these existing habitats received positive I_w indices 92% of the time on average (range 73% to 100%). Field-identified restoration opportunities received positive I_w indices 90% of the time on average (Table 2-7). Patches of positive I_w indices were approximately 7 times more abundant as negative patches. However, the average mean patch size of positive I_w indices was 35% smaller than the average mean patch size of negative I_w indices.

Table 2-7. Comparison of Iw indices to existing hydrologically connected floodplain habitats and field verified restoration opportunities. Existing habitats were identified by positive I_w indices 92% of the time on average across all reaches. Likewise, restoration opportunities were identified by positive I_w indices an average of 90% of the time across all reaches. Reach 6 had the highest rate of positive I_w indices for existing habitats, while Reach 7 had the lowest percentage of positive I_w indices. For restoration opportunities, positive I_w indices coincided most often in Reach 3 and the least often in Reach 7.

Reach	Total Positive Existing (% Area)	Total Negative Existing (% Area)	Total Positive Opportunities (% Area)	Total Negative Opportunities (% Area)
3	88	12	100	0
4	100	0	85	15
5	91	9	89	11
6	100	0	89	11
7	73	27	81	19
8	97	3	94	6

Discussion

This screening procedure for identifying priority habitats for riparian management compliments several restoration paradigms (e.g. Harris and Olson 1997, Russell, et al., 1997). Our procedure provides relative riparian habitat indices in a quantitative, spatial framework to identify locations and qualities (I_{wh} indices) of priority habitats within riparian corridors. The approach allows managers to set management priorities (e.g., restoration) by evaluating landscapes in terms of spatial patterns of habitat and anthropogenic factors among and within reaches. The evaluation of each reach independently permits comparisons of their patch characteristics among index classes and facilitates reach-level riparian management.

Contemporary methods for prioritizing riparian management have been documented in the literature (e.g. Harris and Olson 1997, Kentula 1997, Russell, et al., 1997, Richter and Richter 2000). These studies recognize the importance of physical constraints in the site evaluation process and include biological factors in their analyses. Our procedure improves on these approaches in several ways. The spatial resolution used in our procedure utilizes fine-scale details at the sub-reach scale while retaining useful information at broader scales. In addition, the location, size, and degree of fragmentation provide valuable information for defining management actions.

Analyses of patch compositions and configurations associated with habitat indices provides additional detailed information about spatial characteristics of priority habitat areas. Combinations of factors, that represent spatial patch compositions, also have measurable spatial arrangements, which may vary, in degree of ecological function. Index classes (I_w and I_{wh}) with positive values (2 to 4) commonly have higher patch numbers, larger total areas, and mean patch sizes. Larger patches dominated by habitat factors (e.g., wetlands and relic channels) imply ecologically functional systems in terms of connectivity and minimal landscape fragmentation. Ecologically, larger patches can exhibit greater biodiversity and more complex trophic dynamics and nutrient cycling (Forman and Godron, 1986). Index classes with mid-range values (-2 to 2) and smaller patch characteristics (number of patches, total area and mean patch size) suggest compromised ecological functions. Classes with lower values (-3 and -4) and minimal patch characteristics point to areas with few intact habitats and more frequent anthropogenic factors (Tables 3 and 4). In rivers, ecological processes can be modified through fragmentation (Hanson, et al., 1990, Denysius and Nilsson, 1994) and losses in connectivity (Ward and Stanford, 1995) caused by anthropogenic actions. Common human activities that reduce ecological function include land developments (e.g., residential, commercial, transportation) and management practices that modify channel structures, regulate flows and control floods (King County 1993, Gore and Shields, 1995, Galat, et al., 1998, Wissmar and Bisson 2003).

The application of this procedure to floodplain reaches of the lower Cedar River indicates that cumulative compositions of patches change depending on location within the drainage. Differences in patch patterns defined by our procedure provides a spatially explicit description of riparian conditions within the different floodplain reaches. The progressively focused nature of our procedure demonstrates the importance of landscape configurations in prioritizing management actions. The procedure has the ability to identify changes in habitat conditions changes at different levels of scrutiny. For example, I indices provide a general idea of the relative proportions of habitat and anthropogenic factors. I_w indices spatially focus the analysis on the riparian zone along salmonid-bearing streams (Table 1-2) and I_{wh} indices identify individual grid cell contributions to habitat patch values (Tables 1-3 and 1-4).

The I_{wh} index, and its associated patch characteristics, allows for maximum discrimination of riparian areas with the most intact habitats. The multiplier (1/n+1, equation 1-3) focuses the analysis on grid cells with the most intact habitats by lowering the I_{wh} index for a grid cell where anthropogenic factors occur. In this way, emphasis is focused in the areas that contain the most habitat and the fewest anthropogenic factors.

Conclusions

The inclusion of both habitat and anthropogenic factors, and the spatial nature of the analysis offer an ideal procedure for monitoring the effects of management actions because expected future changes in landscape configurations can be readily incorporated. Important influences on development within the Cedar River drainage include the implementation of the Growth Management Act and the widening of transportation corridors (King County 1998, Wissmar, et al., 2000). Our procedure's inherently spatial nature provides a mechanism to quantify the location, type, and extent, of changes to the landscape through time. Furthermore, the procedure is readily adaptable to using different data sources to address an array of natural resource and management issues.

We recognize that our procedure focuses on identifying the most intact remaining habitats in riparian zones, and may not identify all priority sites within a drainage system. The screening procedure is intended to help managers quickly and objectively quantify riparian habitat condition in order to inform management prescriptions.

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Chapter 3: Response to disturbance in a highly managed alluvial river: Does it conform to Le Chatelier's general law?

Raymond K. Timm, and Robert C. Wissmar

Abstract

A magnitude 6.8 earthquake triggered a channel-damming landslide causing the lower Cedar River, Washington, to occupy an existing floodplain side channel. The channel and floodplain ecosystem initially underwent rapid geomorphic changes until the system energy approached a new system state according to Le Chaterlier's general law. Multiple lines of evidence support observations that channel expansion proceeded rapidly as energy was focused on the banks of the overfit side channel until the channel's geomorphology was consistent with total system energy available for work. Large trees recruited to the channel helped create lateral channel expansion as well as bed topographic variability. One year of pre-disturbance data was compared with three years of post-disturbance data in a spatially explicit analysis of the complexity of channel form and bed surface elevations. Estimates of changes in sediment storage and erosion, and channel conveyance capacity were calculated for all time periods and inter-annual comparisons. Statistical analyses of aggraded and eroded areas of the channel indicated significant differences in complexity as the channel rapidly increased during the first three years and then exhibited decreasing complexity in the final year of the study.

Keywords: Channel-damming landslide; alluvial river; dynamic equilibrium; fractal analysis; channel conveyance; DEM differencing.

Introduction

Geomorphic evolution of many Puget Sound lowland rivers during the past 10,000 – 14,000 years has been driven by fluvial incision through glacially deposited materials (Booth, 1994; Booth et al., 2003; Collins et al., 2003). These Holocene river systems are characterized by dynamic alluvial floodplains and steep valley walls (Beechie et al., 2001). Because the valley walls are prone to landsliding, particularly where river meanders engage the toe (Owczarek, 2008), managers have extensively hardened banks to mitigate natural fluvial geomorphic processes and protect property in developed floodplains pursuant to the Ransdell-Humphreys Flood Control Act (1917). Additionally, dams on many rivers have dampened the natural hydrologic regime (Poff et al., 1997; Ward and Stanford, 1995). That dampening acts synergistically with bank hardening to reduce channel migration and landsliding. In natural channels, cut and fill alluviation mechanics plays a major role in the complexity of the riverscape and is directly affected by changes to the hydrologic regime. In particular lateral channel movements and interactions with the floodplain (Ward, 1989) are limited by hardened banks that are engineered to exceed critical shear thresholds and also because artificially high top-of-bank elevations preclude natural flood frequencies.

Managed channels with hardened banks that cannot change in response to discharges, are forced to focus their energy on the bed (Leopold, 1994). This has a homogenizing effect on the sediment mixture and the channel morphology because relatively little exchange of sediment, large wood, and water happens between the channel and floodplain (Buffington et al., 2003; Julien, 2002). In the Cedar River, Washington, the combination of flow control, water withdrawals, and extensive bank hardening have caused a dramatic simplification of the system compared to historic conditions (Collins et al., 2003; Perkins, 1994; Timm and Wissmar, in review).

This paper presents an empirical study of the fluvial geomorphic response of one highly managed reach of the lower Cedar River to a channel-damming landslide that diverted the channel through the floodplain (Figure 3-1). The disturbance allowed us to measure the relative change in bed surface elevations and channel capacity in response to removal of one of the dominant hydrologic impingements (i.e., bank hardening) that controlled fluvial dynamics in the system.

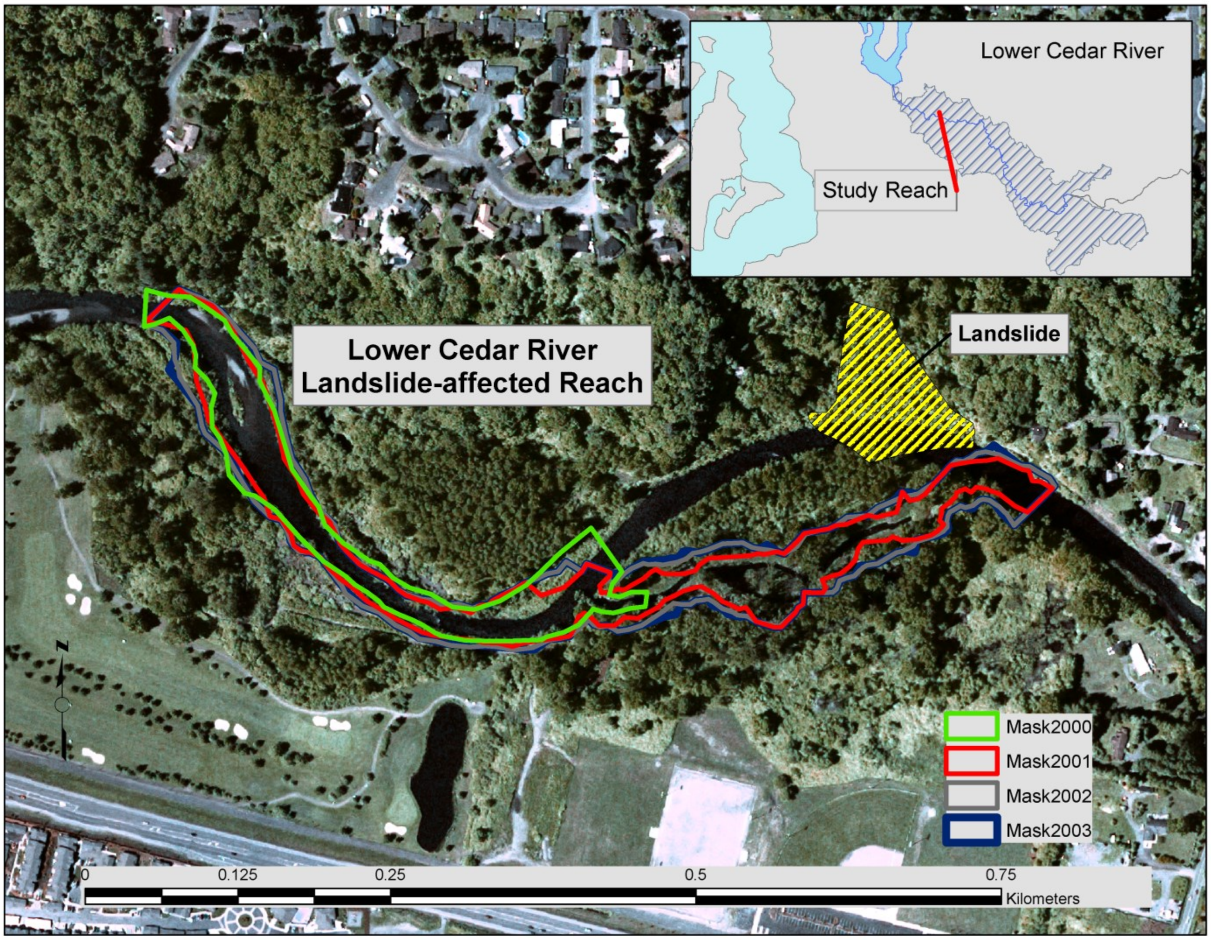

Figure 3-1. Landslide-affected reach of the lower Cedar River, Washington. Analysis masks for 2000, 2001, 2002, and 2003 indicate extent of channel for respective time periods. Flow moves from right to left across figure.

Leopold et al (1964) argued that changes in any of the controlling fluvial geomorphic factors cause a shift toward resilient system components that can absorb the effect of the change. In this case, the dramatic change in bank cohesiveness between armored mainstem and erodible floodplain depositional sediments was the defining demonstration of a shift in resiliency that signaled the disequilibrium. With one year of pre- and three years of post- disturbance data, we quantified the geomorphic shifts in the newly unimpinged channel as it expanded into the floodplain by shifting work from the bed to deformable banks, and then back to the bed as channel capacity expanded rapidly and then began to stabilize. These large changes in channel geometry challenged the concept of equilibria in dynamic alluvial systems in the first two years following the disturbance. However, by the third year post-disturbance, other corroborating lines of evidence began to suggest that

LeChatelier's general law (Mackin, 1948) is consistent with the response of the Cedar River to the landslide disturbance as the channel and bedform appeared to begin to stabilize.

Disturbance Context

On February 28, 2001 a magnitude 6.8 earthquake triggered a landslide that deposited approximately 50,000 m^3 of material in the lower Cedar River at approximately river kilometer (rkm) 8. The landslide runout completely dammed the river and caused upstream flooding. Emergency crews removed bank hardening along the left bank above the slide deposits and allowed the river to enter an existing floodplain side channel that had a downstream connection. The side channel became the new main channel of the river. Initially it was substantially over fit and underwent rapid lateral adjustment to accommodate flows. The lateral adjustments recruited floodplain sediment and large trees to the channel (Figure 3-2). The resulting increase in hydraulic roughness in the channel caused local turbulence and decreased conveyance capacity that in turn caused more erosion.

Figure **3-2.** Aerial view of channel configuration and large trees recruited to the new channel in the first year following the channel-damming landslide. Original channel and landslide runout is visible above the forested island in the center of photo.

The interacting factors controlling the dynamic equilibrium described by Leopold et al., (1964) were width, depth, velocity, slope, discharge, size of sediment, and roughness of the channel. We measured these variables in a spatially explicit framework to estimate changes in the fluvial geomorphic characteristics of the affected channel - floodplain riverscape for three years as the system responded to the disturbance and compared those data with pre-disturbance channel conditions. To monitor changes in channel geomorphology, we employed a differencing technique to estimate changes in serial digital elevation models (DEM) following Wheaton et al., (2010). The inter-annual changes in the study area are reported with respect to local changes in bed surface elevations and corresponding changes in channel capacity and changes in fractal estimates of channel complexity.

Methods

The Cedar River drains from the crest of the Cascade Mountains to Puget Sound. The drainage is managed as two separate basins that collectively drain nearly 500 square kilometers. The upper watershed is primarily managed to provide the City of Seattle's drinking water. There are two dams in the upper watershed, one of which diverts water to the City. The lower watershed has a mix of land uses that range from rural to dense urban near the mouth at Lake Washington (Timm et al., 2004). The study reach is approximately 8 rkm upstream from the confluence with Lake Washington (Figure 3-1). Channel widths ranged between 30m and 50m, and overall gradient through the study area is approximately 0.3%. We studied changes in nearly 1 km of channel and floodplain commencing just above the landslide intersection with the channel for three years following the disturbance and contrasted those data with one year of pre-disturbance channel characteristics. Channel characteristics were measured before the landslide disturbance as part of a larger study of Cedar River habitat restoration potential (Timm et al., 2004), and serendipitously coincided with the landslide disturbance location, providing comparable data for this study.

Field Measurements

Field work was carried out during summer low flow conditions in 2000 (pre-disturbance), 2001, 2002, and 2003. A differential global positioning system (dGPS) with sub-decimeter accuracy in X,Y,Z (Ashtech, 2002) was used to establish channel bed and floodplain ground surface elevations along cross-sections in the channel. Concurrent measurements of water depth, water velocity, and sediment grain size (Wolman, 1954), and large wood (Abbe and Montgomery, 1996) were collected at each location. Due to continuous channel expansion throughout the study period, top-of-bank locations, number of cross-sections, and total number of spot measurements were not consistent year to year (Table 3-1, Figure 3-3). Estimates of channel dimensions were computed in the lab from field measurements using geographic information systems (GIS) to perform spatial calculations.

Table 3-1. Number of cross-sections and points measured during each year of study. Average channel widths and standard deviations are reported for each year. Note the increase in width following the 2001 landslide disturbance.

Year	# X-Sec	# Pt Meas	Avg Width(m)	Std Dev(m)
2000	18	163	34.0	14.8
2001	43	443	39.0	10.6
2002	42	522	41.0	11.1
2003	43	427	41.6	11.9

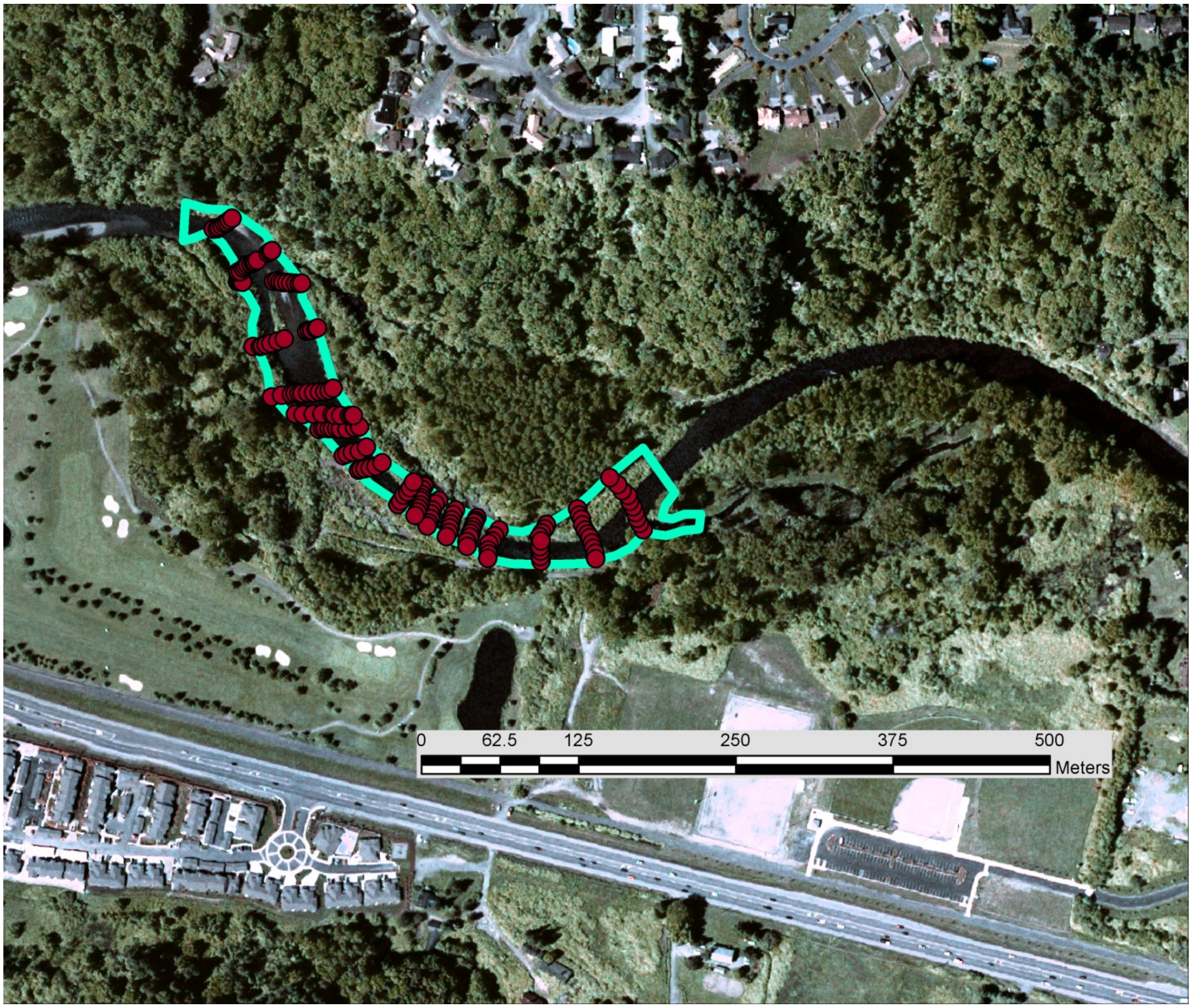

Figure **3-3A.** 2000 extent of analysis and location of channel measurement locations prior to landslide disturbance.

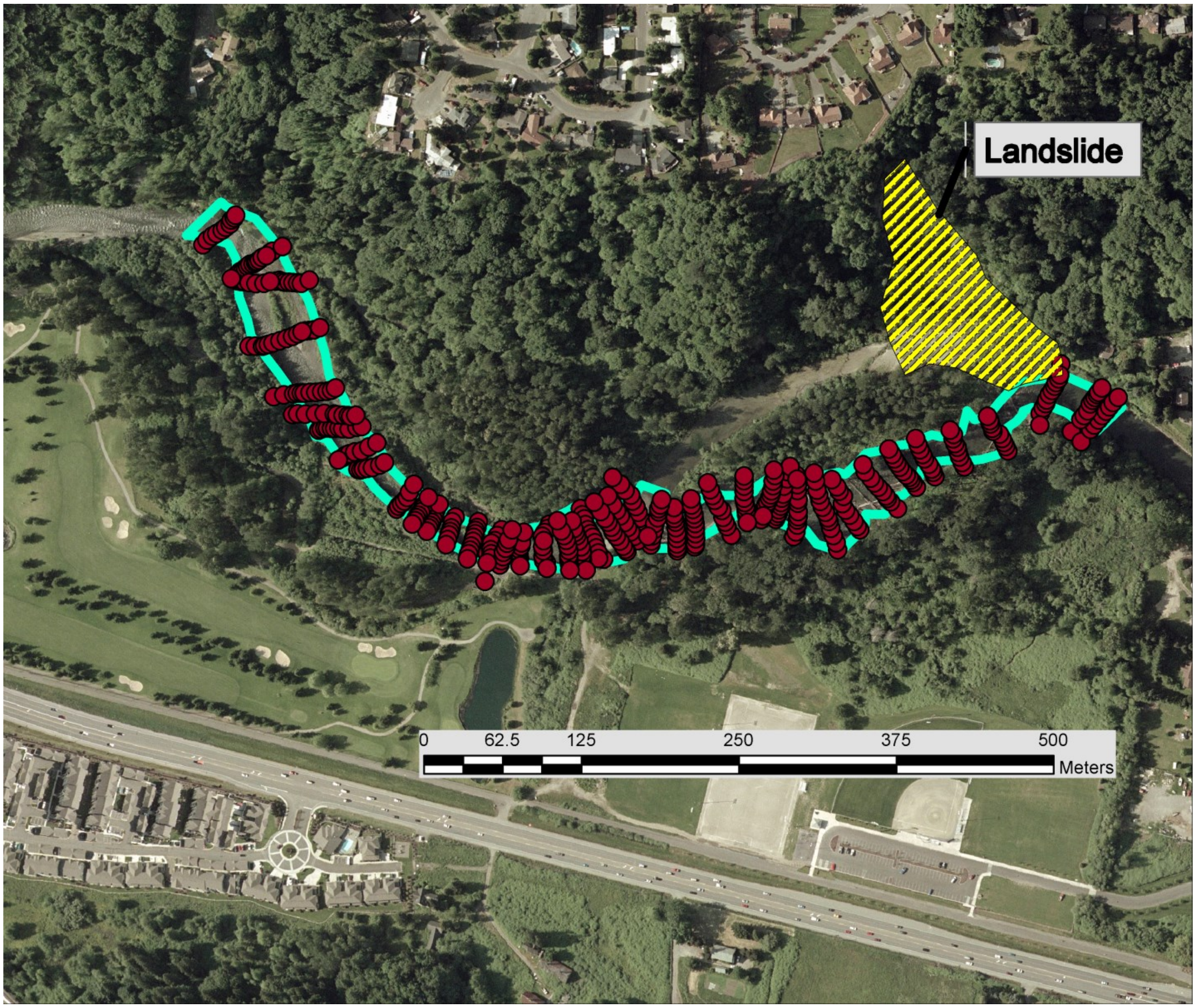

Figure 3-3B. 2001 extent of analysis and location of channel measurement locations.

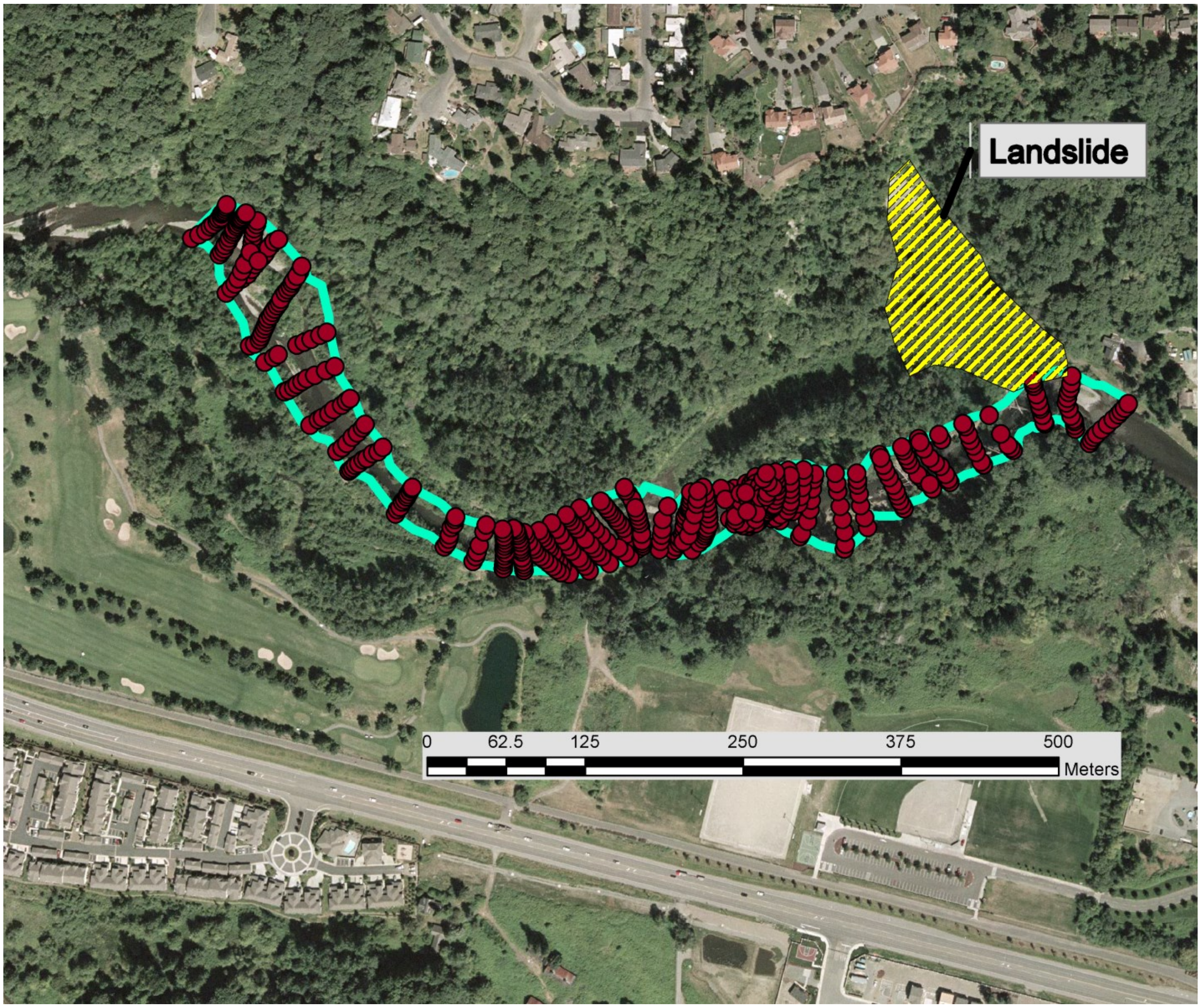

Figure 3-3C. **2002 extent of analysis and location of channel measurement locations.**

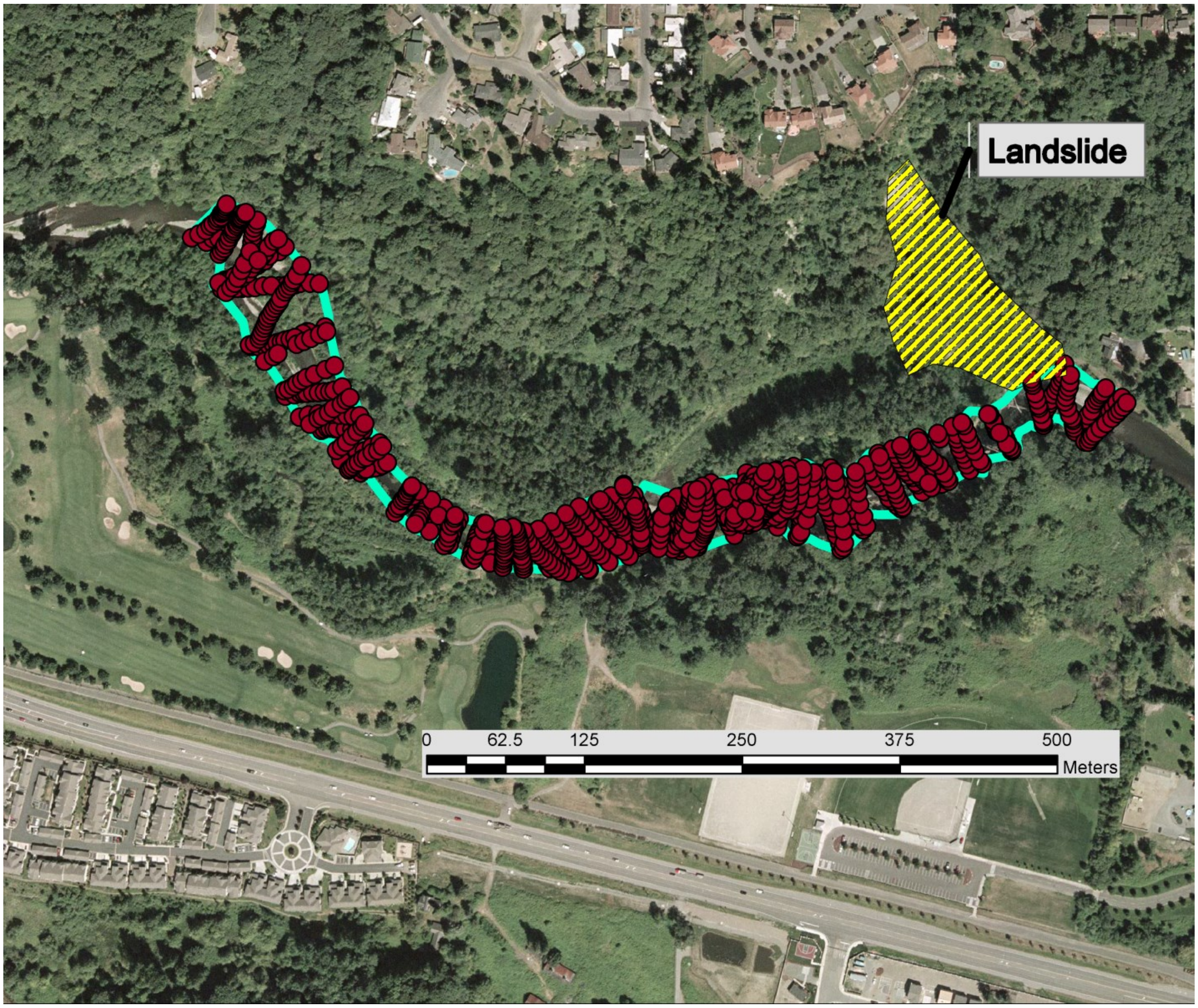

Figure 3-3D. 2003 extent of analysis and location of channel measurement locations.

Spatial Analysis Approach

There are numerous spatial interpolation approaches for estimating surfaces from point data (Goovaerts, 1997; Isaaks and Srivastava, 1989; Li and Heap, 2008). However, because river bed topography varies both abruptly and gradually across space, not all of them are appropriate, or provide the best estimate of the surface (Heuvelink and Hulsman, 2000). We used a tensioned spline interpolation algorithm to generate the river bed topography surfaces because, unlike many kriging methods, the tensioned spline method is a local interpolator that is better at accounting for abrupt variation (Li and Heap, 2008). In addition, spline methods outperform other interpolation methods when the spatial arrangement of the data are dense and regular, such as those collected in our study utilizing river cross-sections (Figure 3-3; (Collins and Bolstad, 1996)).

Continuous river bed elevation surfaces were estimated from annual point field measurements (e.g., bed surface elevation, water depth, sediment size). Point locations were imported into a GIS framework where the X,Y,Z tables were interpolated into grids using a tensioned spline algorithm in ArcGIS (ESRI, 2011). The spatial resolution of the grids was one meter to facilitate merging the annual river bed elevation grids with an existing high-resolution LiDAR-derived floodplain DEM (KCDNRP, 2003).

Each cross-section included “top of bank” measurements at each end with additional point measurements along a more or less straight line across the channel depending on the wadability of the channel or other obstructions such as log jams. The top of bank locations, coupled with orthogonalized aerial photography provided by King County, were used to define the annual extent of the channel area (Figure 3-3). Due to the lateral movement of the banks, the channel extent changed each year and made inter-annual comparisons difficult because consistent spatial extents are required in ArcGIS (ESRI, 2011). To get around that, an analysis mask was established for the channel extent each year. This mask limited the extent of interpolations that were derived from the annual point measurements used to generate channel bed topography. Annual channel elevation grids were then merged into a LiDAR-derived DEM of the floodplain from 2002 that was assumed to be constant for all years. The new, combined DEMs were continuous across the entire study reach and included both floodplain and river bed surface elevations.

For inter-annual comparisons, each year’s DEM was subtracted from the previous year using a differencing technique (Wheaton, 2008). This produced spatially explicit raster datasets of changes in sediment volumes for 2000-2001, 2001-2002, and 2002-2003.

Because of the large populations of grid cells in many grids, statistical tests for differences in serial grids can produce highly significant but meaningless statistics. Instead, we tested differences between years by evaluating the slopes of regression lines that summarized the complexity of aggraded and eroded areas within the riverscape in terms of their fractal dimension (Mandelbrot, 1967). The slope of the line obtained by regressing log(P) on log(A) is equal to 2/D (Gustafson and Parker, 1992; Krummel et al., 1987; O'Neill et al., 1988). Tests for significant differences in the slopes of regressions among all years were calculated with analysis of covariance (ANCOVA) (Zar, 1999).

Fractal analysis was applied to patches of aggraded and eroded areas throughout the entire study reach for all time periods using the perimeter (P) to area (A) relationship:

$$A = k\,P^{2/D} \quad (3\text{-}1)$$

where k is a constant. Grid cells with sediment aggradation had positive integer values to the nearest centimeter; grid cells demonstrating sediment erosion had negative integer values (cm); and areas of the channel with no change received values of zero. The simplest shapes (i.e., circles) evaluate to values approaching one, while complex shapes like the coastline of Great Britain evaluated in Mandelbrot's famous (1967) study had a fractal value of 1.25 (Mandelbrot, 1967).

Estimates of channel conveyance were generated using the channel geometry from the top of bank locations across the channel by reordering Manning's equation to estimate the amount of water that could move through a given location in the channel, and the reach as a whole (Chow, 1959).

$$K = A\,R^{2/3}/n \quad (3\text{-}2)$$

K is the conveyance, *A* is the cross-sectional area, *R* is the hydraulic radius, and *n* represents the roughness in the cross-section. Channel geometry was determined using the *3-D Analyst* profiler tool in ArcGIS (ESRI, 2011) and divided by empirical estimates of Manning's *n* based on substrate size, vegetation, cross-sectional variation, surface irregularity, and degree of obstruction from large wood (Barnes, 1967; Wissmar, 1996).

Results

Channel Erosion and Deposition

Spatially explicit DEM differencing provided highly detailed two-dimensional maps of geomorphic changes, quantified in terms of elevation changes in the floodplain and river bed ground surface elevations, as well as total positive and negative volumetric changes in sediment quantities following the disturbance (Table 3-2). In areas that eroded between surveys, elevation values were less than the previous year and represented by blue colors in the figures. The converse was true in places where bed surfaces aggraded and are represented by red areas in the figures. Areas in the floodplain that exhibited no change in elevation year-to-year are light tan in the figures (Fig. 3-4A; 3-4B; 3-4C).

Table 3-2. Length of surveyed reach during each year of the study. Thalweg elevations, gradient and variability are also reported. Note that highest variability during 2003 was due to deep pools associated with large wood jams in the channel.

Year	Length Surveyed (m)	Upstream Thalweg Elev. (m)	Downstream Thalweg Elev. (m)	Thalweg Gradient (m/Km)	Coeff. Variation *1000
2000	529.5	25.8	23.6	4.2	26.3
2001	929.3	26.8	22.2	5.0	31.7
2002	944.3	27.1	23.1	4.3	33.8
2003	914.8	26.8	22.5	4.8	37.0

The study reach underwent the highest erosion during the first year following the landslide (2000-2001) because lateral erosion removed nearly 14,000 m^3 of material from the floodplain as the side channel expanded to accommodate the river. More than 11,000 m^3 of material was deposited downstream in the original mainstem channel that was surveyed before the landslide disturbance (Fig. 3-4A, Table 3-2). During 2001-2002, the channel continued to widen and recruit large wood into jams that caused more erosion both laterally and vertically in the channel. As the channel expanded laterally, the bed surface became more heterogeneous owing to local scour and deposition around large wood in the upper part of the reach. Increased sediment deposition occurred in the downstream section of channel and was significantly ($\alpha = 0.05$, $P \ll 0.01$) more patchy than in the previous time step (Table 3-3). During 2002-2003, the channel continued to widen and many of the individual pieces of large wood were aggregated into large jams forming deep pools. Bed surface elevations became significantly less patchy ($\alpha = 0.05$, $P \ll 0.01$), and areas of erosion were associated with wood jams. Overall, the reach stored nearly 21% more material than was exported (Table 3-3).

Table 3- 3. Total volume of sediment stored and eroded in the channel and percent change presented for each interannual comparison. Statistical tests for differences in slope of the log of patch area regressed on the log of patch perimeter (Fractal dimension) were performed using analysis of covariance tests. All results were highly significant (P<<.001, α = 0.05). Changes in channel conveyance (K) is presented as reach averages and reach totals for each interannual comparison.

Year	Sediment Aggraded (m^3)	Sediment Eroded (m^3)	Change Sediment Storage (%)	Fractal (D)	Regression Equation	R^2	Average Change in Conveyance (%)	Total Change in Conveyance (%)
2000-2001	11274	13943	-24	1.29	$y = 1.5422x - 1.3559$	0.87	+0.78	+3.90
2001-2002	14311	18528	-29	1.31	$y = 1.5224x - 1.4027$	0.87	-0.84	-8.41
2002-2003	20962	16563	+21	1.27	$y = 1.5664x - 1.8416$	0.85	-0.74	-7.41

Changes in Channel Conveyance

Percent changes in conveyance were estimated based on 10 geographically consistent cross sections year-to-year (Fig. 3-5). Because channel measurements during 2000 only covered the downstream half of the study reach (Fig. 3-4A), the first interannual comparison was done for cross sections 6 through 10 (Fig. 3-5). During 2000-2001, conveyance increased slightly (< 1%) for all downstream cross sections. This was because of channel expansion along the unarmored right bank despite sediment deposition throughout the lower section of the reach (Fig. 3-4A). The second interannual comparison (2001-2002; Fig. 3-4B) indicated that conveyance was much more variable and decreasing at all but the upstream-most cross section where substantial channel widening occurred. Losses in channel conveyance capacity (K) increased in a downstream direction because of the large volumes of sediment recruited from the floodplain at the upper extent of the reach. During this period, the channel widened substantially, and roughness increased sharply because 67 large cottonwood trees, many of them fully spanning the channel, were recruited as the banks moved laterally (Fig. 3-2; Table 3-3). During 2002-2003, conveyance continued to exhibit decreases. The largest losses in conveyance capacity were associated with cross sections intersecting large jams. In particular, a large, channel-spanning jam formed near cross section 4. In addition, while the channel did expand slightly compared to the previous time step, the increases in geometry were small relative to increased roughness owing to channel irregularities and large wood (Fig. 3-4C; Table 3-3).

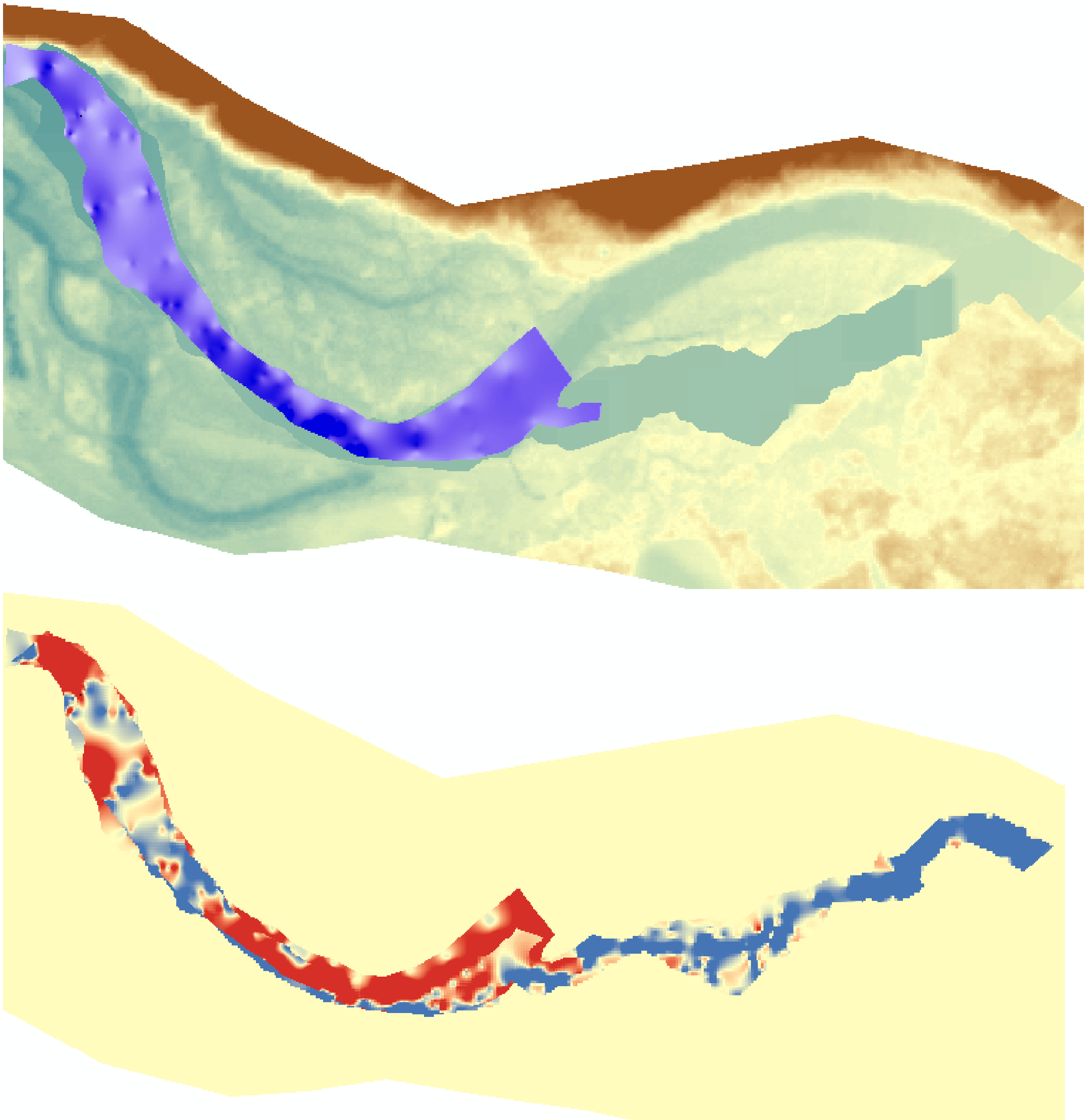

Figure **3-4A.** Spatial model of changes in channel bed surface and floodplain elevations measured during 2000-2001. No pre-disturbance data were collected in floodplain area that was subsequently occupied by the river. So, comparisons were limited to the downstream area. Lower panel illustrates areas of aggradation in red and erosion in blue.

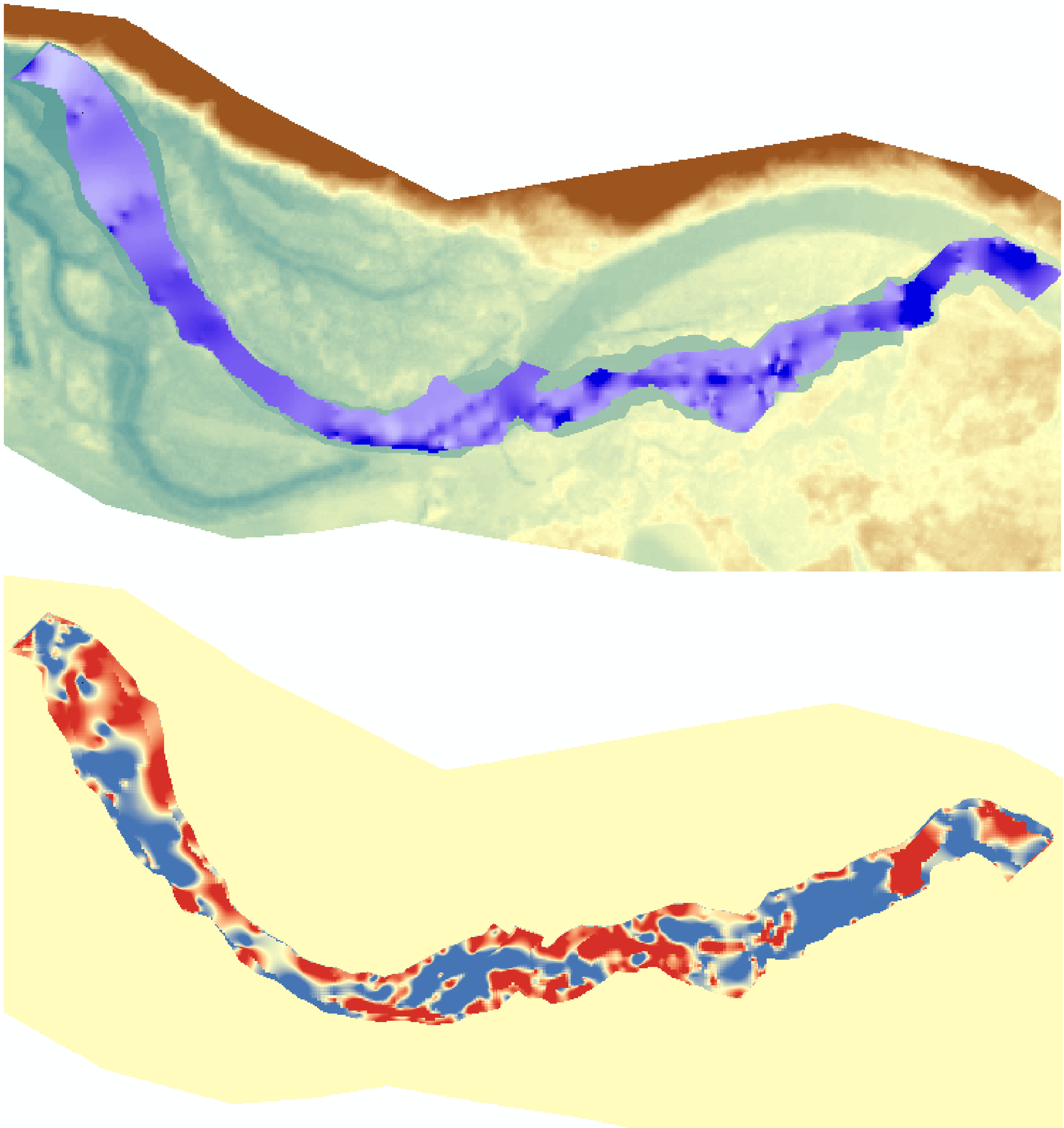

Figure 3-4B. Upper panel shows interpolated model of changes in bed surface elevations during 2001-2002overlain on floodplain DEM. Darkest blue areas indicate the deepest parts of the channel.

Lower panel shows areas of sediment aggradation (red) and erosion (blue) during 2001-2002. Depositional and erosional patches were most complex during this time period.

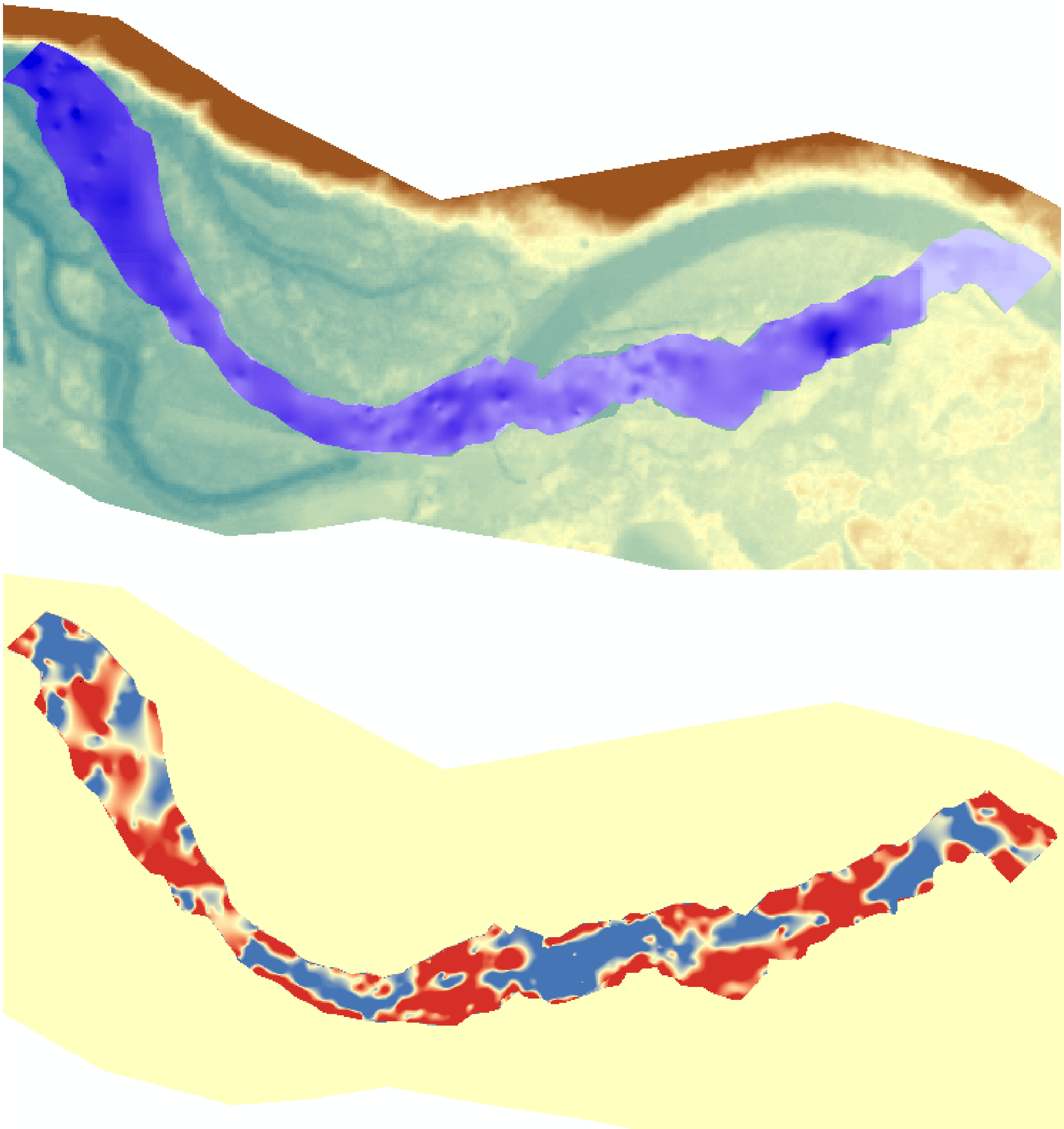

Figure 3-4C. Upper panel shows 2002-2003 changes in channel depths overlain on floodplain DEM. Darkest shades of blue represent deepest parts of the channel.

Lower panel shows areas of aggradation (red) and erosion (blue) during same period Complexity of contrasting patches decreased significantly from previous time step.

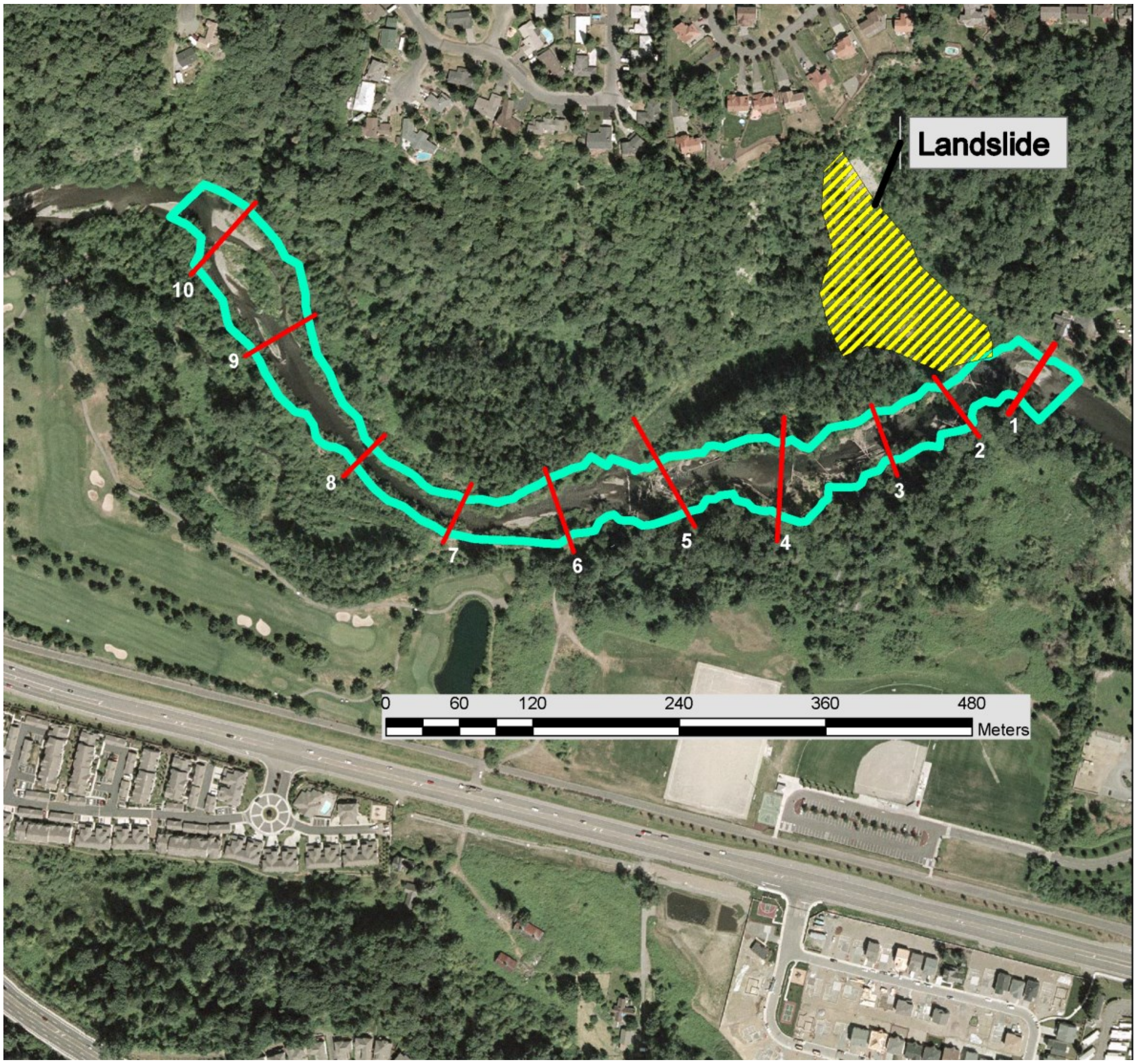

Figure 3-5. Location of ten cross sections used to estimate channel conveyance (K).

Discussion and Conclusion

Two lines of evidence support Le Chatelier's general law as a model for how rivers respond to disturbance. The first is that changes in channel complexity increased dramatically, and then started to decrease as the system assimilated and processed the disturbance (Table 3-3). Neither of these is surprising given that the amount of energy entering the reach, working through the reach, and leaving the reach is roughly the same minus some losses to turbulence and lost potential energy because of decreased energy gradients as channels widen and aggrade (Wolman and Miller, 1960). It follows then that channel capacity to convey discharge is a constant determined by the hydrologic regime

(Rubey, 1933). The second is that even as channel geometry expanded dramatically initially following the landslide, reach-averaged conveyance stayed fairly constant (Table 3-3). The importance of this observation is emphasized because river discharge throughout the study period, exhibited very few high flow events relative to the historic record (Fig. 3-6).

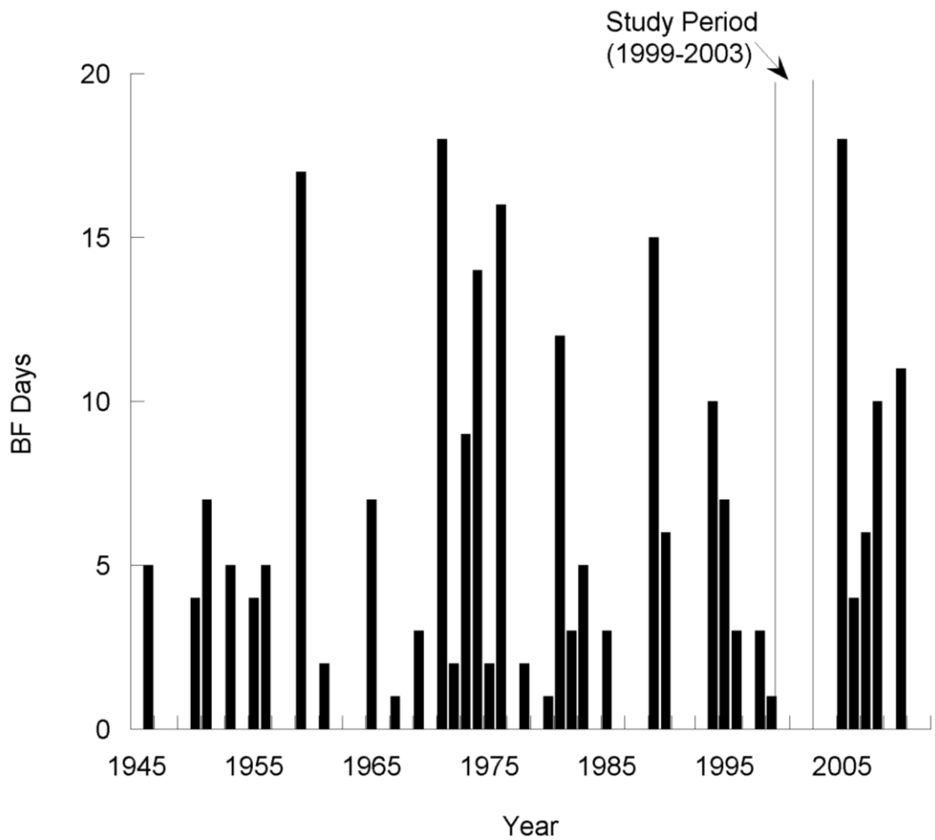

Figure 3-6. Bankfull days (BF Days) estimated from the historic flow record for USGS gauge 12119000. BF Days indicate the number of days when mean daily discharge resulted in river stage exceeded channel capacity. The discharge record covers from 1945 to 2012. Our study period extended from 2000 – 2003. Note, that no BF Days occurred during our study.

Specifically, when the hydrographic record (USGS gage no. 12119000) is examined, the magnitude, intensity, and duration of discharges sufficient to do geomorphic work on the channel can be extracted from the record based on user-defined time periods. By evaluating the number of days when discharges exceeded bankfull stage (Timm and Wissmar, in review), our study period can be placed in the context of the known flow record (Richter et al., 1996).In this case, we compared the discharge record during 2000-2003 with the historic record going back to 1945. The analysis indicated that during our study period, the highest peak discharge was 50cms. The mean discharge was slightly lower, as was the coefficient of variation of small flood discharges when compared with the pre-disturbance discharge record (Fig. 6). In addition, the number of bankfull days (BF Days) during our study was minimal, indicating that geomorphic changes in the study reach were not because of extended periods of high flows.

We also evaluated the discharge record since 2003 because of the influences of contemporary flows on newly deformed banks in our study reach. The number of BF Days increased from zero to more than 6 per year on average in the post-disturbance period (Fig. 3-6). In addition, Gendaszek et al., (in review) studied bed movement in the Cedar River with buried accelerometers across a range of confined and unconfined geomorphic units. Their findings indicate that large bed mobilizing events happened 10 times during 2010 and 2011. Flows required to substantially scour the bed in their study ranged from 63.9 to 154 cms. Gendaszek et al. (in review) found that bed scour in the lower Cedar River begins in the first 24 hours of discharge that approaches 65cms.

Le Chatelier's general law (Le Chatlier, 1884) states that "…for any stress brought to bear on a system in equilibrium, a reaction occurs, displacing the equilibrium in a direction which tends to absorb the effect of the stress…" (Leopold et al., 1964; Mackin, 1948). The removal of bank hardening and subsequent relocation of the river into the floodplain shifted resiliency from the river banks to the bed immediately following the landslide disturbance. By the end of the second year, lateral erosion of the banks stabilized as the channel geometry approached its maximum indicating that through that period, the bed was the most resilient system component. In addition, the bed surface elevations were very heterogeneous relative to the periods before and after because the river's energy available for work was not focused toward the bed. During the third year after the landslide, the channel geometry expanded very little and the bed surface elevations became significantly less patchy, indicating that more of the river's energy was focused on the bed than on the banks.

The channel expanded until the geomorphology matched the river's competency in a *dynamic equilibrium* (Hack, 1960; Strahler, 1957) consistent with what Gilbert (1877) defined as the *Graded River*. As the channel expanded laterally, large trees growing in the floodplain were undercut and recruited to the channel, establishing a feedback until the river's energy was matched to the channel's geomorphology. Additionally, as the channel widened and subsequently aggraded, the lateral movement of erosional forces likely began to interact with tree root systems instead of eroding beneath them. Consistent with Le Chatelier's general law, this would force energy to be expended in other directions, and in this case was manifest as work on the bed.

A spatially explicit examination of LeChatelier's law can be presented in terms of changes in fluvial complexity using fractal analysis. Recall that fractal dimension can be estimated by regressing the log of patch area against the log of patch perimeter (Mladenoff et al., 1993; Turner, 1990). For our study reach, the slope of the regression line increased during the first two interannual comparisons and then decreased below initial post-disturbance levels, demonstrating that system energy was continually redistributed through time following the disturbance.

When applied to dynamic fluvial systems, Le Chatelier's general law is taken that total energy in the river system is determined by the hydrologic regime. Changes in the relative stability of fluvial system components reallocate energy and manifest as changes in geomorphology and complexity (Mackin, 1948). Our findings indicate that the temporal dimension of the response of our study reach was surprisingly short within the domain of flows experienced during our investigation. This short response time was because lateral movement of the banks began to stabilize and shifted energy back to the bed within three years. Prior to the landslide disturbance, bank hardening was the resilient system component that maintained the channel geomorphology. When the bank hardening was obviated by the landslide, discharge became the process governing system complexity. The short equilibration time during our study period was apparently a function of the lack of large flow events. In the interim since our study ended, there were multiple large flow events that initiated more lateral channel movement through the reach. That relation can provide some insight into the amount of energy potentially available to do work on the river (Wolman and Miller, 1960) and what managers could reasonably expect in response to removal of hardened banks in alluvial river ecosystems of the Puget Sound lowland.

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Chapter 4: Changes in habitat complexity, discharge characteristics, and distributions of sockeye spawning populations before and after a landslide disturbance, Cedar River, Washington

Raymond K. Timm, and Robert C. Wissmar

Abstract

In 2001, a channel-damming landslide in the Cedar River, Washington changed habitat conditions and distributions of sockeye salmon (*Oncorhynchus nerka*). Our study evaluates annual changes in river habitat conditions and spawning distributions before and after the disturbance. We used an exhaustive CHAID (chi-squared automatic interaction detection) model to evaluate changes in habitat complexity and spawning distributions. We analyzed 54 years (1952-2006) of weekly surveys of fish distributions. Before the landslide, the spatial and temporal patterns of sockeye distributions were heavily influenced by spawning locations of parental generations. Sockeye densities were highest in the upper-most river reaches. After the landslide, habitat complexity and fish densities increased in the lower river reaches. The CHAID model analyses indicate fluvial habitat complexity, river discharge characteristics, and the fish density of respective parent generations were significant ($P < 0.001$), and explained spawning distributions by reach. Our analysesof how changes in habitat complexity influence salmon populations at the reach-scale, inform questions of the magnitude and intensity of disturbance necessaryto restore vital habitat functions of river landscapes.

Short Title: Population-scale fish response to disturbance-mediated habitat changes.

Keywords: Landslide disturbance, habitat complexity, discharge characteristics, river reaches, salmon spawning distributions, exhaustive CHAID model

Introduction

Aquatic ecologists have long recognized that large scale disturbances can change the structure and function of river ecosystems (Michener and Haeuber, 1998; Wissmar and Swanson, 1990; Poff, 1992; Stanford and Ward, 2001). Effects of natural and human-induced disturbances on sediment and hydrologic regimes of watersheds, channels, and floodplains are well documented (Ward and Stanford, 1983; Allan, 2004; Bisson *et al.*, 2005; Timm and Wissmar, 2012). However, understanding the space and time interactions between changes in habitat characteristics and distributions of fish spawning populations remains a scientific and management challenge. With some notable exceptions (e.g. Montgomery *et al.*, 1999; Fausch *et al.*, 2002; Johnson *et al.*, 2005; Milner *et al.*, 2008), studies documenting the coupling of fluvial processes with changes in salmonid populations are lacking. This shortcoming is largely due to spatial and temporal scale effects of interacting physical and biological variables (Paulsen and Fisher, 2005; Roni *et al.*, 2008).

A primary challenge in understanding the disturbance ecology of river ecosystems includes identifying appropriate factors and units necessary to understand the hierarchical scales of physical and biological processes (Hughes *et al.*, 2006). In river ecosystems, several factors commonly limit the understanding of these processes. For example, independent variables frequently do not adequately discriminate between correlation and causation because of the lack of consistency between spatial and temporal scales of the physical and biological phenomena under investigation (Feist *et al.*, 2003; Wang *et al.*, 2006). For physical aspects of river ecosystems, the properties of fluvial boundaries that govern the formation of habitats are poorly understood (Ward *et al.*, 2002; Wiens, 2002). For dependent variables such as fish populations, there is commonly limited knowledge of fish phenotypic and genotypic responses to physical changes (Reeves *et al.*, 1991; Levin, 1992; Young *et al.*, 2001).

On February 28, 2001 a landslide during a 6.8 magnitude earthquake dammed the Cedar River in western Washington State. The landslide deposited approximately 50,000 m^3 of sediment and debris in the main channel approximately 8 km upstream from Lake Washington (Figure 4-1). The earthquake-induced landslide and subsequent changes in channel and floodplain complexity created unique circumstances for evaluating salmon responses to a large-scale natural disturbance in a river ecosystem. The landslide forced the flow of the main river into floodplain forests, and caused rapid expansion of side-channels. New channels routed increased loads of landslide debris and floodplain sediment, recruited large wood from riparian forests, and created and abandoned fluvial habitats (Timm and Wissmar, 2012).

This study evaluates the temporal and spatial impacts of the 2001 landslide disturbance on the formation of habitats and changes in distributions of spawning sockeye salmon. Using a hierarchical model, we evaluated the response of spawning sockeye to changes in habitat complexity at the reach scale and identified the most important factors related to changes in spawning fish distributions.

Study area

The Cedar River drainage (530 km^2) drains from the Cascade Mountains into Lake Washington near Seattle, Washington. The drainage is managed as two distinct basins. The upper two thirds of the drainage is largely forested and managed by the City of Seattle as a drinking water supply. The lower Cedar River (165 km^2, Figure 4-1) is characterized by a matrix of rural, suburban, and urban areas (Wissmar *et al.*, 2000). Human population growth and increased land and water uses during the past century have fragmented and altered fluvial and riparian habitat in the lower Cedar River (King County, 1993; Timm *et al.*, 2004). In addition, the main river channel configurations and sediment transport processes have been constrained by flood control structures and flow regulation (Perkins, 1994; Wissmar *et al.*, 2004; Timm and Wissmar, 2012).

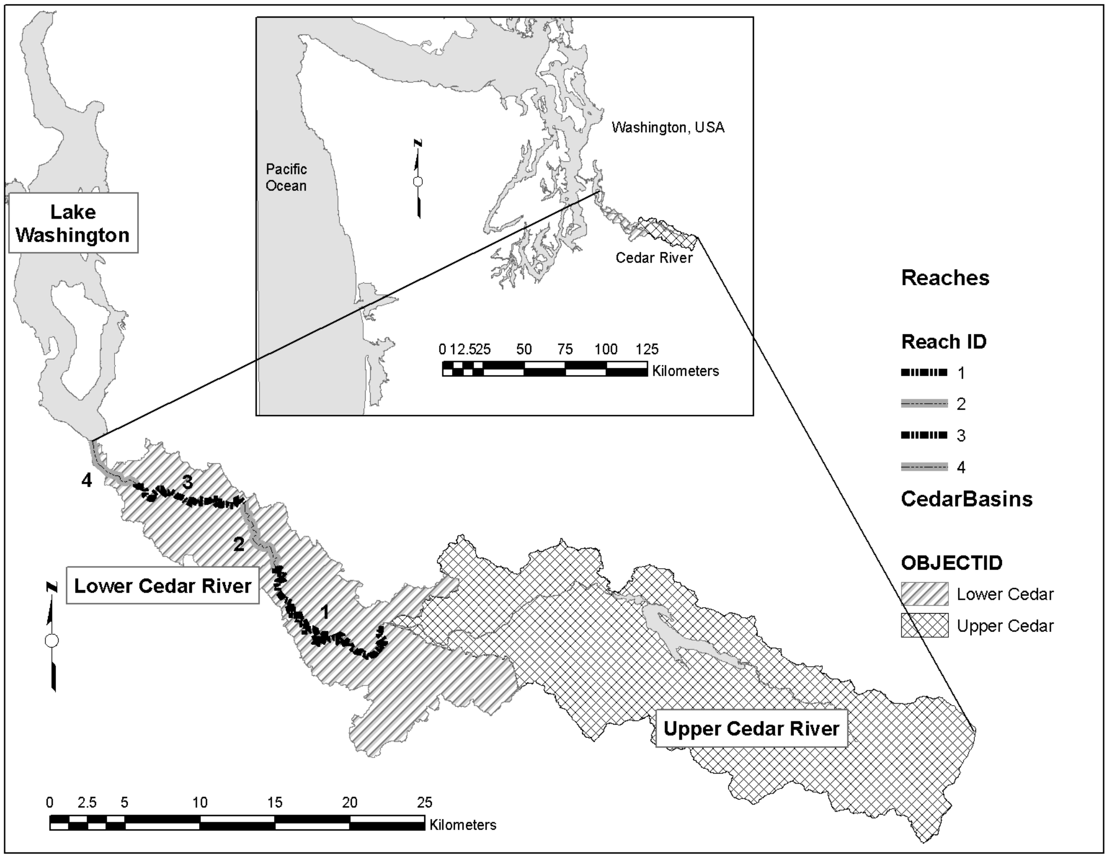

Figure 4-1. Location map of the Cedar River drainage, Washington. The upstream reach is number 1, and the downstream reach is number 4. The asterisk near the downstream end of Reach 3 signifies the approximate location of the 2001 landslide, approximately 8 km upstream from Lake Washington.

The river drainage is relatively young geologically and has experienced a variety of large natural disturbances including tectonic movements and glaciation. Among the most frequent natural disturbances are landslides as the river incises down through glacial deposits (Alt and Hyndman, 1984; Booth *et al.*, 2003). Anthropogenically, the drainage has undergone dramatic hydrologic changes beginning more than a century ago. Coincident with the construction of hydropower and water diversion dams in the upper river basin was the construction of locks and a ship canal between Lake Washington and Puget Sound at the beginning of the 20th century as well as extensive flood control structures and bank hardening throughout the lower river (Chrzastowski, 1983; Perkins, 1994; Gendaszek *et al.*, 2012). Currently, in the lower Cedar River, channel constraints and flow regulation limit sediment routing and storage that contributes to the formation of river channel habitats and determines the quality of spawning areas for sockeye salmon (Beechie and Sibley, 1997; Kerwin, 1999; Kerwin, 2001; Collins and Montgomery, 2002).

The Cedar River sockeye population is the largest outside of British Columbia and Alaska. This fish stock is economically important during years when escapement allows for a sport fishery (Bryant, 1976; Bartlet, 2001; Washington State, 2012). Because of the value placed on this species, the Washington Department of Fish and Wildlife (WDFW) has been monitoring sockeye populations in the Cedar River since 1952 (Ames, 2006). Spawning sockeye surveys were established for four WDFW index reaches in the lower river (Ames, 2006, Figure 1). Reach 1 extends from Landsburg Dam (rkm 34.1) down to rkm 23.4. Reach 2 lies between rkm 23.4 and rkm 14.9. Reach 3 extends from rkm 14.9 to rkm 6.7. The most downstream reach 4, extends from rkm 6.7 to the mouth at Lake Washington.

Methods

CHAID Tree Model

We used an exhaustive chi-squared automatic interaction detection (CHAID) tree model to evaluate the responses of spawning sockeye populations to changes in habitat complexity and discharge characteristics caused by the landslide disturbance (Urban, 2002; PASW, 2009). Our null hypothesis was that sockeye spawning distributions were unrelated to disturbance-mediated changes in independent variables (Table 4-1). Rejected hypotheses resulted in a split on the variable with the most explanatory power (Bak *et al.*, 1988; De'ath and Fabricius, 2000).

Table 4-1. Variables used to evaluate changes in sockeye spawning distributions and habitat complexity before and after the 2001 landslide disturbance, Cedar River, Washington. Sockeye spawning characteristics, Spawning Fish (SF) and Parental Generation (PG, Bryant 1976) represent spawning records from 1953 to 2006 (WDFW 2005, Ames 2006). Edge density (ED, $m \cdot m^{-2}$) was used to quantify spatial characteristics of habitats and channels (McGarigal et al., 2002). Habitat and channel variables include: Low Flow Habitat (LFH), Gravel Bars (GR), Vegetated Patches (VP), Forested Islands (FI), Forested High Flow Channels (FFHF) and Oxbows (OX) (Collins et al., 2003). Mean Daily Discharge (Q) and Bankfull Days (BF Days) were estimated from USGS flow records (1945 to 2006)*.

Variable	Definition
Year	Spawning year based on time of spawning migration
Spawning Fish (SF)	Total weekly number of spawning sockeye counted in each reach
Parental Generation (PG)	Number of parental-sockeye spawning in each reach four years prior to SF
Low Flow Habitat (LFH)	Area -weighted edge density of low flow channel and habitat features
Gravel Bars (GR)	Area-weighted edge density of gravel bar features in the active channel
Vegetated Patches (VP)	Area-weighted edge density of vegetated patches in the active channel
Forested Islands (FI)	Area-weighted edge density of forested islands in the active channel
Forested High Flow Channels (FFHF)	Area-weighted edge density of forested high flow channels in the active channel
Oxbows (OX)	Area-weighted edge density of oxbow features in the active channel
Total Edge Density (ED)	Total area-weighted edge density of habitat and channel features (LFH, GR, VP, FI, FFHF, OX).
Mean Daily Discharge (Q)	Average weekly mean daily discharge at USGS Gage no. 12119000
Bankfull Days (BF-Days)	Number of days mean daily discharge exceeding bankfull stage

* All variables were estimated for four reaches in the lower Cedar River, Washington (Figure 4-1) both before and after the 2001 landslide disturbance.

The CHAID model employs a recursive partitioning method that splits multivariate datasets into hierarchical trees by chi square contingency analysis. Adjusted significance tests are applied until no more paired hypotheses can be rejected. The model searches for significant statistical relationships ($\alpha = 0.05$, $P < 0.001$) through a stepwise process between independent variables (Table 4-1) and the dependent variable (spawning densities of sockeye salmon). The hierarchical order of these pairings indicates the strength of the respective relationships. As the model identifies relationships with the smallest adjusted *P*-values they are represented at nodes where branches of the tree split.

Sockeye salmon

Sockeye spawning distributions were evaluated as a function of habitat complexity, discharge characteristics and patterns of parent generations (spawning distributions) in four reaches of the lower Cedar River over a 54 year period (1952 to 2006). Comparisons included before and after periods, 1952-2000 and 2001-2006, respectively.

Sockeye salmon spawning records were analyzed for the four WDFW index reaches from 1952 to 2006. Escapement was estimated using the area under the curve (AUC) method (Ames, 1984; Perrin and Irvine, 1990). When data from some early surveys were insufficient to satisfy the requirements of the AUC model, linear regression between live fish and escapement was used to estimate the number of spawning fish in each reach (Gallagher and Gallagher, 2005). For spawning Cedar River sockeye salmon, we found live fish counts explained 73% of the variation associated with escapement estimates for all reaches during all time periods. Therefore, live fish numbers were used for all time periods in the model. Total fish counts of spawning fish within each reach were analyzed by the week of the spawning season for every year. This approach allowed segregation of the population’s weekly distribution by reach for every year, before and after the landslide.

Independent variables

Spawning season events of particular interest were spawning times of parental generations and discharge events that mobilize spawning gravels and impact incubating eggs. The parental generation (PG) was considered an independent variable because spawning distributions of parent fish and their homing capabilities represent important determinants of future population structures (Quinn, 2005).

We used spatially explicit datasets of fluvial and floodplain habitat features from orthorectified aerial photography records following Collins *et al.*, (2003, Table 4-1). Habitat characteristics were quantified as area weighted edge density (ED) using ArcGIS (ESRI, 2011) and Fragstats (McGarigal and Marks, 1994) (Figure 4-1). ED metrics were normalized by area to reduce the disproportionate dominance of large patches (McGarigal *et al.*, 2002). This was important because low flow channels (LF) were dominant by habitat area. Area weighted edge densities (ED) were estimated for thirteen series of aerial photographs between 1936 and 2005, and summarized for all 4 study reaches. The ED metrics represent the complexity of patches within the fluvial landscape (Wiens, 2002).

Total area weighted Edge Density (total ED) represents the sum of all sums of the edges of all habitat types divided by the sum of patch areas for all respective habitat types (McGarigal *et al.*, 2002) (Table 4-1). The total ED represents six fluvial patch types after Collins *et al.* (2003). These patch types included low flow habitat (LFH); gravel bars (GR); vegetated patches (VP); forested islands (FI); forested high flow channels (FFHF) and oxbows (OX) (Table 4-1). Descriptions of independent physical variables used in the model including the total edge density (ED) and metrics for other variables are presented in Table 4-1.

Other important variables included the average weekly discharge during spawning surveys (Q), and the number of days discharge met or exceeded the channel's bankfull capacity (BF-Days; Table 4-2). Discharge is an important variable because populations of salmonids can migrate and adapt in response to changes in discharge and stage-related habitat availability (Graybill, 1974; Milner and Bailey, 1989; Ward, 1989; Ward and Stanford, 1995; Quinn, 2005; Tockner *et al.*, 2006; Pess, 2009). Flow records were compared to changes in habitat and biological data (USGS gauge # 12119000). The recurrence interval for BF- Days was calculated for each reach (Dunne and Leopold, 1978).

The average bankfull discharge for each reach was estimated from calibrated King County flood models and USGS discharge records (King County, 2000, USGS gauge # 12119000). Bankfull discharge events in rivers of western Washington occur approximately once every 1.5 years and are the flows most responsible for channel geomorphology and potential bed mobility (Wolman and Miller, 1960; Leopold, 1994; Castro and Jackson, 2001; Julien, 2002). Bankfull discharge rates that induce bed mobility of gravels in spawning areas can reduce the survival of embryos deposited by parental generations (Bryant, 1976; Dunne and Leopold, 1978; Montgomery *et al.*, 1999).

Results

Changes in habitat complexity and bankfull days

Complexity of habitat patch types (LFH, GR, VP, FI, FFHF, OX; Table 4-1) was summarized as total edge density (ED) for all four reaches and time periods (Table 4-2). Before the 2001 landslide, ED ranged from 337 $m \cdot m^{-2}$ to 537 $m \cdot m^{-2}$ in reaches 1 and 2 and from 293 $m \cdot m^{-2}$ to 489 $m \cdot m^{-2}$ in reaches 3 and 4. After the landslide and channel adjustments, ED in reaches 1 and 2 ranged from 337 $m \cdot m^{-2}$ to 450 $m \cdot m^{-2}$, and in reaches 3 and 4 ranged from 427 $m \cdot m^{-2}$ to 480 $m \cdot m^{-2}$ (Table 4-2). Bankfull days, before the landslide disturbance, were highest in reaches 1 and 2. The highest frequencies, 101 and 79 days occurred during 1980 (Table 4-2). After the landslide, the number of BF days ranged from 0 – 1 days in 2002 and 28 – 43 days in 2005(bold data Table 4-2).

Table 4-2. Total Edge Density (ED) and bankfull days (BF Days) of four reaches of the Cedar River, before and after (bold type) the landslide disturbance.

Year	Total ED ($m \cdot m^{-2}$)				BF Days (days)			
	Reach 1	*Reach 2*	*Reach 3*	*Reach 4*	*Reach 1*	*Reach 2*	*Reach 3*	*Reach 4*
1936	441	421	293	358				
1944	420	367	330	404				
1948	415	400	375	454	8	5	5	5
1959	363	537	395	401	72	52	43	42
1964	354	368	398	291	24	17	12	9
1970	401	393	387	287	23	6	4	4
1980	533	337	363	310	101	79	65	63
1985	494	429	479	296	41	29	26	24
1989	423	409	489	389	0	0	0	0
1995	372	351	438	310	48	37	32	31
2000	378	361	326	243	43	28	17	15
2002	**337**	**402**	**427**	**316**	**1**	**0**	**0**	**0**
2005	**441**	**450**	**480**	**282**	**43**	**34**	**28**	**28**

* Total edge density (ED $m \cdot m^{-2}$) for spatial characteristics of habitats and channels (Table 4-1).

Spawning fish distributions

Before the landslide disturbance, 30% to 40% of sockeye salmon spawning occurred during weeks 35 to 45 in each of reaches 1, 2, and 3 (Figures 4-2a, 4-2b, 4-2c respectively). In contrast, spawning sockeye presence in downstream reach 4 was less than 10% prior to week 45 (Figure 4-2d)

After the 2001 landslide, spawning sockeye were redistributed in all four reaches with the most significant changes in reaches 1 and 4 (Mann-Whitney U tests, $P< 0.01$) (Figure 4-2a, 4-2b, 4-2c, 4-2d). The landslide occurred near the downstream end of reach 3 and caused dramatic changes in spawning distributions within reach 4. The highest proportions of spawning sockeye salmon (ranging from 24% to 40%) occurred during weeks 37 to 47 in reach 4 (Figure 4-2d). Differences between fish distributions before and after the landslide indicate that the peak spawning time was in week 48 before the landslide and in week 42 after the landslide (Figure 4-2d). This change was significant at the 0.01 level. In addition, after the landslide, the new peak spawning period in reach 4 was significantly (Mann-Whitney U tests, $P < 0.01$) different than the three upstream reaches (Figures 4-2a, 4-2b, 4-2c, 4-2d).

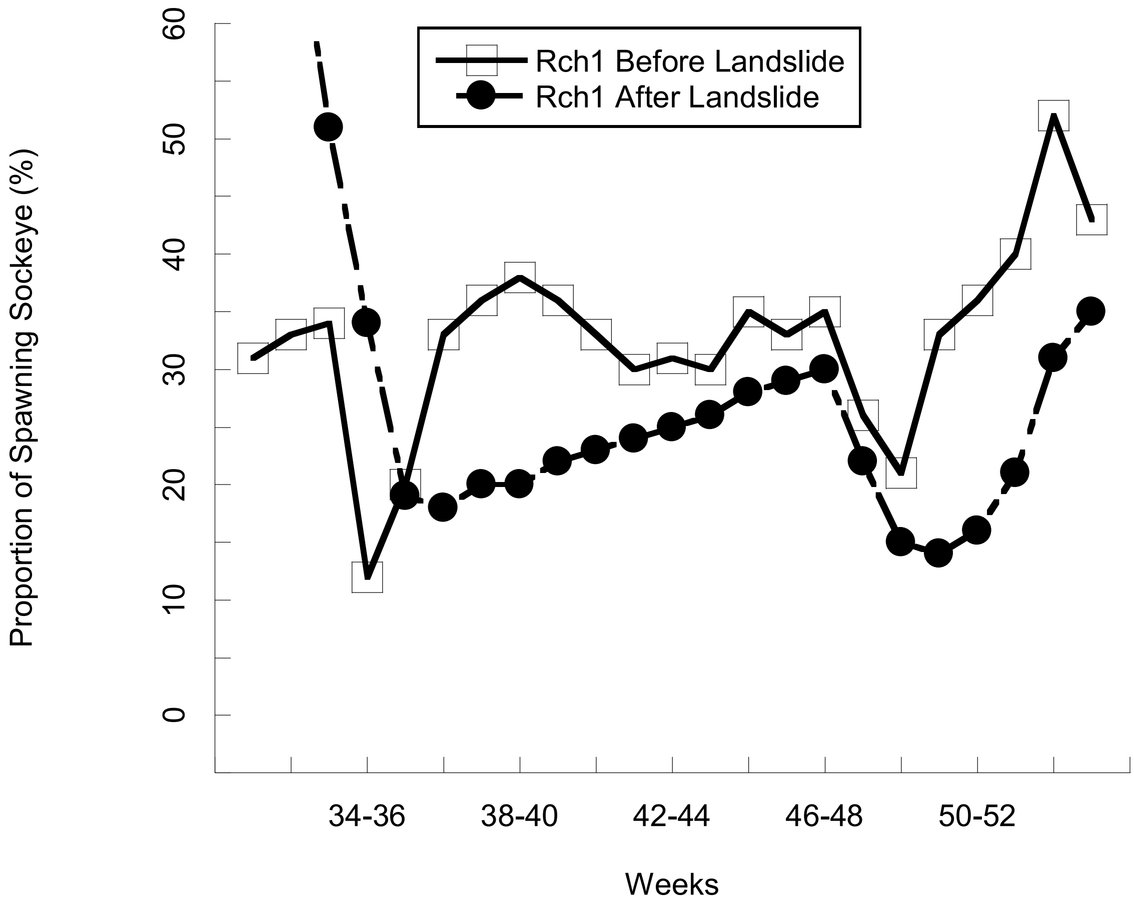

Figure 4-2a. Spawning sockeye salmon distributions in Reach 1 as a proportion of total weekly fish densities in all reaches, both before (1952-2000) and after (2001-2006) the landslide disturbance. Historically, the greatest number and earliest fish spawned in reach 1.

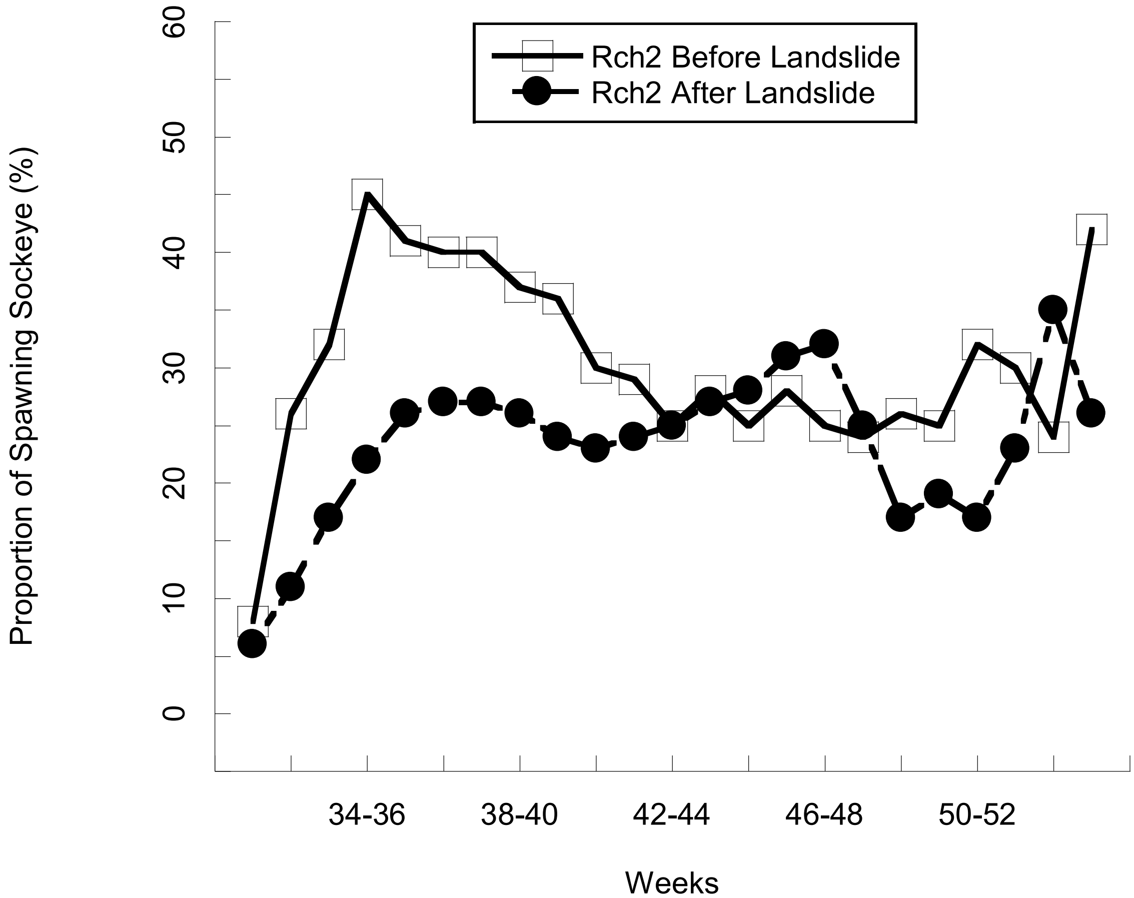

Figure 4-2b. Spawning sockeye densities in reach 2 of the lower Cedar River, as a proportion of total weekly run size across all reaches during the spawning season. Analyses included the spawning surveys from before the disturbance (1952-2000), and after the landslide disturbance (2001-2006). Spawning fish distributions in this reach were not significantly affected by the disturbance.

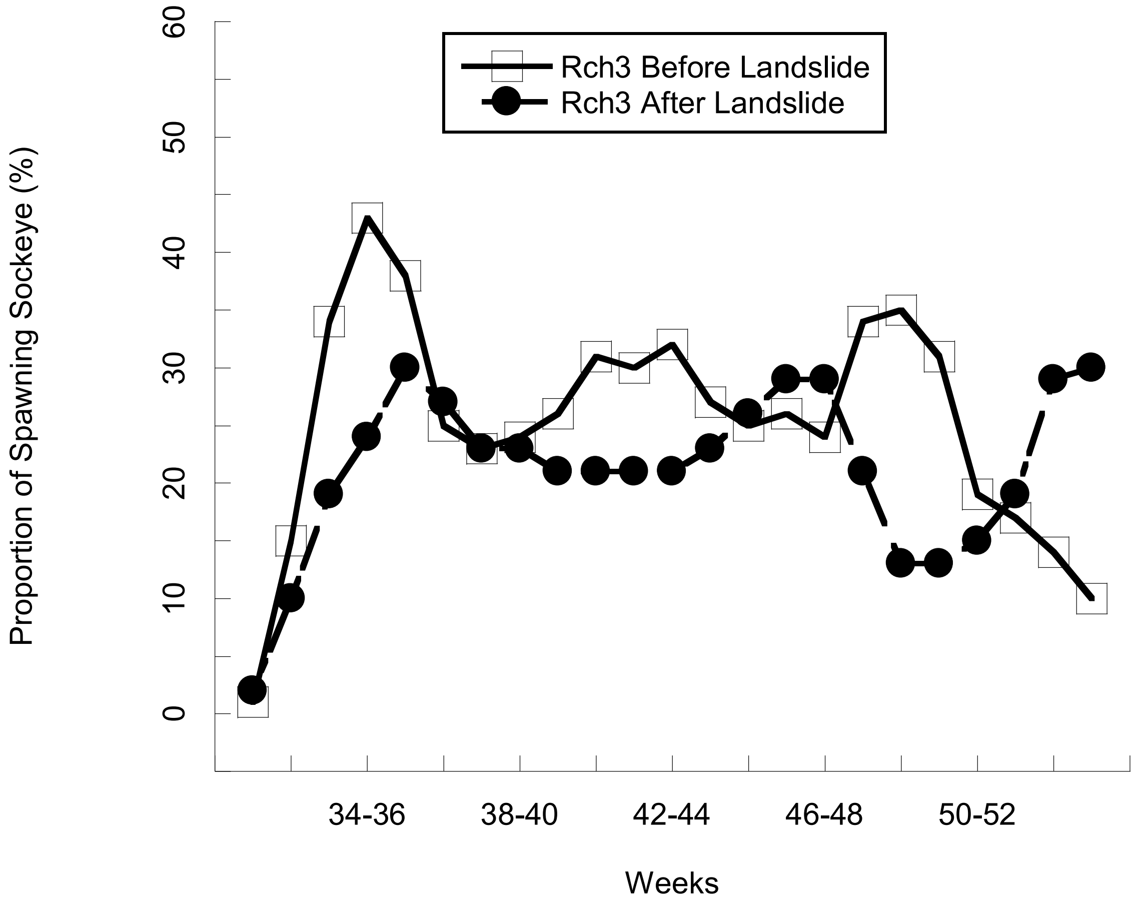

Figure 4-2c. Spawning sockeye densities in reach 3 of the lower Cedar River, as a proportion of total run size across all reaches by week during the spawning season Analyses included the spawning surveys from before the disturbance (1952-2000), and after the landslide disturbance (2001-2006). The timing of fish use of this reach was relatively unaffected by the landslide. The landslide disturbance occurred near the downstream extent of reach 3 (Figure 4-1).

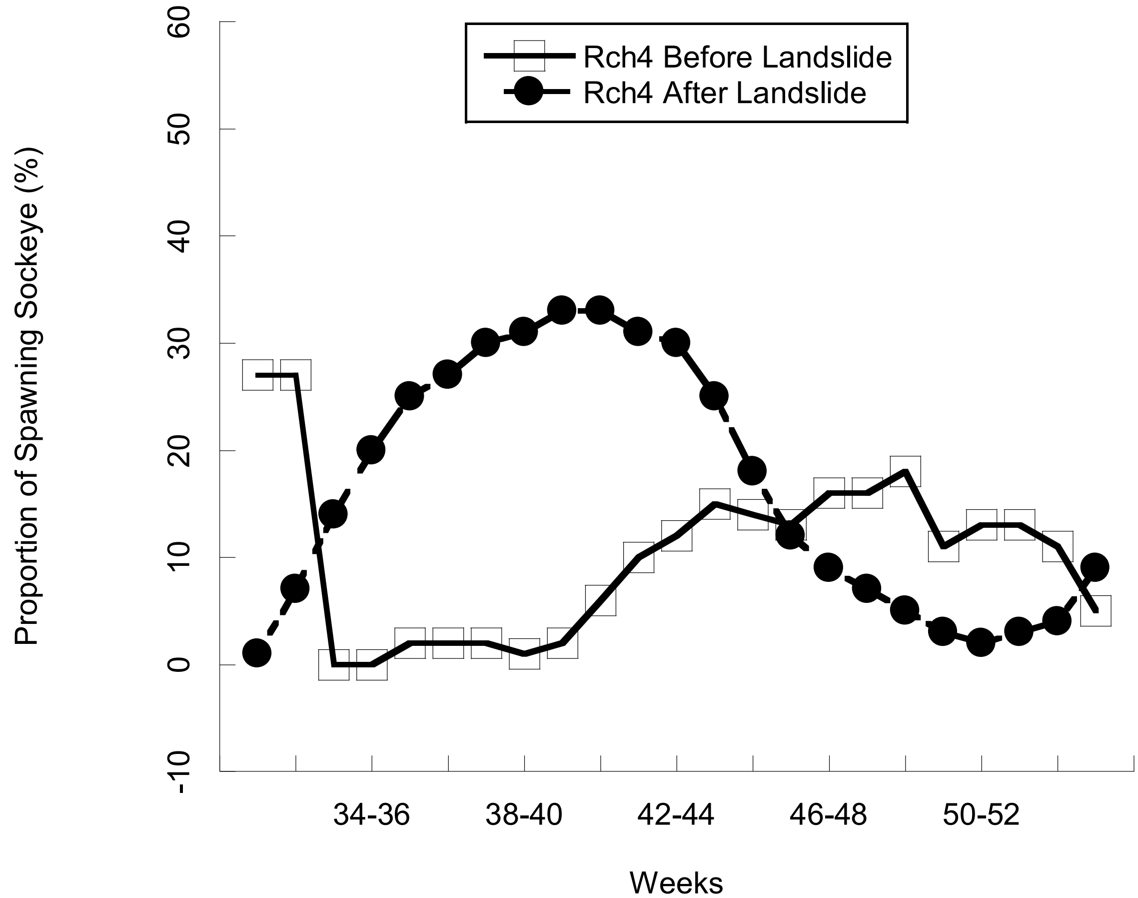

Figure 4-2d. Spawning sockeye salmon distributions in Reach 4 as a proportion of total weekly fish densities in all reaches, both before (1952-2000) and after (2001-2006) the landslide disturbance. Peak spawning fish use of this reach was significantly earlier in the period after the landslide compared to spawning distributions before the landslide disturbance.

Model outputs

Before the landslide disturbance, the CHAID tree model indicated for the most upstream reach 1, the number of spawning fish (SF) was significantly related to the edge density (ED) of low flow channel habitat (LFH) followed by the size of the parent generation (PG) and average weekly discharge (Q) (F tests, $P < 0.001$, Table 4-3). Analyses for reach 2 indicated SF was most significantly related to the complexity of forested islands (FI), followed by PG, Q, and then LFH. Analyses for the downstream reaches 3 and 4 indicated spawning fish numbers (SF) were most significantly related to PG.

Before the landslide the model indicated for the most downstream reach 4 an average of 16,745 spawning fish (SF within box, Figure 4-3). Influences of significant independent variables are shown where the tree splits. The most significant determinant was the size of the parent generation (PG) which split when there were 13,170 fish. The spawning fish decreased to 7,461 fish when the complexity of gravel bars (GR) exhibited edge density (ED) > 23 $m \cdot m^{-2}$. The next split indicates a decrease in spawning fish to 1,669 when ED of GR < 23 $m \cdot m^{-2}$. Where GR complexity values exceeded an ED of 23 $m \cdot m^{-2}$, 9,595 spawning fish were present. At the first split, when PG exceeded 13,170 fish, the complexity of the low flow channel habitat (LFH, ED = 257 $m \cdot m^{-2}$) was the most important factor and 51,226 spawning fish were present (Figure 3). As LFH complexity values declined below ED = 257 $m \cdot m^{-2}$, 102,425 spawning fish were present, whereas LFH complexities exhibiting ED > 257 $m \cdot m^{-2}$ indicated 49,222 spawning fish.

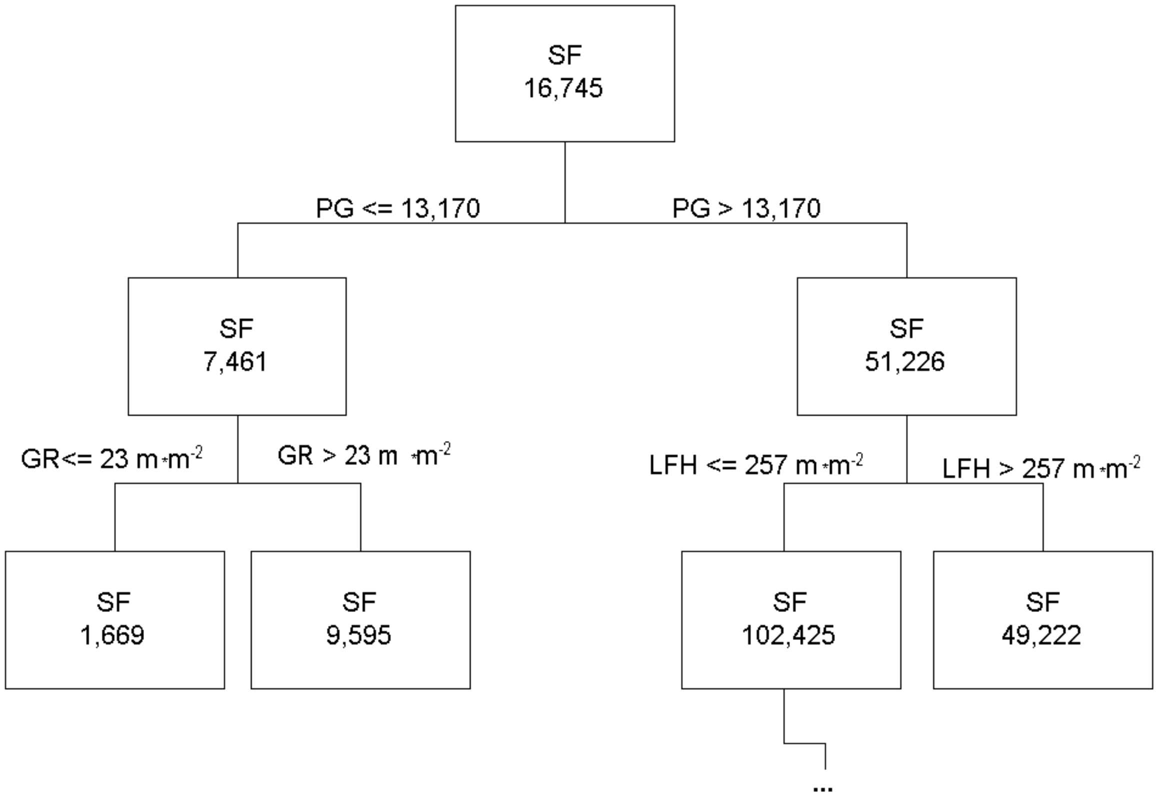

Figure 4-3. Pre-landslide CHAID tree diagram of factors explaining the presence of spawning fish in reach 4. Figures inside boxes indicate the average spawning sockeye numbers (SF) for reach 4 for years 1952 to 2000. Independent variables with significant relationships to spawning sockeye split on the value presented above connecting lines. The ellipsis (three dots in a row) indicates that this tree contains more information than is presented in the figure (see Appendix A for full results of CHAID tree models).

After the landslide, for upstream-reaches 1 and 2, the most important factors influencing spawning numbers were the size of their parent generation (PG) (Table 4-3). The complexity of low flow-channel habitat (LFH) and mean weekly discharge (Q) were the next most important variables determining SF in both upstream reaches. In reach 3, the most important factors influencing spawning densities were LFH followed by GR and PG. Downstream in reach 4, the most significant factors were PG, LFH and Q (Table 4-3).

After the landslide, the tree model for the downstream-reach 4 indicates 44,910 spawning fish were present (Figure 4-4). The first split in spawning fish occurred when LFH was 242 m·m^{-2}. When LFH was less than 242 m·m^{-2}, 60,378 fish were present in the reach. For spawning fish less than 60,378 fish, the parent generation (PG) was the most important (38,000 fish). As PG declined below 38,000 fish, there were 61,980 spawning fish present. When PG exceeded 38,000 fish, 57,173 spawning sockeye were present in the reach. At the first split, when the complexity of LFH was greater than 242 m·m^{-2}, there were 29,442 spawning fish in the reach. A secondary split occurred when Q was 15 cms indicating 28,875 and 30,577 spawning fish, above and below this discharge respectively (Figure 4-4).

Table 4-3. Tree model outputs of weekly spawning sockeye salmon in four reaches of the Cedar River, before (1953-2000) and after (2001-2006) the landslide disturbance. Table columns indicate the reach (1-4), significant* variables (LFH, PG, Q, FI, GR, Table 4-1), the number of significant pairings (*n*), and model iterations (*i*).

	Reach	Significant Variables	*n*	Iterations (*i*)
Before Disturbance	1	LFH, PG, Q	36	3
	2	FI, PG, Q, LFH	21	3
	3	PG, Q, GR, LFH	17	3
	4	PG, GR, LFH, Q	18	3
After Disturbance	1	PG, LFH, Q	9	3
	2	PG, LFH, Q	9	3
	3	LFH, GR, PG	7	3
	4	PG, LFH, Q	7	2

*F tests at $P = 0.001$.

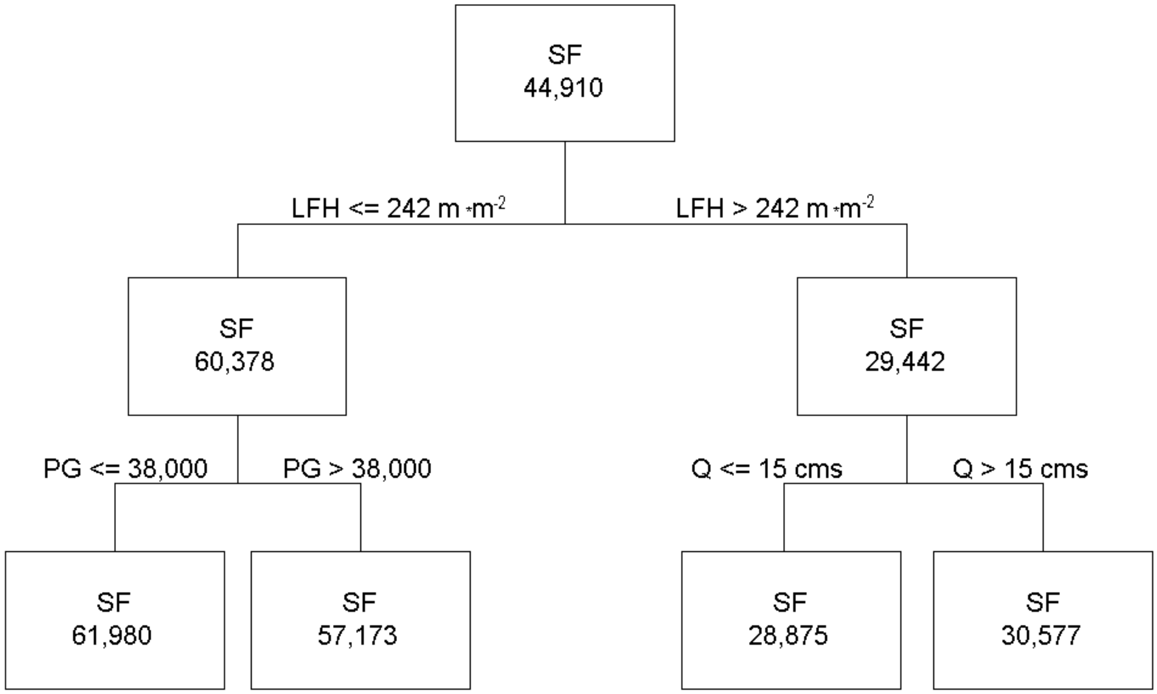

Figure 4-4. Post-landslide CHAID tree diagram of factors explaining the presence of spawning fish in reach 4. Numbers inside boxes indicate the average spawning sockeye numbers for reach 4 for years 2001 to 2006. Independent variables with significant relationships to spawning sockeye split on the value presented above connecting lines.

Discussion

The Cedar River and other Holocene river basins of Puget Sound, have a history of frequent landslides as the rivers incise down through glacially deposited material (Collins and Montgomery, 2002; Booth *et al.*, 2003). Historic reconstruction (1936 to 2002) of cliff erosion and landslide events in the lower Cedar River indicates that the recurrence interval for landslides approaching the magnitude (50,000 m^3) of the 2001 landslide has a frequency of approximately 7 years (Perkins Geosciences and Harper Houf Righellis, 2002). These observations support retrospective analyses that identify pulses of sediment and debris loadings necessary to sustain salmonid habitats in coastal rivers of the Pacific Northwest (Benda *et al.*, 1992; Reeves *et al.*, 1995; Beechie, 1998).

The long-term record of spawning sockeye salmon in the lower Cedar River demonstrates well-developed run times and spatial segregation by reach (Ames, 2006). Our analyses indicate that before the landslide disturbance (2001), early run fish were most abundant and preferred the upstream reaches where channels and habitats were most complex. After the landslide, sockeye spawning distributions shifted to the most downstream reach. The redistributed spawning sockeye populations corresponded to changes in channel and habitat complexity that increased dramatically in this reach. In the landslide-impacted reach, sediment and debris initially blocked the channel. Subsequently, these materials were eroded and transported to the most downstream reach, resulting in enhanced channel and habitat complexity, and greater numbers of spawning fish.

Temporally, weekly changes in distributions of spawning populations demonstrated the reach-scale changes in habitat quality following the landslide disturbance. These findings indicate how sockeye populations adapt to new habitats within the same river ecosystem. Although salmonids are known to exhibit spawning site fidelity, their capabilities to colonize newly formed habitats have been widely demonstrated (Schlosser, 1991; Reeves *et al.,* 1991; Reeves *et al.*, 1995; Benda *et al.*, 2004; Pess, 2009). Our study findings are consistent with previous research on the importance of landscape-scale disturbances and the capacity of salmonid populations to colonize yearly and thrive in new habitats distributed across large drainage areas (Milner and Bailey, 1989).

Our findings reinforce concepts that fluvial landscapes are hierarchically structured and spatially dynamic across reaches (Fausch et al., 2002). The resolution of our datasets (reach lengths 6 km to 10 km, and weekly spawning surveys) revealed important variability that is obscured at larger spatial and temporal extents. The response of spawning sockeye in the Cedar River was measurable and significant when analyzed at these scales. Accordingly, our results indicate thresholds for reach-scale habitat complexity that can contribute to higher numbers of spawning fish.

Recent studies of landscape-scale fish responses have focused on catastrophic events like the eruption of Mt. St. Helens, barrier removal such as Hell's Gate landslide on the Fraser River, Canada, and glacial retreat that created new coastal river networks in Alaska (Bisson *et al.*, 2005; Milner *et al.*, 2008; Pess, 2009). These studies indicate how fish populations can recolonize and stray into new habitats over multiple generations within riverine landscapes. Most of these studies are based on discrete samples of fish densities along stream networks to infer population responses (Pess, 2009). Our study supports previous work that fish responses should be quantified across spatial continua (Schlosser, 1991; Fausch *et al*., 2002) and advances concepts of scale that integrate river ecosystems and the landscapes they drain (Wiens, 2002). We provide new perspectives on thresholds for reach-scale habitat complexity that can affect where fish choose to spawn. The weekly changes in distributions of spawning sockeye demonstrated that the reach-scale changes in habitat quality following the landslide disturbance triggered a biological response at the population scale. These findings provide insight into the magnitude of habitat change necessary to induce a population of salmon to adopt new habitats within the same river ecosystem. This is critical information for managers engaged in salmon restoration activities because it answers the question: How big does a restoration action need to be before it will affect population behavior?. Moreover, results from this work should inform new efforts to measure changes in other important population metrics like productivity, as a large scale restoration strategies, such as the removal of the Elwah River dams in the Pacific Northwest become more common (Brenkman *et al.*, 2012). River ecosystem research, based on hierarchical paradigms that integrate watershed, reach and habitat scales, facilitates understanding of habitat-forming processes and fish responses, improves predictive capability, and promotes better understanding of potential outcomes of ecosystem management.

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Appendix 4-A

Tree model comparisons of the weekly sum of spawning sockeye salmon in four index reaches in the lower Cedar River, Washington, before and after a channel-damming landslide. Exhaustive CHAID model analyses by reach, before and after the landslide disturbance where nodes indicate significant relationships between the dependent and independent pairings. Sum of Live Fish (SF) represent the dependent variable and N indicates the number of comparisons made per node. Split values indicate the value at which variables had significant relationships with SF. Sum of Live Fish values represent the numbers of spawning fish for each reach that occurred at each node. Corresponding independent variables, statistical significance levels (α = 0.05) of each relationship, and the value at which each node occurred are presented for pre- and post-landslide analyses. See Table 4-1 for more explanation of model variables.

Reach	Model Results Before the Landslide					
	Node	Sum of Live Fish (SF)	N	Parent Node	Variable	Split Values
	0	52128	33			
	1	74497	16	0	Q	<= 9
	2	31074	17	0	Q	> 9
	3	33874	4	1	VP	<= 4
	4	88039	12	1	VP	> 4
	5	17452	12	2	PG	<= 41811
1	6	63766	5	2	PG	> 41811
	7	108987	5	4	GR	<= 45
	8	73076	7	4	GR	> 45
	9	9822	5	5	GR	<= 45
	10	22902	7	5	GR	> 45
	11	69154	4	6	LFH	<= 280
	12	42214	1	6	LFH	> 280
	0	50178	21			
	1	62683	25	0	FI	<= 8
	2	27848	14	0	FI	> 8
	3	22745	1	1	PG	<= 5908
	4	83642	8	1	PG	(5908, 35522]
	5	49564	14	1	PG	(35522, 95563]
	6	90645	2	1	PG	> 95563
2	7	44270	6	2	Q	<= 10
	8	15532	8	2	Q	> 10
	9	55510	1	4	Q	<= 7
	10	94600	6	4	Q	(7, 10]
	11	46026	1	4	Q	> 10
	12	39530	11	5	LFH	<= 253
	13	86354	3	5	LFH	> 253
	14	87405	1	6	Q	<= 6

	15	93886	1	6	Q	> 6
	16	88817	1	7	PG	<= 5908
	17	45877	3	7	PG	(5908, 82529]
	18	19587	2	7	PG	> 82529
	19	12839	7	8	PG	<= 35522
	20	34386	1	8	PG	> 35522
3	0	34659	48			
	1	11871	12	0	PG	<= 8091
	2	42256	36	0	PG	> 8091
	3	2968	9	1	Q	<= 13
	4	38578	3	1	Q	> 13
	5	34140	22	2	GR	<= 65
	6	55008	14	2	GR	> 65
	7	18803	1	3	LFH	<= 225
	8	989	8	3	LFH	> 225
	9	45644	2	4	FFHF	<= 3
	10	24445	1	4	FFHF	> 3
	11	55854	3	5	PG	<= 11932
	12	30712	19	5	PG	> 11932
	13	35292	2	6	Q	<= 7
	14	153830	1	6	Q	(7, 8]
	15	55931	9	6	Q	(8, 13]
	16	21160	2	6	Q	> 13
4	0	16744	33			
	1	7461	26	0	PG	<= 13170
	2	51226	7	0	PG	> 13170
	3	1669	7	1	GR	<= 23
	4	9595	19	1	GR	> 23
	5	102425	1	2	LFH	<= 2577
	6	49221	5	2	LFH	(257, 321]
	7	10050	1	2	LFH	> 321
	8	1173	1	3	Q	<= 6
	9	2700	1	3	Q	(6, 11]
	10	1718	4	3	Q	(11, 13]
	11	941	1	3	Q	> 13
	12	6622	9	4	PG	<= 5945
	13	19340	3	4	PG	(5945, 10050]
	14	9241	7	4	PG	> 10050
	15	31761	2	6	PG	<= 16110
	16	86610	1	6	PG	(16110, 30767]
	17	47988	2	6	PG	> 30767

Reach	Model Results After the Landslide					
	Node	Mean	N	Parent Node	Variable	Binary Split Values
1	0	58519	7			
	1	99516	3	0	PG	<= 8259
	2	27771	4	0	PG	> 8259
	3	114904	1	1	LFH	<= 257
	4	91822	2	1	LFH	> 257
	5	11369	1	2	LFH	<= 257
	6	33239	3	2	LFH	> 257
	7	23923	1	6	Q	<= 15
	8	37897	2	6	Q	> 15
2	0	51048	6			
	1	72457	3	0	PG	<= 13223
	2	29639	3	0	PG	> 13223
	3	88817	1	1	LFH	<= 248
	4	64277	2	1	LFH	> 248
	5	21611	1	2	Q	<= 15
	6	33653	2	2	Q	> 15
	7	34386	1	6	LFH	<= 248
	8	32921	1	6	LFH	> 248
3	0	39085	6			
	1	52721	2	0	LFH	<= 279
	2	32267	4	0	LFH	> 279
	3	45794	2	2	GR	<= 20
	4	18740	2	2	GR	> 20
	5	15477	1	4	PG	<= 41303
	6	22004	1	4	PG	> 41303
4	0	44910	6			
	1	60378	3	0	LFH	<= 242
	2	29442	3	0	LFH	> 242
	3	61980	2	1	PG	<= 38000
	4	57173	1	1	PG	> 38000
	5	28875	2	2	Q	<= 15
	6	30577	1	2	Q	> 15

CHAPTER 5:

Overall Conclusions

Each of the three chapters in this dissertation complements the others in a multi-disciplinary approach that addresses management and restoration challenges from the watershed to the reach scale and how changes in physical habitat conditions shape spawning fish use of the river. Human development in the Lower Cedar River watershed influences hydrology, and riparian and channel habitat-forming processes. Predictably, the alteration of watershed and fluvial habitats has affected the distribution of spawning sockeye salmon throughout the 57 year management history that was evaluated in this study. Both watershed landscape and fluvial habitat quality generally decrease in a downstream direction as the land use grades from rural to urban. Consequently, length of flood control levees and revetments increases in a downstream direction to protect human infrastructure. Conversely, historic use of the river system by spawning fish was highest in the uppermost, least developed reaches and lowest in the most constrained urban reaches downstream. After the landslide disturbance in 2001, new complex alluvial habitat was created near the highly urban City of Renton, Washington. Sockeye salmon responded to the new habitat by spawning in greater densities in the landslide affected reaches than they had previously, and also in higher densities than in the upstream reaches where most of the run had spawned before the landslide disturbance.

Chapter 2

A screening procedure for prioritizing riparian management

The Cedar River, like many rivers throughout the world, is a highly managed system. There are two major impingements affecting the hydrologic regime in the Cedar: dams, and extensive bank hardening. These changes facilitated development of the floodplain and riparian areas throughout the twentieth century. The model presented in this chapter quantified the composition and configuration of watershed landcover, and their proximity to the riparian zone. The inclusion of both habitat and anthropogenic factors, and the spatial nature of the analysis facilitates planning and monitoring the effects of management actions because changes in landscape configurations are readily quantified. The location, type, extent, and relative habitat condition provides managers with information that can improve success of restoration efforts. Furthermore, the procedure is readily adaptable to using different data sources to address an array of natural resource and management issues. The screening procedure is intended to help managers quickly and objectively quantify riparian habitat condition in order to inform management prescriptions by providing an intuitive rating of relative habitat quality.

Efficacy of the model was tested when a landslide dammed the channel in the Elliott Reach. The river was forced through a section of the floodplain that was quantified as having very high habitat quality relative to surrounding areas. The landslide obviated the bank hardening for nearly a kilometer of river, thereby allowing the river to fully occupy floodplain and riparian habitat in an undeveloped gallery forest. As the new river channel expanded, large trees were recruited from the floodplain forest creating highly complex and dynamic fluvial habitat.

Chapter 3

Response to disturbance in a highly managed alluvial river: Does it conform to Le Chatelier's general law?

Chapter 3 addresses the physical responses of the river-floodplain to the channel-damming landslide that was highlighted in Chapter 2. Findings from the model presented in the previous chapter were used to plan sampling in the landslide-affected reach, as well as other reaches in the lower river. When the landslide occurred, focus shifted to quantifying the response to the disturbance and subsequent field studies were limited to the Elliott Reach. Therefore, data from before the landslide included physical measurements of the channel for one year prior to the disturbance. After the landslide, the channel-floodplain was measured for an additional three years. The channel geomorphology expanded dramatically as the river was forced through an existing, overfit, floodplain side channel. Large trees were recruited to the channel causing turbulence that created more erosion in a feedback that lasted through the first two years post-disturbance. By the third year, channel expansion had slowed and the river's energy became focused on the bed rather than the banks. Changes in the spatial complexity of patches of aggraded and eroded channel were quantified in a fractal framework as an indicator of how dynamic the channel was following the disturbance.

The study reach underwent the highest erosion during the first year following the landslide (2000-2001) as the side channel expanded. Much of that material was deposited downstream of the landslide deposits. During 2001-2002, the channel continued to widen and recruit large wood into jams. As the channel expanded laterally, there was substantial local scour and deposition associated with large wood in the upper part of the reach. Increased sediment deposition occurred in the downstream section of the channel and was more patchy than in the previous time step. During 2002-2003, the channel continued to widen and large wood aggregated into large jams facilitating the formation of deep pools. Bed surface elevations became significantly less patchy ($\alpha = 0.05$, $P << 0.01$) and areas of erosion were associated with wood jams. During this time step, the reach stored nearly 21% more material than was exported.

During 2000-2001, conveyance increased slightly (less than 1%) for all downstream cross-sections due to channel expansion along the unarmored right bank. The second inter-annual comparison (2001-2002) indicated that conveyance was much more variable and decreasing at all but the upstream-most cross-section where substantial channel widening occurred. Losses in channel capacity increased in a downstream direction due to the amount of sediment recruited from the floodplain at the upper extent of the reach. During this period, substantial channel widening occurred but, was ultimately limited by the increased roughness owing to 67 large cottonwood trees recruited as the banks expanded laterally. During 2002-2003, large losses in conveyance capacity were associated with cross-sections intersecting large jams. In particular, there was a large, channel-spanning jam on cross-section 4. In addition, while the channel did expand slightly compared to the previous time period, the increases in geometry were small relative to increased roughness due to channel irregularities and large wood.

This study has broad management implications for restoration of fluvial process and function in lowland rivers. This is particularly true in rivers on the west coast of North America where laws mandate the recovery of imperiled salmon populations in many river systems. This study documented the change as one reach reverted from a highly regulated, fixed channel configuration to a dynamic alluvial lowland river. The magnitude and temporal dimension of change observed following the disturbance should guide managers as they adopt restoration actions that include approaches like levee setbacks and large wood installations. The relatively short response time for the channel to adjust to the disturbance fits within project management timeframes for restoration projects that are designed to reconnect channels and floodplains. In addition, the magnitude of geomorphic changes observed provide important guidance for what managers should reasonably expect following these kinds of manipulations.

Chapter 4

Changes in habitat complexity, discharge characteristics, and distributions of sockeye spawning populations before and after a landslide disturbance, Cedar River, Washington

This chapter investigates the long-term distribution of spawning sockeye salmon in the lower Cedar River as a response to channel-floodplain management from 1952-2005. Spawning survey data beginning in 1952 demonstrate well-developed run times and spatial segregation by reach (Ames, 2006). Analyses indicate that before the landslide disturbance (2001), early run fish were most abundant and preferred the upstream reaches where channels and habitats were most complex. After the landslide, sockeye spawning distributions predominantly shifted to the most downstream reach. The redistributed spawning sockeye population corresponded to changes in channel and habitat complexity that increased dramatically in this reach. In the landslide-impacted reach, sediment and debris initially blocked the channel. Subsequently, these materials were eroded and transported to the most downstream reach, resulting in enhanced channel and habitat complexity, and greater numbers of spawning fish.

The resolution of the datasets in this investigation (reach lengths 6 km to 10 km, and weekly spawning surveys) revealed important variability that is obscured at larger spatial and temporal extents. The response of spawning sockeye in the Cedar River was measurable and significant when analyzed at these scales. Accordingly, our results indicate thresholds for reach-scale habitat complexity that can contribute to higher numbers of spawning fish. The weekly changes in distributions of spawning sockeye demonstrated that the reach-scale changes in habitat quality following the landslide disturbance triggered a biological response at the population scale. These findings provide insight into the magnitude of habitat change necessary to induce a population of spawning sockeye to adopt new habitats within the same river ecosystem. This is critical information for managers engaged in salmon restoration activities because it answers the question: How big does a restoration action need to be before it will affect a population trajectory?.

VITA

Raymond K. Timm II
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Education:

Ph.D., Aquatic and Fishery Sciences

University of Washington, Seattle, WA. Winter 2013.

- Salmonid habitat restoration coupled with flood reduction initiatives.
- Doctoral Dissertation: *Definition of Channel and Riparian Dynamics across a Disturbance Continuum: Implications for Salmonid Restoration.*

M.S., Environmental Studies 1996

Eastern Michigan University, Ypsilanti, MI

- Area of concentration in Remote Sensing and Geographic Information Systems (GIS).
- Masters Thesis: *Changes in Submersed Aquatic Macrophyte Distributions in Lake St. Clair, Michigan and Ontario, 1985-1995, as Mapped with LANDSAT TM Imagery.*

B.S., Biology 1992

Northern Michigan University, Marquette, MI

- Specialization in Water Science.
- Minor in Chemistry.

Employment, Consulting and Management Experience:

Senior Aquatic Scientist, King County Watershed Ecological Assessment Team, Water and Land Resources Division, Seattle, WA, April 2005 – Present

- Project Manager for Boise Creek Microbial Source Tracking Study.
- Project Manager for Routine Water Quality Monitoring Study in the King County waters of the Snohomish River drainage.
- Co-Author of proposal to EPA to study effects of landuse regulation on natural resources processes and functions following implementation of the critical areas ordinance (CAO). Funded Spring 2008, $625,000.

- Use of SONAR and underwater digital photography to map bathymetry, current velocities, shear stress, and sediment storage and recruitment dynamics following a levee setback on the Snoqualmie/ Tolt Rivers (pending).
- Lead author on scientific opinion paper regarding effects of November 2006 floods on salmonid resources in King County.
- Fluvial geomorphic and biological assessment of Stuck River levee repair, White River, WA (2008).
- Studied effects of low impact development on high-value headwaters aquatic resources.
- Lead scientist on spatially explicit water quality study in Soos Creek to assess restoration potential related to temperature and dissolved oxygen listings under 303(d) of the Clean Water Act.
- Spatially explicit model estimating cumulative effects of future development along King County shorelines for Shoreline Master Program (SMP).
- Project Ecologist on Stuck River Revetment Repair of 400 feet of flood-damaged flood control facility on the White River.

<u>Seattle Public Utilities, Seattle, WA,</u> January – September 2005

- Temporary employee
  - "Habitat Complexity" enhancement work in Seattle's urban streams.
  - Key member of team charged with "Improving Use and Quality of Science" at the Utility.
  - Provided technical template in the Utility's effort to manage "Desired Future Conditions" of Seattle's aquatic resources.

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<u>King County Department of Natural Resources, Seattle, WA</u>

- Consultant – Lower Jones Road bridge project, Spring 2004
- Student Intern, Summer 2000

<u>Geographic Information & Solutions, Inc. Ann Arbor, MI,</u>

November 1996 – December 2000.

- Business Owner and President.
- Start-up Capital acquisition.
- Daily Business/Project Management.

- 3-D and 2-D GIS Modeling and Analysis.
- Resource Modeling and Mapping

Institute for Geospatial Research and Education (IGRE), Eastern Michigan University, Ypsilanti, MI, February 1998 – April 1999

- GIS Manager of one of the premier GIS Research Centers in southeast Michigan.
- Managed and implemented approximately $1.5 Million in grants and contracts.
- Certified (ESRI) GIS Training.

J & L Consulting, Ypsilanti, MI, May 1992 - November 1996.

- Project Management.
- Wetland mapping.
- Assessment of wetland ecology and function.
- Wetland mitigation and permitting.
- Environmental Assessments.
- Lake and Stream Hydrologic and Ecological Studies.
- Phase I Environmental Audits.
- Endangered species surveys/assessments.
- Tree surveys - species identification and mapping.

Johnson, Johnson & Roy/inc, Ann Arbor, MI, March 1994 - April 1995.

- Designed, Managed, and Populated database of Public Comments regarding highway construction impacts.
- Performed statistical analyses on Public Comments.
- Environmental Inspector for natural gas pipeline construction.
- Placed sediment control structures in high-risk erosion areas.
- Acted as intermediary between pipe-yard crews, construction management, and regulatory agencies.
- Wetland mapping.
- Tree surveys/GPS.

Research

Senior Aquatic Scientist, King County Department of Natural Resources and Parks, Seattle, WA, April 2006 – Present

- Regulatory effectiveness monitoring for developing rural areas. 2009 – currently. $625,000 Funded by USEPA Region 10 Targeted Watersheds Grants – 2008 Puget Sound Initiative.
- Fluvial geomorphic response to increased roughness in a bioengineered revetment repair on the White River, Washington. 2008 – 2009.
- Soos Creek TMDL water quality investigation. 2007 – 2008.
- Effectiveness of best management practices (BMP) in a large Urban Planned Development, 2006 - 2009.

Research Assistant, School of Aquatic and Fishery Sciences, University of Washington, Seattle, WA, May 1999 - Present

- Use of a RADAR-derived digital elevation model to quantify watershed and stream characteristics as a predictor of fish habitat on Prince of Wales Island, AK.
- Empirical and modeling study of ecological impacts of natural and anthropogenic disturbances across continua of spatial and temporal scales in the Cedar River, WA.
- Hydrologic dynamics of fluvial ecosystems and interactions between riparian and chanel systems in Western Washington.
- Human/ Socioeconomic influences on habitat quality and restoration potential.
- Salmonid habitat preferences of off-channel and mainstem habitat types through empirical models.
- Spatially explicit probabilistic modeling of floodplain inundation/ off-channel linkage with mainstem habitats.
- Modeled erosion risk in west slope Cascades drainages to produce variable-width buffers to protect stream channels.

Institute for Geospatial Research and Education (IGRES), Eastern Michigan University, Ypsilanti, MI, February 1998 – April 1999.

- Assisted in the implementation of the Fully Integrated Environmental Location Decision

Support (FIELDS) system.

- Directed team of graduate students in QA/QC of 1.8 million stereo, digital images collected along Wayne County, Michigan roads.
- Key member of the NSF-funded *WorkSite / Alliance* (WSA) team of researchers.
- Geocoded all known sites of environmental contamination (brownfields) in Wayne County, Michigan as part of a *Brownfields Redevelopment Potential* study.

<u>Geographic Information & Solutions, Inc, Ann Arbor, MI,</u> April 1997 – January 2001.

- Spatially modeled contaminant levels of 21 persistent organic and metal analytes in both surface waters and sediments at a petroleum refinery site in Texas.
- Planned, performed field sampling, and populated data bases for a comprehensive GIS model to assess the extent of contamination in a dredged-spoils island in the Detroit River, Michigan, under contract to the United States Geological Survey, Biological Resources Division.
- Spatially modeled contaminant levels of 40 analytes, including metals, metalloids, and organic contaminants in a dredged-spoils island in the Detroit River, Michigan.

<u>Eastern Michigan University, Ypsilanti, MI,</u> April 1995 - December 1996.

- Member of Inter-agency team to assess, and manage the ecology of Lake St. Clair, Michigan.
- Utilized satellite imagery to quantify the response of submersed aquatic vegetation distributions related to the invasion of the zebra mussel (*Dreissena polymorpha*) in Lake St. Clair.
- Performed supervised and unsupervised classifications of raw satellite data using *ERDAS Imagine* software package.
- Assessment of hydrologic and ecological impacts on an urban drain in Southfield, Michigan.
- Geomorphic and biological restoration of Hennepin Marsh, Detroit River, Michigan.
- Bio-physical Characterization of a Fen in the Flemming Creek Watershed, Washtenaw County, Michigan.

U.S. National Biological Survey, Ann Arbor, MI, August 1993- December 1994.

- Established a computer archive on aquatic *Oligochaete* worms.
- Performed particle size analysis on sediments taken from 47 stations in the western basin of Lake Erie and 14 stations in the St. Mary's River.
- Assisted in an investigation into "swim-up syndrome" in *Salvelinus namaycush* fry.

Northern Michigan University, Marquette, MI, February 1991.

- Self-directed undergraduate study. Assessment of spawning success by *Salvelinus fontinalis* in rehabilitated habitat.

Teaching Experience:

Teaching Assistant

The University of Washington, Seattle, WA

- FIS 428 *Restoration of Fish Communities and Habitat in River Ecosystems*, Spring 2003, Spring 2005.

Adjunct Lecturer

The University of Michigan, Dearborn, MI

- ENST 340 *Remote Sensing*, Fall 1997.

Eastern Michigan University, Ypsilanti, MI

- GEO 582, *Remote Sensing*, Fall 1997.
- GESC 476 *Introduction to Geographic Information Systems*, Winter 1998.

Guest Lecturer

- CFR 521, *Ecological Scale*, College of Forest Resources, The University of Washington, Spring 2009.
- GIS 414, *Advanced Applications of GIS*, Department of Urban Studies, The University of Washington Tacoma, Spring 2009.
- FIS 428, *Restoration of Fish Communities and Habitat in River Ecosystems*, School of Aquatic and Fishery Sciences, The University of Washington, Spring 2001, Spring 2007.

- GEO 575, *Interpretation of Aerial Photography*, Eastern Michigan University, Fall 1998.
- Michigan Metro Girl Scout Council, Detroit Michigan, September 1997.
- Michigan Student Congress, Pontiac Silverdome, October 1996.
- Biogeographical Resources, GEOG 568, Eastern Michigan University, March 1996, and February 1997.
- Quantitative Methods for Geography & Geology, GESC 470, Eastern Michigan University, November 1995.

Software Instructor

- Earth Systems Research Institute (ESRI) certified ArcView 3.X instructor, 1996 – 2001.
- Taught numerous short courses on the functionality of GIS software.
- Developed specialized datasets and wrote curricula to facilitate specific training objectives.

Publications and Gray Literature:

Timm, R. K., C. B. Knutson, G. Lucchetti, L. Fore, J. J. Latterell, C. Gregerson, J. O. Wilhelm, and K.O. Richter. (in prep.). Potential Effective Impact: A spatially explicit framework for connecting land cover changes to stream ecosystems. Ecological Applications

Timm, R.K., and R.C. Wissmar. (In prep.). Fluvial geomorphic mechanisms shift sockeye salmon (*Oncorhynchus nerka*) spawning distributions: How big is a population-scale disturbance? Freshwater Biology

Timm, R.K., and R.C. Wissmar. 2013. Response to disturbance in a highly managed alluvial river: Does it conform to LeChatelier's general law? Geomorphology **182**: 116-124.

Timm, R.K., G. Lucchetti, J.J. Latterell, K. Richter. (In prep.). Developing a multi-scale, spatially explicit estimator of the impacts of land cover change on aquatic resources. Landscape Ecology.

Schaefer, R., **R.K.Timm**, K, Akyuz, J. Koon, L. Brandt. (In review). Best Management Practices (BMP) for limiting impacts during river construction projects in King County, WA. King County River and Floodplain Management Section. Seattle, WA.

Timm, R.K., 2012. Boise Creek Microbial Source Tracking (MST) Investigation: Year 1 Report. King County Department of Natural Resources. Seattle, WA

Wissmar, R.C**., R.K. Timm,** and M.D. Bryant. 2010. Radar-Derived Digital Elevation Models and Field-Surveyed Variables to Predict Distributions of Juvenile Coho Salmon and Dolly Varden in Remote Streams of Alaska. Transactions of the American Fisheries Society. **139** (1) 288-302.

Logsdon, M. G., **R. K. Timm**, R. C. Wissmar, P. Storck, and D. C. Pflugh. (In review). Variation of Impervious Areas and Urban Watershed Hydrology. Environmental Assessment and Monitoring.

Timm, R.K. 2009. Fluvial Geomorphic Evaluation of a Bioengineered Revetment in the White River – Before and One Year after Construction. King County Water and Land Resources Division. Seattle, WA.

Timm, R.K. 2008. Soos Creek Total Maximum Daily Load (TMDL) Sampling and Analysis Plan (SAP). King County Water and Land Resources Division. Seattle, WA.

Timm, R.K. 2008. Biological Evaluation of ESA-Listed fish resources in the White River. King County Water and Land Resources Division. Seattle, WA.

Timm, R.K., G. Lucchetti, J. Moe, L. Casey. 2007. Cumulative Effects Analysis, Technical Appendix D. *In:* King County Shoreline Master Program (SMP) Update. King County, Water and Land Resources Division. Seattle, WA.

Wilhelm J.O., **R.K. Timm**, K.O. Richter, S. Abella, K. Comanor, D. Funke, and K. Johnson. 2006. Trilogy and Redmond Ridge Urban Planned Development (UPD) Natural Resources Monitoring Midpoint Review. King County, Water and Land Resources Division. Seattle, WA.

Wissmar R. C. and **R. K. Timm**. 2006. Effect of landcover change on the hydrology of urbanizing watersheds. Proceedings of the ninth biennial watersheds management council conference: Watersheds across boundaries: Science, Sustainability, Security (eds) C. W. Slaughter and N. Berg. Watershed Management Council. Water Resource Center Report 107, University of California, Berkley, CA.

Timm, R. K. and R. C. Wissmar. 2006. Multi-scale prioritization of riparian habitats for restoration and protection. Proceedings of the ninth biennial watersheds management council conference: Watersheds across boundaries: Science, Sustainability, Security (eds) C. W. Slaughter and N. Berg. Watershed Management Council, Water Resource Center Report 107, University of California, Berkley, CA.

Wissmar R. C. and **R. K. Timm**. 2006. Watershed and Stream Landscapes, Prince of Wales Island, Alaska. USDA Forest Service, Ketchikan, Alaska.

Pess, G. R., S. R. Morley, J. L. Hall, and **R. K. Timm**. 2005. Monitoring Floodplain Restoration. *In*: P. Roni (ed.) Methods for Monitoring Stream and Watershed Restoration. American Fisheries Society, Bethesda, MD.

Wissmar, R. C., **R. K. Timm**, and M. L. Logsdon. 2004. Effect of Changing Forest and Impervious Landcovers on Discharge Characteristics of Watersheds. Environmental Management. **34**(1) 91-98.

Timm, R. K., R. C. Wissmar, J. W. Small, T. M. Leschine, and G. Lucchetti. 2004. A Screening Procedure for Prioritizing Riparian Management. Environmental Management. **33**(1) 151-161.

Wissmar, R.C. and **R. K. Timm**. 2004. Changes in land uses, hydrology, and fish habitats in an urban drainage, Cedar River, Washington. *In:* the Proceedings of the First Interagency Conference on Research in the Watersheds, Benson AZ.

Wissmar, R. C., W. N. Beer, and **R. K. Timm**. 2004. Spatially Explicit Estimates of Erosion Risk Indices and Variable Width Riparian Buffers. Aquatic Sciences

Hall, J. L., **R. K. Timm**, and R. C. Wissmar. 2000. Riparian Ponds as Sockeye Salmon Spawning Habitat in the Cedar River, Washington. *In:* P. J. Wigington and R. L. Beschta (eds.) Riparian Ecology and Management in Multi-Land Use Watersheds.

R. C. Wissmar, D. C. Pflugh, and **R. K. Timm**. 2000. Changes in Developed Land Cover (1991-1998): Cedar River, Washington. *In:* P. J. Wigington and R. L. Beschta (eds.) Riparian Ecology and Management in Multi-Land Use Watersheds.

Timm, R. K. and E. Jaworski 1996**.** Affected Environment and Resource Value, Lake St. Clair, Michigan Aquatic Plant Management Investigation, *in:* U.S. Army Corps of Engineers, Detroit District, Lake St. Clair, Michigan Aquatic Plant Management Investigation, Detroit, MI.

Timm, R. K. and E. Jaworski 1996. Aquatic Plant Distribution Mapping and Review of 1995 Field Studies, Lake St. Clair, Michigan Aquatic Plant Management Investigation. *In:* U.S. Army Corps of Engineers, Detroit District, Lake St. Clair, Michigan Aquatic Plant Management Investigation, Detroit, MI.

Timm, R. K. and E. Jaworski 1996. Assessment of Selected Remote Sensing Techniques for Mapping Submersed Aquatic Plants in Lake St. Clair, Michigan and Ontario. *In*: Proceedings of the Second International Airborne Remote Sensing Conference and Exhibition, June 1996.

Papers Presented:

Timm, R.K., 2012. Zeroing in on sources of microbial contamination in Boise Creek, Washington. King County Department of Natural Resources Science Seminar. Seattle, WA.

Timm, R. K., C. B. Knutson, G. Lucchetti, L. Fore, J. J. Latterell, C. Gregerson, J. O. Wilhelm, and K.O. Richter. 2012. Potential Effective Impact: A spatially explicit framework for connecting land cover changes to stream ecosystems. SCB North American Congress for Conservation Biology. Oakland, CA.

Timm, R. K., and R. C. Wissmar. 2011. Fluvial Geomorphic Adjustments Following a Channel-Damming Landslide in the Cedar River, Washington. American Fisheries Society Annual Meeting. Seattle, WA.

Timm, R. K., J. J. Latterell, G. Lucchetti, C. B. Knutson, and K. O.Richter. 2011. A Spatially Explicit Framework for Connecting Land Cover Changes to Stream Ecosystems. American Fisheries Society Annual Meeting. Seattle, WA.

J. L. Michalak, G. Lucchetti, **R. K. Timm**, J. J. Latterell, and M. Alberti. 2011. Implications of Land-Cover Change History for Monitoring Present and Future Ecological Condition in Nine Basins on the Urban Fringe of Seattle, Washington. American Fisheries Society Annual Meeting. Seattle, WA.

Lucchetti,G., J. J. Latterell, **R. K. Timm**, J. L. Michalak, M. Alberti, C. E. Torgersen, and C. B. Knutson. 2011. Assessing the Effectiveness of Land Use Regulations in Developing, Rural King County, WA. American Fisheries Society Annual Meeting. Seattle, WA.

Timm, R. K., 2009. Potential Cumulative Impact: Developing a multi-scale, spatially explicit estimator of the impacts of land cover change on aquatic resources. King County Department of Natural Resources Science Seminar. Seattle, WA.

Timm, R. K., 2009. Fractals: Do they describe ecologically important heterogeneity? Guest lecture to CFR 521. University of Washington. Seattle, WA.

Timm, R. K., 2009. How is GIS used in a management agency? Guest lecture to GIS 414. University of Washington. Tacoma, WA.

Timm, R. K., 2007. Population-scale response of sockeye salmon (*Oncorhynchus nerka*) to a landslide disturbance in the Cedar River, Washington. American Fisheries Society Annual Meeting. San Francisco, CA.

Timm, R. K., and J.O. Wilhelm. 2006. Stream and Wetland Response to Landscape Changes in the Redmond Ridge and Trilogy UPDs. King County Department of Natural Resources Science Seminar. Seattle, WA.

Timm, R. K., and H.B. Berge. 2006. Disturbance in a highly managed river: How much is enough for fish?. Northwest Regional Floodplain Managers Association Annual Meeting. Bow, WA.

Timm, R. K. 2006. Population-scale response of sockeye salmon (*Oncorhynchus nerka*) to a landslide disturbance in the Cedar River, Washington. Graduate Student Symposium, School of Aquatic and Fisheries Sciences, University of Washington. Seattle, WA.

Timm, R. K., R. C. Wissmar, H. B. Berge, and S. Foley. 2005. Changes in Spawning Salmon Distributions Following Disturbance Regime Shifts in the Cedar River, Washington. 2005 Joint Assembly: AGU, NABS, SEG, SPD/AAS, New Orleans, Louisiana. June 2005.

Timm, R. K., R. C. Wissmar, H. B. Berge, and S. Foley. 2005. Spawning Habitat Preferences of Salmon Following Landslide-Induced Damming and River Channel Adjustments. Society of Ecological Restoration Northwest Chapter Annual Meeting. Seattle, Washington. April 2005.

Wissmar, R. C. and **R. K. Timm**. 2004. Landscape Perspectives for Managing Riparian Areas. North American Benthological Society. Vancouver, British Columbia. June 2004.

Wissmar, R. C. and **R. K. Timm**. 2004. Realities of Fish Habitat Improvement in a Developed River. 4th World Fish Congress. Vancouver, British Columbia. May 2004.

Wissmar, R.C. and **R. K. Timm**. 2003. Changes in land uses, hydrology, and fish habitats in an urban drainage, Cedar River, Washington. *In:* the Proceedings of the First Interagency Conference on Research in the Watersheds, Benson AZ.

Timm, R.K. 2002. Multi-Scale Prioritization of Riparian Habitat Restoration. Watersheds Across Boundaries: Science, Sustainability, Security. Stevenson, Washington. November 2002.

Timm, R.K. 2002. Biophysical Research Synopsis of Cedar River Studies. Cedar River Watershed Council. Renton, Washington. October, 2002.

Timm, R.K. 2002. Multi-Scale Prioritization of Restoration and Preservation Opportunities of Available Riparian Habitat. Foster Wheeler Environmental Corp. Bothel, Washington, March 2002.

Timm, R.K. 2002. Multi-Scale Prioritization of Restoration and Preservation Opportunities of Available Riparian Habitat in the Cedar River, Washington. CSS Annual Review. College of Forest Resources, University of Washington, Seattle, Washington, February 2002.

Timm, R.K. 2001. Recent Changes in Distributions of *Homo sapiens*, and Implications for Salmonid Habitat Restoration in the Lower Cedar River, Washington. Graduate Student

Symposium, School of Aquatic and Fishery Science, University of Washington. Seattle, Washington, October 2001.

Timm, R.K. 2000. Changes in Developed Land Cover (1991-1998): Cedar River, Washington. International Conference on Riparian Ecology in Multi-Land Use Watersheds. American Water Resources Association. Portland, Oregon, August 2000.

Timm, R.K. 1999. Effects of Strong El Ninõ on Michigan Snowpacks, 1948 – 1998. The Michigan Academy of Science Arts and Letters. Albion, Michigan. March, 1999.

Timm, R.K. 1999. Changes in Michigan Snowfall Depths and Distributions during 1900 - 1998. The Michigan Academy of Science Arts and Letters. Albion, Michigan. March, 1999.

Timm, R.K. 1998. Online Spatial Data Sharing and Integrated Mapping: AVIMS vs MOIMS, Third Annual Counties and Local Users GIS Conference, Crystal Mountain, Michigan, October 1998.

Timm, R.K. 1998. GIS in Community-Based Problem Solving – Mapping Crime with ArcView. First International Conference on GIS in Education, Ypsilanti, Michigan, October 1998.

Timm, R.K. 1998. Use of High Resolution, Multi-Spectral Airborne Scanner Imagery of the Detroit River for Mapping and Environmental Assessment, Fourth International Conference on Remote Sensing for Marine and Coastal Environments, Orlando, Florida, March 1997

Timm, R.K. 1996. The Utility of LANDSAT-5 TM as Compared to SHOALS, SAVEWS, and Grapnel Data, When Mapping Submersed Aquatic Plants in Lake St. Clair, Michigan and Ontario, Summer 1995. The Michigan Academy of Science, Arts, & Letters, Alma, Michigan, March 1996.

Timm, R.K. 1996. Assessment of Selected Remote Sensing Techniques for Mapping Submersed Aquatic Plants in Lake St. Clair, Michigan and Ontario. The Second International Airborne Remote Sensing Conference and Exhibition, San Francisco, California, June, 1996.

Timm, R.K. 1996. The Utility of LANDSAT-5 TM as Compared to SHOALS, SAVEWS, and Grapnel Data, When Mapping Submersed Aquatic Plants in Lake St. Clair, Michigan and Ontario, Summer 1995. American Water Resources Association, Michigan Chapter, Mt. Clemens, Michigan, July 1996.

Professional Memberships:

- American Geophysical Union
- American Fisheries Society
- Ecological Society of America
- Society for Conservation Biology

Service and Pro bono work*:*

- One of three Americans on the Board of Directors of the Freshwater Working Group for the Society for Conservation Biology.
- Anonymous reviewer for several scientific journals including Ecological Applications, Environmental Management, Bioscience, Fisheries, Landscape Ecology, Transactions of the American Fisheries Society.
- Expert witness: Cedar River Sockeye hatchery hearing. City of Seattle, Hearing Examiner's office. 2005.
- Mentor to 2 U W undergraduate science and engineering students in the Washington State Achievers Program. 2003 to present.
- Tutored groups of Garfield High School students in math and science in after school program for disadvantaged kids.
- Used GIS technologies to Map Holiday Meal Delivery Routes, Ypsilanti Meals on Wheels, Thanksgiving, Christmas and New Year 1997-1998.