Characterizing lowland streams: riparian and watershed influences on urban and non-urban channels

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and have found it is complete and satisfactory in all respects, and that any and all revisions required by the final examination committee have been made.

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Abstract

Characterizing lowland streams: riparian and watershed influences on urban and non-urban channels

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This thesis presents a suite of studies focused on the channel network of the Chico Creek watershed, a resource-rich stream system on the Kitsap Peninsula in western Washington State. These studies include: a rapid geomorphic assessment of the main stream network of the Chico Creek watershed, a comparative analysis of two channel-assessment methods, and an analysis of the morphological influences of the near-riparian zone on channel morphology and channel responsiveness to urbanization. In addition to study sites in the Chico Creek watershed, comparative sites were also included from the more highly urbanized watersheds of Juanita, Thornton, Squibbs, and Lewis creeks, all located in and east of the City of Seattle.

The Chico Creek stream network has a variety of channel types, which reflect both human alteration and the interactions of geological, biological, and climatic conditions of the basin. Most of the surveyed reaches were classified as forced pool-riffle (FPR) and were located in low-disturbed areas dominated by forested cover. Plane-bed (PB) and constrained plane-bed (PBc) reaches are in almost all cases the result of human alteration. Cascade and step-pool (SP) reaches were uncommon and located in high-gradient areas in the upper section of the basin tributaries.

A multimetrix index of geomorphic channel conditions, the Physical In-Stream Condition Index (PSCI), provided a coarse, but apparently robust, discrimination of the current geomorphic conditions across the channel network of the Chico Creek watershed. Comparisons with an alternative methodology

indicated few scoring discrepancies, which were almost entirely located in reaches with gradients higher than about 0.02. Problem were evident from the inclusion of variables in channel-assessment and monitoring methods that are neither replicable across observers nor based on reference conditions common to all encountered channel types.

The PSCI scores were unrelated to the contributing basin land cover. However, some correspondence was found between the score and the local land cover, suggesting that the physical attributes measured by the PSCI are probably influenced by local drivers.

Remarkably different channel morphology was observed between low and high urbanized reaches. Low-urbanized reaches of the Chico Creek watersheds (mostly FPR channels) have more in-stream wood, pools, and sediment storage and less bank erosion than reaches on the Eastside with equivalent gradient and basin area (mostly PB and constrained morphologies). Channel morphology in low-urbanized watersheds correlate to the level of channel confinement and to characteristics of the near-riparian vegetation. High-urbanized reaches are substantially less sensitive to the condition of the near-riparian zone, due to the disconnection of the stream with its floodplain triggered by the placement of armoring structures in the banks.

From a management perspective, increased in-stream wood in PB reaches could yield an eventual morphologic shift to FPR. However, increased wood load in these channels is not the only requirement for generating such a shift. These channels also need to be reconnected to a forested floodplain and to the channel-bank sediment that provide long-term recruitment of both LWD and gravel. In the case of anthropogenically confined channels, restoration is even more challenging because sustainable morphologic improvements require the elimination of bank-armoring structures to facilitate that reconnection. The mere addition of logs is not likely to provide a sustainable solution, offering short-term improvements but not addressing the underlying geomorphic processes that commonly yield degraded channels in urban environments.

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CHAPTER 1

1 Introduction

Human alteration of Pacific Northwest streams has proceeded for over a century with neither a basic understanding of watershed dynamics nor appreciation of the long-term consequences of land-use alterations (Naiman et al., 1992). Changing the natural land cover of watersheds to other land uses has degraded the physical, biological, and chemical condition of streams, lakes, and wetlands. The degree to which development affects these systems is not only dependent on the development activity itself (logging, agriculture, flow control, or urbanization) but also on the environmental setting in which it takes place (geology, climate, gradient, confinement, and riparian vegetation). Therefore, the spatial distribution of reach types within a drainage basin, which results from that environmental setting, influences the distribution of potential impacts and responses of stream channels to disturbance (Montgomery and Buffington, 1998). Recognizing the dominant geomorphologic processes in fluvial channels provides guidance for defining current channel condition and identifying possible monitoring sites to show response to upstream impacts. In addition, this understanding can illuminate areas where restoration efforts are appropriate and can contribute to creating or defining target morphologic features.

Urbanization effects have been identified as some of the most pervasive to the integrity of stream. Detrimental effects of urbanization in terms of the physical, chemical, and biological condition of streams have been studied in the Pacific Northwest for the past 20 years (Booth, 1990; Booth, 1991; Booth and Jackson, 1997; Moscrip and Montgomery, 1997; May et al., 1997; Booth and Henshaw, 2001; Brett et al., in press; McBride, 2001; Nelson and Booth, 2002; and Morley and Karr, 2002, among others). Many of these studies used total impervious surface area (TIA) or percent urbanization as measurements of urbanization.

TIA represents the fraction of a watershed covered by constructed, non-infiltration surfaces such as concrete, asphalt, and buildings (Hill et al., 2003). Percent urban land cover includes both vegetated and non-vegetated areas located in highly developed zones. Both metrics are conventionally derived from interpreted land-cover images (Hill et al., 2003). Imperviousness, although an imperfect measure of human influence, is clearly associated with stream system decline (Booth et al., 2002; May et al. 1997; McBride, 2001; Morley and Karr, 2002). A wide range of stream conditions can be associated with any given level of imperviousness, but there is a greater range at lower levels of development (Booth et al., 2002).

The current physical condition of a given stream can be assessed by the evaluation of morphologic features interpreted in the context of the surveyed network channel type. Some of the stream physical attributes that have shown high potential to describe current stream condition in urbanizing watersheds are gradient, bank erosion, and frequency of in-stream wood and pools (Scholz and Booth, 2001).

Both physical and biological conditions in urban streams in the Puget Sound Lowland region have shown strong relationships with land cover change. McBride (2001) found that physical condition of streams, measured with a multi-metric index of physical condition (Physical In-stream Condition Index) declines with increasing percentage of total urban land cover in both the contributing watershed and a 500-m zone closest to the sampling point (R^2 = 0.4 in both cases). Morley and Karr (2002) found that biological “health,” measured with the multi-metric index of biological integrity (B-IBI), responded strongly to land cover change (measured as percent urban and TIA) measured over two different spatial scales (basin and 200-m local scale) (R^2 ranged between 0.6 and 0.7 in all cases).

This study presents the results of a large-scale, rapid geomorphic assessment conducted along 12 km of alluvial systems of the main stream

network of the Chico Creek watershed. The study basin is located on the east side of the Kitsap Peninsula, approximately 30 km west of the city of Seattle in western Washington (Figure 1- 1). This analysis included characterization of the stream network into channel types (Montgomery and Buffington, 1997) and a rapid assessment of the current geomorphic condition of these streams. In addition, the relationship between urbanization metrics (based on land cover) and the current physical condition of the stream channels was explored. This analysis allowed the identification the relatively pristine sites and also identified potential monitoring and restoration areas. This characterization is a contribution to the physical understanding of the basin's stream channels in the context of the recent completed study, "The Chico Creek watershed planning project." The overall objective of this project was to develop a science–based vision of the Chico Creek watershed for the future under different trajectories of future urban development.

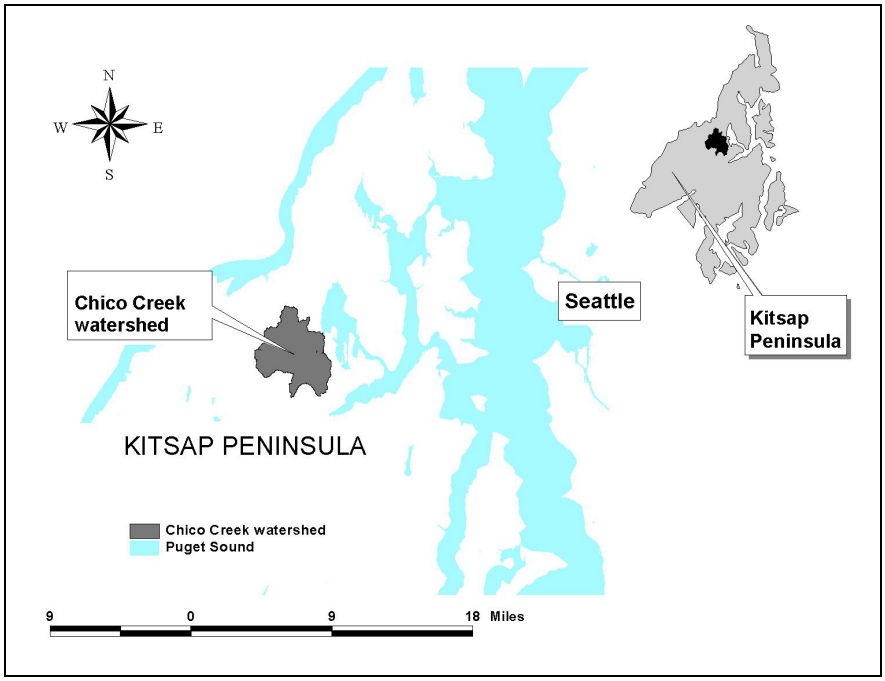


Figure 1- 1: Location of the Chico Creek watershed

2 METHODS

2.1 Study Sites

Study sites included the main channel network of the Chico Creek watershed (Figure 1- 2). Bedrock underlies the upper sections of the watershed tributaries (Lost, Wildcat, Kitsap and Dickerson creeks). The lower areas are underlain by glacial till, recessional outwash, and advance outwash deposited during the last ice-sheet advance about 15,000 years ago; and some recent alluvial deposits (Haessuler and Kenneth, 2000; revised by D. Booth, written commun., 2002) (Appendix A, Figure A-1). Chico Creek watershed includes approximately 11 km of in-stream habitat that are accessible to anadromous salmonids. It supports four salmonids: chum (Oncorhynchus keta), coho (Oncorhynchus kisutch), steelhead (Oncorhynchus mykiss), and cutthroat trout (Oncorhynchus clarki). Chico Creek's chum population is one of the largest in the South Puget Sound, with annual escapements averaging 25,000 adults (T. Ostrom, Suquamish Tribe, unpublished data 2002).

Before European settlement the study area was characterized by Western Hemlock old-growth forests, which were dominated by Douglas Fir (*Pseudotsuga menziesii*), Western Hemlock (*Tsuga heterophylla*), and Red Cedar (*Thuja plicata*) (Franklin and Dyrness, 1988). Human activity (mainly logging and urbanization) has eliminated all relicts of old growth, but there are still a few patches of mature second-growth forest in the middle section of the watershed. These second-growth forests are mainly composed of conifers (*Pseudotsuga menziesii*, *Tsuga heterophylla*, and *Thuja plicata*) and some hardwood species (*Alnus rubra*, *Acer macrophyllum*), primarily in the riparian areas of Wildcat and Lost creeks.

Most of the urbanization in this watershed has been concentrated in its lower sections. Total impervious surface area in the watershed, calculated from

the 1998 Landsat image using the relative percentages developed by Hill et al. (2003), is approximately 15%.

Geomorphic surveys and spatial analysis of 58 reaches covering 12.1 km of the main stream network of the Chico Creek watershed were conducted (Figure 1- 2), both to classify the reaches into channel types (based on the classification described by Montgomery and Buffington, 1997), and to assess their geomorphic condition through an adaptation of the Physical In-stream Condition Index (PSCI) described by McBride (2001). The surveyed network included all of the alluvial channels accessible to fish in the watershed.

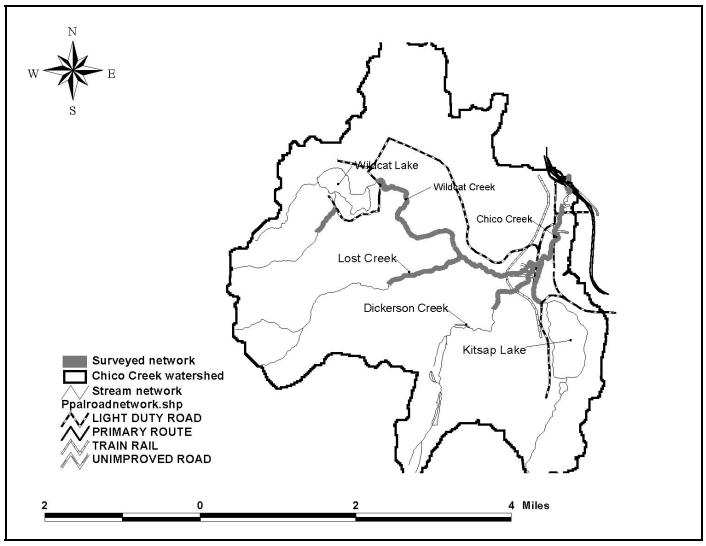


Figure 1- 2: Surveyed network

2.2 Field methods

Field methods were based on the protocol for monitoring urbanizing streams first articulated by Henshaw and Booth (2000) and further refined by McBride (2001). Surveys of the main channel network of the Chico Creek watershed occurred during spring and summer 2002. The survey was conducted throughout the main stem (Chico Creek) and its main tributaries (Lost, Wildcat, Dickerson, and Kitsap creeks). The survey consisted of collecting quantitative and qualitative reach-scale information on bankfull dimensions (width and depth),

stream bank condition (bank stability), substrate condition (cementation), and channel complexity (large woody debris and pool abundance).

The location of each reach surveyed was determined using a Garmin 12XL GPS unit in decimal degree coordinates.

Data was collected using reaches as the unit of the survey. The minimum reach length was 20 channel widths to capture repetitive patterns of the streams (MacDonald et al., 1991; Montgomery and Buffington, 1997; Martin, 2001). The break between reaches was established not only by length but also by natural and anthropogenic breaks, such as change in confinement, tributary confluences, change in condition of the near-riparian zone, or road and railway crossing.

Bankfull dimensions were measured for every reach using a pre-marked stick in metric units. The presence or absence of perennial vegetation, topographic breaks in the bank, and changes in sediment characteristics were the indicators used to define the bankfull depth (BFD) and the bankfull width (BFW) dimensions (Dunne and Leopold, 1978).

Every reach was given a single reach-averaged bank stability score according to the categories defined by Henshaw and Booth (2000) (Table 1- 1). An additional bank stability category was included to describe reaches where banks were consistently armored by artificial structures. This category was given the same score as class 1 (completely unstable) based on the assumption that armoring structures exist as an attempt to stabilize unstable conditions. When the reach was not uniformly in one bank stability class (i.e. neither of them were continually stable, class 4, nor continually armored, class 1), scores were assigned to describe the dominant observed bank condition. Figure 1- 3 presents examples of unstable banks.

Table 1- 1: Categories of bank stability adapted from Henshaw and Booth (2000)

Class	Description
4	STABLE: Perennial vegetation to waterline No raw or undercut banks No recently exposed roots No recent tree falls
3	SLIGHTLY UNSTABLE Perennial vegetation to waterline in most places Some scalloping of banks Minor erosion and/or bank undercutting Recently exposed tree roots rare but present
2	MODERATELY UNSTABLE Perennial vegetation to waterline spare (mainly scoured or stripped by lateral erosion) Bank held by hard points (tree boulders) and eroded bank elsewhere Extensive erosion and bank undercutting Recently exposed tree roots and fine root hairs common
1	COMPLETELY UNSTABLE No perennial vegetation at waterline Bank held only by hard points Severe erosion of both banks Recently exposed tree roots common Tree falls and/or severely undercut tree common
1	ARMORED BANKS Banks hold by placed structures such as boulders, contention walls etc.

Figure 1- 3: Examples of unstable banks (class 1 of Table 1- 1) in the Chico Creek watershed. Right: unstable bank in Chico Creek. Left: unstable bank in Lost Creek

Pool abundance was tallied for each reach using minimal dimensions dependent on channel size. A “pool” was defined to have a minimum residual

depth of 25% of the BFD and a minimum pool length of 10% of the BFW (Montgomery et al., 1995).

The longitudinal location of large woody debris (LWD) in each reach was recorded as well as its relative position within the channel (i.e. spanning or adjacent). This information allows identifying wood pieces that are a potential component of a LWD jam. Recorded LWD met the minimum criteria of 1 m in length and 25 cm in diameter (Montgomery et al., 1995).

A measure of substrate cementation was performed on a riffle in each reach, gauging the degree to which the channel bed had hardened by pushing a boot heel a few cm into the channel bed. The reaches were ranked according to the criteria used by McBride (2001) (Table 1- 2).

Table 1- 2: Categories of bank substrate cementation (McBride, 2001)

Class	Description
4	Excellent: grains easily yield under heel pressure and release little or no sediment plume.
3	Good: grains mode with some heel pressure, small sediment plume.
2	Fair: grains yield only with considerable effort, substantial sediment plume.
1	Poor: heel cannot be driven into the channel bed without great pressure.

2.3 Analytical methods

Available digital elevation and land cover information, together with the data collected through the field surveys, were processed and spatially displayed using the GIS software ArcView 3.2.

2.3.1 Reach classification

Channel gradient was established with available digital LIDAR survey data for the basin at a 6-foot resolution. The average slope for each reach was calculated based on the elevation difference between the initial and ending point of each surveyed reach. Reach slope information was categorized by the groupings defined by Montgomery and Buffington (1997).

Stream classification was based on the alluvial reach types designated by Montgomery and Buffington (1997). Each reach was categorized into a channel type based on observed morphologic features.

Pools and LWD data were analyzed to yield number of pools/100 m, amount of LWD/100 m, and relative location of LWD pieces in the channel (spanning or adjacent).

2.3.2 Channel geomorphic condition

McBride (2001) defined the Physical In-stream Condition Index (PSCI) to characterize the geomorphic condition of urbanizing streams. This index was developed based on field evaluation of 6 physical parameters: channel size, bank stability, LWD abundance, complexity, embeddedness, and cementation. In this study, a condensed version of this index was computed for each reach of the surveyed streams. The considered attributes were bank stability, LWD and pool frequency (used as quantitative surrogates for channel complexity), and cementation (Table 1- 3). Each attribute was scored from 1 to 4, giving each reach a total possible score between 4 and 16 points. The total score range was divided into 3 equal bands to simplify the display of overall geomorphic condition: “low quality” for scores between 4 and 8 (inclusive); “intermediate quality” for scores between 9 and 12; and “high quality” for scores between 13 to 16 points. The utility of the PSCI is in providing an initial classification of the current geomorphic conditions within the stream network of the watershed.

Large woody debris score categories were developed using the observed range of wood counts in the surveyed reaches and applying a recent methodology to define regional in-stream wood targets (Fox et al., 2003). LWD counts were divided into four categories based on the 25, 50, and 75 percentiles of the data set (Table 1- 3).

Table 1- 3: Components of the physical stream conditions index (PSCI), adapted from McBride, 2001.

Parameter	Description	Scoring			
		1	**2**	**3**	**4**
Bank stability	Scores used in the survey	1	2	3	4
Cementation	Scores used in the survey	1	2	3	4
LWD abundance	Pieces/100 m	<7	>7 - 21	22 - 33	>33
Pool abundance	Units/100 m	<5	>5- 7	8	>8

Pool counts, as in the case of LWD counts, were divided into 4 categories using the 25, 50, and 75 percentiles (Table 1- 3). This approach was chosen in the absence of a consensus about pool targets in the literature. For example, targets have been published for unmanaged watersheds, but they range between 2 and 17 pools/100 m. This broad range has been established from surveys over variable regions, gradients, and channel sizes and with variable pool-size criteria, and they therefore provide little guidance.

Analysis of variance was used to establish differences in frequencies of pools and LWD, and in the percentage of spanning LWD pieces per channel type.

2.3.3 Urbanization and channel geomorphic condition

The level of urbanization of the surveyed sites was measured with total impervious surface area (TIA) based on the Landsat image of 1998 (Hill et al., 2003) and analyzed in relation with the PSCI scores. Two spatial scales analogous to those used by Morley and Karr (2002) were calculated. TIA associated with each of the surveyed reaches was calculated for the contributing watershed and for the local riparian zone, which consisted of a buffer of 50 m on each side of the channel reach, over the extend of each reach. The intention was to test whether “local” or “total basin” land cover control the physical condition of the surveyed streams to a greater or lesser degree. All of the reaches are located in suburban watersheds with lower TIA (<15%) than sites evaluated by McBride (2001) and Morley and Karr (2002), which were above 20%, in most cases. The analysis used linear regression to explore the presence of significant relationships between sub-basin and local TIA (predictor variables) and the PSCI results (response variable). SPSS 10.1 statistical software^{tm} (SPSS Inc., Chicago IL) was used for the statistical analyses using an alpha level of 0.05.

Data collected through the surveys is presented by reach in Appendix A, Table A-1.

3 RESULTS

3.1 Channel classification

The channel classes based on field observations are presented in Figure 1- 4. Thirty-two out of 58 surveyed reaches (with an aggregate length of 7086 m) are forced pool-riffle. The rest of the channel types had low occurrence within the surveyed reaches. Five reaches were classified as step-pool (768 m), 13 as plane-bed (2782 m), 2 as pool-riffle (320 m), 4 as constrained plane-bed (922 m), and 2 as cascade (280 m) (Figure 1- 5).

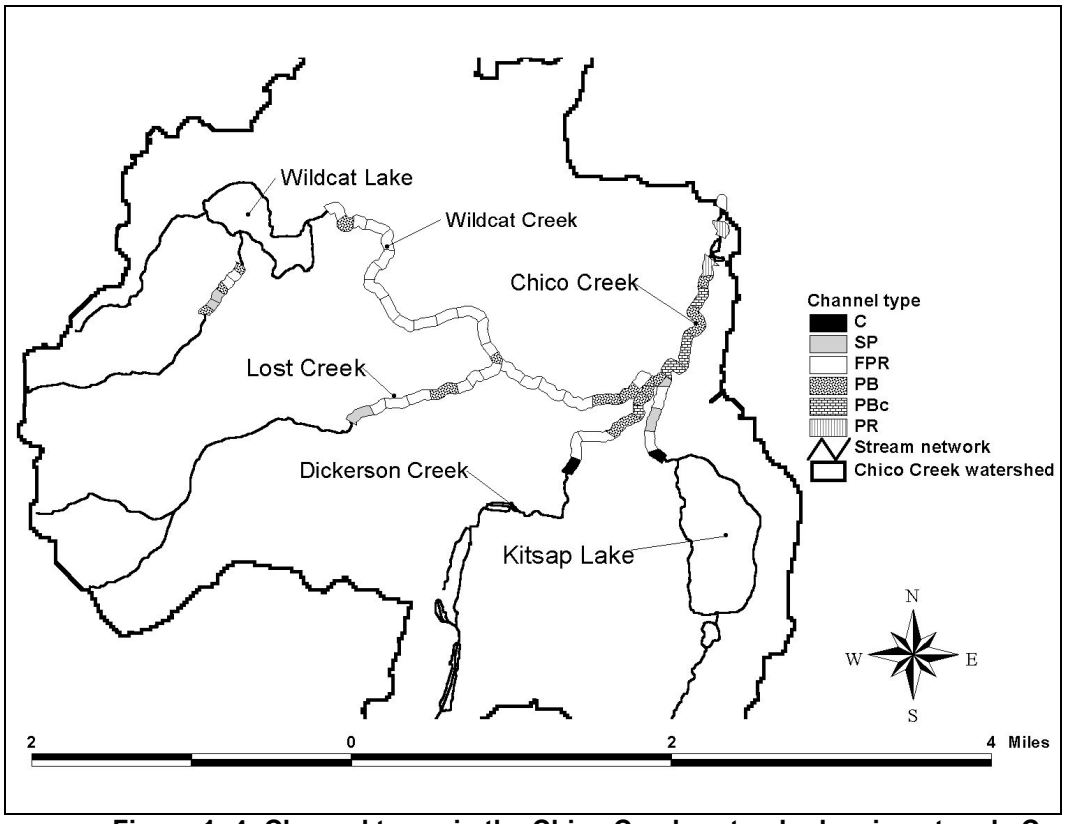


Figure 1- 4: Channel types in the Chico Creek watershed main network. C: Cascade; SP: Step-pool; FPR: Forced pool-riffle; PB: Plane-bed; PBc: Constrained plane-bed; and PR: Pool-riffle

One grouping of channels with plane-bed morphology was distinctly different from plane-bed channels originally defined by Montgomery and Buffington (1997). These channels have low pool and LWD frequencies (less than 5 pools/100 m and 9 LWD/100 m) as the result of urban encroachment,

limited or no hydraulic connection to the floodplain, and/or the absences of well-developed riparian vegetation. These generally low-gradient reaches have lost most or all their self-forming alluvial character. The existence of lateral constraining structures (bank armoring) restricts them from interacting with the floodplain, leading them with simplified morphologies. I define them here as constrained plane-bed (PBc) channels.

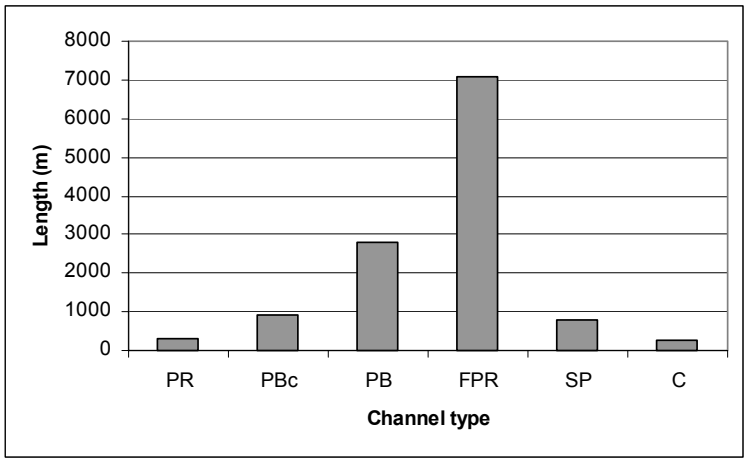


Figure 1- 5: Survey stream network length per channel type. C: Cascade; SP: Step-pool; FPR: Forced pool-riffle; PB: Plane-bed; PBc: Constrained plane-bed; and PR: Pool-riffle

The surveyed channel network had gradients between 0.001 and 0.09. The vast majority of the reaches (85%) had gradients between 0.001 and 0.04. Steeper slopes (>0.04) were infrequent (5%) among the surveyed sites (Figure 1-6). The upper sections of the watershed tributaries, not accessible to fish and therefore not included in the survey, also tended to occupy steeper gradients and were mainly underlain by bedrock deposits (geologic map, Appendix A, Figure A-1).

Observed channel types tended to stratify by gradient. Cascade reaches were found with slope greater than 0.05, SP with gradients between 0.02 and 0.04, FPR channels with gradients between 0.01 and 0.04, PB and PBc channels with gradient between 0.01 and 0.02, and PR reaches with gradients below 0.01.

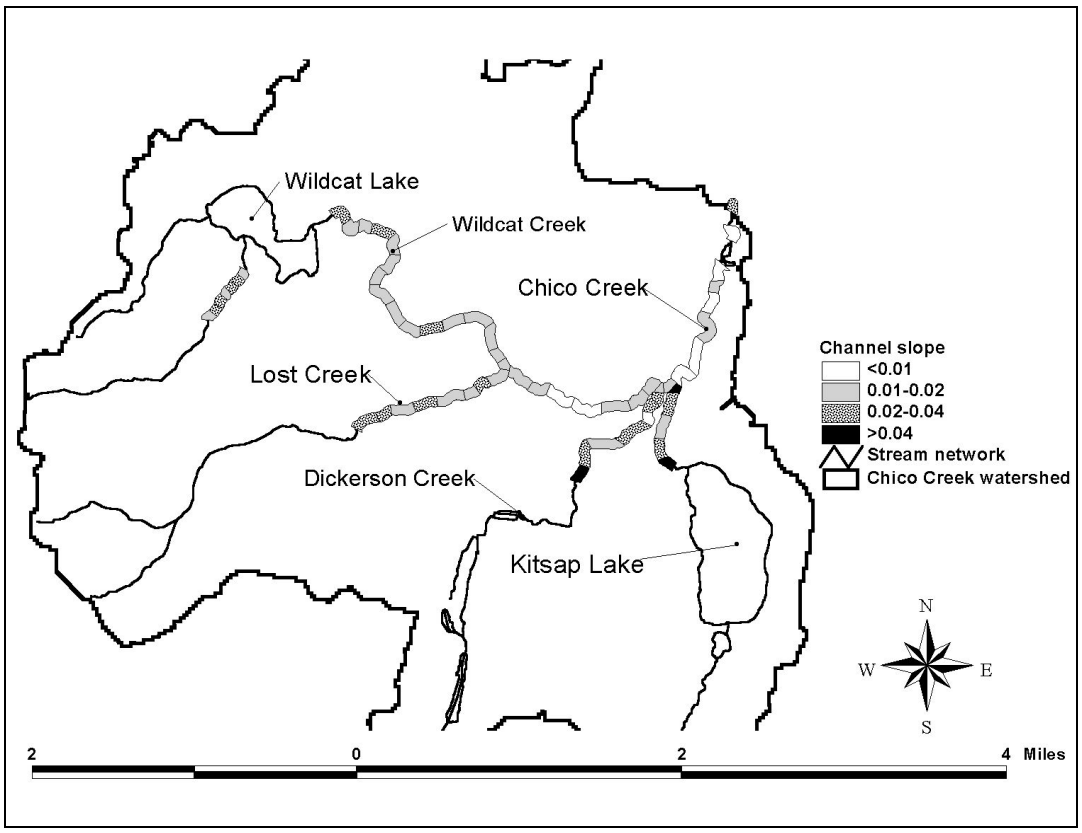


Figure 1- 6: Chico Creek watershed Channel gradients

Forced pool-riffle reaches were located in most of the surveyed sectors of Wildcat and Lost creeks, and in some portions of Chico and Dickerson creeks. Kitsap and Dickerson creeks had the steepest gradient and were generally characterized by cascade, step-pool, and plane-bed reaches. Most of Chico Creek was characterized by plane-bed and constrained plane-bed morphologies, reflecting the increased human influence along these channel reaches (Figure 1-4).

3.2 Channel geomorphic condition

The Chico Creek watershed stream network has variable geomorphic conditions, as reflected by in-stream wood and pool frequencies, bank stability, and substrate cementation. LWD in the basin varied between 0 and 76 pieces per 100 m, pool frequency ranged from 2.2 to 12.4 per 100 m, bank stability showed variable stages from completely unstable or armored (score =1) to stable

(score =4), and cementation scores were mostly indicative of “good” substrate conditions (score 3 and 4) with only few “fair” or “poor” conditions (scores 1 and 2). “High” overall quality (i.e. PSCI score above 13 points) were found in the basin tributaries (mainly in Wildcat and Lost creeks), whereas the main stem (Chico Creek) had generally “low” geomorphic quality conditions (i.e. PSCI scores below 8 points).

Reaches with high LWD frequencies (i.e. above the 75th percentile, Table 1- 3) were mainly located in the mid-sections of Lost and Wildcat creeks. Reaches with LWD frequencies below the 25th percentile (7 pieces per 100 m) were mostly located in Chico Creek and in the lower portions of Dickerson and Kitsap creeks (Figure 1- 7).

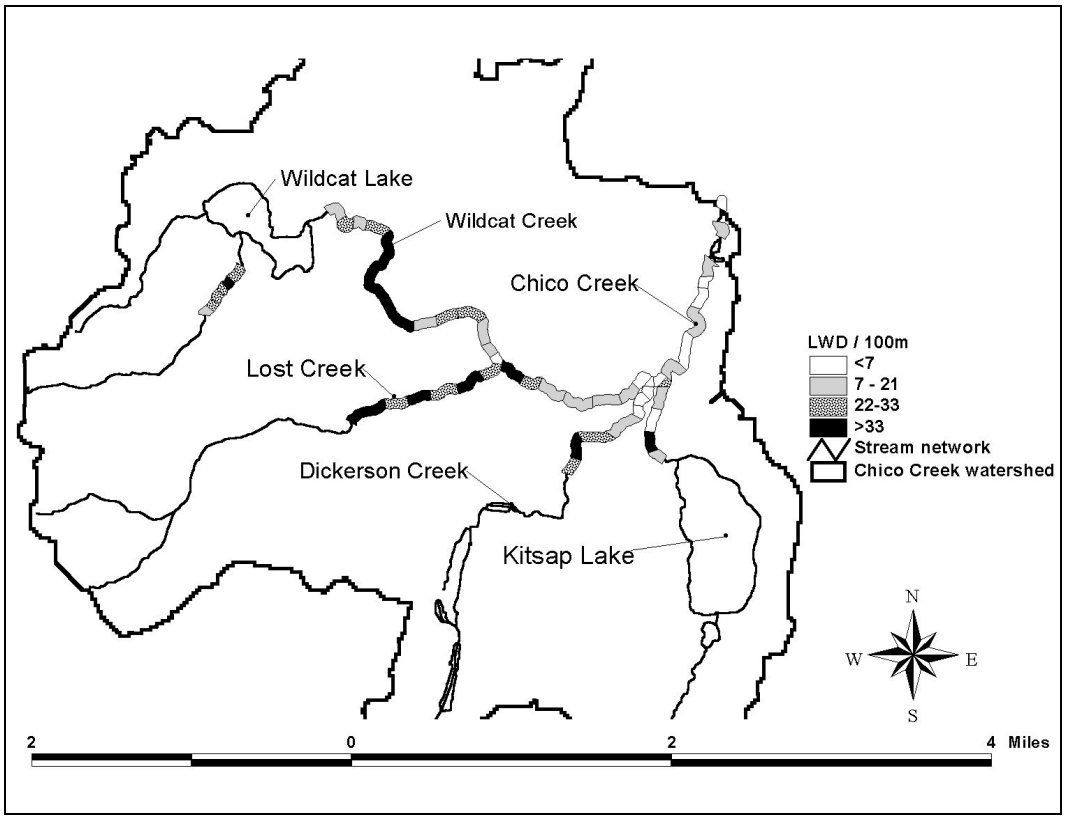


Figure 1- 7: LWD/100 m Chico Creek watershed.

Pool abundance varied between 2 and 12 per 100 m in the surveyed network. High pool frequency values (above the 75th percentile) were located in mid-portions of Wildcat and Lost creeks, in most of the surveyed section of

Kitsap Creek, and in the upper portion of Dickerson Creek. Reaches with low pool frequency (below the 25th percentile) were found at Chico Creek (Figure 1-8).

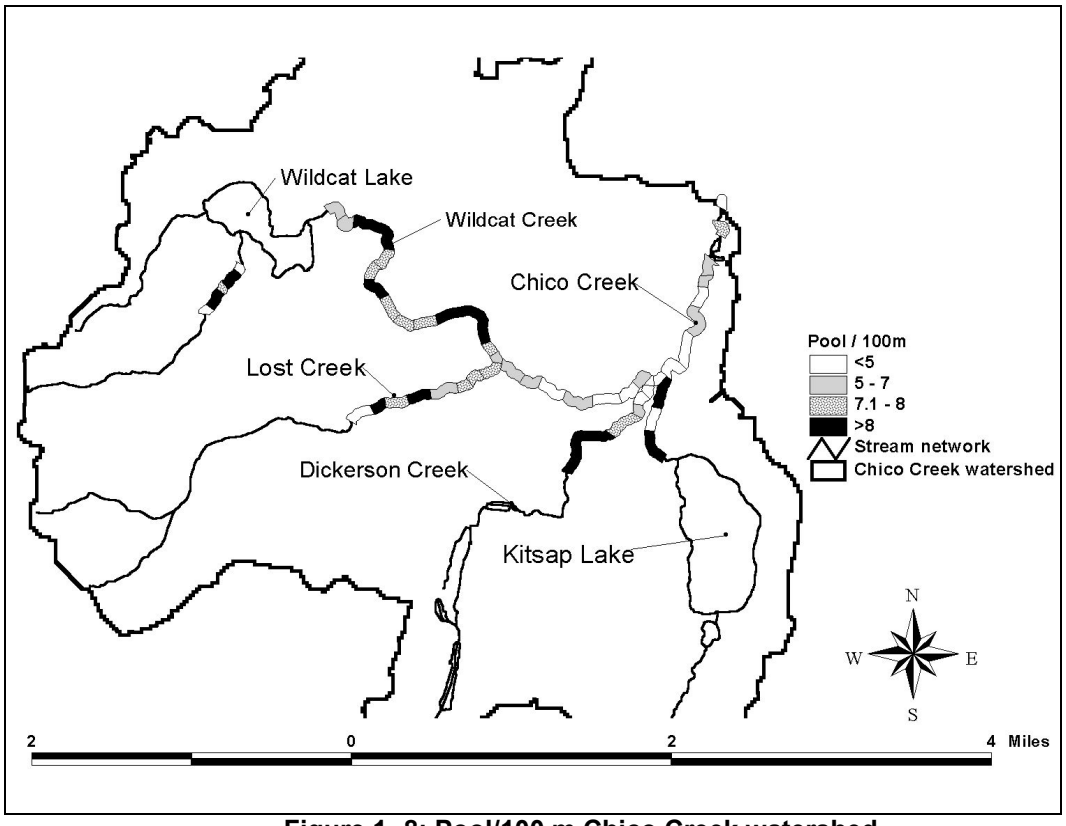


Figure 1- 8: Pool/100 m Chico Creek watershed

LWD data (Figure 1- 7) and pool frequency (Figure 1- 8) cluster strongly by channel type (Figure 1- 9). Forced pool-riffle reaches had the highest median LWD per 100 m (30 pieces), followed by SP and cascade reaches. PB, PR, and PBc channels had the lowest LWD frequencies with medians below 9 pieces per 100 m (Figure 1- 9a). Statistically significant differences in LWD frequencies were found between FPR and PB channels ($p = 0.005$) and between FPR and PBc reaches ($p= 0.008$). Pool spacing was high (i.e. low pool frequency) at PB, PBc, and SP reaches, with medians above 2 BFW; while FPR, PR, and SP reaches had low pool spacing (high frequency) with medians below 2 BFW (Figure 1- 9b). Statistically significant differences were found between FPR and PB, PBc, and SP ($p < 0.001$, $p= 0.02$, and $p = 0.03$, respectively). The distinction

between “low” and “high” pool frequency appeared to be close to 2 BFW between pools. Montgomery et al. (1995) first found this distinction in a study conducted in western Washington, in which 83% of the surveyed FPR systems had pool spacing values narrower than 2 BFW. This pool spacing has been also identified as adequate for salmonid migration Peterson et al. (1992).

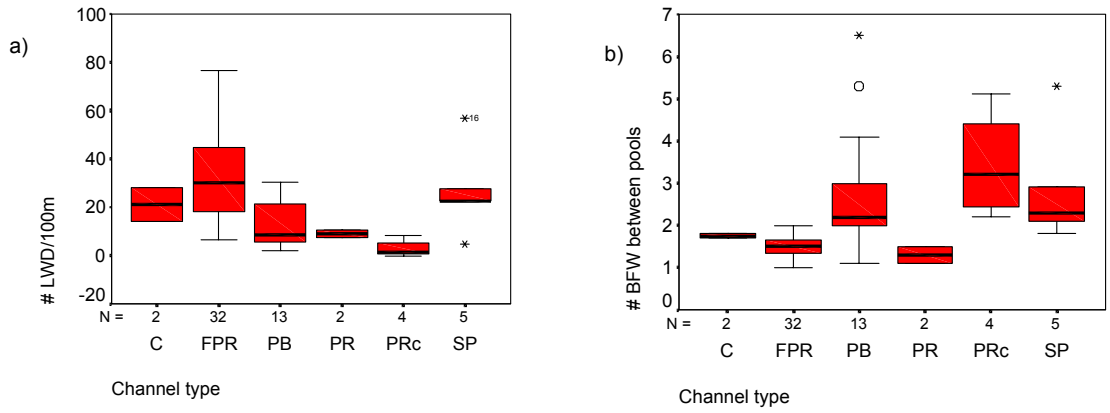


Figure 1- 9: LWD (pieces/100 m) (a) and pool frequency (channel BFW between pools) (b) per channel type. C: Cascade; SP: Step-pool; FPR: Forced pool-riffle; PB: Plane-bed; PBc: Constrained plane-bed; and PR: Pool-riffle.

The position of the LWD pieces in the channel was highly variable among channel types (Figure 1- 10). FPR channels had a higher median percentage of spanning wood pieces in contact with the flow (62%) than PB (47%), cascades (55%), PR (41%), PBc (31%), and SP (46%). Statistically significant differences in the percentage of spanning LWD pieces were found only between FPR and PBc reaches (p = 0.03).

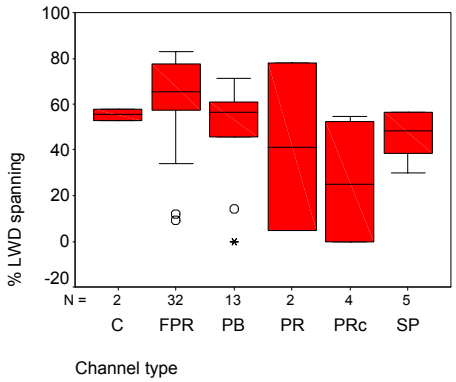


Figure 1- 10: Percentage of full-width-spanning LWD pieces

Bank stability results were variable within the surveyed reaches. Most of the reaches (37%) were classified as stable (i.e. score = 4) and relatively few (17%) were found unstable or armored (score =1) (Table 1- 4).

Table 1- 4: Bank stability results for the surveyed network

Channel stability	Length (m)	%
Stable (score = 4)	4552	37
Slightly unstable (score = 3)	2634	22
Moderately unstable (score = 2)	2914	24
Completely unstable (score = 1)	816	7
Armored (score = 1)	1242	10

Banks showed a progressive tendency towards increasing instability from the tributaries to the main stem. Most of the reaches in Wildcat and Lost creeks were either stable or slightly unstable (i.e. scores of 4 and 3), whereas most of the reaches in Chico Creek were classified as moderately unstable, completely unstable, or armored (i.e. scores of 2 and 1) (Figure 1- 11). Sections in Dickerson, Kitsap, and Chico creeks located close to urban development (Figure 1- 14) were less stable than channel banks in Wildcat and Lost creeks, which flow through second-growth forest. Completely unstable and unarmored banks where found in the upper section of Lost Creek and near the confluence of Dickerson and Chico creeks. Bank armoring structures, to stabilize residential yards or road and railway crossings, were observed only in reaches along Dickerson and Chico creeks (Figure 1- 11).

The degree of cementation of the sediment in the surveyed reaches showed generally high values (Figure 1- 12). Thus, most of the reaches (86%) were ranked as “good” or “excellent.” Cementation was most pervasive in Chico Creek, with nearly all reaches classified as “fair” (Figure 1- 12). Only one reach, located in Dickerson Creek (reach 21), was classified as “poor;” this reach was dominated by bedrock, however, with only sparse alluvial sediment.

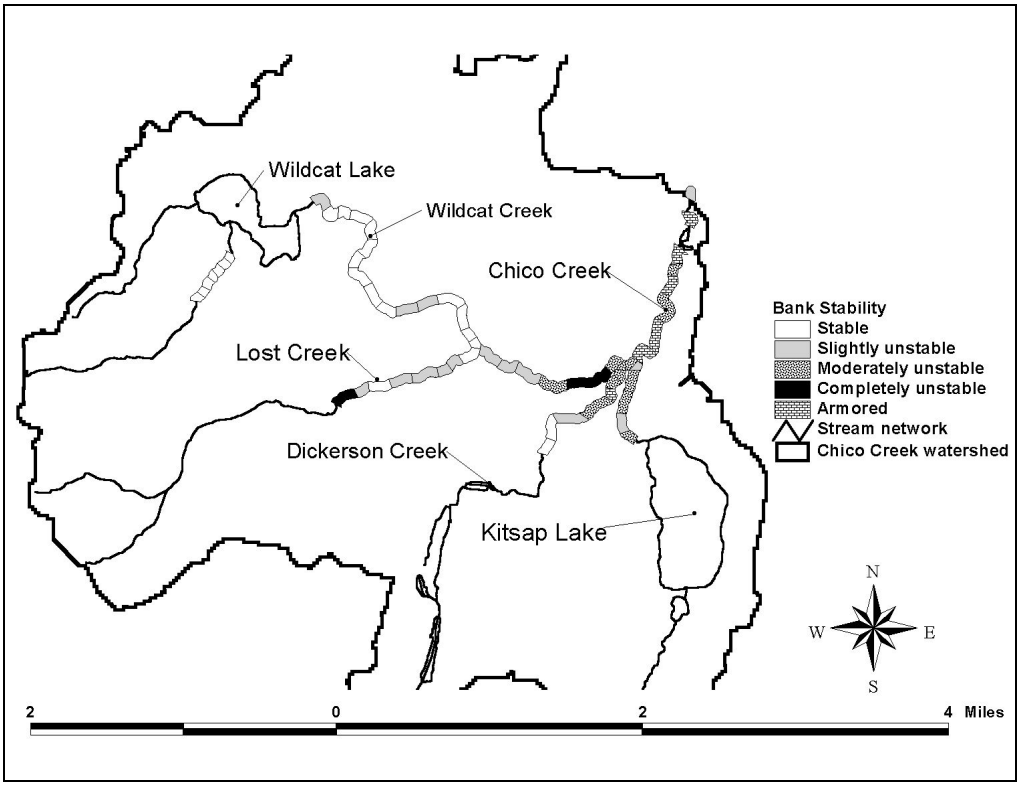


Figure 1- 11: Chico Creek watershed bank stability

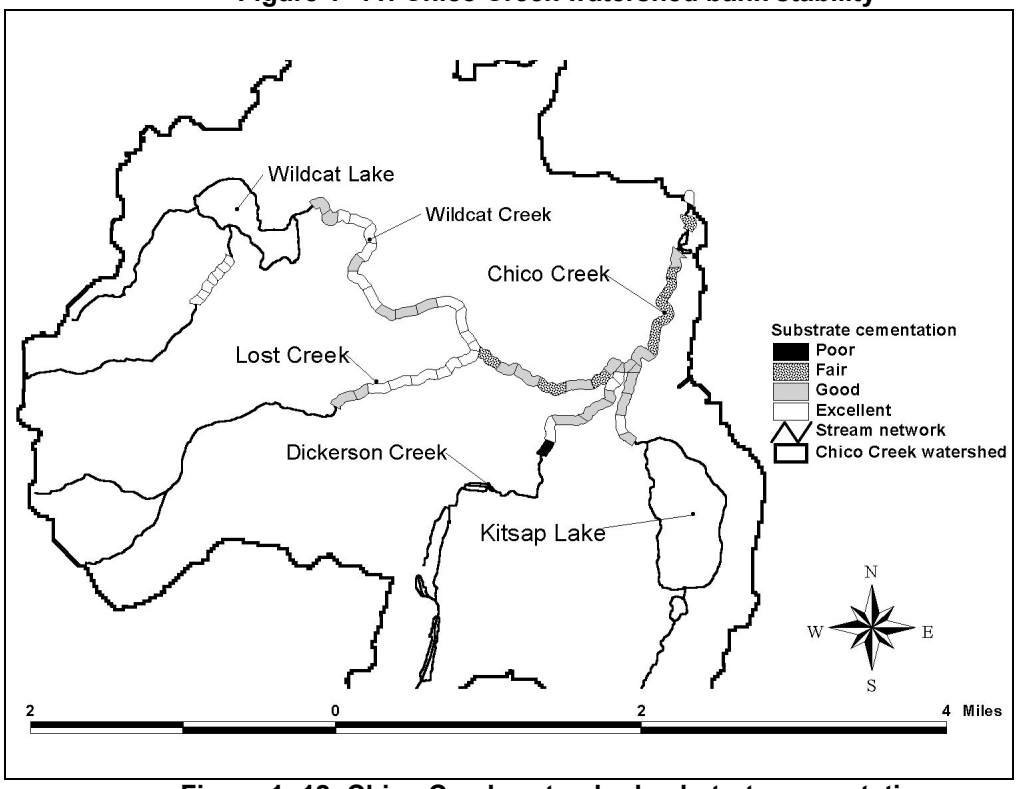


Figure 1- 12: Chico Creek watershed substrate cementation

Channel stability was positively correlated with substrate cementation (R^2 = 0.6, including 57 out of the 58 reaches) (Figure 1- 13), indicating that bank stability increases with decreasing amounts of fine sediment and suggesting bank erosion as a significant source of fine sediment in the streams. The highlighted outlier in Figure 1- 13 corresponds to reach 21 in Dickerson Creek.

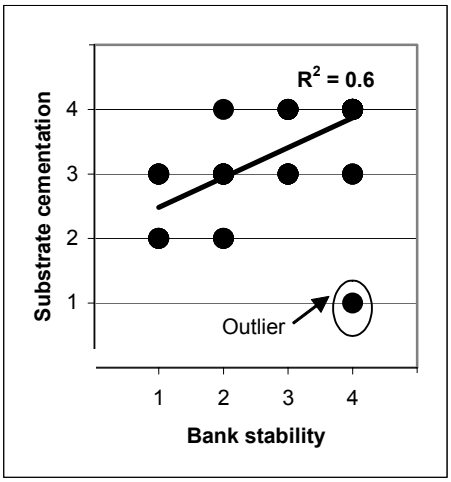


Figure 1- 13: Bank stability versus substrate cementation

A Physical In-stream Condition Index (PSCI) was calculated by summarizing the individual scores from measurements of LWD and pool frequencies, cementation, and bank stability. Values showed wide variation across the watershed, with scores between 5 and 16 points (Figure 1- 14). PSCI indicated relatively high-quality physical conditions in the upstream portions of the Chico Creek watershed tributaries (Wildcat, Lost, and Dickerson creeks) and a pattern of decreasing in-stream physical quality towards the lower reaches of the basin. Reaches in the lower sections of Chico, Dickerson, and Kitsap creeks were mainly categorized in the intermediate- and low-quality bands (scores below 13) (Figure 1- 15). In particular, the main stem of the watershed (Chico Creek) was characterized by low values (less than 8 points) in most reaches.

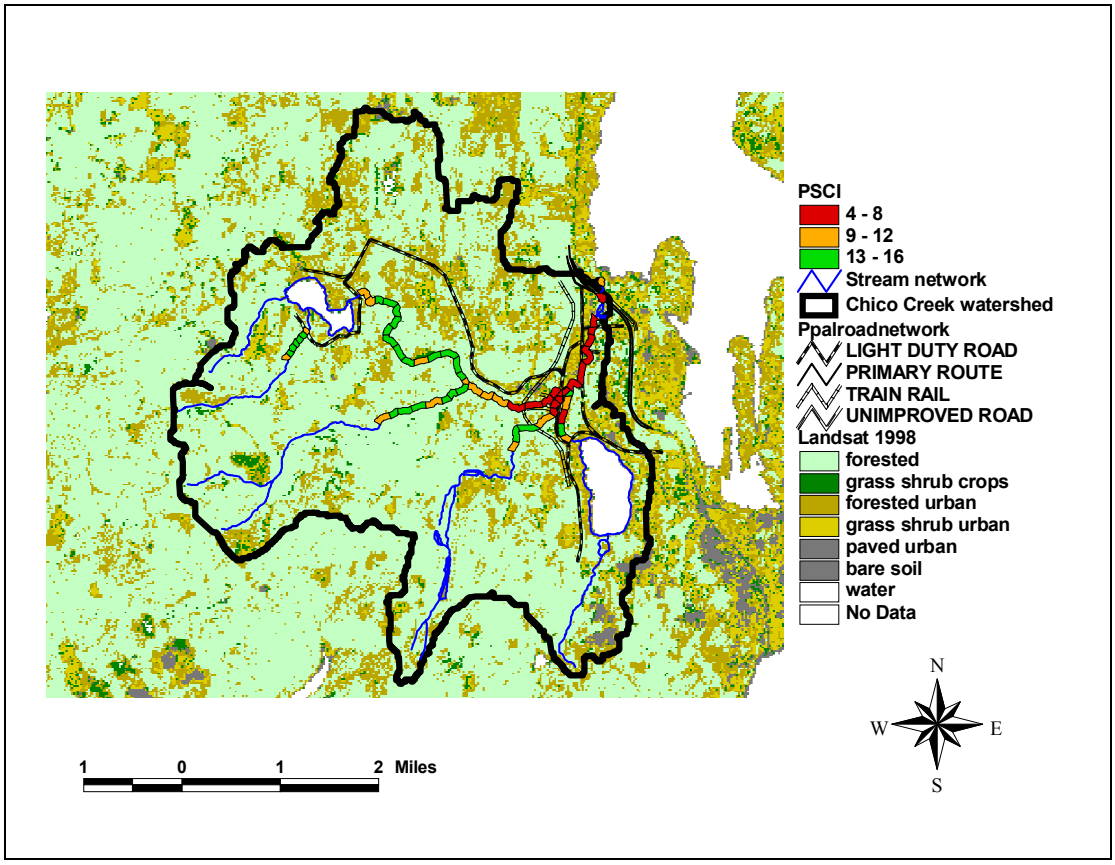


Figure 1- 14: Chico Creek watershed Physical Stream Condition Index and land cover (from Hill et al., 2003)

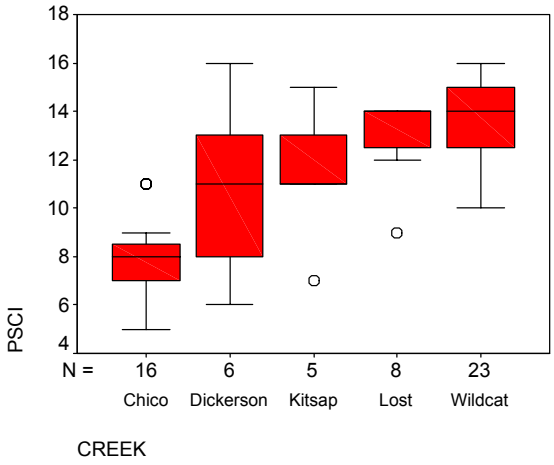


Figure 1- 15: PSCI reach scores by creek

3.3 Urbanization and associated channel geomorphic condition (PSCI)

The overall land cover of the basin has a high percentage of forested areas. Wildcat, Lost, and Dickerson creeks, in particular, have high densities of

forested areas in the riparian zone of the channels, as well as overall well-forested contributing watersheds (Appendix A, Tables A-2 and A-3). Chico and Kitsap creeks, in contrast, are less pristine and are more commonly surrounded by the categories “grassy urban,” “paved urban,” and “grass shrub crops” (Figure 1- 14).

Total impervious surface area (TIA) in the Chico Creek watershed is approximately 15%. The spatial distribution of the land cover types associated with imperviousness (grassy/shrubby vegetation, bare earth, forested urban, grassy urban, and intense urban), however, is not uniform across the watershed. High levels of development are mainly located in the lower sections of Dickerson, Kitsap, and Chico creeks (Figure 1- 14). The contributing drainage area to each reach (i.e. the sub-basin scale) shows relatively low variability of impervious surface coverage (between 9 and 20%).

A spatial analysis for TIA percentage in the 50-m riparian buffer showed much higher variability than for the sub-basin scale, with values ranging from 3 to 55%. More than half of the reaches had TIA lower than 10% in their 50-m riparian buffer zone. High TIA (above 30%) was observed at 40% of the reaches along Chico Creek and at more than 50% of the reaches in Kitsap Creek (Table 1- 5). In contrast, none of the surveyed reaches in Wildcat and Lost creeks had TIA in the riparian zone above 30%. Chico and Dickerson creeks had variable TIA percentage in the riparian area distributed across the complete observed range.

Table 1- 5: Reach distribution according to riparian impervious surface area (from Landsat image 1998 and percentages developed by Hill et al., 2003).

Creek	<10% TIA	10-30% TIA	>30% TIA	Total sample per creek
	Reaches/length	Reaches/length	Reaches/length	Reaches/length
Wildcat	19 / 3541m	4 / 852m	-	23 / 4393m
Lost	8 / 1779m	-	-	8 / 1779m
Dickerson	3 / 670m	2 / 563m)	1 / 131m	6 / 1364m
Kitsap	-	2 / 285m	3 / 483m	5 / 768m
Chico	4 / 1156m	5 / 1006m	7 / 1692m	16 / 3854m
Total	**34 / 7146m**	**13 / 2706m**	**11 / 2306m**	**58 / 12158m**
%	**59%**	**22%**	**19%**	

The prevalence of some channel types was related to riparian zone TIA (Figure 1- 16). FPR channels had less than 30% TIA in the 50-m buffer in all cases except for reach 37 in Kitsap Creek. The near-riparian area in PBc reaches had TIA above 20% in all cases. PB and SP channels had variable values (between 3 and 55%).

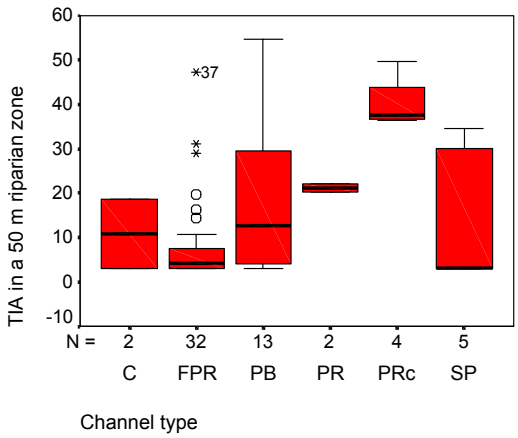


Figure 1- 16: Total impervious surface area by channel type in a 50 m riparian zone

For this data set, TIA in the drainage area contributing to each reach does not explain the variability of the PSCI (Figure 1- 17a). In contrast, 53% of the PSCI variability is explained by TIA in the 50-m riparian area ($p < 0.001$) (Figure 1- 17b). Wildcat and Lost creeks reaches, which showed the lowest imperviousness percentages, flow through second-growth Tsuga heterophilla forest. The interaction of the channel with this terrestrial ecosystem is likely to explain their high PSCI scores. Reaches located in the lower sections of Dickerson, Chico, and Kitsap creeks flow very close to highly developed areas (Figure 1- 14) and had correspondingly lower scores (Figure 1- 17b).

Although PSCI scores show high variability for a given 50-m riparian TIA value, individual tributaries displayed more systematic relationships. For example, reaches in Chico Creek with TIA percentages in the 50-m riparian area between 10 and 50% have consistently lower values than reaches in Kitsap Creek at comparable urbanization levels (Figure 1- 17b). Considering TIA in the contributing drainage area, reaches in Chico Creek had lower PSCI scores than

reaches in Kitsap Creek, even though the latter had higher TIA values in their contributing basin (Figure 1- 17a).

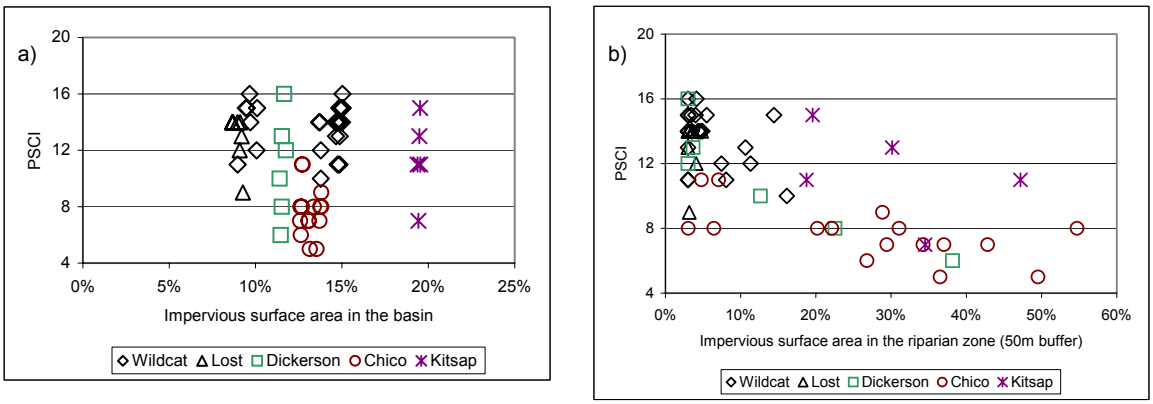


Figure 1- 17: TIA v PSCI at the basin (a) and riparian-area scales (b)

4 Discussion

Channel types in the Chico Creek watershed are the result both of the natural setting and the influence of anthropogenic drivers. Forced pool-riffle reaches were associated with the less disturbed areas of watershed, whereas plane-bed (PB) and constrained plane-bed (PBc) reaches were mainly located near highly urbanized areas. Some of these PB reaches are likely to have been FPR channels in pre-development time. FPR are highly dependent on the recruitment of LWD and the connectivity of the channel with the floodplain.

PSCI results provide a coarse discrimination of the channel network, whose attributes showed good correspondence to the near-stream land cover. However, some variability was observed for any given level of total impervious surface area in the near-riparian zone, likely associated with lower sensitivity of the attributes incorporated in the PSCI in high-gradient reaches and/or the morphological effects of upstream lentic systems in some of the surveyed systems.

The variety of channel types reflects the heterogeneity of the basin. In pristine ecosystems, spatial and temporal distribution of channel types is the result of geologic, biological, and climatologic patters. The Chico Creek

watershed is a semi-rural basin with low development, but anthropogenic driving forces appear to be influencing the otherwise natural setting of the stream channels and their response. This is particularly evident in Chico and Dickerson creeks downstream of their railway crossings (Figure 1- 14). These reaches have the greatest riparian urbanization (TIA > 20%) relative to the other surveyed sites. These sectors exhibit altered channel morphology, expressed by the absence of a well-configured sequence of riffle and pools. From a biological perspective, low pool frequency could harm salmonid populations because pools are important as both holding points for adults and rearing habitats for juveniles in forested low-gradient streams of the Pacific Northwest (Peterson et al., 1992).

PB and PBc channels now found in the basin are likely to have been FPR systems in pre-development time. Since development started, these reaches have been depleted of both LWD, needed to maintain the riffle-pool configuration at the gradient of those channels, and sediment delivered from the banks in the case of constrained reaches. In the absence of historic data it is not feasible to reliably describe past channel condition; however, it is likely that the fluvial and sediment regime of current PB reaches in the basin have been drastically altered, leading to a stream channel with few roughness elements. It is likely that at least 8 out of 13 surveyed PB reaches, mainly located in Chico and Dickerson creeks below the railway crossing, are the product of human disturbance. Other PB reaches located in Wildcat and Lost Creeks might be the expression of the natural conditions rather than the result of human disturbance, as these reaches have very low human influence and are well surrounded by mature second-growth forest.

In the FPR channels, located in the more pristine reaches of the basin, high amounts of LWD and many pools were found. Alteration, or elimination, of riparian vegetation would have enormous impact on the morphology of these channels. In the absence of debris recruitment, these forced reaches could change their morphology to plane-bed (Montgomery and Buffington, 1998). Step-

pool (SP) channels would not be likely to replace these FPR channels in the event of riparian vegetation disturbance, because they lack a supply of coarse sediments.

The level of development (percentage TIA) correlated with the frequency of armored banks (all PBc reaches had TIA above 20% in the near-riparian area). Reaches with armored banks have undoubtedly been protected due to their highly unstable character. Yet armored banks also commonly isolate the flow from the floodplain and give rise to less complex systems (generally, a change from PR and FPR to simple PB channels).

Cementation results suggest a low proportion of fine sediment and low levels of compactness of the gravel in most of the survey reaches. Higher levels of compactness, which could have detrimental effects on fish spawning habitat, were only found in the middle and lower sections of Chico Creek. These “fair” cementation conditions (i.e. score = 2) may be a result of increased fine sediment supply triggered by the altered hydrologic regime and disturbed ground in the nearby developed areas. They may also reflect a greater influx of sediment as a result of bank erosion (Nelson and Booth, 2002). Reaches with “fair” cementation also had low bank stability scores.

The Physical In-stream Condition Index provided a coarse, but apparently robust, discrimination of the current geomorphic conditions across the channel network. This index was not related to basin-area land cover. However, some correspondence was found with local land cover, suggesting that the physical attributes incorporated in the PSCI are probably influenced by local drivers. Despite this correspondence, variable PSCI scores were observed for a given local TIA level between reaches in Chico and Kitsap creeks. According to the data collected, the difference in PSCI scores between Chico and Kitsap creeks for comparable local TIA, could have either or both of the following explanations: 1) differences in channel-type responsiveness or 2) existence of a hydrologic buffer upstream of the surveyed reaches in Kitsap Creek.

Reaches in Kitsap Creek, which were associated with high-gradient channel types (cascade, SP, and FPR), had higher PSCI scores (between 7 and 15) than reaches in Chico Creek (between 5 and 9), which were dominated by low-gradient channel types (PR, PBc, PB, and FPR). Reaches in both of these creeks extended across comparable ranges of local TIA. Bank stability, LWD, and pool frequency were considerably higher at reaches in Kitsap Creek than at reaches in Chico Creek, suggesting the higher sensitivity of low-gradient reaches to the measured geomorphic features.

Yet higher bank stability scores in Kitsap Creek compared to Chico Creek could also be an expression in the data of different hydrologic regimes, likely to be less flashy below lentic systems. Reduced discharge peaks are also suggested in the data by the high bank-stability scores (4 points) in most of the reaches downstream of Wildcat Lake, in contrast to a much broader range of stability scores in Lost Creek, which lacks of an up-stream lentic system. These findings are consistent with the results obtained by Booth and Jackson (1997), who observed anomalously low flow increases associated with impervious area where “large” lakes (surface area equals or exceeds 10% of the watershed area) are present upstream of the observation point. Wildcat Lake occupies between 3 and 7% of the contributing drainage area of the reaches surveyed downstream of it. Although bank stability scores in reaches below Kitsap Lake (which extends over more than 12% of the drainage area of the surveyed reaches) are not as high as in Wildcat Creek below Wildcat Lake, they are higher than in Chico Creek. The slightly to moderate unstable conditions observed in Kitsap Creek are likely a consequence of impacts triggered by both the road crossing upstream (Avolio, 2003) and the proximity of residences in the riparian zone, which have apparently not been fully moderated by Kitsap Lake.

Correspondence between PSCI scores and biological condition is sparse but suggestive. High PSCI scores in stream reaches of Wildcat, Lost, and Chico creeks near their confluence corresponded well to reported fish spawning and

rearing habitat. These reaches support significant chum spawning and are key migratory pathway for coho and steelhead moving into the headwaters to spawn (Kitsap County, 2000). Dickerson Creek upstream of the railway crossing is also important spawning and rearing habitat for chum, coho, and steelhead (Kitsap County, 2000), and these reaches also had high PSCI scores (between 13 and 16 points). There is also correspondence between PSCI and B-IBI scores (Morley and Karr, 2003) available for 3 reaches (P. Nelson, Kitsap County, unpublished data, 2002). Reaches 9 and 23 in Wildcat and Dickerson creeks had high PSCI scores (14 and 13, respectively) and high B-IBI (40 and 36, respectively), while reach 33 in Chico had low PSCI (7 points) and low B-IBI (34 points). The only contradiction to these corresponding patterns of physical and biological data was found in reach 38 of Kitsap Creek, which has a low B-IBI of 14 but a high PSCI of 13. This is not entirely surprising, however, because biological condition depends on a variety of factors of which physical habitat is only one (Karr and Chu 1999). Water quality in Kitsap Creek, for example, has been reported to be poor, with temperature as high as 21.4 ºC and exceedance of total phosphorous and fecal coliform standards (Washington State Conservation Commission, 2000).

From a geomorphologic viewpoint, degraded reaches of the basin (especially those located in Chico Creek) would ideally be restored to mimic the conditions found in the reaches with “high” geomorphic quality (PSCI above 13 points), which were mainly located in the FPR reaches of Lost and Wildcat creeks. To create the morphologic condition observed in FPR reference sites, the stream would have to be reconnected with its floodplain to modify the fluvial regime by allowing both the dissipation of energy at high flows and the sediment deliver from the channel banks. At high flow, reestablished unconfined conditions of degraded reaches would allow the spread of the stream flow across the broad valley floor, dissipating much of the energy of the current (Gregory et al., 1991). Encroaching human development in these same floodplains, however, makes this a challenging restoration approach.

Protecting existing riparian vegetation should be a priority, particularly establishing additional forested cover to along degraded reaches as source of wood required for the FRP configuration. Once a LWD piece enters the channel, it exerts significant controls on the physical characteristic of streams, influencing channel type, sediment storage, and bedform roughness (Bilby and Bisson, 1998). Mere installation of LWD in alluvial channels, however, does not necessarily lead to biological improvement. Results by Larson et al. (2001) showed that although LWD restoration projects can modestly improve physical habitat in a stream reach over a time scale of 2-10 years, they apparently do not achieve commensurable improvement in biological conditions.

FPR channels are the most feasible reaches for monitoring the response of the channel to disturbance, due to their alluvial configuration and their established connection with the floodplain. In particular, such reaches are located in Wildcat and Lost creeks. Other low-gradient reaches (PR and PBc) are not good candidates, either because they have lost their alluvial character or because they are influenced by nearby urbanization and therefore have limited remaining potential for response. Survey areas of Dickerson and Kitsap creeks are also not expected to be good sites to track future impacts, because they are locally influenced by rigid bedrock channel boundaries or nearby road and railway crossings.

The scope of this study was not adequate to fully analyze every component of the channel morphology. Further work could address detailed analysis of the LWD recruitment regime, investigate the relationship between riparian-zone condition and channel morphology, and the influence of natural and anthropogenic confinement on channel responsiveness to disturbance. In addition, comparative analysis between the PSCI results with other rapid geomorphic assessment over the same analyzed network could provide an evaluation of the robustness of the PSCI protocol and of its individual metrics.

5 Conclusion

The Chico Creek watershed stream network has a variety of channel types, which reflect both human alteration and the interactions of geological, biological, and climatic conditions of the basin. Most of the surveyed reaches were classified as forced pool-riffle and were located in low-disturbed areas dominated by forested cover. Plane-bed and constrained plane-bed reaches, mainly in the lower section of the watershed, are in almost all cases the result of human alteration. Pre-development, these reaches are also likely to have been forced pool-riffle channels. Cascade and step-pool reaches were uncommon and were located at high gradients in the upper section of the basin tributaries.

Frequencies of LWD and pools were distinctly different in different channel types. Forced pool-riffle channels had the highest LWD and pool frequency. In the absence of debris recruitment, these forced reaches could change their morphology to plane-bed, decreasing pool frequency and placing at risk the fish populations dependent on pools as holding points and rearing habitat.

Most of the reaches in the watershed were characterized by stable or slightly unstable banks that also corresponded with “excellent” or “good” substrate cementation scores. Pervasive bank instability and cementation conditions were progressively more common downstream along the main stem of the watershed. The correspondence between bank stability and cementation scores suggest bank erosion as an important source of fine sediment.

A multimetric index of physical habitat condition, the Physical In-stream Condition Index, provided a coarse discrimination of the current geomorphic condition of the channel network. PSCI scores had no correlation with watershed TIA but fair correspondence with TIA in the near-riparian zone, suggesting that local drivers influence the physical attributes incorporated into this index.

Differences in PSCI scores for a given TIA level were associated with intrinsic characteristics of the basin tributaries. Kitsap Creek had higher PSCI

scores than reaches in Chico Creek at comparable local TIA. This difference in scores could be related to different responses for channel types, or it could be the result of the hydrologic buffering (i.e. less flashiness) provided by Kitsap Lake for downstream reaches. High-gradient channel types in Kitsap Creek showed lower geomorphic sensitivity to bank stability, LWD frequency, and pool frequency than low-gradient types in Chico Creek. Effects of different hydrologic regimes (reduced discharge peaks) were also suggested in the data by higher bank-stability scores in reaches of Wildcat Creek, below Wildcat Lake than in reaches in Lost Creek.

From a geomorphologic viewpoint, low-gradient degraded reaches of the basin should be the highest priority for restoration to mimic the conditions of FPR channels found in the reaches with “high” geomorphic quality. In this enterprise, the connection of the stream with the floodplain would have to be enhanced. In addition, existing riparian vegetation should be given priority. Conserving additional forested cover would be desirable to establish a source of wood required for the FRP configuration.

FPR channels in Wildcat and Lost creeks are the most feasible reaches in which to monitor the response of the channel to future disturbance (most likely development impacts), due to their alluvial configuration and their established connection with the floodplain that allow a high level of responsiveness.

CHAPTER 2

1 Introduction

Two rapid assessments, both designed to characterize current in-stream geomorphic conditions, were applied by two independent field crews to 11 km of the main stream network of the Chico Creek watershed, located in the Kitsap Peninsula approximately 30 km west of the city of Seattle in western Washington State (Figure 2- 1). The purpose of this study was to compare the overall results achieved by the two methods, as well as the results obtained by individual metrics used in each method. The individual metrics were evaluated in comparison with detailed surveyed data collected by others, available for about half of the reaches. These evaluations took into consideration the geomorphic context of the surveyed network expressed by their channel type (Montgomery and Buffington 1998) (Chapter 1).

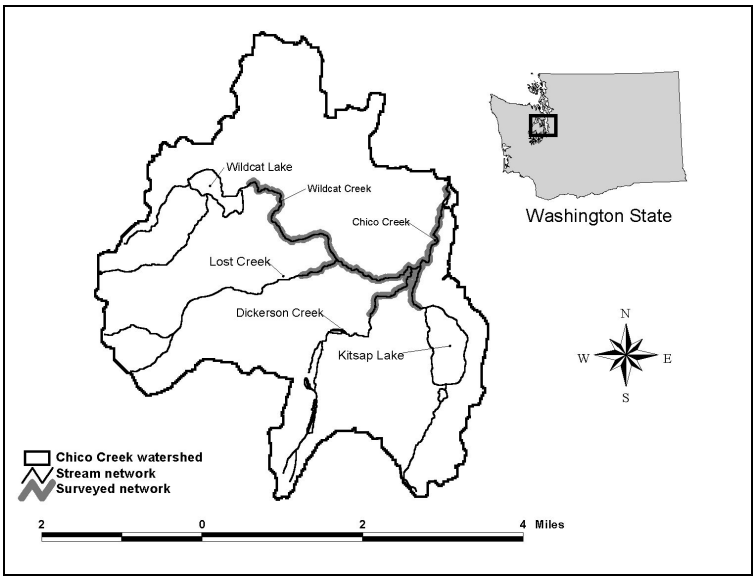


Figure 2- 1: Location of the study area

The assessment of the current in-stream conditions of a watershed is a common part of the agenda of management agencies. These agencies typically experience difficulties in designing and carrying out effective evaluations

because of (1) limited time, (2) limited scientific resources, and (3) limited field-staff resources.

While fully quantitative approaches may provide an apparent benefit through their high precision and documentation, they are of limited value if the institutional resources simply do not exist to carry them out (Scholz and Booth, 2001). Repeatability of results across multiple observers is also commonly much poorer than the apparent precision of the raw data might suggest. Finally, management actions commonly occur on a very coarse scale, the range of options is often limited, and even where a high degree of discrimination between different levels of condition might be achieved the management response to many of those potential outcomes might be identical. As a result, rapid assessment techniques that can cover a channel network rapidly (on the order of miles per day) may provide nearly equivalent benefit to land managers as more laborious survey-based techniques, particularly if the rapid approach is calibrated and tested against more precise methods.

2 Methods

Data sources included the results obtained from 41 reaches surveyed in the main stream network of Chico Creek watershed by a rapid qualitative assessment (”rapid 1”) applied by P. Nelson and M. Rylko, Kitsap County (unpublished data, 2002) and the Physical In-stream Condition Index for the same reaches (“rapid 2 ”) (Chapter 1, this thesis). Morphologic data from a detailed quantitative survey (P. Nelson and M. Rylko, Kitsap County, unpublished data, 2002) and estimates of large woody debris (LWD) recruitment potential, developed from spatial analysis in GIS (Roberts, 2003), were also used to evaluate the geomorphic metrics used under each scheme.

2.1 Study sites

Study reaches were located in the main stream network of Chico, Wildcat, Lost, Dickerson, and Kitsap creeks (Figure 2- 1). Bedrock underlies the upper

sections of the watershed tributaries (Lost, Wildcat, Kitsap, and Dickerson creeks). The lower areas are underlain by glacial till, recessional outwash, and advance outwash deposited during the last ice-sheet advance about 15,000 years ago, and some recent alluvial deposits (Haessuler and Kenneth, 2000; revised by D. Booth, written commun., 2002). The Chico Creek watershed includes approximately 11 km of in-stream habitat that are accessible to anadromous salmonids. It supports four salmonids species (chum, coho, steelhead, and cutthroat trout). Chico Creek's chum population is one of the largest in South Puget Sound, with annual escapements averaging 25,000 adults (T. Ostrom, Suquamish Tribe, unpublished data 2002). The mid-section of the watershed supports important second-growth forest relicts composed of conifers (*Pseudotsuga menziesii*, *Tsuga heterophilla,* and *Thuja plicata*) and some hardwoods (*Alnus rubra*, *Acer macrophyllum*) which are mainly located in the riparian areas of Wildcat and Lost creeks.

Most of the urbanization in the watershed is concentrated in the lower sections, mainly around Dickerson, Kitsap, and Chico creeks. Total impervious surface area in the watershed, calculated from the 1998 Landsat image using the relative percentages developed by Hill et al. (2003) is approximately 15 %.

2.2 Field methods

Both "rapid" assessment techniques were based on the collection of four categorical evaluations of channel morphology. For "rapid 1," analyzed features included channel stability, bed sediment cementation, channel complexity, and riparian condition. For "rapid 2," data were collected to describe bank stability, cementation, and numbers of LWD and pools (Table 2- 1).

Table 2- 1: Metrics considered by each rapid assessment methodology

"Rapid 1"	"Rapid 2"
Channel stability	Bank stability
Cementation	Cementation
Channel complexity	Pool counts
Riparian condition	LWD counts

Data were collected using reaches as the survey unit. The minimum reach length was 20 channel widths in order to capture repetitive patterns of the streams (MacDonald et al 1991; Montgomery and Buffington 1997; Martin, 2001). The break between reaches was established based not only on length but also on natural and anthropogenic divisions, such as change in confinement, tributary confluences, change in condition of the near-riparian zone, and road and railway crossings.

2.2.1 "Rapid 1" assessment methodology

Field methods for this technique included the qualitative assessment of 4 geomorphic features. They were based on the protocol by Henshaw and Booth (2000), the Kitsap Peninsula salmonid refugia study (Kitsap County, 2000), the West Kitsap Watershed analysis (WDNR, 1995), stream-channel reference sites (Harrelson et al., 1994), the standard methodology for conducting watershed analysis (Washington Forest Practices Board, 1993), and the summary of channel stability condition categories by Rosgen (2002) (P. Nelson, Kitsap County, personal communication, 2002).

Field data collection took place during the summer of 2002 and was performed by a two-member field crew. The survey included the collection of four geomorphic indicators average along a reach: channel stability, reach complexity, bed cementation, and riparian conditions. Scores for each indicator ranged between 1 and 4 and were assigned based on qualitative comparison between pre-established reference reaches in the Chico Creek watershed network and after on-site discussion by the crew of key morphology features. Selected reference reaches with "best" conditions (i.e. individual metric scores = 4) were identified in the mid-section of Wildcat Creek (reaches 5 to 8); each of these reaches received a total score above 14 points. "Poorest" reference reaches (metric scores = 1) were located in Chico Creek (reaches 25 through 29) and received total scores below 6 points (Appendix B, Table B-1).

Channel stability scores were based on visual field indicators of bank stability, channel form, and bedload transport capacity. Bank stability indicators used the classes described by Henshaw and Booth (2000). Channel form was assessed by a qualitative evaluation of horizontal stability, vertical stability, and connectivity of the main channel with the floodplain or overflow channels. Bedload transport capacity was evaluated by considering the downstream/upstream routing barriers, available storage capacity, and the extent of upstream sediment inputs (Table 2- 2). The channel stability score was assigned after walking the total length of each reach and selecting that best description of the "general" or "average" condition of each reach (Table 2- 2).

Table 2- 2: Channel stability indicators for "rapid 1" (P. Nelson and M. Rylko, Kitsap County, unpublished data, 2002)

Indicators	Score (1 to 4)
Bank stability perennial vegetation to waterline exposed fine roots actively undercutting banks erosion indicators bank held by hard points bank armoring	1: Unstable channel 2: Moderately unstable channel 3: Slightly unstable channel 4: Stable/resilient channel
Channel form horizontal stability (i.e. width/depth) vertical stability (aggradation, entrenchment) connectivity w/ floodplain or overflow channels	
Bedload transport capacity downstream/upstream routing barriers available storage capacity (e.g. presence of channel braiding) extent of upstream sediment inputs	

Substrate cementation was measured at one riffle on each reach. The assessment considered the extent of the substrate surface compaction, the extent of surface armoring, and the extent of inter-gravel spaces filled by fine sediment. Scores were given based on the qualitative comparison between the observed conditions at each reach and that registered at the reference reaches (Table 2- 3).

Table 2- 3: Channel cementation indicators for "rapid 1" (P. Nelson and M. Rylko, Kitsap County, unpublished data, 2002)

Indicators	Score (1 to 4)
Extent of substrate compaction	1: Tightly packed bed materials and/or excessive fines 2: Slightly packed bed material 3: Moderately loose bed material 4: Loosely packed bed material with pore space
Extent of substrate surface armoring	
Extent of filling of inter-gravel spaces (in glides) with fines	

Reach complexity was defined by a qualitative visual estimation of the following factors: LWD abundance within the active channel, pool frequency, pool depth, and existence of side channels (Table 2- 4). Scores were assigned after comparing the conditions found at each reach with the conditions observed in the reference sites.

Table 2- 4: Reach complexity indicators for "rapid 1" (P. Nelson and M. Rylko, Kitsap County, unpublished data, 2002)

Indicators	Score (1 to 4)
a. LWD abundance within the active channel	1: Non-complex channel 2: Slightly complex channel 3: Moderately complex channel 4: Complex channel
b. Pool frequency	
c. Pool depths	
d. Side channels frequency	

The riparian condition was evaluated in the field in the near-channel area over a width defined by the site-potential tree height or the limit of the active floodplain (whichever was narrower (Table 2- 5). The following indicators were visually evaluated: degree of shading provided to the channel, existence of multi-aged stands with near-term recruitment potential, presence of conifer species, and the degree of vegetation/soil disturbance in the immediately adjacent land.

Table 2- 5: Reach riparian condition indicators for "rapid 1" (P. Nelson and M. Rylko, Kitsap County, unpublished data, 2002)

Indicators	Score (1 to 4)
a. Degree of shading provided	1: Few or no trees in riparian zone 2: Sparse trees in the riparian zone, with few conifers in a moderately disturbed riparian zone 3: Moderately diverse, multi-aged stand, largely dominated by conifers. 4 : Diverse, multi-aged stand dominated by conifers in an undisturbed riparian zone
b. Multi-aged stands with near term recruitment potential	
c. Presence of conifer species	
d. Degree of vegetation/soil disturbance in the immediately adjacent land.	

2.2.2 “Rapid 2” assessment methodology

Field methods for this technique were based on the protocol for the monitoring of urbanizing streams first articulated by Henshaw and Booth (2000) and further refined by McBride (2001). Channel surveys of the main channel network of the Chico Creek watershed occurred during spring and summer of 2002 by one field worker. The survey consisted of quantitative and qualitative reach-scale information collected on stream bank condition, substrate condition (cementation), and two components of channel complexity (tallies of large woody debris and pool abundance by reach). Complete descriptions of these four metrics are given in Chapter 1. In comparison to the “Rapid 1” method only the bed cementation scoring protocol was equivalent for both. Stream bank condition (rapid 2) is similar to channel stability (rapid 1), and pool and LWD abundance (rapid 2) are both significant components of channel complexity (rapid 1). The riparian condition metric “rapid 1” has no analogous in “rapid 2”

2.2.3 Scoring method

For both “rapid 1” and “rapid 2,” each of the four categorical evaluations received a score between 1 and 4 points. This gave a total possible reach score ranging between 4 and 16 points. The total score range was divided into 3 equal bands to display overall reach geomorphic condition: “low quality” for scores between 4 and 8; “intermediate quality” for scores between 9 and 12; and “high quality” for the remaining 13 to 16 points.

The results achieved by each scheme were spatially displayed using the GIS software ArcView 3.2.

2.3 Analytical methods

Analytical methods included spatial comparison of results considering the channel type context, statistical comparison (paired t-test), and regression analysis (Zar, 1996; Neter et al., 1996). Both total results and individual metrics

of the two methodologies were compared. To evaluate the accuracy of individual metrics in comparison to more rigorously (and laboriously) collected data, several metrics were contrasted with quantitative detailed information available for 18 reaches (40% of the surveyed reaches) and with an alternative method of LWD recruitment potential developed with GIS analysis (Roberts, 2003). SPSS 10.1 statistical software^{tm} (SPSS Inc., Chicago IL) was used for the statistical analysis using an alpha level of 0.05.

Channel cementation was the only metric common to both schemes. However, other comparisons could be made between similar metrics; i.e. channel stability from “rapid 1” versus bank stability from “rapid 2,” and the complexity score from “rapid 1” versus pool counts and LWD counts scores from “rapid 2.” The “rapid 2” assessment did not include metrics for riparian conditions; therefore, a comparison between the two schemes was not possible. However, the riparian condition score results from “rapid 1” could be compared to the recruitment potential calculated for each reach using orthophotos, tree height (from LIDAR), and field observations (Roberts, 2003). Recruitment potential was summarized by Roberts (2003) into three categories (high, medium, and low) considering species composition, vegetation density, and tree size. In this study, riparian condition (“rapid 1”) was contrasted with this LWD recruitment potential for a buffer 30 m on each side of the channel.

Independent detailed morphologic data for 18 reaches (P. Nelson and M. Rylko, Kitsap County, unpublished data, 2002) permitted an evaluation of some of the metrics considered by the two assessments (Figure 2- 2). Correlation analysis was used to evaluate the relationship between cementation scores and abundance of fine sediment in the channel, using D_{16} calculated from riffle pebble counts as an index of fine sediment abundance. Cementation is a measure of bed sediment compactness, which occurs in the presence of high levels of fines. Finally, wood counts performed as part of these detailed surveys but not included

in the “rapid 1” assessment were correlated against the wood counts performed as part of the “rapid 2” assessment.

Data collected through by both the two rapid assessments and the detailed surveys is presented by reach in Appendix B, Table B-1.

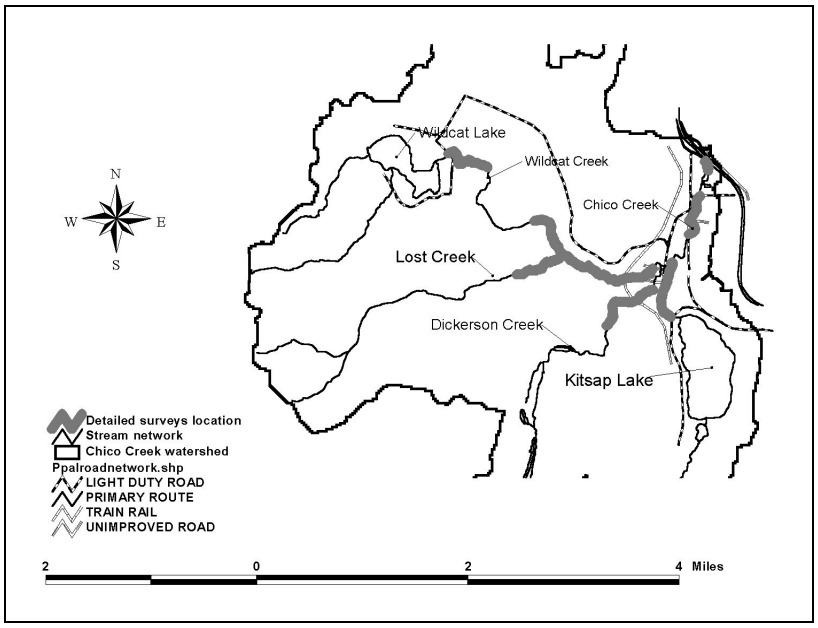


Figure 2- 2: Location of the detailed surveys.

3 Results

3.1 Total scores analysis

The summary results of the two methods discriminated similar in-stream geomorphic conditions among the surveyed reaches (Figure 2- 3 nd Figure 2- 4). Both rapid assessment methods recognized relatively high-quality physical conditions in the upstream portions of the Chico Creek watershed tributaries (Wildcat, Lost, and Dickerson creeks) and a pattern of decreasing in-stream physical quality towards the lower sections of the basin. Reaches in the lower sections of Chico, Dickerson, and Kitsap creeks were mainly categorized in the intermediate-and low-quality bands (scores below 12) by both methods.

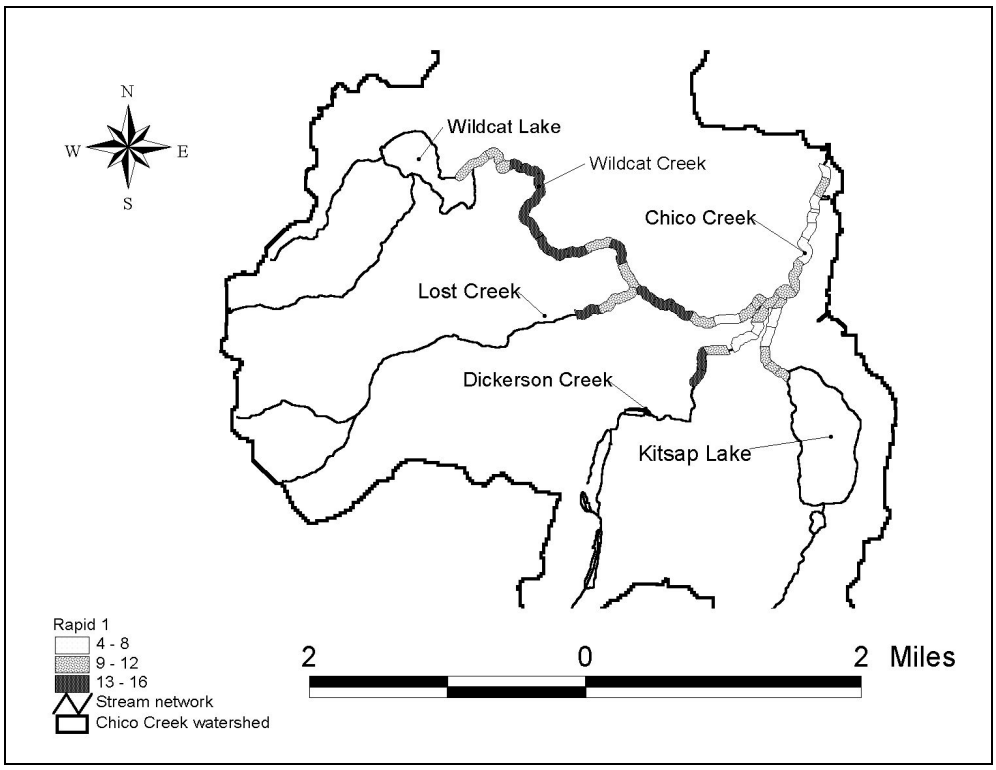


Figure 2- 3: Geomorphic characterization by the "rapid 1" method

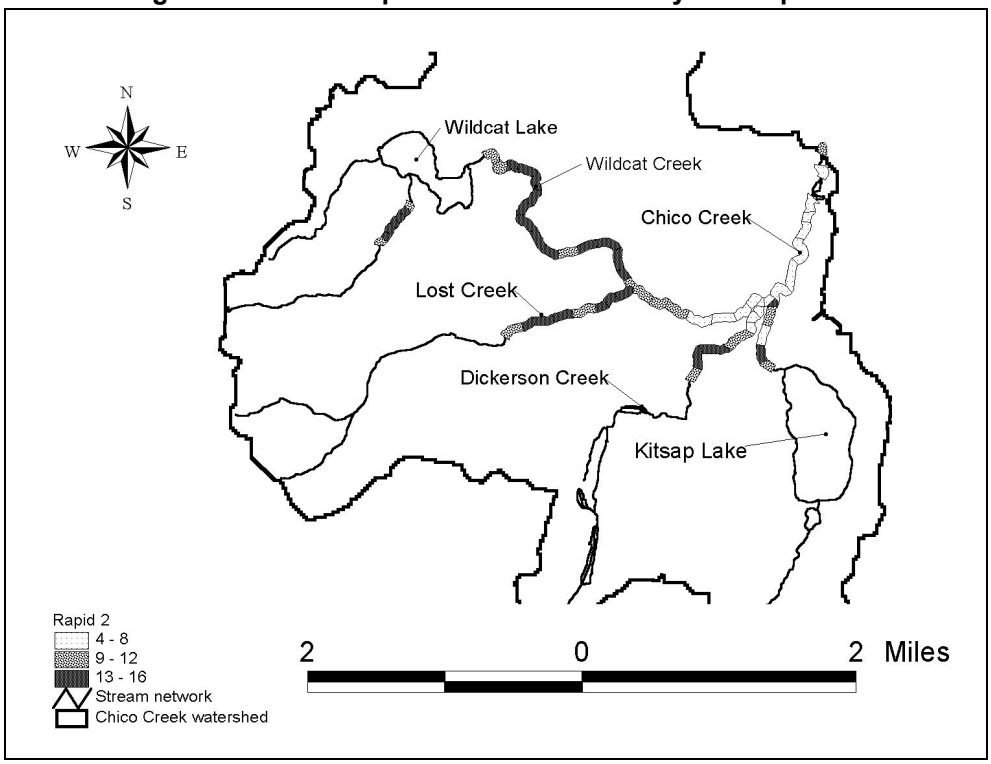


Figure 2- 4: Geomorphic characterization by the "rapid 2" methods

Averaged by individual creek, the scores were very similar in all streams for both methods, except in Kitsap Creek. According to both schemes, Wildcat and Lost creeks are within the highest category (scores 13-16); Dickerson Creek is within the intermediate category (scores 9-12); and Chico Creek is within the lowest category (scores 4-8). Kitsap Creek, which had on average the highest discrepancies between the methods on individual reaches, was intermediate under the “rapid 2” assessment and low by the “rapid 1”assessment (Figure 2- 5).

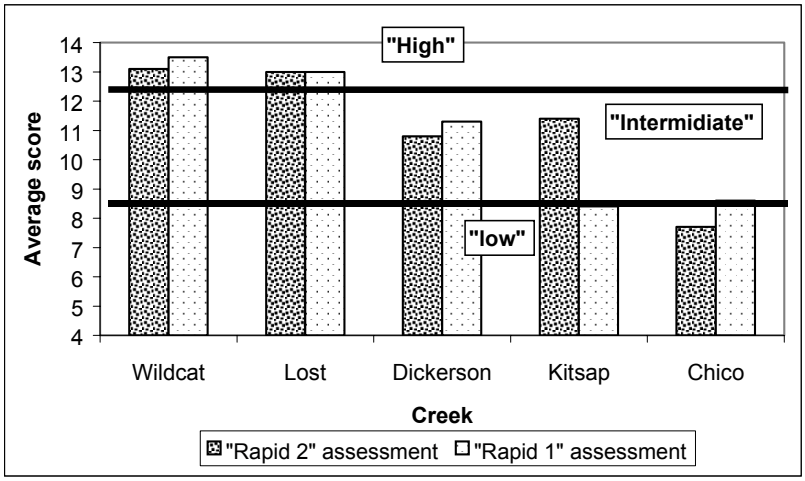


Figure 2- 5: Average results per creek for both rapid assessment methodologies

Total scores were graphically compared across the surveyed reaches in terms of both the difference between total scores assigned by each methodology, and by the number of reaches classified into different physical condition categories by the two schemes. The absolute discrepancies between total scores assigned by each methodology were below 3 points for 32 reaches (78%). At four reaches (10%) the difference between total scores was 3 points, and at the remaining 5 (12%) the differences were as much as 6 points (Figure 2- 6). The distribution of the surveyed reaches among the defined categories showed very good correspondence for reaches classified at the highest level but variable results for reaches into the two lower categories. In other words, the methods are most consistent in identifying the best reaches (Table 2- 6).

Table 2- 6: Number of reaches classified into each physical quality category by both rapid assessment methodologies

Physical quality	Rapid 1	Rapid 2	Difference (%)
High (13-16 points)	14	12	14
Intermediate (9-12 points)	16	12	25
Low (4-8 points)	11	17	50

The channel type of the 5 reaches (reaches 19, 21, 23, 31, and 39) where discrepancies were above 3 points suggests that the correspondence of the two methods, in terms of comparability, decreases at channel types with gradient above 0.02 and at reaches where the natural morphology has been altered by anthropogenic influence (Figure 2- 6 and Appendix B, Table B-1). Channel types of three out of these five reaches had slopes above 0.02 (reaches 19, 21, and 23). Reach 31 is a constrained plane-bed type (i.e. a low-gradient channel in which the stream is isolated to the floodplain by the placement of artificial armoring structures). Reach 39 is the only exception, a forced pool-riffle (FPR) with a gradient of 0.01 and no obvious direct anthropogenic influence.

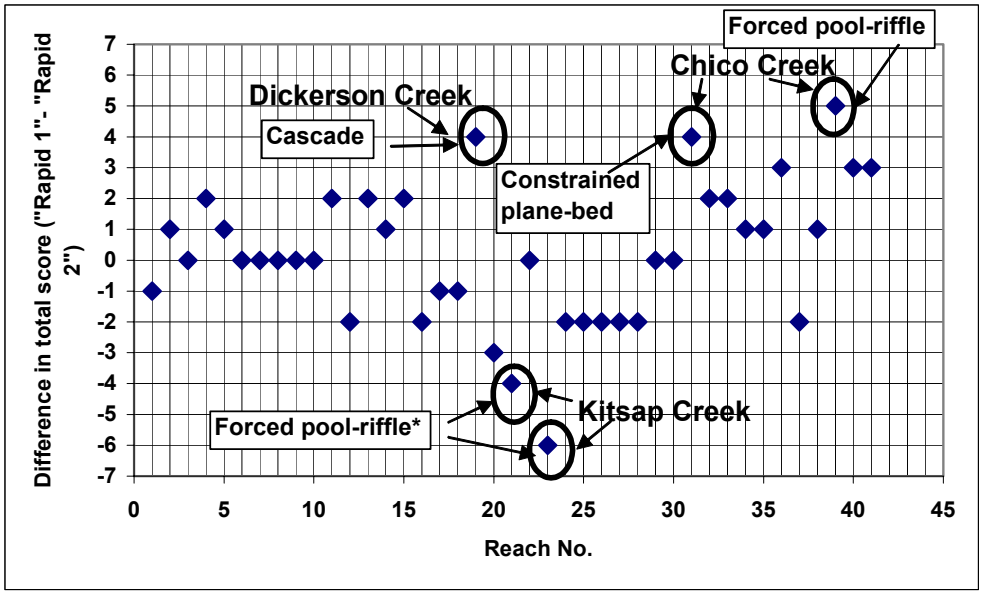


Figure 2- 6: Differences of total scores between the two methodologies. Differences between total scores higher than 3 points are highlighted; *: forced pool-riffle reaches with slopes above 0.02.

An R^2 of 0.57 was found between the total results (Figure 2- 7). A paired t-test of the total scores indicated that the mean difference between total scores is 0.2 points, not significantly different throughout the sample (p = 0.59). The linear regression between the total scores indicated a significant relationship between the two measurements (F = 51, p <0.00); and a slope of 0.8 (i.e. nearly a 1-to-1 relationship, with a slight tendency for “rapid 1” scores to be higher) (Figure 2- 7).

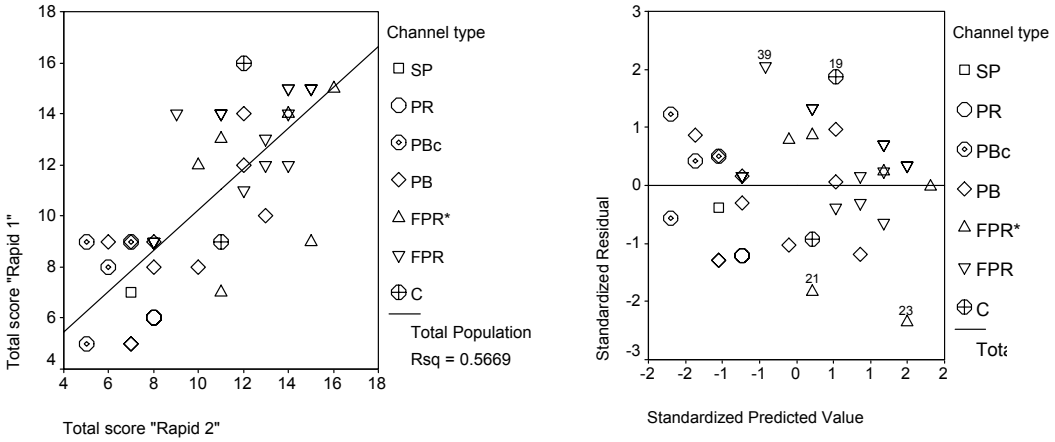


Figure 2- 7: Scatter plot (left) and residuals plot (right) of the relationship between total results of the two methodologies

The channel type of the 4 reaches above 1.5 standard deviations from the fitted regression line between total scores (Figure 2- 7, right) emphasized the decreasing correspondence between the two methodologies at slopes above 0.02. Three of these 4 reaches had slopes above 0.02: 1 cascade (reach 19) and 2 FPR (reaches 21 and 23). The fourth reach was a FPR with a slope of 0.01.

3.2 Analysis on individual metrics

Individual metrics used in each methodology were analyzed in terms of the coefficient of determination between similar pairs of metrics from both techniques (Table 2- 7 and Figure 2- 8). In addition, a paired t-test was used to evaluate the null hypothesis of equal mean difference between a given pair of similar scores (Table 2- 1).

Table 2- 7: Coefficient of determination (R^2) between similar metrics

	Metric	'Rapid 2"			
		Bank stability	Cementation	Pools	LWD
	Channel stability	0.71			
	Cementation		0.03		
	Channel complexity			0.16	0.41

The analysis of the individual metrics considered by the two techniques indicates that both bank stability ("rapid 2") and channel stability ("rapid 1") gave similar results in the surveyed reaches (R^2 = 0.71). Cementation scores assigned by the two methodologies, in contrast, yielded entirety uncorrelated scores (R^2 = 0.03). Channel complexity ("rapid 1") was related to LWD counts ("rapid 2") (R^2 = 0.41). However, essentially no relationship was found between channel complexity ("rapid 1") and pool counts ("rapid 2") (R^2 = 0.16) (Table 2- 7 and Figure 2- 8).

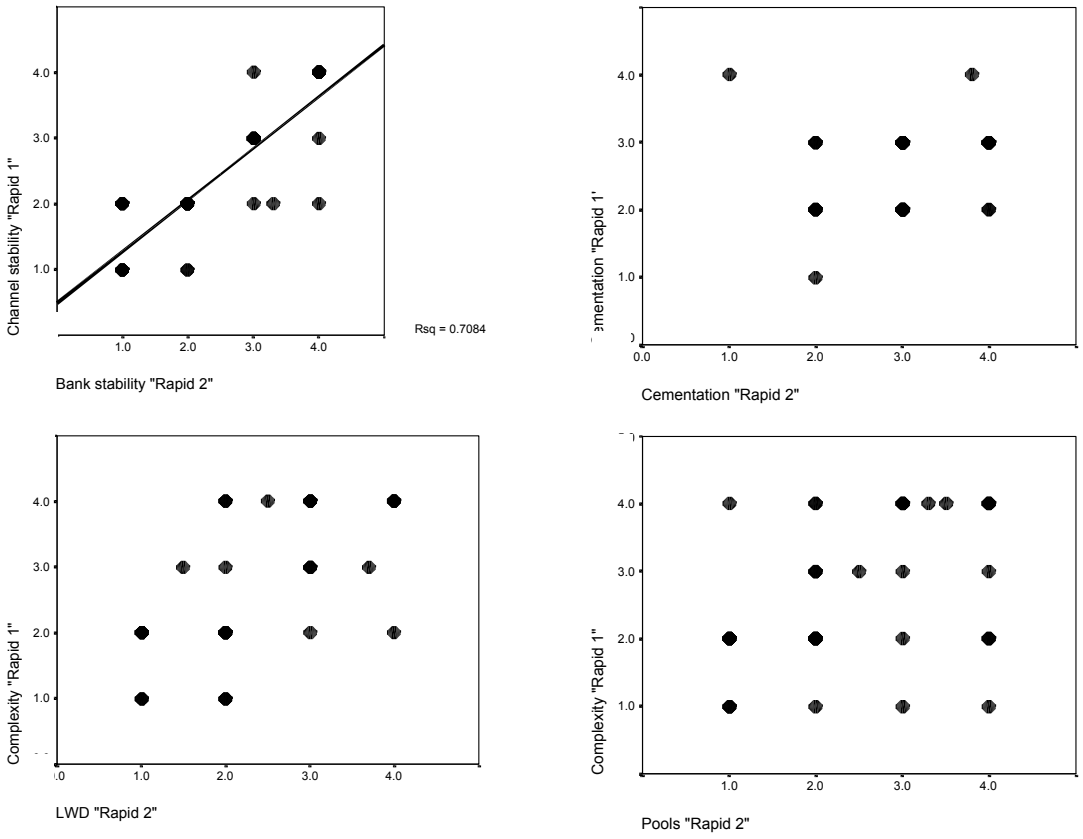


Figure 2- 8: Scatter plots of similar metrics from the rapid assessments

No statistically significant differences were found between the bank and channel stability scores of the two methods. Statistically significant differences were found between the two methods' cementation scores, and between LWD tally (rapid 2) and complexity scores (rapid 1) (Table 2- 8). Mean difference between similar pairs of metrics were found to be as high as 0.39 points (cementation scores) and as low as 0.06 points (bank and channel stability) (Table 2- 8). Bank stability and channel stability gave the same score to 73% of the surveyed reaches (30 reaches); but less than half the reaches had the same score for cementation, LWD vs. complexity, or pools vs. complexity (Table 2- 9).

Table 2- 8: Paired t-test of differences between total scores and individual metrics

Pair	Variables	Paired Differences		t	df	Sig
		Mean	Std. Deviation			
1	Total score "rapid 2" - Total score "rapid 1"	-0.20	2.28	-0.55	40	0.59
2	Bank stability "rapid 2" - Channel stability "rapid 1"	0.06	0.60	0.60	40	0.56
3	Cementation "rapid 2" - Cementation "rapid 1"	0.39	0.89	2.76	40	0.01
4	LWD "rapid 2" - Complexity "rapid 1"	-0.32	0.89	-2.33	40	0.03
5	Pools "rapid 2" - Complexity "rapid 1"	-0.19	1.20	-1.00	40	0.32

Table 2- 9: Differences between scores for similar metrics of the rapid assessments

Difference	Bank and channel stability	Cementation scores	LWD and complexity	Pools and complexity
0	30	17	20	17
1	10	21	17	16
2	1	2	4	6
3	0	1	0	2

The analysis of the relationship between riparian condition score, included in the "rapid 1" assessment, and LWD recruitment potential (Roberts, 2003) in the 30-m riparian zone, showed no significant relationship ($R^2 = 0.08$). This indicates that the riparian condition score does not capture the same information as the LWD recruitment potential from GIS analysis. It is likely that the riparian condition score represents only these conditions of the near-riparian zone that can be visually assessed from the channel, whereas the LWD recruitment

potential describes the condition of a near-riparian area more uniformly across all the surveyed reaches.

Comparison of the individual metrics suggests that:

- bank stability ("rapid 2") and channel stability ("rapid 1") provide similar results;
- cementation scores measured by both methods are consistently unrelated;
- the relationship between complexity ("rapid 1") and LWD counts ("rapid 2") is fair (R^2 =0. 42) but the relationship between complexity ("rapid 1") and pool counts ("rapid 2") is very weak (R^2 = 0.16); and
- the riparian condition score ("rapid 1") does not corresponded to a systematic GIS-based assessment of the riparian cover.

Partial comparisons between the methods were performed by excluding the cementation scores, and by excluding both the cementation scores and the scores for pools ("rapid 2") and riparian condition ("rapid 1"). In the first case the coefficient of determination between total scores increased from 0.57 (F = 51, p <0.00) to 0.61 (F = 61.6, p <0.00) and in the second case it increased to 0.72 (F = 100.5, p <0.00).

3.3 Evaluation of individual metrics using detailed geomorphic data

The accuracy of several metrics used by the two methods could be evaluated using detailed survey information for 18 of the 41 reaches (Figure 2- 2, Appendix B, Table B-1). A strong relationship was found between LWD/100 m from detailed geomorphic surveys and both LWD/100 m from the "rapid 2" assessment and the complexity score ("rapid 1") with R^2 = 0.61 and 0.50, respectively (Table 2- 10 and Figure 2- 9). Cementation scores from both rapid methods, however, were not related with to the measured D_{16}.

Table 2- 10: Coefficient of determination (R^2) between metrics from the rapid assessment methodologies and data from detailed surveys

Rapid assessment metrics	Detailed surveys	
	D_{16}	LWD /100
Cementation ("rapid 1")	0.05	
Cementation ("rapid 2")	0.02	
LWD/100m ("rapid 2")		0.61
Channel complexity ("rapid 1")		0.50

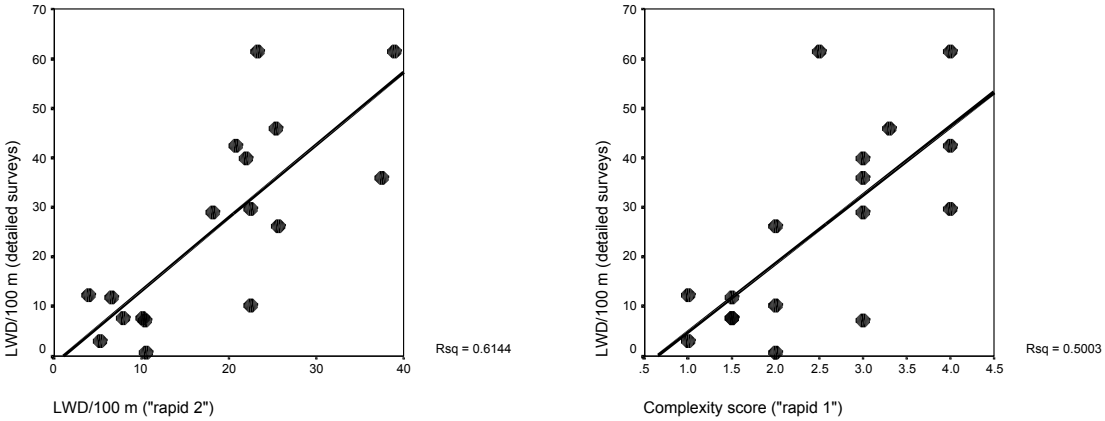


Figure 2- 9: left: Scatter plot of the relationship LWD counts from the detailed surveys and the "rapid 2". Right: Scatter plot of the relationship LWD counts from the detailed surveys and channel complexity ("rapid 1")

4 Discussion

4.1 Utility and reliability of individual metrics

Bank stability and channel stability are both qualitative metrics that provide the same discrimination among the surveyed reaches (R^2 = 0.71 F= 94.76, p= 0.00). However, because the bank stability metric of "rapid 2" only considered the evaluation of one attribute (i.e. stability of the banks) it probably makes that scheme easier to apply.

LWD counts ("rapid 2") and channel complexity ("rapid 1") provided similar discrimination between the surveyed network. Discrepancies are likely to be related both to the natural variability of the measurements and to differences in the geomorphic indicators considered by each metric. Channel complexity incorporates the evaluation of other indicators in addition to in-stream wood (pool

and side-channel frequency) and is dependent on the features observed at the reference reaches of a particular channel type.

Since LWD counts and channel complexity scores provided the same overall discrimination for the surveyed reaches, either one could presumably be used. However, the transferability of the LWD counts was tested and confirmed with results from an independent detailed survey. Furthermore, LWD are easier to measure because they only require the field crew to do one task, collecting tallies of LWD. Channel complexity, on the other hand, requires the field crew to have a qualitative sense of the amount of wood and the frequency of pools and side channels in relation to predetermined reference conditions, which requires special training and experience together with a high degree of subjective judgment.

The relationship between pool counts (“rapid 2”) and channel complexity (“rapid 1”) showed a weak relationship, most likely because channel complexity is a channel-type-dependent metric. “Good” channel complexity conditions are naturally different, depending on channel type. Considering in-stream wood and pool frequencies as surrogates for complexity, Montgomery et al. (1995) reported variable pool spacing values for different channel types in Alaska and Washington. According to their study, forced pool-riffle channel have more pools than step-pool and plane-bed channels, and they also have relatively more pools formed by LWD. Since the “rapid 1” assessment assigned complexity scores based on reference conditions that were uniformly at FPR channels in this watershed, scores assigned to other channel types will tend to be “low,” implying that this metric is not transferable across all channel types observed in the Chico Creek watershed network. Even though pool counts (“rapid 2”) is also a channel-type-dependent metric, it provided a quantitative approach based on a tally of a unique feature, which was not biased by expected conditions registered at a particular channel type.

Channel cementation metrics yielded ambiguous results. Cementation is a metric developed to describe the compactness and hardness of a riffle substrate, which is largely a result of silt and clay intrusion into the interstices of a gravel bed (McBride, 2001). The fact that cementation scores (by either crew) were not related to D_{16} indicated that it did not actually capture the condition what it was designed to describe. This metric was (1) not comparable between two set of observers and (2) not a good predictor of fine sediment in the channel bed. Results indicated better correspondence between methodologies when excluding cementation scores corroborating their poor transferability across observers.

The riparian condition metric, used only by the “rapid 1” as an in-stream estimate of corridor vegetation density, showed no relationship with the LWD recruitment potential calculated from GIS (Roberts, 2003). Riparian condition visually assessed from the channel is likely to be dependent on site conditions that may limit the extent of the riparian area that can be visually assessed during the survey. As an example, Figure 2- 10 shows the LWD recruitment potential displayed from GIS (Roberts, 2003) compared to the riparian area as observed from the channel. This reach, located in Kitsap Creek, was given a riparian score of 3, whereas only 19% of the 30-m riparian zone was classified in the high LWD recruitment potential category. Discrepancies as the one illustrated in Figure 2-10 are likely to be the common denominator of the surveyed reaches. A field assessment of the riparian area can provide more detailed and refined information than the GIS approach, but it would not be rapid since it requires observations outside of the channel (i.e. vegetation plots or transects). The GIS approach provided an easy, rapid alternative to broadly discriminate among reaches.

Regression analysis indicated better correspondence between total scores when excluding the cementation for both methods scores and the riparian-condition (“rapid 1”) and pool (“rapid 2”) scores. The coefficient of determination increases in 26% (from 0.57 to 0.72) indicating the high correspondence between

channel stability and channel complexity (“rapid 1”) and bank stability and LWD counts (“rapid 2”). The contrasted methodologies also lost robustness at channel gradients higher than 0.02, which corresponds to the typical shift from predominantly pool-riffle channels (at gradients below 0.02) to forced pool riffle (FPR) and cascade channels (identified at gradients above 0.02) in the surveyed network.

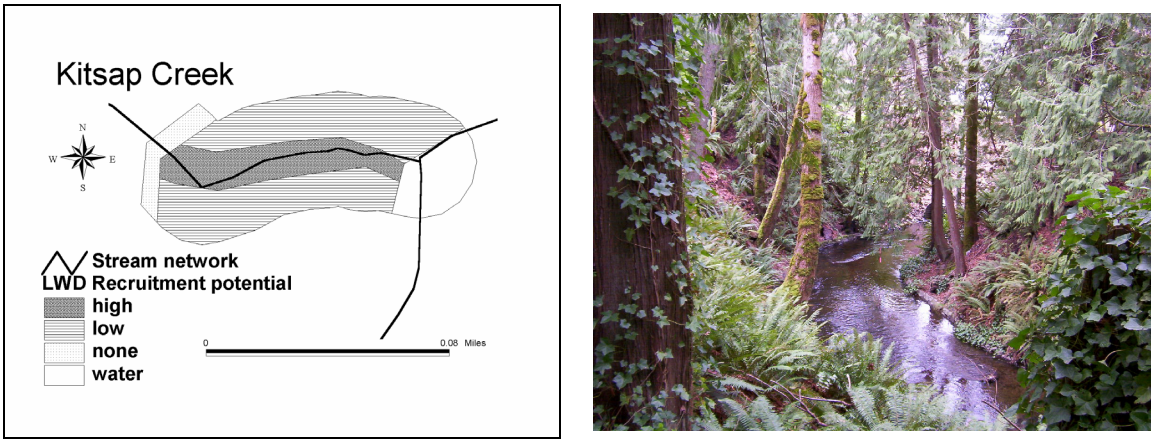


Figure 2- 10: Contrast between riparian condition metric and LWD recruitment potential. Left, LWD recruitment potential calculated in GIS; right, riparian zone in the same reach as it is observed from the channel

4.2 Comparison with NMFS criteria

In an attempt to find a more broad-based interpretation of the results obtained with the “rapid 2” assessment, a comparison of the metrics included in that method was made with the conditions described in the Matrix of Pathways and Indicators (NMFS, 1996) for evaluating the effects of human activities on anadromous salmonid habitat. According to the NMFS matrix, most if not all of the surveyed reaches in Chico would be associated with “not properly functioning conditions” with regards to bank stability. The matrix criteria define reaches with “functioning conditions” to have over 90% of the banks in stable conditions; “at risk” reaches have between 80 and 90% stable banks. Over two-thirds of the reaches at Chico would be in “not properly functioning” category, because reaches with bank stability scores below 4 points have more than 80% of their bank length eroded. In-stream wood and pool frequency criteria in the NMFS

matrix indicate that “properly functioning” conditions as more than 4.7 wood pieces of at least 0.6 m in diameter and 15 m in length per 100 m, and pool frequencies between 2 and 3 pools per 100 m with a minimum pool depth of 1 m. Wood and pool counts for “rapid 2” considered minimum dimensions documented for similar stream size in the region (Montgomery et al. 1995), but the size criteria for both are much smaller than the one used in the NMFS matrix. Therefore, the application of the NMFS criteria to our results is not possible.

Because the criteria in the NMFS matrix may not be entirely suited to smaller streams such as Chico, further analysis of the rapid assessment in relation to biological measurements would be necessary to establish if the physical condition categories used by the assessment have any relationship to the functionality of the surveyed reaches. Sections within the Chico Creek watershed support significant chum, coho, and steelhead spawning habitat (Kitsap County, 2000); therefore, this watershed clearly must have some “functioning” sections. The results of this study are insufficient to determine if the physical conditions as described appropriately identify their location in the watershed.

4.3 Use of the Rapid Channel Assessment

These results suggest that a rapid channel assessment can provide useful, coarse discrimination of stream quality in a channel network. The ranges of total scores used to discriminate the channel network into “low,” “intermediate,” and “high” physical conditions, however, should be only interpreted in context of what they are: a discrimination solely in terms of the physical condition. Correlation analyses of the rapid assessment results with biological data (e.g., fish surveys or benthic macroinvertebrates communities) would be required to establish whether or not these physical condition categories have any meaning in terms of the biological condition of the streams.

Despite these limitations, these results show that rapid assessment methods are justified wherever a limited number of management options are being considered. For many jurisdictions, the overriding need is for identifying a few general categories of stream condition; typically, the management responses will be to protect those streams that have “good” conditions, to maintain and/or rehabilitate those that are showing some signs of impairment, and to acknowledge the need for future, intensive remedial actions for those that are already significantly degraded by human action. Where intensive rehabilitation work is planned, detailed quantitative assessments ultimately will be needed. To include such detailed measurements as part of a preliminary regional assessment, however, makes little sense.

5 Conclusions

- The categorical results of the two assessment methodologies were the same at more than three-quarters of the surveyed reaches. The largest discrepancies occurred almost exclusively at reaches with slope above 0.02, implying that the reliability of such geomorphic metrics depend on channel type.
- In general, discrepancies between the two methods are largely a result of the use of reference reaches for “rapid 1” that were restricted to channels with gradients below 0.02 (reference reaches).
- Measurements of bank stability are particularly robust, yielding similar discriminations among the surveyed network for the two methods.
- Measurements of channel cementation, common to both schemes, are apparently not a useful metric, showing statistically different results between the two sets of observers and no relationship with the amount of fine sediments in the channel.
- Rapid assessments are adequate to determinate general stream physical condition categories. However, caution should be used when including

variables, such as cementation, that cannot be replicated, or using channel-type-dependent metrics, such as measures of pools or “complexity”.

- In order to assess functional consequences of these physical discriminations, biological data, such as fish surveys and biological indexes (i.e. B-IBI), need to be included in the analysis of the channel network.

CHAPTER 3

1 Introduction

Urbanization has pervasively modified the physical, biological, and chemical natural character of freshwater systems. In terms of the physical condition, urbanization has altered the natural stream flow regime and the geomorphic state of streams. With urbanization the natural land cover is replaced with impervious surfaces altering not only the magnitude of the discharges but also the delivery of sediment to the stream network (Booth and Jackson, 1997). Other negative impacts of urbanization are the degradation of riparian ecosystems and the disconnection of stream channels from their floodplain. In general, urbanization results in simplified channels morphologies with uniform beds and few pools or developed riffles to break up the planar surface (Booth, 1991). These simplified conditions, triggered by alteration of both the watershed hydrologic regime and the near-riparian zone, create low-quality habitats for fish and macroinvertebrates, with associated declines in diversity and population. Moscrip and Montgomery (1997), for example, found that declines in salmon populations in some Puget Lowland drainage basins were closely related to hydrologic or habitat changes that accompany urbanization.

Over the past two decades the effects of urbanization on streams in the Pacific Northwest have been intensely studied by several researchers including Booth (1990), Booth (1991), Booth and Jackson (1997), Moscrip and Montgomery (1997), May et al. (1997), Booth and Henshaw (2001), Brett, in press, McBride (2001), Nelson and Booth (2002), and Morley and Karr (2002). These studies have established relationships between land cover change and alterations to streams: physically (hydrologic regime, sediment production and transport, and channel morphology), chemically, and biologically (via various population metrics for bentic macroinvertebrates and fish). While the cumulative effects of watershed land-cover change have been intensely studied, the effects

of the near-riparian zone alteration in urbanizing watersheds has received little attention.

Fully understanding the function of stream ecosystems is far from complete, and so the challenge for managers and planners in urbanizing watersheds is to find development patterns adequate to preserve or to positively influence such ecosystems, given the current state of the science. Furthermore, urbanization is progressing rapidly in the Pacific Northwest. In 1940, the area's population totaled 860,000; since then it has increased by about 400,000 people every 10 years (NOAA, 1998). In part from this rapid rate of growth in the context of poor understanding of aquatic systems, the National Marine Fisheries Service listed Bull trout (*Salvelinus confluentus*) in 1998 and Puget Sound Chinook (*Oncorhynchus tshawytscha*) in 1999 as endangered species under the Endangered Species Act.

1.1 Conceptual model

Research has demonstrated that urbanization negatively affects the physical, chemical, and biological condition of streams. According to the conceptual model described by Karr and Chu (1999), human activities alter biochemical processes to influence one or more of five “factors”: flow regime, physical habitat, water quality, energy sources, and biological interactions. These in turn affect the geophysical and biological conditions of streams. The first two of these five factors are relevant to this study.

The flow regime is strongly correlated with many critical characteristics of rivers, such as water temperature, channel morphology, and habitat diversity. It has been called a “master variable” that limits the abundance and distribution of river species and regulates the ecological integrity of flowing water systems (Poff et al., 1997). The flow regime of an urbanizing watershed, in comparison with previous forested conditions, is flashier, meaning that urbanized watersheds

experience larger and more frequently peak flows, but typically with a shorter duration of individual events (Booth, 1991).

Physical habitat, expressed as channel morphology, is the result of the interaction of three major factors: sediment supply, transport capacity, and vegetation (Montgomery and Buffington, 1998). Through the channel network of a given basin, different patterns and interactions of these driving factors are expressed as sediment delivery, hydraulic discharge, and channel slope. They give rise to spatial and temporal variation in the channel morphology and response. Under urbanized conditions, other factors are introduced as drivers of the physical condition and response potential of stream channels. Channel morphology is influenced by both the cumulative effects of land cover change on hydrology and the direct effects over the channel and the riparian area. Pizzuto et al. (2000) established that urban streams are straighter and smoother than comparable streams in rural watersheds. May et al. (1997) found that both the prevalence and quantity of LWD declined with increasing basin urbanization. They also found that basin urbanization in the Puget Sound streams have the potential to cause locally excessive scour and fill, particularly in streams with gradients greater than 0.02 that lack of LWD.

Under similar geologic and climate conditions, the relevant factors that can guide evaluation of channel condition and response potential in forested (or once-forested) mountain drainage basins are channel bed morphology, confinement, position in the channel network, and external influences (such as riparian vegetation and in-channel woody debris) (Montgomery and Buffington, 1998). According to Montgomery and MacDonald (2002), stream channel condition reflects the capability of the channel to accommodate or resist change due to inputs of sediment, water, organic matter, or alterations of the riparian vegetation. They found that valley bottom characteristics useful to diagnose channel condition are slope, confinement, entrenchment, riparian vegetation, and

over-bank deposits. They identified the primary active channel indicators useful for diagnosing channel conditions as channel pattern, bank conditions, gravel bars, pool characteristics, and bed material. Most of these indicators are incorporated in the present study.

The main focus of this study is to understand influences of local conditions, specifically confinement and riparian vegetation, on channel morphology and responsiveness to urbanization. The approach compares developed and undeveloped scenarios, looking at relationships between confinement, riparian vegetation, and channel morphology. Surveyed sites were selected to match geologic conditions, position in the channel network, drainage area, and gradient. The presence of lentic systems in the study watersheds is also considered in the analysis, recognizing that a channel downstream from a large wetland or lake may be buffered from high flows or upstream sediment inputs (Booth and Jackson, 1997; Montgomery and MacDonald, 2002).

This study is intended to gain knowledge that makes it possible to predict impacts of urbanization and near-channel development on stream morphology. Relationships between riparian vegetation, valley configuration, and channel morphologic features (such as LWD abundance and pool spacing) have been studied for pristine areas in the past (Fetherston et al., 1995; Montgomery et al., 1995; Harris, 1988; Hupp and Osterkamp 1996; Millar, 2000; Rot et al., 2000); however, very few such studies have been conducted at urbanizing watersheds.

Error! Reference source not found. presents the conceptual model of this study. Channel morphologic conditions are evaluated in relation to riparian vegetation, confinement, channel type and channel morphology.

Riparian vegetation

Riparian vegetation links lotic and terrestrial ecosystems in forested landscapes. For streams, it influences channel form and stream function; it also provides LWD and particulate organic matter, shade, bank stability, sites for

organic matter storage, and nutrients recycling (Gregory et al., 1991). In terms of geomorphology, the riparian vegetation has been identified as a key player of channel morphology, especially through its addition of LWD to the stream.

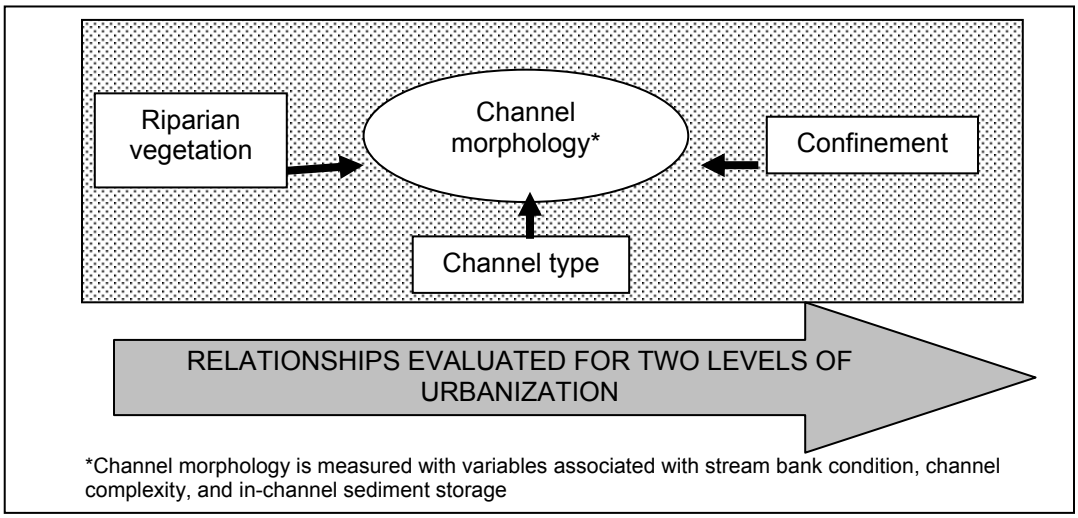


Figure 3- 1: Controls of channel morphology evaluated in this study, modified from Montgomery and MacDonald (2002)

Forced pool-riffle channels in forested humid environments are highly dependent on the addition of LWD (Montgomery et al., 1995; Montgomery and Buffington, 1998; Rot et al., 2000). Riparian vegetation species composition influences the amount and distribution of LWD. For example, Fetherston et al. (1995) established that more LWD were found in forest streams dominated by conifers than by hardwoods.

Confinement

In natural conditions, the degree of channel confinement restricts the development of an active floodplain. Valley bottom conditions (confinement and riparian vegetation) can affect the channel by altering flow resistance and bank strength, promoting local sedimentation, and providing a source of woody debris (Hupp, 1999). As channel confinement increases, the influence of LWD upon riparian forest distribution decreases due to a decrease in the area of the active floodplain (Fetherston et al., 1995). Fox et al. (2003) found that the number of

wood pieces per unit channel width and the in-stream are inversely correlated with confinement. Studies have documented that the level of confinement partially determines the riparian species composition in pristine areas. Rot et al. (2000) found that active floodplains contain more deciduous trees than conifers and greater conifer basal area than deciduous.

Confinement can also be a condition anthropogenically imposed to the channel. Bank-armoring structures placed in urban streams commonly isolate the channel from the floodplain. Both confinement types, natural and anthropogenic, are considered in this study.

Channel type

Channel types within a stream network result from the interactions between geology, climate, gradient, confinement, and riparian vegetation. The spatial distribution of channel types within a drainage basin influences the distribution of potential impacts and responses of streams channels to disturbances (Montgomery and Buffington, 1998). In general, high-gradient channel types (cascade and step-pool) are more resilient to most discharge or sediment-supply perturbations, due to their high transport capacities and generally supply-limited conditions. Lower gradient plane-bed and pool-riffle reaches become progressively more responsive to altered discharge and sediment supply with increasing ratios of transport capacity to sediment supply, smaller grain sizes, and less channel confinement (Montgomery and Buffington, 1998).

Channel morphology

According to past studies, channel morphologic features useful to measure urbanization impacts are bank stability, channel-complexity measures using LWD frequency and wood-jam organization, pool frequency and pool-forming agent, and frequency and volume of channel-sediment storage features.

Bank stability: Bank stability can be interpreted as a condition of streams that expresses channel responsiveness to changes in peak flows. However, other factors such as topography, bank substrate, channel type, and the amount of bank protection offered by vegetation and woody debris also determine the rate of channel change or erodability (Booth and Henshaw, 2001; Montgomery and MacDonald, 2002).

The effects of vegetation of channel stability have been documented in the past. Beeson and Doyle (1995) found for 4 streams in Southern British Columbia that non-vegetated bends were almost 5 times more likely to have undergone erosion than vegetated bends. Stream channels flowing through forested reaches have less bank erosion, due not only to the bank strength and cohesion provided by the vegetation root system but also to the addition of LWD, which increases roughness that in turn decreases available shear stress and provides bank stability by the mechanical protection offered by the wood. LWD provides significant resistance to flow, traps sediment, and dissipates stream power (Keller and Swanson, 1979). Finkenbine et al. (2000) found that bank erosion was related to the quality of the riparian vegetation and to the frequency of LWD. Within the sites studied by them, between 5 and 10 wood pieces per 100 m were apparently sufficient to stabilize 90% or more of the stream banks.

Channel complexity: The amount and volume of LWD, and the frequency, size, and depth of pools, are typically altered by urbanization. May et al. (1997), for example, found less LWD in streams with increasing watershed urbanization. Changes in sediment supply or increases in discharge triggered by urbanization may cause changes in a number of habitat units such as pools (Montgomery and MacDonald, 2002).

Sediment storage: Channel bars with lengths on the order of the channel width or greater are considered sediment-storage features (Knighton, 1998). The size, stability, and location of channel bars can be a strong indicator of a change

in sediment supply or transport capacity of the channel. However, gravel-bar characteristics need to be interpreted according to channel type, valley configuration, position in the channel network, and the nature of the bar-forcing mechanisms. Ideally, the historic condition of both the reaches in question and their continuing watersheds should be considered (Montgomery and MacDonald, 2002), but this aspect of the study watersheds was not included in the analysis.

1.2 Study questions

The goal of this study is to understand the interaction between confinement, riparian vegetation, and channel morphology in the once-forested urbanized basins of the lowland Puget Sound region, and to predict the responsiveness of these stream channels to yet higher intensities of urbanization. This study attempts to answer the following questions:

How is stream morphology related to the level of channel confinement?

What are the relations between channel morphology and species composition, size, and abundance of riparian vegetation?

Overall, which sets of conditions (confinement, gradient, riparian vegetation) result in a more vulnerable (responsive) channel to urbanization disturbance?

1.3 Hypotheses

The working hypotheses of the study are the following:

- As confinement level increases, channels tend to lose complexity due to limited interaction with a small or inconspicuous floodplain and with its riparian vegetation.
- The riparian-vegetation condition, expressed in terms of species composition, density, and basal area, correlates with channel complexity and bank stability.

- Urbanized channels with anthropogenically confined reaches (e.g., where bank armoring has prevented the interaction of the flow both with the banks and the floodplain) have lower level of complexity than naturally confined channels.
- Channel confinement mediates flood disturbance and therefore the species composition of the riparian vegetation.

2 Methods

The influences of the near-riparian zone on channel morphology were evaluated for several Puget Sound Lowland watersheds (Western Washington State). Study sites were located in the Chico Creek watershed, a low-urbanized catchment on the Kitsap Peninsula near the city of Bremerton, and at four highly developed watersheds in and east of the city of Seattle (**Error! Reference source not found.**). The intent was to investigate a variety of different channel types across a range of urban development in the contributing watersheds.

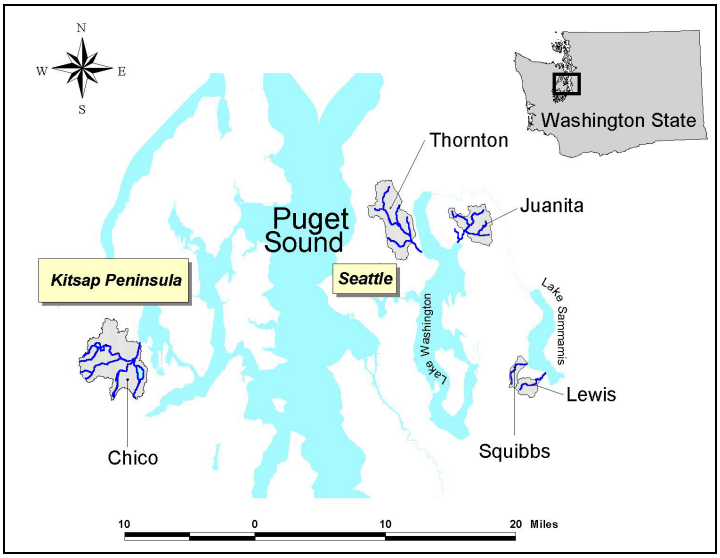


Figure 3- 2: Study Watersheds, located in the Puget Sound region, Western Washington State.

Low- and high-urban sites were selected to be comparable in terms of drainage area, underlying geology, location within the stream network, and channel gradient. These factors were targeted because they are recognized to

influence the geomorphic condition of a stream and its responsiveness to disturbance (Montgomery and Buffington, 1997; Montgomery and MacDonald, 2002). Controlling for these variables improves the likelihood of identifying differences in channel morphology due to impacts of watershed urbanization and riparian-zone alteration.

The riparian zone was characterized in terms of both the near-riparian vegetation (density of the overstory, species composition, and tree basal area) and valley confinement. Channel morphology was assessed by data on channel size, stream-bank condition, sediment storage, and channel complexity. Data sets were graphically and statistically analyzed to investigate a variety of plausible relationships, differences, and trends relative to reaches within the same degree of urbanization and the same channel type.

2.1 Site selection

Twenty-two reaches were surveyed in the Chico Creek watershed, with total impervious areas (TIA) between 9 and 20%, and 22 reaches in the Eastside watersheds, where TIA ranges between 37 and 57%.

Before European settlement the study area was characterized by Western Hemlock old-growth forests, which are dominated by Douglas Fir (*Pseudotsuga menziesii*), Western Hemlock (*Tsuga heterophylla*), and Red Cedar (*Thuja plicata*) species (Franklin and Dyrness, 1988). Currently, there are still a few patches of mature second-growth forest in the middle section of the Chico Creek watershed primarily in the riparian areas of Wildcat and Lost creeks (Chapter 1).

The spatial analysis was performed to identify suitable reaches was based on the following data sources:

- Geomorphic characterization of the Chico Creek watershed main stream network (Chapter 1)

- Percentages of TIA developed by Hill et al. (2003) using a classified Landsat land-cover image 1998 for the Puget Sound Lowland at 30-m resolution
- Digital elevation model (DEM) at 10-m resolution for the Puget Sound Lowland
- LIght Detection And Ranging (LIDAR) topographic survey available for the Chico Creek watershed at 6-foot resolution
- Puget Sound geologic data (Booth et al., 2003)
- A geologic map that includes the Chico Creek watershed (Haessuler and Kenneth, 2002; revised by D. Booth, written comun., 2002).

The reaches selected in the Chico Creek watershed included a broad representation of the watershed stream network. Reaches were selected randomly and stratified by channel type and creek. A total of 4.3 km were surveyed over the main watershed tributaries (Wildcat, Lost, Dickerson, and Kitsap creeks) (Table 3- 1 and Figure 3- 3).

Table 3- 1: Selection of surveyed reaches

CREEK	C	SP	SPc	FPR	PB	PBc	FPR	No. reaches surveyed
Channel slope	**0.04**	**0.02-0.04**			**0.01-0.02**			
Dickerson	1			1	1	1	1	5
Kitsap	1	1		1				3
Lost		1		2			2	5
Wildcat				1	2		3	6
Wildcat *				2	1			3
Thornton		1	2			5	1	9
Juanita					4	3		7
Squibbs			3					3
Lewis		1	1		1			3
No. reaches surveyed	**2**	**4**	**6**	**7**	**9**	**9**	**7**	**44**

* Upstream of Wildcat Lake (Figure 3-3).
C: Cascade, SP: Step-pool, SPc: Constrained step-pool, PB: Plane-bed, PBc: Constrained plane-bed, FPR: Forced pool-riffle.

After spatial analysis of several highly urbanized watersheds of the Seattle region, Thornton, Juanita, Squibbs, and Lewis creeks were identified as the best matches with the geomorphic setting of Wildcat, Lost, Dickerson, and Kitsap

creeks in the Chico Creek watershed. Table 3- 1 presents the number of reaches surveyed per channel type and creek on these Eastside watersheds, where a total of 3.9 km of channel were surveyed (Figure 3- 3).

a)

b)

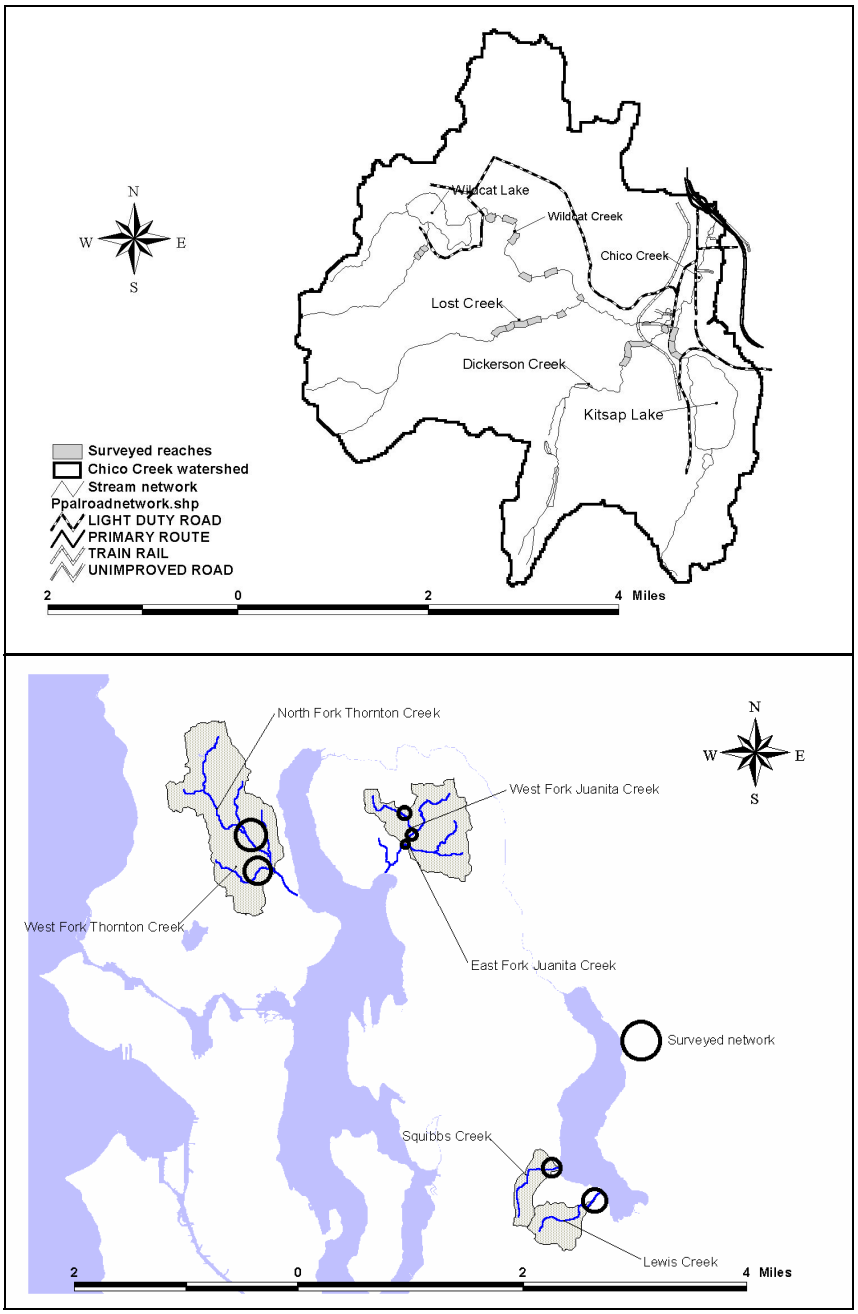


Figure 3- 3: Location of the study sites: a) Reaches in the Chico Creek watershed and b) The Eastside reaches in Thornton, Juanita, Squibbs, and Lewis watersheds

2.2 Site characterization of the surveyed reaches

Of the 44 surveyed reaches, 16 pairs matched well in terms of drainage area and channel gradient (circled pairs in Figure 3- 4). These matches were not always consistent in regards to channel type (Figure 3- 5), however, mostly because more simplified and constrained morphologies (such as plane-bed channels and those with artificially armored banks), are much more common in the Eastside urban streams regardless of their geomorphic setting. “Constrained morphologies” were defined in this study as having above 26% of the bank length armored, which corresponded to the 50th percentile of the data set.

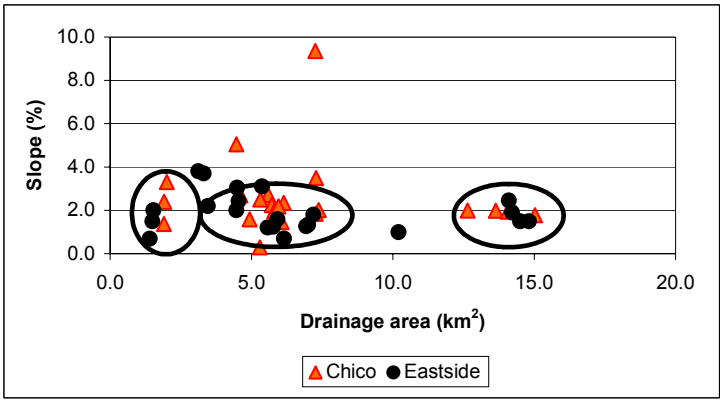
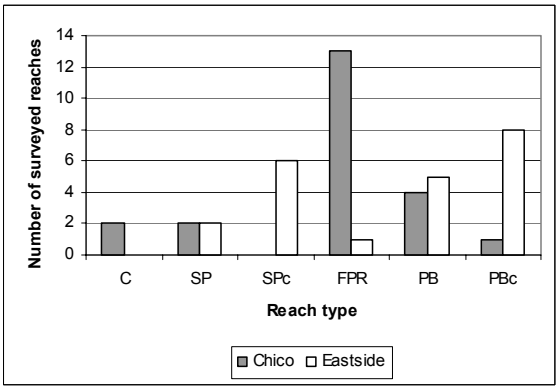


Figure 3- 4: Drainage area and channel gradient of the surveyed sites. Circle data considered for comparative purposes.

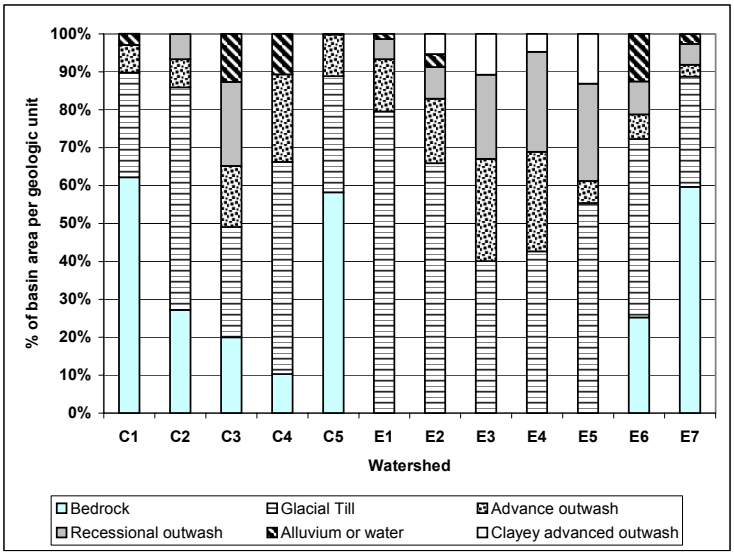


C: Cascade, SP: Step-pool, SPc: Constrained step-pool, FPR: Forced pool-riffle, PB: Plane-bed, PBc: Constrained plane-bed.

Figure 3- 5: Channel type of the surveyed reaches

Figure 3- 6 presents the relative percentages per geologic units in each of the watersheds. Glacial deposits from the last ice-sheet advance in the region

cover between 35 and 99% of the ground surface of the analyzed basins. Advance and recessional outwash underlie between 7 and 38% of the Chico Creek watersheds and between 9 and 53% of the Eastside watersheds; glacial till underlies between 29 and 59% of the Chico Creek sub-basins and between 29 and 78% of the Eastside watersheds. Bedrock deposits, mostly located in the headwater portion of the watersheds, underlie between 10 and 62% of basin areas in Chico Creek and between 0 and 60 % of the Eastside watersheds.

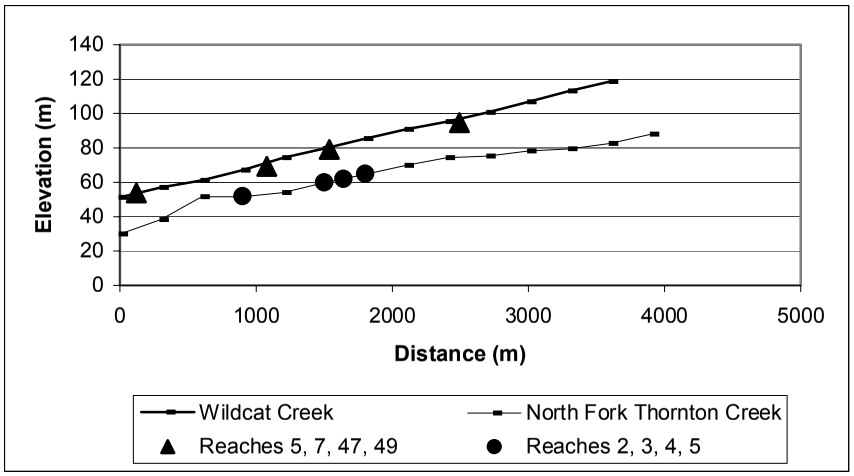


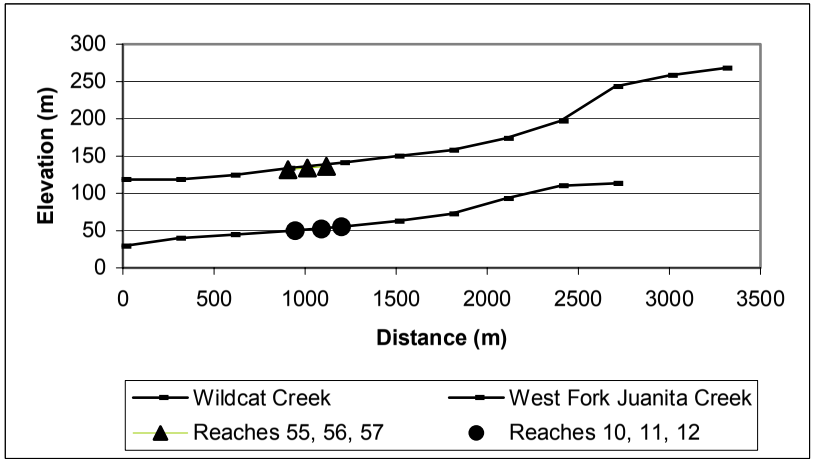
C1: Wildcat Creek upstream of Wildcat Lake, C2: Dickerson Creek, C3: Kitsap Creek, C4: Wildcat Creek, C5: Lost Creek, E1: North Fork Thornton Creek, E2: West Fork Thornton Creek, E3: West Fork Juanita Creek, E4: Main stem Juanita Creek, E5: East Fork Juanita Creek, E6: Squibbs Creek, E7: Lewis Creek.

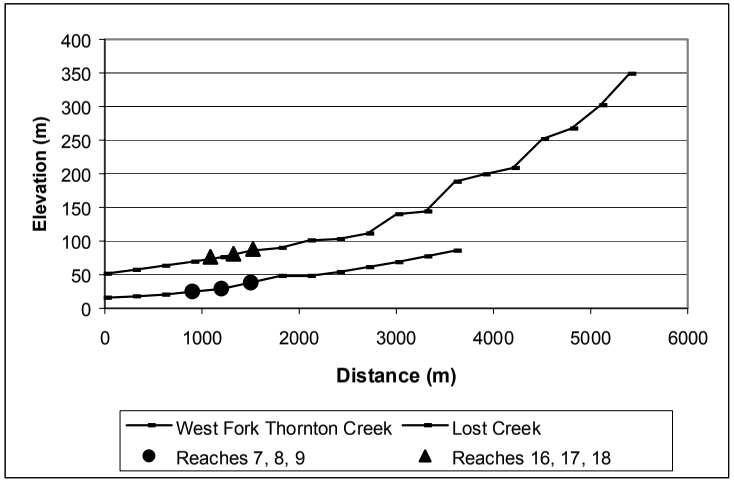
Figure 3- 6: Relative surface area per geologic formation in the study watersheds

Although the fluvial regime of a watershed is influenced by the presence of bedrock deposits, suitable sites are sparse in highly urbanized areas where headwater sections are underlain by this material. Urban development does not tend to occupy watershed areas with bedrock, mostly due to their generally steep topography.

Stream profiles of the selected streams in both the low and highly urbanized areas are presented in Figure 3- 7. Paired reaches (including the sixteen identified pairs in Figure 3- 4) are located at analogous positions within the stream network.







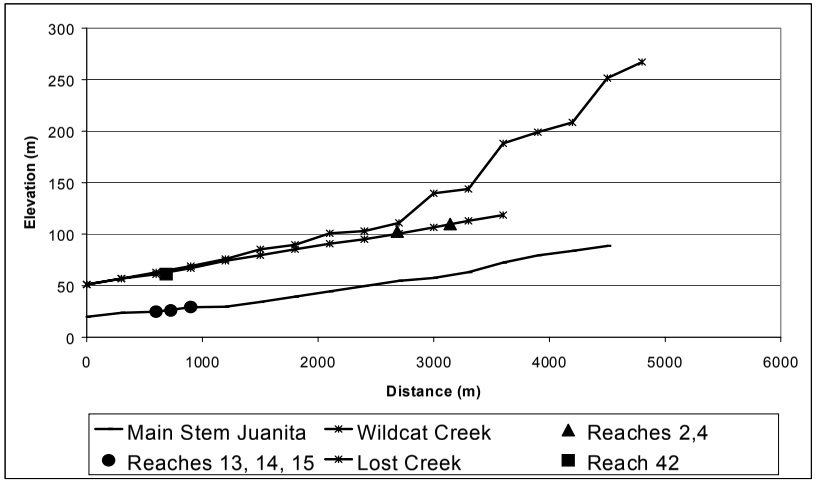
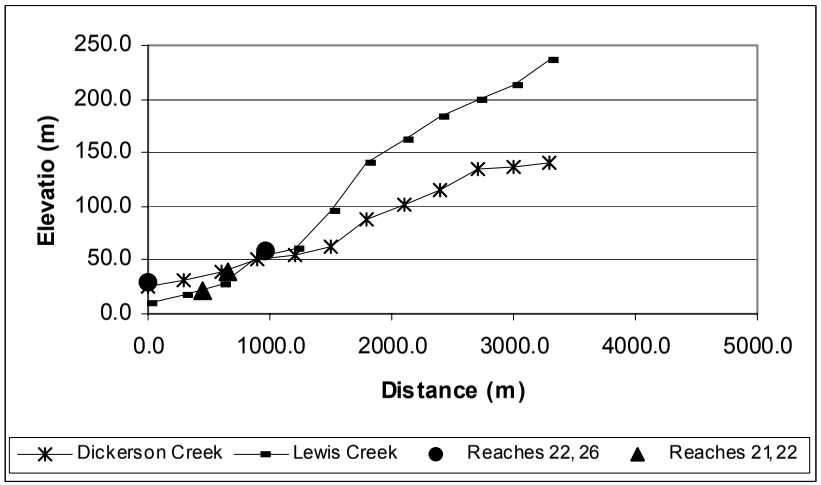


Figure 3- 7: Channel profile and location of the surveyed reaches. Each graph includes the pair of reaches selected for further analysis



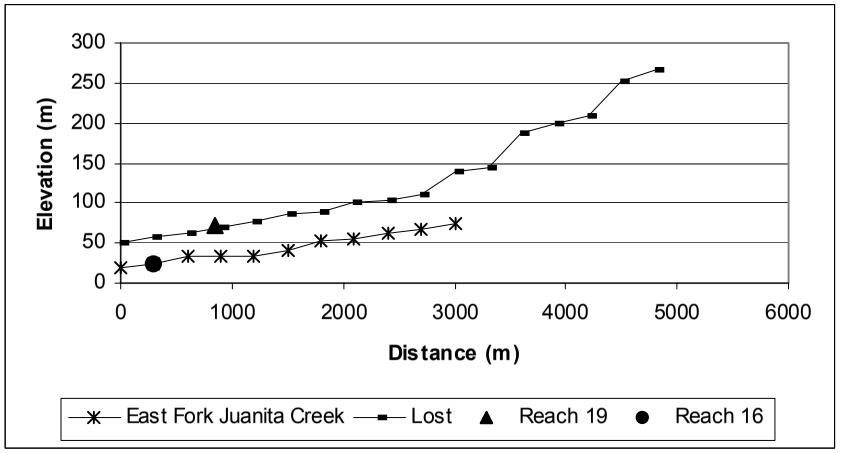


Figure 3- 7 (continued).

The relief ratio of a stream is defined as the ratio of the difference between the lowest and the highest points of the watershed to the length of the watershed measured roughly parallel to the major drainage (Dunne and Leopold, 1978). It can be interpreted as a gross measure of the system's stream power potential. The relief ratio of the surveyed reaches is summarized in Table 3- 2.

Table 3- 2: Relief ratio of the surveyed streams (highlighted creeks are located in the Chico Creek watershed)

Creek	No Reaches	Average Relief ratio
Lost Creek	5	0.0640
Dickerson Creek	2	0.0564
Lewis Creek	2	0.0564
Wildcat Creek upstream Wildcat Lake	3	0.0541
West Fork Juanita Creek	3	0.0370
Wildcat Creek	6	0.0291
East Fork Juanita	1	0.0177
Main stem Juanita Creek	3	0.0154
North Fork Thornton Creek	4	0.0092
West Fork Thornton Creek	3	0.0061

2.3 Field data collection

Detailed channel geomorphic surveys of the selected reaches were conducted during the summer of 2002. Channel features likely to be directly modified or otherwise affected by urbanization in general, and by the condition of the near-riparian zone in particular, were measured. The surveys included the collection of in-channel geomorphic conditions and the measurements of riparian and channel confinement at consecutive locations over the length of each reach. Geomorphic data included:

- Bankfull dimensions (width and depth)
- Stream-bank condition (length of channel bank undergoing erosion or anthropogenic armoring structures)
- Sediment storage (frequency and volume of channel bars)
- Channel complexity (characterized by large woody debris (LWD) and pool abundance).

Each surveyed reach constituted one sample unit. The minimum sample size length was 20 channel widths in order to fully represent repetitive patterns of the streams (MacDonald et al., 1991; Montgomery and Buffington, 1997; Rot et al., 2000: Martin, 2001). Each geomorphic feature was longitudinally located using a metric hip chain.

2.3.1 Channel size

Bankfull dimensions were recorded for every reach using a stadia rod and a metric tape. The presence or absence of perennial vegetation, topographic breaks in the bank, and changes in sediment characteristics were the indicators to define the bankfull depth (BFD) and bankfull width (BFW) (Dunne and Leopold, 1978).

2.3.2 Bank erosion and sediment storage

Erosion was recorded by its longitudinal location along the reach and its dimensions (height and length). This same information was recorded for bank armoring. Channel bars were recorded for each reach in terms of longitudinal location along the reach and size (height from the thalweg, length, and width). Bed-sediment accumulations of at least one channel width in longitudinal dimension were considered as bars (Knighton, 1998; Montgomery and MacDonald, 2002).

2.3.3 Pools and large woody debris (LWD)

The location of pools in each reach was recorded, considering minimal dimensions dependent on channel size. A pool unit was defined as having a minimum residual depth of 25% of the BFD and a minimum pool length of 10% the BFW (Montgomery et al., 1995). The formation agent of pools was also recorded. Recorded LWD information included location along each reach, its relative position (spanning or adjacent), and its functionality (pool formation, sediment storage, or not functioning). According to Montgomery et al. (1995), the

influence of LWD on channel morphology depends on its size relative to the channel size, orientation relative to the flow, and height above the bed. Due to time constrains, only the position within the channel was recorded. Recorded woody debris were located in the wetted or bankfull portion of the channel (zones 1 and 2 as described by Shuett-Hames et al., 1994) and met the minimum criteria of 1 m in length and 25 cm in diameter (Montgomery et al., 1995).

2.3.4 Riparian vegetation and confinement

Riparian vegetation per reach was characterized with 8 plots located at 4 transects on both sides of the channel. In the case of reaches longer than 160 m, data was collected at 40-m intervals. For reaches shorter than 160 m the plots were located every 25 m (no reach was less than 100 m long). For reaches longer than 200 m, data were collected at 5 intervals, in which case vegetation values were normalized to 4 intervals and only the confinement scores of the four initial observations were considered. Each vegetation plot was 20 m long and 10 m wide (200 m^2), located perpendicular to the channel starting at the edge of the bankfull width (Figure 3- 8). The size of the plots was selected to characterize the near-riparian vegetation. Measurements were taken on the following parameters for each tree: stem DBH, species, and landform location (floodplain-FP, terrace-T, or hillslope-HS). Additional landform categories had to be incorporated in highly disturbed areas where the riparian vegetation was either part of a residential backyard or where it was on top of a bank-armoring structure. Vegetation located in these additional categories has limited interaction with the stream and therefore is more isolated from the channel.

Confinement was analyzed at the same locations as the vegetation plots. For the purpose of this study, confinement is defined according to Rosgen (1994) as the ratio of the “floodprone” width to the bankfull width, where the floodprone width is the width of the valley at an elevation of two times the BFD depth (Figure 3- 8). Three different confinement categories were found: unconfined, where the floodprone width is twice as wide as the bankfull width; confined, where the

floodprone width is less than twice the bankfull width; and partially confined, where confined conditions are present but only on one side of the channel (Figure 3- 8).

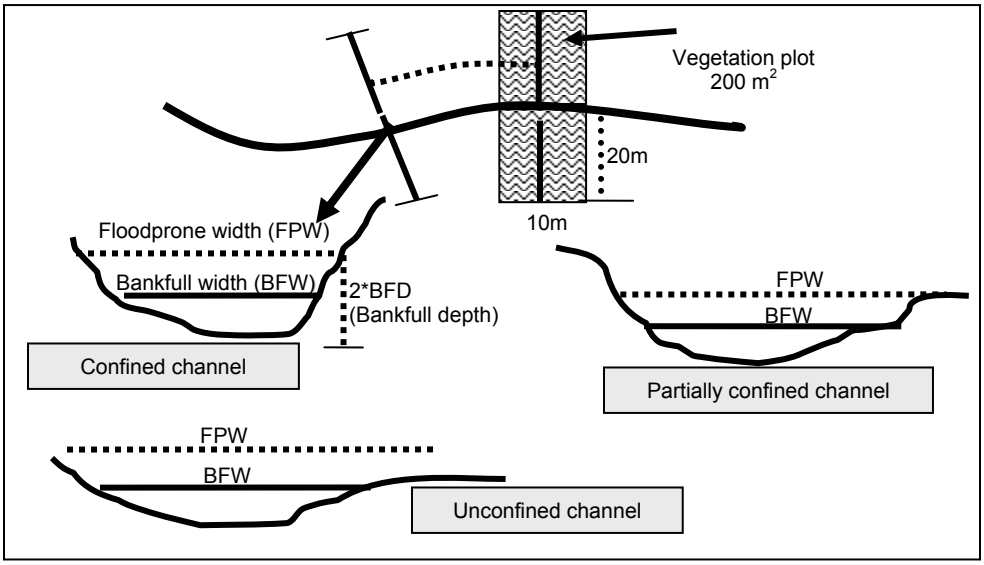


Figure 3- 8: Riparian vegetation and confinement measurements

2.4 Data analysis

Three different data sets (using the variables displayed in Table 3- 3) were generated:

- Sites surveyed at low-urbanized conditions (Chico Creek watershed, n=22);
- Sites surveyed at high urbanization levels (Eastside watersheds, n=22); and
- A subset of the first two, consisting of sixteen matched pairs of reaches from both the low and high urbanization groups (n=32) (Figure 3- 4).

2.4.1 Development of variables

Bank erosion, sediment storage, LWD, and pools

Each geomorphic feature (bank erosion, channel bars, LWD, and pools) was standardized by reach length in terms of abundance per 100 m. The types of data collected for each feature are summarized on Table 3- 3. Channel-bank erosion was calculated as the percentage of the channel length eroded and the

percentage of the bank length armored. LWD pieces were categorized by functional category (pool formation, sediment storage, or no morphologic influence) and by position in the channel (spanning or adjacent). In addition, the percentage of the LWD jams containing a single piece of wood, more than 5 pieces, and more than 10 pieces was calculated. The relative percentage of pools formed by each of the considered factors (LWD, bed morphology, meandering, boulder, or anthropogenic influence) was calculated (Table 3- 3).

Table 3- 3: Variables developed from the field observations and spatial analysis of each reach.

Variable group	Variables developed
Drainage area features	Drainage area (km^2) Relief ratio (km/m) TIA (%)
Reach condition	Confinement (1)* Confinement (2)* Channel type
LWD	LWD frequency (#/100 m) LWD distribution (% LWD jams with more than 5 wood-pieces and % of LWD single-piece LWD jams)
Pools	Pool frequency (#/100 m) % of pool per formation agent (LWD, meandering, bed, boulder, or anthropogenic influence)
Sediment storage	Bars frequency (#/100 m) Sediment storage – volume of bars (m^3/100 m)
Erosion	%bank length eroded
Riparian vegetation	Number of trees (#/1600m^2) Basal area (m^2/ 1600m^2) % of trees per landform location (HS, T, FP, HSby, FPby TA)*** % of trees per type (conifers and deciduous) % of trees isolated from the channel****

* Two different confinement variables were calculated. “Confinement (1)” scored unconfined and partially confined intervals with a value of 0 and confined intervals with a value of 1. By “confinement (2)” confined intervals received a score of 1, partially confined a score of 0.5 and unconfined a score of 0.
*** HS: Hillslope, T: Terrace, FP: Floodplain, HSby: Hillslope at a back yard, FPby: Floodplain at a back yard, TA: On top of bank-armoring structure.
****Sum of percentages of trees located in HS, HSby, Fpby, and TA.

Riparian vegetation and confinement

Based on the measurements taken, the following variables were derived (Table 3- 3):

- Number of trees/1600m^2 (i.e. total plot area per reach)
- Basal area (m^2/1600m^2), summarizing the number and the size of trees in the near-riparian zone.

- Percentage of the trees in each landform location (floodplain, terrace, hillslope, hillslope at a residence back yard, floodplain at a residential back yard, and on top of bank-armoring structures)
- Percentage of trees isolated from the channel (sum of percentage of trees on the hillslope, in a residential back yard, and on top of bank-armoring structures)
- Percentage of the trees per type (conifer and deciduous)
- Confinement observations per reach, taken at each of the four locations where vegetation plots were established. A score of zero was given to "unconfined" reaches (floodprone width greater than twice the BFW) and a score of 1 to "confined" reaches (floodprone width narrower than twice the BFW) (Figure 3- 8).

The fundamental difference between confined and unconfined conditions is that at high flow, unconfined streams have an opportunity to spread across the valley floor, dissipating much of the energy of the current (Gregory et al., 1991). In confined reaches the flow does not spread but piles up, resulting in progressively higher shear stresses at progressively higher flows. From the hydraulic perspective one confinement score was calculated given a score of zero to both unconfined and partially confined scenarios, and a score of 1 to confined conditions. "Confinement (1)" was calculated per reach as the average of the 4 confinement scores along them, thus yielding a score that ranged from 0 to 1 (Table 3- 3).

A second confinement variable ("Confinement (2)") was developed for the purpose of analyzing interactions between confinement and vegetation. From the vegetation perspective, it is relevant to distinguish between one-side confined and fully unconfined situations because the interaction between the vegetation root system and flooded conditions influences the community composition of the riparian vegetation. Species adapted to periodic flooded conditions should be present at unconfined and partially confined settings, whereas flood-intolerant

species should not appear. The scheme gives alternative scores to confined and partially confined intervals (confined intervals received a score of 1, partially confined a score of 0.5, and unconfined a score of 0). The score per reach was calculated as the average of the 4 interval scores per reach, thus also ranging between 0 and 1 points (Table 3- 3).

2.4.2 Analytical methods

Analytical methods included the investigation of hypothesized relationships between near-riparian zone condition (vegetation and confinement) and channel morphology, and between confinement and riparian plant community.

The approach consisted of graphical exploration of hypothesized relationships and regression analysis to test the significance of graphically established trends. All statistical analyses were performed using an experiment alpha of 0.05. Prior to each statistical analysis, the normality of the variables was graphically assessed and in some cases enhanced by logarithmic or square-root transformations (Zar, 1996; Neter et al., 1996).

The data was analyzed for relationships between channel confinement and riparian vegetation abundance, size, species composition, and relative location to the channel and channel morphology. These conditions were expressed as:

- Abundance and distribution of LWD: LWD/100 m and number of wood pieces per LWD jam
- Pool frequency: pools/100 m
- Sediment storage: bars/100 m and volume of bars/100 m
- Percentage of the bank length eroded

Expected channel-type-dependent trends were investigated. For example, the amount of wood associated with each channel type (expected to be higher at

FPR channels than at cascade, SP, or PB channels); the pool-forming agent, expected to be different between channel types (pools in FPR channels are expected to be highly depend on LWD); or the relative amount of sediment stored in the channel which is expected to be higher at channel types observed at low gradient and in unconfined conditions.

Data sets 1 and 2 were analyzed separately in order to identify particular functional relationships at each urbanization scenarios (the Chico Creek watershed and Eastside watersheds); and for data set 3 (i.e. 16 reaches from the Chico Creek watershed paired with 16 reaches from the Eastside). The working hypothesis is that some functional relationships, particularly those resulting from of the interaction of the flow with a functional riparian area, will disappear at high urbanized levels. Other relationships, however, such as the interaction between anthropogenic confinement (provided when bank armoring structures are present) and channel morphology, might only be present in highly urbanized watersheds. The analysis with data set 3 would presumable allow the identification of relationships and trends only evident over a wide range of urbanization levels, which might be directly related to channel configuration changes attributed to urbanization impacts.

The interaction between channel confinement and riparian vegetation was evaluated for data sets 1 and 2. This analysis focused on finding the impact of confinement on anticipated riparian vegetation features (number of trees, percentage of conifers, species composition, and landform location of the trees).

Data collected through the surveys is presented by reach in Appendix C, Table C-1.

3 Results

This section presents the observed correlations between near-riparian zone (vegetation and confinement) and channel features (LWD, pools, channel bars, and bank erosion) across variable levels of urbanization. The riparian-zone

variables that correlated with morphologic features included channel confinement, basal area, and percentage of trees isolated from the channel (i.e. located on the hillslope). In contrast, the kind of riparian vegetation (conifer or deciduous) and the relative percentage of trees on the other landform types (i.e. floodplain and terrace) did not correlate with channel morphology.

3.1 LWD

Confirming a hypothesis of this study, the frequency of LWD pieces in the surveyed channels was found to correlate with the abundance and size of the trees located in the near-riparian vegetation and with the level of channel confinement. The distribution of wood pieces in LWD jams also correlates with the abundance and size of the riparian vegetation (Appendix C, Table C-2).

3.1.1 In-stream LWD frequency

Basal area, a measurement that incorporates both the abundance and the size of the trees in the near-riparian zone, correlated with in-channel LWD per 100 m (R^2 = 0.38) (Appendix C, Table C-2). This relationship was found to be channel-type-dependent, with the highest coefficients of determination being 0.50 for FPR and 0.51 for PB reaches. Constrained morphologies (PBc and SPc) located in the Eastside were observed with the lowest values of LWD regardless of the near-riparian vegetation basal area. SP reaches had variable amount of LWD independent of basal area (Figure 3- 9a). As expected, FPR channels had significantly more LWD pieces than PB ($p = 0.001$) or constrained channels (PBc and SPc) ($p < 0.0001$) (Figure 3- 9b).

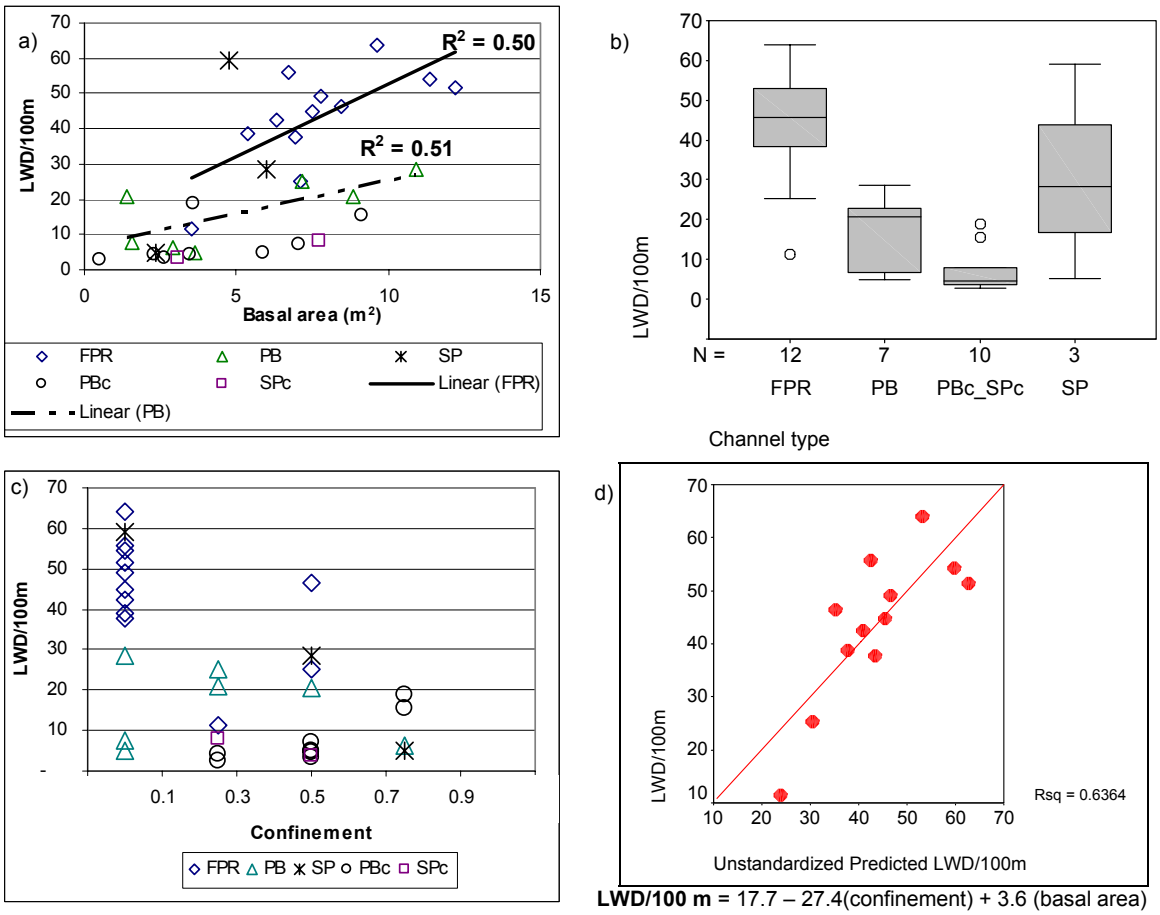


Figure 3- 9: Scatter plots of: a) and b) basal area versus LWD/100 m; c) confinement versus LWD/100 m; and d) predicted versus observed LWD/100 m in FPR channels.

Confinement was inversely correlated to LWD/100 m (R^2 = 0.32) (Appendix C, Table C-2). However, high variability was observed at unconfined reaches (i.e. confinement score = 0) (Figure 3- 9b). FPR channels were mostly located at unconfined reaches with high amounts of wood, with a trend of decreasing LWD frequency as confinement increases. The amount of wood in PB and PBc channels was consistently low and unrelated to the level of channel confinement.

A linear multi-regression model which predicted LWD in FPR channels using basal area and confinement as predictor variables had an R^2 of 0.63 (F = 7.9, p =0.01, n = 14) (Figure 3- 9d).

Analyses performed at each level of urbanization independently (subsets 1 and 2) showed similar results to those found for the complete data set (data set 3). LWD in FPR and PB channels had distinct trends in relation with basal area within reaches surveyed in the Chico Creek watershed with coefficients of determination of 0.42 (FPR) and 0.86 (PB) (Appendix C, Figure C-1a).

In contrast, LWD in the Eastside reaches was only slightly correlated with basal area (R^2 = 0.29). Constrained morphologies (SPc or PBc) had fewer wood pieces regardless of the near-riparian zone tree basal area (Appendix C, Figure C-1b). No correlations were observed between LWD frequency and channel confinement within these reaches, most likely because confined conditions (dominated by anthropogenic confinement) inhibit the addition of LWD pieces.

3.1.2 Wood distribution in LWD jams

The number of wood pieces per LWD jam was correlated to the number and size of the trees in the riparian zone. Single-piece wood jams were inversely correlated to basal area (R^2 = 0.30) (Appendix C, Table C-2) (Figure 3- 10a). Conversely, the abundance of LWD jams with more than 5 pieces was positively correlated to the near riparian vegetation basal area (R^2 = 0.46). This relationship for FPR and PB channels had coefficients of determination of 0.42 and 0.79, respectively (Figure 3- 10b).

Graphical exploration indicated that PB and constrained morphologies had higher proportion of single-piece jams than FPR channels (Figure 3- 10a) and that FPR channels had higher proportion of LWD jams with more than 5 pieces than PB reaches (Figure 3- 10a). Constrained morphologies lacked of LWD jams with more than 5 wood pieces and SP channels had variable behavior apparently unrelated to basal area.

LWD distribution within either low or high urbanized reaches analyzed independently were not significantly correlated to basal area, owing to smaller

sample sizes. This suggests that these trends are descriptors of channel morphology changes across only the broadest range of urbanization.

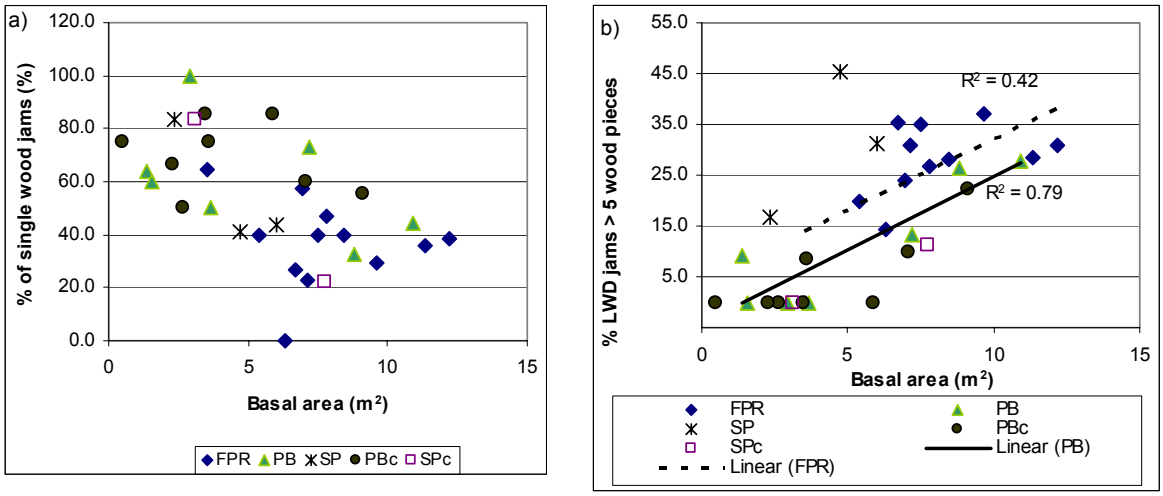


Figure 3- 10: Scatter plots of: a) basal area versus percentage of single-wood-piece jams; and b) basal area versus percentage LWD jams with more than 5 wood pieces

3.2 Pool frequency

Contradicting one of the hypotheses of the study, pool frequency was related neither to channel confinement nor to the abundance, size, or species composition of the riparian vegetation. However, a weak negative correlation was observed with the percentage of trees isolated from the channel (R^2 = 0.24) (Appendix C, Table C-2). Neither confinement nor characteristics of the near-riparian vegetation correlated with pool frequency within sites in either the Chico Creek watershed or the Eastside analyzed independently.

Pool frequency decreased with fewer trees connected to the channel (R^2 = 0.24) (Appendix C, Table C-2). This relationship was slightly stronger for FPR channel (R^2 = 0.25) (Figure 3- 11a). PB channels had consistently low pool frequencies regardless of the position of the near-riparian vegetation, and SP and constrained reaches had few pools and, in most cases, high percentages of trees isolated from the channel (Figure 3- 11a).

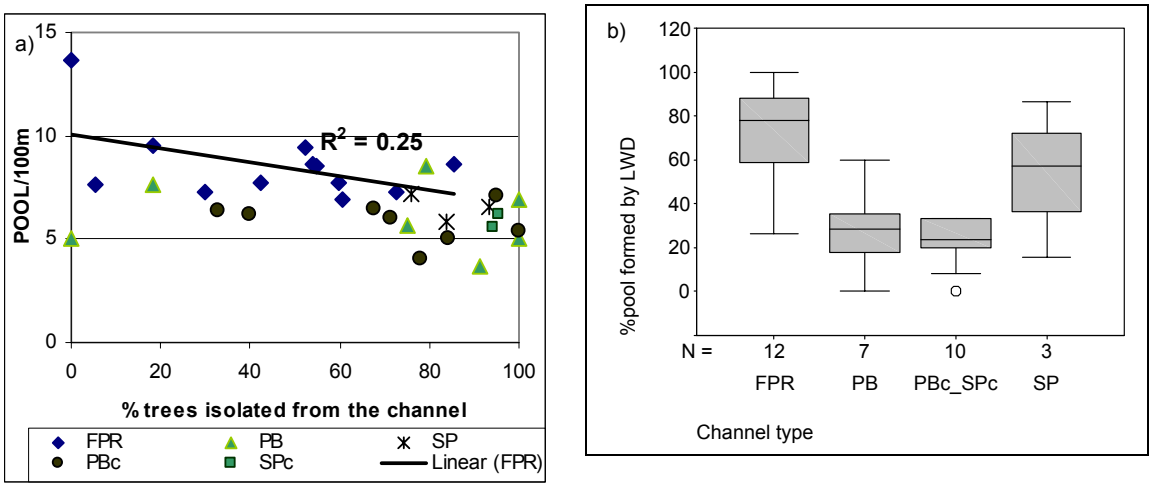


Figure 3- 11: a) scatter plot of percentage of the trees isolated form the channel versus pools/100 m and b) percentage of pools formed by LWD per channel type

The relationship between pool frequency and the near-riparian vegetation was found to be mediated by the presence of LWD, which in turn is influenced by both the abundance and size of the riparian vegetation and the level of confinement. As expected, more pools were formed by LWD in FPR than in PB ($p = 0.002$) or constrained channels (PBc and SPc) ($p = 0.0001$). SP reaches had variable behavior (Figure 3- 11b).

3.3 Sediment storage

Correlations between sediment storage and characteristic of the riparian zone were observed within reaches at each level of urbanization analyzed independently. Sediment storage did not correlate with the near-riparian zone across the complete range of urbanization. For reaches surveyed in the Chico Creek watershed, the landform position of the near-riparian trees and the level of channel confinement correlated with the frequency and volume of channel bars. In contrast, the frequency of channel bars in the Eastside reaches was correlated simply with the frequency of in-stream wood.

3.3.1 Bar frequency

Within reaches surveyed in the Chico Creek watershed, bar frequency was inversely correlated to the percentage of trees in the hillslope, particularly in

FPR channels (R^2 = 0.53) (Figure 3- 12a). Bar frequency in the Eastside reaches correlated positively to the frequency of LWD (R^2 = 0.42) (Figure 3- 13a), suggesting that significant sediment within these channels is stored behind wood pieces (Figure 3- 13a). In low-urbanized channels, sediment was also found as "free" point and mid-channel bars.

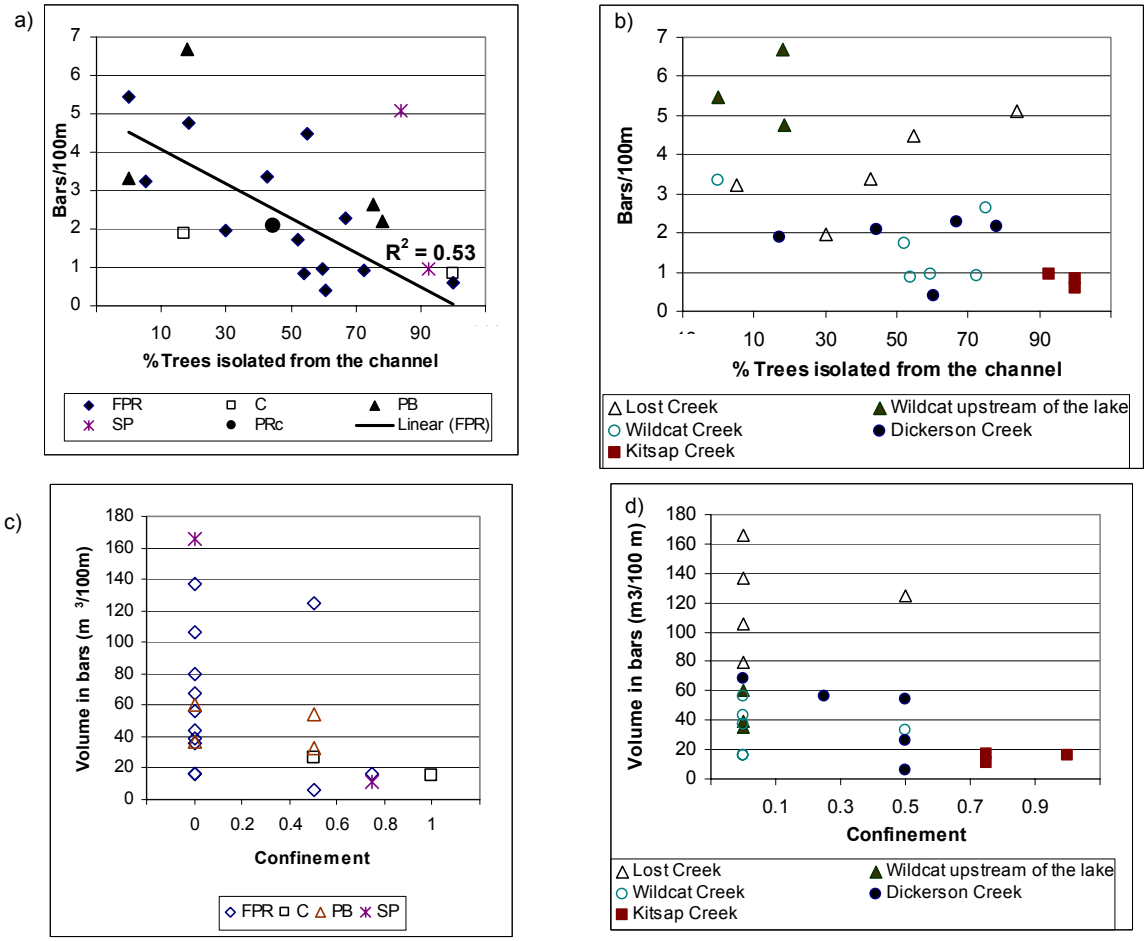


Figure 3- 12:Scatter plot of a) and b) percentage of trees isolated from the channel versus bar frequency, and c) and d) confinement versus volume of bars in reaches in the Chico Creek watershed

The position of the reaches within the stream network also appeared to be influential. Sites in Wildcat Creek upstream of Wildcat Lake and Lost Creek had higher channel bar frequencies and volume than reaches in Wildcat and Kitsap creeks downstream the lakes and in Dickerson Creek (Figure 3- 12b and Figure 3- 12d).

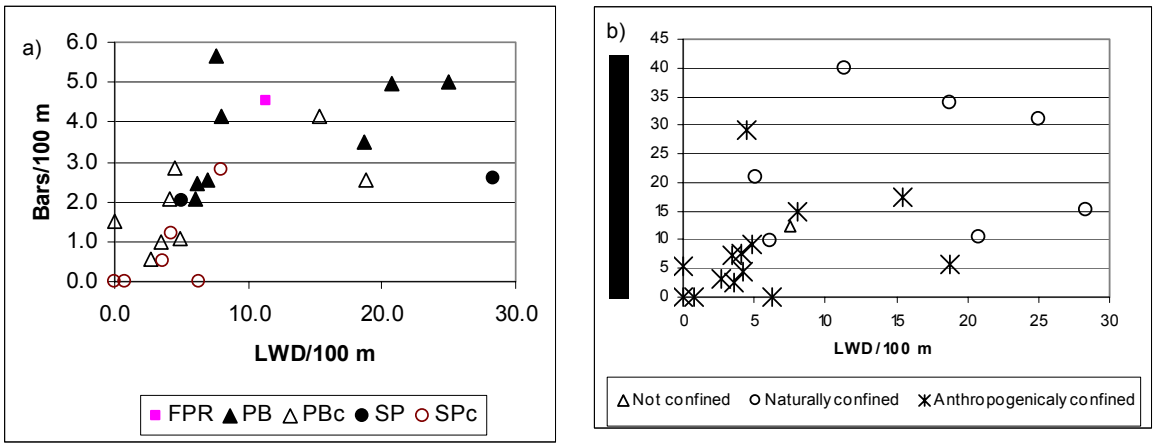


Figure 3- 13 Scatter plot of a) LWD/100 m versus bars/100 m and b) LWD m versus volume in bars in reaches in the Eastside

3.3.2 Bar volume

Bar volume within reaches surveyed in the Chico Creek watershed was inversely related to channel confinement, with high variability at unconfined reaches but uniformly low volumes with high confinement (Figure 3- 12c). Sediment stored in reaches surveyed in the Eastside was not correlated to in-stream LWD (Figure 3- 13b). The reach here with the highest stored volume correspond to the only FPR channel in the data set. The rest of the surveyed reaches had low sediment storage regardless of the frequency of LWD. Anthropogenically confined channels had less sediment stored than unconfined and naturally confined reaches, indicating either low sediment input or high transport capacity in these systems (Figure 3- 13b).

3.4 Bank erosion

As hypothesized, bank erosion (measured by the percentage of the bank length eroded) was correlated with characteristics of the near-riparian vegetation (Appendix C, Table C-2). Bank erosion (using a square-root transformation) was inversely correlated to both the near-riparian trees basal area (R^2 = 0.33) (Figure 3- 14a) and the frequency of LWD (R^2 = 0.53) (Figure 3- 14b). It was positively

correlated to the percentages of trees isolated from the channel (R^2 = 0.37) Figure 3- 14c).

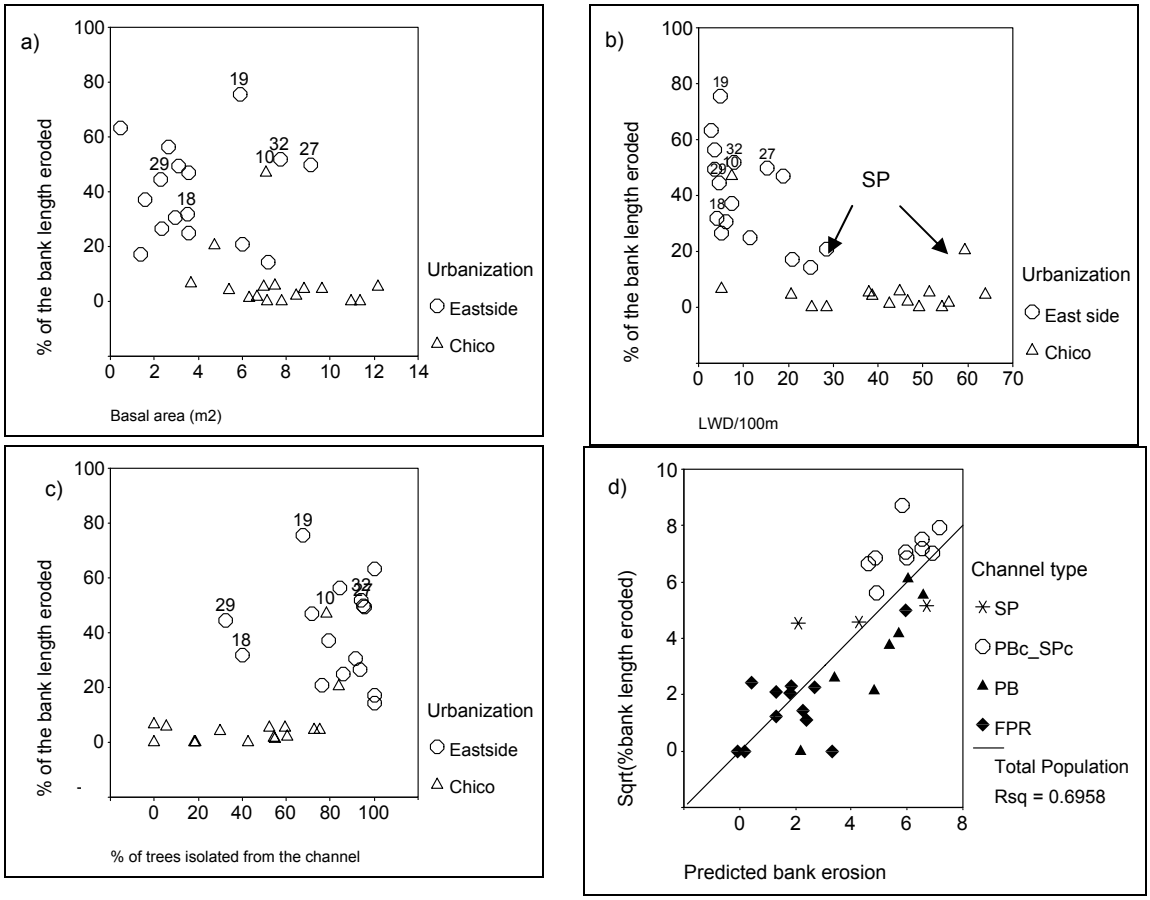


Figure 3- 14: Scatter plots of a) basal area versus bank erosion; b) LWD/100 m versus bank erosion; c) percentage trees isolated from the channel versus bank erosion; and d) predicted versus observed bank erosion

Reaches in the Chico Creek watershed with basal area between 5 and 12 m^2 had less than 4% of their bank length eroded. Conversely, most of the channels observed with high erosion (located in the Eastside) drained areas with little near-riparian vegetation (basal area below 4 m^2) (Figure 3- 14a). Four reaches (10, 19, 27, and 32), were observed with relatively high basal area (between 6 and 9 m^2) and unusually severe bank erosion (above 45%). The effect of the riparian vegetation in these reaches is limited, however, because they have more than 65% of the near-riparian trees isolated from the channel (Figure 3- 14c).

Reaches with more than 40 in-stream wood pieces per 100 m had less than 5% of the bank length eroded. Conversely, reaches with less than 10 pieces per 100 m had more than 20% of their bank length eroded. SP reaches had higher erosion values than other channel types at comparable LWD quantities. Apparently, the stabilization effect of wood pieces is less effective in this high-gradient type (Figure 3- 14b).

Extensive bank erosion was observed at reaches with high percentage of the near-riparian overstory isolated from the channel (Figure 3- 14c). Reaches in the Chico Creek watershed had less than 5% of the bank length eroded and variable range of trees isolated from the channel (between 0 and 80%). Conversely, reaches in the Eastside had high erosion and more than 70% of near-riparian vegetation isolated from the channel. The only two reaches (29 and 18) with low percentage of trees isolated from the channel (less than 40%) and high bank erosion (more than 30%) also had low LWD frequencies (below 5 pieces/100 m) (Figure 3- 14b).

A linear regression model to predict bank erosion based on LWD/100 m and percentage of trees isolated from the channel as predictor variables has an R^2 of 0.69 ($F = 33.16$, $p < 0.0001$, $n = 32$) (Figure 3- 14d). Channel-type analysis indicates that although erosion in the surveyed reaches is correlated to these two variables, there is significantly less bank erosion in FPR channels than in PBc and SPc ($P<0.0001$) and SP channels ($P<0.048$). In fact, PB is the only type with high erosion variability that increases linearly with decreasing LWD and increasing number of trees isolated from the channel (Figure 3- 14d and Figure 3- 15).

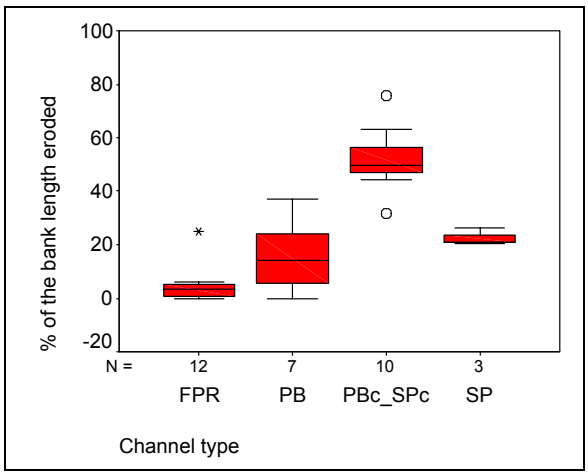


Figure 3- 15: Percentage of the bank length eroded per channel type

3.5 Relationships between confinement and riparian vegetation

Graphical analysis displays a correlation between channel confinement and the vegetation species in the near-riparian zone in the low-urbanized reaches (the Chico Creek watershed) (Figure 3- 16). These relationships were not found in the high-urbanized settings (Eastside). The confinement scoring methods (2) used for this analysis distinguishes between partially confined and unconfined conditions.

Graphical and statistical analysis indicated that confinement is a strong predictor of the near-riparian-area species composition. The relative percentage of conifer species (Western hemlock, Red cedar, and Douglas fir) in the near-riparian area increases in direct relation to the level of channel confinement (Figure 3- 16a). This trend was stronger for Red cedar alone (R^2 =0.46) (Figure 3- 16b) and for Red cedar plus Douglas fir (R^2 = 0.53) (Figure 3- 16c). Western hemlock abundance was not as sensitive to channel confinement as the other two conifer species; it corresponded to a relatively high proportion of the overstory vegetation in all landforms.

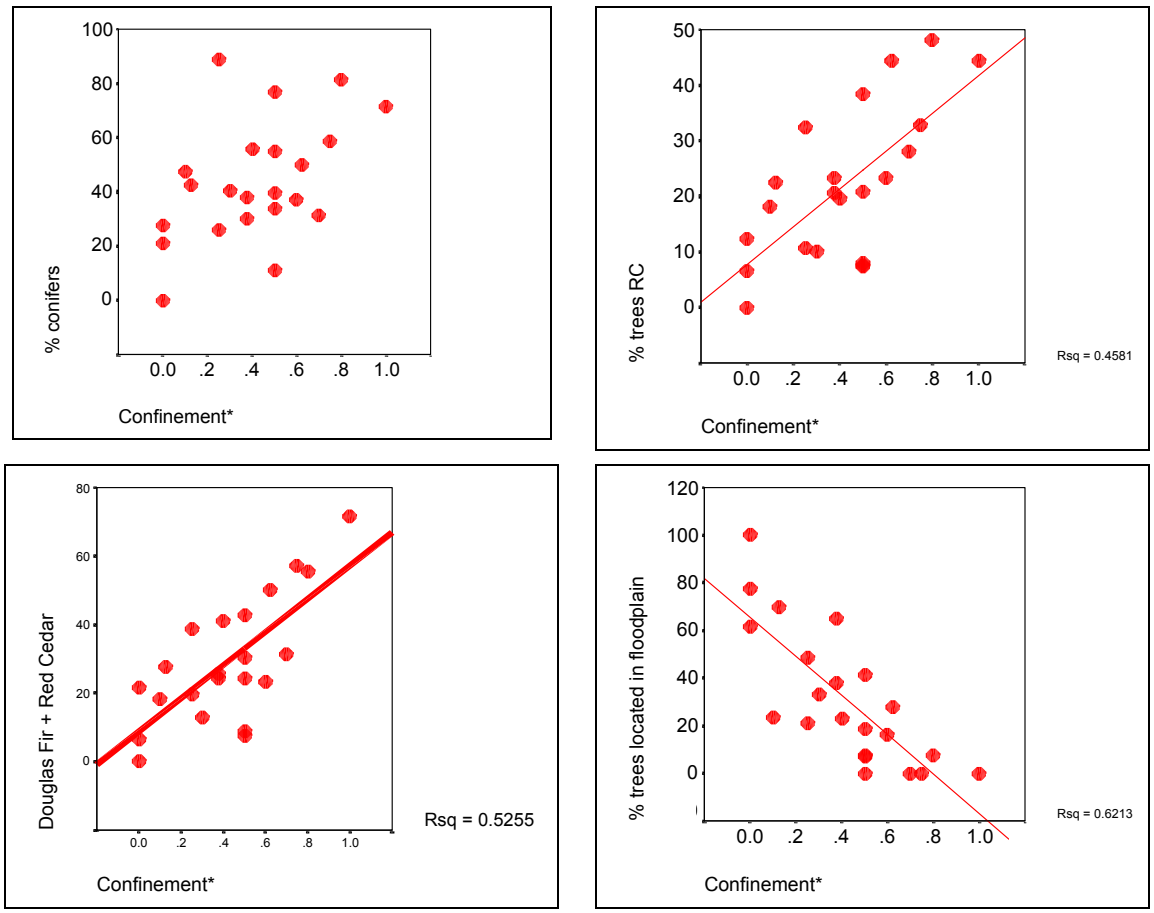


Figure 3- 16: Scatter plots from the Chico Creek watershed of a) channel confinement versus percentage of conifers; b) confinement versus percentage of Red cedar; c) confinement versus Douglas fir plus Red cedar; and d) confinement versus percentage of trees isolated from the channel

In addition, confinement was found inversely related to number of trees located in the floodplain, indicating consistency of the field observations (R^2 =0.62) (Figure 3- 16d).

In reaches surveyed in the Chico Creek watershed, more conifer species were observed on the hillslope than in the floodplain. 26% of the trees in the floodplain corresponded to conifers species versus 60% on the hillslope (Appendix C, Table C-3). Conifer basal area followed this same trend: 42% of the area covered by trees corresponded to conifer species versus 62% of area covered by trees on the hillslope. Within the floodplain, the Red cedar basal

areas was comparable to the Red alder's, whereas basal area of Western hemlock and Douglas fir were less.

Species composition of the near-riparian zone in the Eastside did not show the trends observed for the Chico Creek watershed. Half of the trees in both the floodplain (49%) and the hillslope (46%) are conifers (Appendix C, Table C-4).

3.6 Results summary

Over the full range of urbanization, some channel morphologic features were correlated to characteristics of the near-riparian zone. LWD frequency and distribution correlate to the abundance and size of the trees in the near-riparian area and to channel confinement. Pool frequency and bank erosion inversely correlate to the relative percentage of trees isolated from the channel. Bank erosion also correlates to the abundance and size of the riparian vegetation and to the frequency of LWD.

Strong correlations exist mostly in unconfined or naturally confined low-gradient reaches (FPR and PB). Other channel types, such as SP, SPc, and PBc, are less sensitive to the condition of the near-riparian zone (Table 3- 4).

Table 3- 4: Relative sensitivity of channel morphology to riparian zone variables per channel type

Channel type	LWD/ 100 m	LWD distribution	Pool/ 100 m	Sediment storage	Bank erosion
FPR	X	X	X	X	-
PB	X	X	-	X	-
SP	-	X	-	-	-
PBc	-	-	-	-	-

X: Channel-type-dependent correlation present
-: Channel-type-dependent correlation absent

Correlations found for the complete data set were almost entirely expressed in data set 1 (the Chico Creek watershed), except for pool frequency and LWD distribution. Conversely, analysis using the Eastside reaches only had only one of these correlations (basal area versus LWD/100 m).

Some correlations that were absent for the complete data set were observed at a particular urbanization level. Within the Chico Creek watershed, sediment storage was correlated to the percentage of trees isolated from the channel and to channel confinement (FPR reaches were particularly sensitive). Sediment storage also appeared to be influenced by the presence of lentic systems in the Chico Creek watershed. Within reaches in the Eastside, bar frequency was correlated with LWD/100 m.

Anthropogenically confined reaches were less complex than naturally confined channels. They had low LWD and pool frequencies and less sediment stored, and they had simplified morphologies regardless of the abundance or size of the near-riparian vegetation.

The riparian vegetation species composition was correlated with the level of channel confinement within reaches surveyed in the Chico Creek watershed. These correlations were not identified for Eastside reaches.

4 Discussion

Results indicated that the morphology of the evaluated streams correlates with measured conditions of the near-riparian zone (confinement and vegetation). Low-gradient FPR reaches, located in the less urbanized basin (Chico Creek), were more sensitive to the condition of the near-riparian zone than both higher gradient channels and reaches located in more densely urbanized watersheds (Eastside). Some correlations were only observed in low-urbanized reaches, suggesting that some relationships between channel morphology and the near-riparian zone disappear in urban systems; this was the case for sediment storage features and riparian vegetation species composition. On the other hand, some correlations were only observed across a full range of urbanization (LWD distribution, pool frequency, and bank erosion), suggesting that some geomorphic changes are triggered by urbanization.

Low-gradient channels were more sensitive to the condition of the near-riparian zone than high gradient or constrained reaches. High sensitivity of low-gradient reaches to the condition of the near-riparian zone has been described in the past (Montgomery and Buffington, 1998; Montgomery and MacDonald 2001). FPR channels, observed at gradients between 0.015 and 0.03, were the most sensitive reaches; in these channels, the amount and distribution of in-stream wood, the pool frequency, and the abundance and volume of sediment storage features were correlated to conditions of the near-riparian zone. Reaches of this channel type are highly dependent on the LWD input from the riparian area; they also tend to occupy unconfined sections where the stream has the opportunity to spread out during high flows and so interacting with the riparian zone. Conversely, constrained channels at low gradients (between 0.012 and 0.015) were the most resilient to the condition of the near-riparian zone. These reaches have simplified morphology because they are isolated from the floodplain, having restricted not only the LWD and bank sediment input but also the possibility of meandering, which otherwise would be an expected characteristic of channels with this gradient.

Channel morphology is influenced by both the hydrologic regime and the local conditions of the riparian area. Even though a hydrologic study of the surveyed reaches was beyond the scope of this study, prior studies permit a few broad inferences to be made. Because both sets of reaches were located within the same climatic region and had comparable geology, drainage area, and slope, it is expected that reaches surveyed in the Eastside are subject to larger and more frequent peak flows than surveyed reaches in the Chico Creek watershed due to a higher proportion of watershed imperviousness. Less LWD, fewer bars, and more extensive bank erosion are one expression of these larger and more frequent peak flows, together with the conditions of the near-riparian zone.

The following discussion is organized around the initial hypotheses of this study:

4.1 Confinement is inversely correlated with channel complexity and sediment storage

Channel complexity is expressed in this study in terms of LWD and pools. In general, confinement yielded simplified morphologies. Under natural conditions, confinement results in a decreasing trend of LWD and pool frequency due to a decreased LWD input. Additionally, confined reaches have less floodplain area available and higher slopes and therefore sediment storage is drastically reduced. Within highly urbanized sites, confinement has apparently resulted in even more simplified morphologies, due to the complete isolation of the riparian vegetation from the channel, the effect of higher stream power during peak flows, and perhaps the direct impact of human encroachment.

4.1.1 Complexity

LWD frequency was inversely correlated to the level of channel confinement within Chico Creek reaches (low level of urbanization). This correlation has been observed in the past in undisturbed watersheds (Rot et al., 2000; Fox et al., 2003).

The negative relationship between confinement and LWD/100 m appears for several possible reasons: 1) confined channels have less floodplain area than unconfined reaches, and therefore fewer trees are in direct contact with the stream; 2) in confined reaches the tree boles often break when they fall, resulting in shorter and more mobile wood pieces (Nakamura and Swanson, 1993), and/or 3) confinement is commonly associated with high-gradient streams, such as SP and cascade reaches, which have higher transport capacities (i.e. higher shear stress) (Montgomery and Buffington, 1998) than low-gradient streams, and consequently higher in-stream wood mobility.

Channel confinement was not correlated to LWD frequency within anthropogenically confined reaches. Armoring structures along the banks of some of the surveyed reaches (PBc and SPc) results in the total disconnection of the stream with the floodplain, leading to not only limited interaction with existing vegetation but also more severe effects of hydrologic alteration triggered by land-cover changes and impervious surfaces. Further analysis would be necessary to evaluate how the local condition in an urban system, in terms of channel connectivity with the floodplain, is related to the watershed land cover. However, it is expected that the physical conditions of a stream at a given level of urbanization largely depend to this local condition rather than on the watershed land cover.

As mentioned, the addition of LWD is correlated with the level of channel confinement. This correlation is therefore relevant to the pool frequency of FPR channels in which the major pool-forming agent is in-stream wood. This relationship exists not only because confinement influences the size of the available floodplain and therefore the interaction of the stream with the riparian vegetation, but also because it mediated the flood regime. Flood disturbance under natural conditions has shown to be the major determinant of the species composition of the riparian area (Rot et al., 2000). Studies have showed that channels flowing through forests dominated by conifers tend to have higher amounts of LWD (Bilby and Ward, 1991; Harmon et al., 1986). Visual observation indicated that LWD pieces in reaches in the low urbanized watersheds here (Wildcat and Lost creeks in the Chico Creek watershed) which drain within Western Hemlock second-growth forest are bigger with deeper associated pools. Pools frequency in reaches in the Eastside reaches was not related to channel confinement; they were shallower and formed mainly by agents other than LWD.

4.1.2 Sediment storage

As hypothesized, channel confinement was correlated to sediment storage within low-urbanized reaches; however, the existence of lentic systems upstream from some of the surveyed reaches was influential. Conditions other than channel confinement were correlated to sediment storage within channels in the Eastside, implying different sediment-delivery and flow regimes between the two sets of reaches.

Channel bars represent major storage sites for the traction load that is moved only sporadically by high flows. The formation of channel bars depends on the rate of sediment supply, the availability of suitable sites for their accumulation, and the energy environment of the river (Knighton, 1998). In FPR channels a strong negative correlation between the percentage of trees located in the hillslope and bar frequency was observed; as the relative percentage of trees in the hillslope increases (i.e. increase in confinement), the available floodplain area is reduced, limiting meandering and thus resulting in scarcer sediment-storage features.

Some of the variability observed in sediment storage for a given level of channel confinement in the Chico Creek watershed might be explained by the presence of lentic systems. Reaches that lack of upstream lentic systems (Lost Creek and Wildcat upstream of Wildcat Lake) had the highest bar frequency and volume. Wildcat and Kitsap lakes may be buffering high floods flows and/or upstream sediment inputs. Less sediment in reaches downstream of the lakes could be an expression of hydrologically less flashy systems, with less bank erosion and thus less sediment available to store. Bank erosion in Wildcat Creek below Wildcat Lake was never above 10%, whereas in Lost Creek it was as high as 20%. Erosion is a process that depends not only of the flow regime but also on the susceptibility of the bank material and the condition of the riparian vegetation. Reaches upstream Wildcat Lake had no erosion likely because they

are draining low levels of development in which the hydrologic regime has not been changed, as in other sections of the Chico Creek watershed. For example, reaches in Kitsap Creek, which drain a highly urbanized riparian zone (Chapter 1), had high erosion values (between 20 and 42%) regardless of the upstream lentic system. However, sediment delivery in these reaches is constrained by the placement of armoring structures along a substantial section of the channel banks (between 12 and 40%). Part of these findings are consistent with the results obtained by Booth and Jackson (1997), who observed anomalously low flow increases associated with impervious area where “large” lakes (surface area equals or exceeds 10% of the watershed area) are present upstream of the observation point. Wildcat and Kitsap lakes occupy between 3 and 13% of the contributing drainage area of the reaches surveyed downstream of them. In addition, sediment generated upstream of the lakes could be being trapped on them, reducing its availability to form sediment storage features. According to Montgomery and MacDonald (2002), a channel downstream from a large wetland or lake may be buffered from both high flood flows and upstream sediment inputs.

Changes in stream power, sediment supply, or available sites to form channel bars could modify the sediment transport and deposition patterns, altering channel morphology. For example, the isolation of FPR channels from the active forest floodplain could both limit sediment supply rates and decrease LWD recruitment, reducing the available sites for bar formation and increasing available shear stress. These reaches could then shift to a PB morphology (Chapter 1).

Bars in the Eastside reaches had less sediment stored than in the channels of Chico Creek network. Bar frequency within these reaches was correlated to the frequency of in-stream wood, indicating that channel bars tend to form behind LWD structures. Reaches in the Eastside had mostly simplified

morphologies (PB or constrained reaches) in which sediment deposition is scare. These low-roughness channels would have sporadic “forced” sediment deposition where the roughness is locally greater, for example behind a LWD piece. Furthermore, sediment supply from channel banks is inhibited in constrained morphologies by the presence of bank-armoring structures, and these reaches are likely to experience even higher shear stress than the other urbanized reaches (section 4.3). All these factors are likely to explain the reduced amount of sediment storage in these systems.

4.2 Characteristics of the near-riparian vegetation are correlated with channel complexity and with bank stability

4.2.1 Channel complexity

Contradicting the findings by Rot et al. (2000) for pristine areas of the Pacific Northwest, basal area of the near-riparian was found positively correlated to LWD frequency. This correlation was particularly strong for low-gradient reaches (FPR and PB) because they have higher LWD recruitment than high-gradient reaches (SP), in which wood mobility is higher due to higher stream energy (higher transport capacity). Constrained morphologies had low LWD recruitment regardless of the size and abundance of the riparian vegetation, not only because they had generally fewer and smaller trees but also because they experience higher in-stream wood mobility (section 4.3).

LWD in PB channels was well correlated to basal area. It is likely that if wood load increases in these reaches, they could eventually shift morphology from PB to FPR. However, other conditions would have to be met, such as the active connection with the floodplain and sufficient sediment input and transport capacity to generate pool-riffle forms. Although some PB reaches have comparable in-stream wood quantities to FPR channels, wood pieces in PB channels are not big enough to increase roughness necessary to generate a

morphologic shift. Although specific dimensions per wood piece were not collected, wood pieces in PB reaches in the Eastside were typically observed to be smaller than pieces in FPR channels in the Chico Creek watershed, with diameters smaller than 0.5 m and length below 4 m. This observation appears consistent with the smaller size and abundance of the near-riparian vegetation in the Eastside relative to the Chico Creek watershed.

The amount and distribution of LWD in a channel should be influenced by the species composition of the riparian vegetation (Harmon et al., 1986; Bilby and Ward, 1991; Fetherston et al., 1995). This study did not characterize the entire riparian forest zone recognized as potential source of LWD, a zone that has been defined as equal to the height of the tallest tree growing along the stream (Fetherston et al., 1995). A complete characterization of the riparian forest and more detailed information of in-stream wood (volume and species) would be necessary in order to evaluate whether or not riparian area species composition has some influence in the amount of the observed in-stream wood. This is particularly the case for reaches surveyed in the Chico Creek watershed, which drain through second-growth forest. Reaches in the Eastside were not located near well-developed riparian forest; in fact, field observations indicated that the 20-m vegetation plots were often excessive rather than insufficient to include all the overstory vegetation near to the channels. The species composition of the near-riparian area of reaches located in highly urbanized watersheds is irrelevant to the frequency and distribution of LWD, because the interactions observed within undisturbed streams are lost. Flood disturbance no longer determined species composition or LWD recruitment.

Within low-urbanized FPR channels, the frequency of pools depends on the addition of LWD; over 70% of the pools in these reaches were formed by LWD. Therefore fewer pools were observed in these channels as the percentage of trees in direct contact with the stream (i.e. in the floodplain) decreases. The number of pools in the other channel types was not related to the condition of the

near-riparian vegetation. Pools were always scarce in PB and constrained channels regardless of the landform position of the near-riparian vegetation. Pools formed by LWD within SP reaches were not as common as in FPR channels; they also appeared between large channel spanning accumulations of clasts (Montgomery and Buffington, 1997).

The variability of the wood distribution in LWD jams at a given level of tree basal area indicates that even though the amount of wood that could potential enter the system (measured with basal area) influences the distribution of LWD, there are other relevant factors. The organization of wood pieces in LWD in jams is a complex process that dependents on the availability of LWD (including key-pieces), the species composition, the riparian vegetation age, and the stream power. For example, FPR channels had fewer LWD jams with a single-wood piece and more LWD jams with more than 5 wood pieces than PB channels due to a combination of circumstances. These reaches have both high availability of LWD, including potential key-wood-pieces, associated with the relatively undisturbed conditions of the riparian zone, and low LWD mobility because they have not only high roughness but also are at low gradient in low urbanized reaches with comparable fewer and smaller peak flows than reaches in the Eastside. Constrained morphologies, on the other hand, were dominated by wood accumulations with less than 5 pieces, regardless of their gradient and the size of the near-riparian vegetation. These reaches lack the natural input of key-wood pieces and are subject not only to much higher and frequent peak flows that accompany urbanization but also to much higher shear stress triggered by the anthropogenically confined conditions (section 4.3).

4.2.2 Bank stability

Higher bank erosion values were registered within high urbanized reaches than within reaches in watersheds with low level of urbanization. This outcome suggests that watersheds in which the hydrologic regime has been drastically

altered by land cover change are more susceptible to bank instability. However, the analysis of the near-riparian area also suggests the importance of local drivers in the observed erosion values. The condition of the riparian vegetation and the frequency of LWD correlated bank erosion. The results indicate similar relationships to those found by Finkenbine et al. (2000): less bank erosion was observed in reaches with greater tree basal area and frequency of LWD. Reaches with more than 90% stable banks were associated with more than 30 LWD pieces per 100 m. Riparian vegetation root system provides cohesion to the bank material and is source of LWD which increases roughness, mitigating stream power and therefore limiting bank erosion.

High bank-erosion variability was observed for reaches with low basal area, few LWD, and a high percentage of trees isolated from the channel. Within these reaches (mostly located in the Eastside), other factors are likely to control the amount of bank erosion, such as the presence of armoring structures, the erosion-susceptibility of the bank material, and the size and frequency of peak flows (Booth and Henshaw, 2001). Most of the reaches located in the Eastside had a significant fraction of the near-riparian vegetation isolated from the channel (i.e. on the hillslope, on top of armoring structures, or in back yards isolated by concrete surfaces). In these channels the effect of the riparian vegetation is limited, if not irrelevant.

4.3 Channel complexity in confined reaches (anthropogenic versus natural confinement)

The morphology of natural confined reaches showed more variability than in anthropogenically confined channels. Naturally confined channels had variable number of LWD and pools, whereas anthropogenically confined reaches had consistently fewer pools. Constrained channels (PBc and SPc) located in highly urbanized watersheds had little in-stream wood and fewer LWD jams with more than one wood piece (i.e. low LWD retention) because of several reasons:

1) absence of vegetated floodplains accessible to interact with the these streams 2) absence of big trees that could potentially provide key-wood-pieces necessary for facilitated jam formation; and 3) the high shear stress that these reaches are likely to experience during peak flows. Furthermore, these channels run through highly populated areas (parks and near homes) and are likely to be subject to LWD removal by residents. The only two reaches (27 and 30) with unusually low percentages of single-wood jams and a high percentage of LWD jams with more than 5 pieces, are separated from residences and back yards by a buffer area more than 20 m wide that has apparently isolated the channels from direct human intervention.

Constrained reaches also had high bank erosion, mostly in the form of bank armoring. Even though bank armoring structures were placed to prevent erosion, they have yielded other consequences. These reaches have less LWD and lower pool frequencies, fewer sediment-storage features, and have higher potential for incision. Restoring the natural physical condition of these reaches is more challenging than for other disturbed channels, because sustainable morphologic improvements require the reconnection of the channel with its floodplain and a long-term source of woody debris and gravel. The mere addition of logs is not likely to provide a sustainable solution; this might provide short-term improvements before the anthropogenic confined conditions result in much more incised channels or before such logs are washed out by high peak flows. The addition of wood logs would only treat a “symptom” of the major underlying “disease” (i.e. bank armoring leading to confinement).

4.4 Confinement influences riparian species composition

As expected, the level of channel confinement influences the species composition of the riparian vegetation in low-urbanized channels, because the floodplain environment of unconfined channels is different in critically important ways to vegetation.

The vegetation of the streamside are different from those upslope because they experience frequent inundation, soil saturation, and physical disturbance of streamside vegetation due to flood flows, mass soil movements, or ice damage (Hickin, 1984; Brinson, 1990; Gregory et al., 1991). Several studies have identified flood disturbance as the most important factor in determining vegetation community composition (Harris, 1988; Brinson, 1990). The effects of flood disturbance on species composition are reflected in the data of the correlation between confinement and species composition. The abundance of conifer species increases with increasing confinement. The floodplain species composition was dominated in number by deciduous trees, especially Red alder (*Alnus rubra*). This species is well-suited to outcompete conifers in gravel substrates. It fixes nitrogen (which is limited in sand-gravel substrate), grows faster than all native conifers as a juvenile, and reaches sexual maturity at age 3-4 (Harrington et al., 1994). Douglas fir (*Pseudotsuga menziesii*) was the most rare conifer species in the floodplain. It is a shade-intolerant species that can colonize floodplains only after disturbance in the absence of Red alder (*Alnus rubra*). Douglas fir can be easily eliminated in dense young alder stands while more tolerant species, such as Western hemlock (*Tsuga heterophylla*) and Red cedar (*Thuja plicata*), can survive and over time grow through the Red alder canopy and ultimately dominate the site (Harrington et al., 1994). Red cedar and Western hemlock were over 6 times more frequent in the floodplain than Douglas fir, probably because they are shade-tolerant and because both are considered relatively tolerant to flooding (Walters et al. 1980). Rot et al. (2000) also found less conifer species in the floodplain with an increasing prevalence towards the hillslope. However, they found that floodplain tree basal area was dominated by conifers. In this study, the basal area of Red cedar was comparable to the basal area of Red alder, and other conifers such as Douglas fir and Western Hemlock had low basal area.

Species composition in highly urbanized reaches was not correlated to channel confinement because the natural interactions of flooding disturbance no longer exist. Most of the vegetation observed in highly urbanized sites is not in contact with the flow, due to it isolation by armoring structures. The species composition and the abundance of the near-riparian area vegetation of these reaches correspond to the whim or preference of the land owner, rather than the result of flood disturbance.

5 Conclusions

Channel morphology in low-urbanized watersheds, as expressed by the frequency and distribution of large woody debris, pool frequency, sediment storage, and bank erosion, is correlated to the level of channel confinement and to characteristics of the near-riparian vegetation. Highly urbanized reaches are substantially less sensitive to the condition of the near-riparian zone, mostly due to the common stream disconnection with the floodplain as a result of bank armoring. These bank-armoring structures were initially placed to prevent erosion; however, they have also resulted in lower LWD and pool frequencies, less sediment storage, and a higher potential for channel incision. Restoring these reaches is more challenging than other disturbed channels, because sustainable morphologic improvements require the reconnection of the channel with the floodplain and the bank material in order to have a long-term source of woody debris and gravel.

- Significantly different channel morphology was observed between low and high urbanized reaches. Low-urbanized reaches (mostly FPR channels) have more in-stream wood, pools, and sediment storage and less bank erosion than reaches in the Eastside (mostly PB and constrained morphologies). Channel morphology in low-urbanized watersheds, as measured by in-stream wood frequency and distribution, pool frequency, sediment storage, and bank erosion, correlate to the level of channel

confinement and to characteristics of the near-riparian vegetation. High-urbanized reaches are substantially less sensitive to the condition of the near-riparian zone, due to the frequent stream disconnection with the floodplain triggered by the placement of armoring structures in the banks.

- In low-urbanized conditions, confinement mediates flood disturbance, which in turn influences species composition of the near-riparian area. The type and abundance of trees strongly influences LWD recruitment and ultimately pool characteristics in several common channel types. On the other hand, species composition in urbanized channels was not correlated to channel confinement because the natural interactions of flooding disturbance no longer exist. Species composition and abundance of the near-riparian vegetation of these channels correspond to the preference of the land owners, and the choice of vegetation in such settings does not influence in-stream physical conditions.
- Tree basal area and channel confinement correlate with LWD frequency, particularly within FPR and PB channels (mostly located in low urbanized basins). Conversely, LWD frequency in PBc and SPc (mainly located on high urbanized basins) was only slightly correlated to tree basal area. The persistence anthropogenically confined conditions of these reaches limits LWD recruitment by both inhibiting the direct contact of the stream with the near-riparian vegetation and promoting high stream power, which results in higher wood mobility.
- The distribution of LWD pieces in jams was sensitive to the abundance and size of the near-riparian vegetation, particular in FPR and PB channels. Constrained morphologies, on the other hand, had consistently small jams due to less availability of key-wood-pieces, smaller near-riparian vegetation, and higher stream power that apparently inhibits the formation of big LWD jams.

- Pool frequency of FPR reaches, mostly located in low-urbanized watersheds, was dependent on the near-riparian vegetation in direct contact with the stream because most pools in these channels are formed by LWD. On the other hand, channel types common in high-urbanized reaches (PB and constrained channels) had low pool frequencies unrelated to the condition of the near-riparian vegetation because these channels are mostly isolated from the floodplain and the input of LWD.
- Results suggested different sediment-delivery and transport regimes between high and low urbanized reaches. High-urbanized reaches had less sediment stored than channels at low level of urbanization, due to fewer suitable sites for bar formation and less coarse sediment input from the channel banks where bank armoring structures are present.
- Within low-urbanized reaches, sediment storage inversely correlates to channel confinement. Conversely, channel bar frequency in the Eastside reaches correlates with the frequency of LWD, probably because the only suitable places for bar formation in these channels is behind LWD pieces, where the local roughness increases. The presence of lentic systems upstream of some low-urbanized reaches also influences bar frequency and volume. Reaches downstream big lakes had fewer bar volume than reaches upstream of then. These results suggest a buffering effect from lentic systems to both sediment delivery from upstream reaches and peak flows, which reduced sediment input from the banks due to reduce bank erosion.
- Bank erosion was significantly greater at highly urbanized reaches than at reaches at low level of urbanization, suggesting a general increase in bank instability with bigger and more frequent peak floods brought by urbanization. Bank erosion reflects not only the impacts of urbanization on the timing and size of peak flows, however, but also the condition of the

near riparian zone. Tree basal area and the frequency of in-stream wood were correlated to bank erosion. However, within highly urbanized reaches, variable levels of erosion were observed at a given amount of in-stream wood and for a given tree basal area. This variability is partially explained by the presence of armoring structures in some reaches that have inhibited the interaction of the stream with the riparian vegetation. In such settings, the effect of the riparian vegetation is limited, if not irrelevant.

- From a management perspective, an increased in-stream wood in PB reaches could yield an eventual morphologic shift to FPR. However, increased wood load in these channels is not the only requirement for such a shift. These channels also need to be actively connected to a forested floodplain and to the channel-bank material that provides log-term recruitment of both LWD and gravel required to generate a pool-riffle morphology. In the case of anthropogenically confined channels, bank armoring structures were initially placed to prevent erosion; however, they have also resulted in less LWD and pools, less sediment storage, and higher potential for incision. Restoring these reaches is more challenging than for other types disturbed channels, because sustainable morphologic improvements apparently requires the reconnection of the channel with the floodplain and the bank material. The mere one-time addition of logs or gravel is not likely to provide a sustainable solution. Without also addressing the potential in urban channels for incision, for washout of wood and sediment by high peak flows, and for LWD removal by residents.

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Appendix A: Basic data Chapter 1

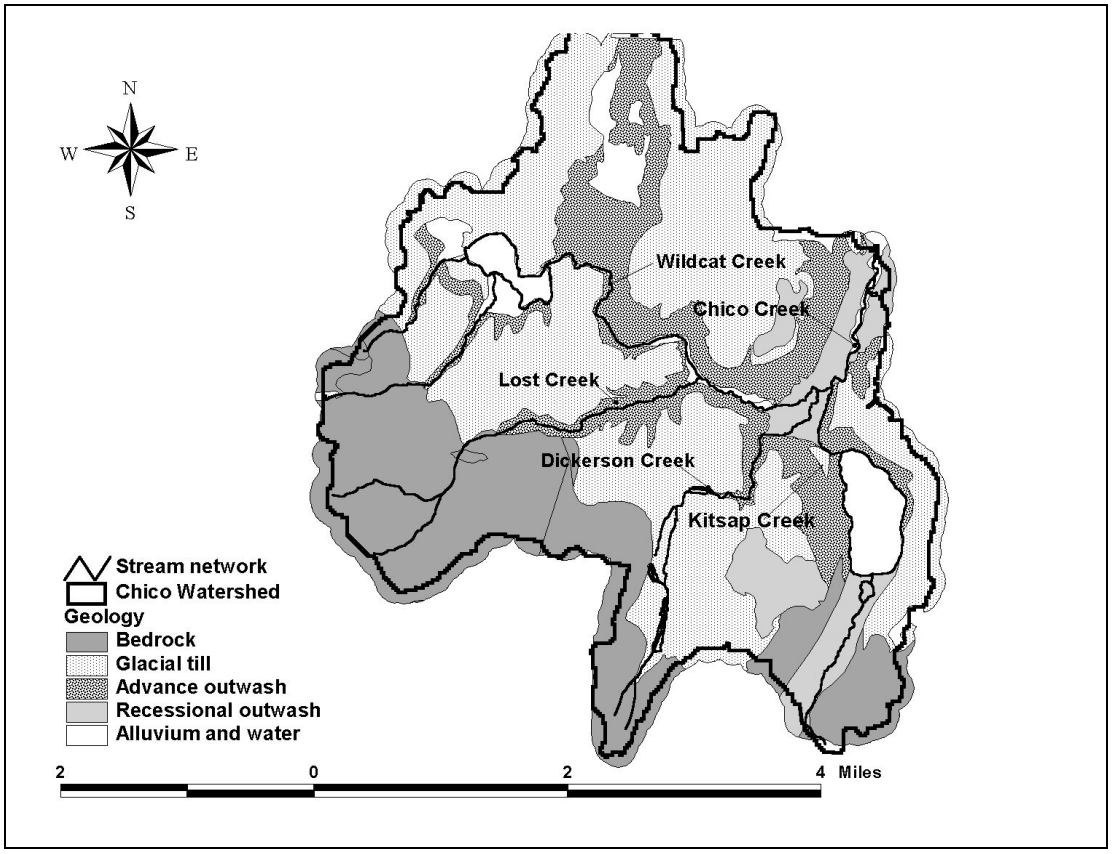

Figure A-1: 1Geologic map of the Chico Creek watershed

Table A-1: Morphologic results per reach. Reach length, channel type, bankfull depth (BFD), bankfull width (BWD), LWD and pool frequencies, and scores for: cementation (CEM), bank stability (BS), LWD and pools, and Physical In-stream condition Index (PSCI) results

ID*	CREEK	LENGTH (m)	CHANNEL TYPE (*)	BFD (m)	BFW (m)	LWD/ 100 m	Pools/ 100 m	CEM	BS	LWD	POOL	PSCI
1	Wildcat	242	FPR	1.00	10	14.9	5.4	3	3	2	2	10
2	Wildcat	265	PB	0.60	8	21.1	5.7	3	4	3	2	12
3	Wildcat	237	FPR	0.60	8	16.5	8.9	4	4	2	4	14
4	Wildcat	219	FPR	0.45	9	25.6	8.7	4	4	3	3	14
5	Wildcat	233	FPR	1.00	11	37.8	7.7	3	4	4	3	14
6	Wildcat	227	FPR	0.80	9	19.8	7.1	3	3	2	3	11
7	Wildcat	233	FPR	0.60	11	28.8	9.4	3	3	3	4	13
8	Wildcat	288	FPR	0.80	9	24.7	8.3	4	4	3	3	14
9	Wildcat	276	FPR	1.00	8	20.3	8.7	4	4	2	4	14
10	Chico	256	FPR	1.25	12	36.3	6.3	3	2	4	2	11
11	Chico	238	FPR	1.15	13	32.8	5.5	3	3	3	2	11
12	Chico	313	FPR	0.70	14	10.9	4.2	3	2	2	1	8
13	Chico	349	FPR	0.85	12	12.6	5.4	2	2	2	2	8
14	Chico	323	PB	0.80	11	7.4	3.4	3	1	2	1	7
15	Chico	238	PB	1.25	8	8.4	4.2	2	1	2	1	6
16	Lost	255	SP	0.75	8	56.9	4.3	3	1	4	1	9
17	Lost	200	FPR	0.70	8	44.5	8.5	3	3	4	3	13
18	Lost	237	FPR	0.60	8	21.5	7.2	4	4	3	3	14
19	Lost	248	FPR	0.80	8	37.1	8.1	4	3	4	3	14
20	Lost	292	PB	1.00	9	21.9	5.5	4	3	3	2	12
21	Dickerson	160	C	0.55	6	28.1	9.4	1	4	3	4	12
22	Dickerson	245	FPR	0.60	8	46.1	9.8	4	4	4	4	16
23	Dickerson	265	FPR	0.50	8	31.3	9.8	3	3	3	4	13
24	Dickerson	288	PB	0.85	7	16.0	7.3	3	2	2	3	10
25	Dickerson	131	PBc	1.00	7	1.5	5.3	3	1	1	1	6

Table A-1 (continued)

ID*	CREEK	LENGTH (m)	CHANNEL TYPE (*)	BFD (m)	BFW (m)	LWD/ 100 m	Pools/ 100 m	CEM	BS	LWD	POOL	PSCI
26	Dickerson	275	PB	1.00	7	4.0	2.2	4	2	1	1	8
27	Chico	220	FPR	1.50	10	6.4	6.8	3	2	1	2	8
28	Chico	200	PB	1.30	12	2.0	4.0	3	2	1	1	7
29	Chico	263	PBc	0.85	12	8.4	3.8	3	1	2	1	7
30	Chico	350	PBc	0.95	11	1.1	2.6	2	1	1	1	5
31	Chico	300	PB	0.60	15	8.3	6.3	2	2	2	2	8
32	Chico	178	PBc	1.00	7	0.0	2.8	2	1	1	1	5
33	Chico	181	PB	1.00	9	3.9	6.1	2	2	1	2	7
34	Kitsap	120	C	1.00	5	14.2	11.7	3	2	2	4	11
35	Kitsap	165	FPR	1.00	8	33.9	9.1	4	3	4	4	15
36	Kitsap	212	SP	0.60	5	4.7	3.8	3	2	1	1	7
37	Kitsap	200	FPR	0.60	5	8.5	10.0	3	2	2	4	11
38	Kitsap	71	SP	0.70	5	22.5	11.3	3	3	3	4	13
39	Chico	120	PR	0.60	14	7.5	6.7	3	1	2	2	8
40	Chico	200	PR	0.70	9	10.5	7.5	2	1	2	3	8
41	Chico	125	FPR	1.50	17	6.4	3.2	4	3	1	1	9
42	Lost	152	FPR	0.65	9	52.0	7.2	4	3	4	3	14
43	Lost	176	FPR	0.70	9	44.9	7.4	4	3	4	3	14
44	Lost	219	FPR	0.70	9	21.5	7.3	4	4	3	3	14
45	Wildcat	260	FPR	0.60	9	76.5	7.3	4	4	4	3	15
46	Wildcat	160	FPR	0.55	8	13.8	7.5	4	4	2	3	13
47	Wildcat	120	PB	0.50	8	5.8	5.8	4	4	1	2	11
48	Wildcat	193	FPR	0.60	8	59.6	8.8	4	4	4	4	16
49	Wildcat	208	FPR	0.50	9	45.2	7.7	4	4	4	3	15
50	Wildcat	200	FPR	0.60	8	53.0	7.5	3	4	4	3	14
51	Wildcat	287	FPR	0.60	8	44.3	8.4	4	4	4	3	15
52	Wildcat	105	PB	0.50	4	13.3	4.8	4	4	2	1	11

Table A-1 (continued)

ID*	CREEK	LENGTH (m)	CHANNEL TYPE (*)	BFD (m)	BFW (m)	LWD/ 100 m	Pools/ 100 m	CEM	BS	LWD	POOL	PSCI
53	Wildcat	115	SP	0.50	5	27.8	9.6	4	4	3	4	15
54	Wildcat	115	SP	0.55	5	22.6	9.6	4	4	3	4	15
55	Wildcat	105	PB	0.60	5	30.5	7.6	4	4	3	3	14
56	Wildcat	105	FPR	0.60	6	46.7	12.4	4	4	4	4	16
57	Wildcat	110	FPR	0.60	6	26.4	9.1	4	4	3	4	15
58	Wildcat	90	PB	0.45	6	24.4	4.4	4	4	3	1	12

(*) C: Cascade, SP: Step-pool, FPR: Forced pool-riffle; PB: Plane-bed, PR: Pool-riffle, PBc: Constrained plane-bed.

Table A-2: Land cover in the contributing basin area per reach

CREEK	ID*	Forest urban	Grass shrub urban	Paved urban	Forested	Grass shrub crops	Water	Bare soil	Total area (Ha)	TIA (%)
Wildcat	1	114.8	32.4	2.7	395.2	18.4	38.8	0.1	602.4	13.8%
Wildcat	2	116.1	32.4	2.7	397.5	18.4	38.8	0.1	606.1	13.8%
Wildcat	3	116.4	32.4	2.7	400.6	18.4	38.8	0.1	609.5	13.7%
Wildcat	4	116.6	32.4	2.7	404.8	18.4	38.8	0.1	613.9	13.7%
Wildcat	5	326.6	60.2	5.7	891.6	36.5	42.8	0.1	1363.4	14.9%
Wildcat	6	327.1	60.2	5.7	904.8	36.5	42.8	0.1	1377.1	14.7%
Wildcat	7	331.3	61.0	5.7	927.3	37.7	42.8	0.1	1405.9	14.7%
Wildcat	8	336.5	62.3	5.7	937.9	40.2	42.8	0.1	1425.4	14.7%
Wildcat	9	337.7	62.4	5.7	949.6	40.3	42.8	0.1	1438.6	14.6%
Chico	10	458.9	81.2	5.8	1643.4	68.9	42.8	0.1	2301.1	12.7%
Chico	11	460.1	81.4	5.8	1651.8	68.9	42.8	0.1	2310.8	12.7%
Chico	12	462.3	81.4	5.8	1663.6	68.9	42.8	0.1	2324.8	12.7%
Chico	13	462.4	81.4	5.8	1676.2	69.0	42.8	0.1	2337.7	12.6%
Chico	14	462.7	81.4	5.8	1687.7	69.0	42.8	0.1	2349.4	12.6%
Chico	15	466.2	82.5	5.8	1694.4	69.5	42.8	0.1	2361.3	12.6%
Lost	16	72.7	12.7	0.0	448.8	24.4	0.0	0.0	558.7	9.3%
Lost	17	73.9	12.7	0.0	460.4	24.5	0.0	0.0	571.5	9.2%
Lost	18	74.1	12.7	0.0	469.0	24.5	0.0	0.0	580.2	9.1%
Lost	19	74.1	12.7	0.0	483.8	24.6	0.0	0.0	595.3	9.0%
Lost	20	82.7	12.9	0.0	514.7	24.6	0.0	0.0	634.9	9.1%
Dickerson	21	81.4	14.8	0.0	344.8	5.8	0.0	0.0	446.9	11.8%
Dickerson	22	83.6	14.9	0.0	357.3	5.9	0.0	0.0	461.7	11.7%
Dickerson	23	88.6	15.5	0.0	382.7	6.8	0.0	0.0	493.6	11.5%
Dickerson	24	89.9	15.5	0.0	394.8	6.8	0.0	0.0	507.0	11.4%
Dickerson	25	96.1	15.5	0.0	411.5	6.8	0.0	0.0	530.0	11.5%

Table A-2 (continued)

CREEK	ID*	Forest urban	Grass shrub urban	Paved urban	Forested	Grass shrub crops	Water	Bare soil	Total area (Ha)	TIA (%)
Dickerson	26	97.1	15.7	0.0	411.8	6.9	0.0	0.0	531.4	11.5%
Chico	27	467.1	82.7	5.8	1695.4	69.5	42.8	0.1	2363.4	12.6%
Chico	28	506.8	94.0	8.6	1780.6	75.0	42.8	0.6	2508.3	13.1%
Chico	29	507.8	94.3	8.6	1781.1	75.0	42.8	0.6	2510.3	13.1%
Chico	30	510.2	96.3	8.6	1786.2	75.2	42.8	0.6	2519.9	13.1%
Chico	31	523.8	104.2	10.2	1818.5	77.4	42.8	0.6	2577.5	13.4%
Chico	32	531.1	109.8	10.5	1829.1	78.3	42.8	0.7	2602.3	13.5%
Chico	33	538.4	115.3	10.8	1839.8	79.2	42.8	0.8	2627.1	13.7%
Kitsap	34	150.9	59.7	21.6	373.6	21.2	89.9	8.2	725.1	19.5%
Kitsap	35	151.8	59.7	21.6	375.5	21.3	89.9	8.2	728.0	19.5%
Kitsap	36	153.9	59.9	21.6	382.3	21.5	89.9	8.2	737.2	19.4%
Kitsap	37	157.3	60.7	21.6	391.0	22.2	89.9	8.2	751.0	19.4%
Kitsap	38	159.5	61.7	21.6	391.5	22.2	89.9	8.2	754.6	19.5%
Chico	39	541.1	116.8	10.9	1842.8	79.8	42.8	0.8	2635.1	13.7%
Chico	40	545.8	119.8	11.3	1856.4	81.9	42.8	0.9	2658.8	13.8%
Chico	41	545.8	119.8	11.3	1856.4	81.9	42.8	0.9	2658.8	13.8%
Lost	42	87.5	14.1	0.0	600.0	25.5	0.0	0.0	727.1	8.7%
Lost	43	87.5	14.1	0.0	602.1	25.5	0.0	0.0	729.2	8.6%
Lost	44	94.1	14.6	0.0	634.4	27.5	0.0	0.0	770.4	8.7%
Wildcat	45	321.9	60.0	5.7	884.1	36.2	42.8	0.1	1350.9	14.8%
Wildcat	46	360.1	66.6	5.8	983.2	41.5	42.8	0.1	1500.1	14.9%
Wildcat	47	360.2	66.6	5.8	985.3	41.4	42.8	0.1	1502.2	14.9%
Wildcat	48	304.6	55.8	5.4	807.3	35.1	42.8	0.1	1251.1	15.0%
Wildcat	49	307.8	56.5	5.4	816.2	35.3	42.8	0.1	1264.0	15.0%
Wildcat	50	307.9	56.5	5.4	821.0	35.3	42.8	0.1	1268.9	15.0%
Wildcat	51	308.8	56.5	5.4	829.2	35.3	42.8	0.1	1278.0	14.9%
Wildcat	52	22.1	3.8	0.0	145.6	4.2	0.0	0.0	175.6	9.0%

Table A-2 (continued)

CREEK	ID*	Forest urban	Grass shrub urban	Paved urban	Forested	Grass shrub crops	Water	Bare soil	Total area (Ha)	TIA (%)
Wildcat	53	24.0	4.7	0.0	149.1	4.2	0.0	0.0	182.1	9.5%
Wildcat	54	24.0	4.7	0.0	150.7	4.2	0.0	0.0	183.7	9.4%
Wildcat	55	25.1	5.4	0.0	155.2	4.5	0.0	0.0	190.2	9.7%
Wildcat	56	25.1	5.4	0.0	156.3	4.5	0.0	0.0	191.3	9.7%
Wildcat	57	26.8	6.7	0.0	162.2	5.0	0.0	0.0	200.6	10.1%
Wildcat	58	26.8	6.7	0.0	162.9	5.0	0.0	0.0	201.4	10.1%

Table A-3: Land cover in the riparian zone (50 m buffer)

CREEK	ID*	Forest urban	Grass shrub urban	Paved urban	Forested	Grass shrub crops	Water	Bare soil	Total area (Ha)	TIA (%)
Wildcat	1	0.9			1.4				2.3	16.1%
Wildcat	2	0.3			1.8				2.1	7.4%
Wildcat	3				1.6				1.6	3.0%
Wildcat	4	0.1			2.2				2.3	4.9%
Wildcat	5	0.1			2.0				2.1	4.3%
Wildcat	6	0.3			1.9	0.1			2.3	8.1%
Wildcat	7	0.4			1.0	0.8			2.3	10.6%
Wildcat	8	0.1			2.6	0.1			2.8	4.6%
Wildcat	9	0.0			2.5				2.5	3.0%
Chico	10	0.1			2.6				2.7	4.8%
Chico	11	0.3			1.9				2.2	7.1%
Chico	12				3.0	0.1			3.1	3.0%
Chico	13	0.1	0.1		3.1				3.3	6.4%
Chico	14	0.9	0.6		0.9	0.4			2.8	29.5%
Chico	15	1.0	0.3		1.0	0.0			2.3	26.8%
Lost	16	0.0			2.6				2.6	3.2%
Lost	17				1.5				1.5	3.0%
Lost	18				2.4				2.4	3.0%
Lost	19	0.1			2.3				2.4	4.8%
Lost	20	0.1			2.8				2.9	4.1%
Dickerson	21				1.8				1.8	3.0%
Dickerson	22	0.0			2.5				2.5	3.0%
Dickerson	23	0.1			3.1				3.2	3.7%
Dickerson	24	0.9	0.0		2.5				3.4	12.6%
Dickerson	25	1.0	0.2		0.1	0.1			1.3	38.2%

Table A-3 (continued)

CREEK	ID*	Forest urban	Grass shrub urban	Paved urban	Forested	Grass shrub crops	Water	Bare soil	Total area (Ha)	TIA (%)
Dickerson	26	0.9	0.2		1.1	0.3			2.6	22.5%
Chico	27	0.4	0.6		0.7	0.3			1.9	31.1%
Chico	28	0.8	0.4		0.5	0.1			1.7	34.2%
Chico	29	0.9	1.0		1.0	0.1			2.9	37.0%
Chico	30	0.6	0.9	0.3	1.1	0.5			3.5	36.5%
Chico	31	0.8	1.4	0.7	0.6	0.2		0.0	3.7	54.7%
Chico	32	0.4	0.7	0.3	0.3	0.4		0.1	2.2	49.6%
Chico	33		0.5	0.1	0.2	0.4		0.1	1.3	42.8%
Kitsap	34	0.7	0.0		0.8	0.0			1.5	18.7%
Kitsap	35	0.7	0.1		1.1	0.1			2.0	19.6%
Kitsap	36	1.6	0.3		0.5	0.1			2.5	34.5%
Kitsap	37	1.3	0.9		0.3				2.5	47.2%
Kitsap	38	0.4	0.1		0.2				0.8	30.2%
Chico	39	0.4	0.3	0.0	1.0	0.3		0.0	2.1	22.1%
Chico	40	0.7	0.1		1.0	0.2			2.0	20.2%
Chico	41	0.2	0.4	0.0	0.5	0.3			1.3	28.9%
Lost	42	0.0			1.4				1.4	3.7%
Lost	43	0.0			1.7				1.7	3.6%
Lost	44	0.0			2.2				2.2	3.1%
Wildcat	45	0.2			2.3				2.5	5.5%
Wildcat	46				1.3				1.3	3.0%
Wildcat	47				1.0				1.0	3.0%
Wildcat	48				2.0				2.0	3.0%
Wildcat	49	0.1			2.1				2.2	4.0%
Wildcat	50	0.0			1.8				1.8	3.5%
Wildcat	51	0.8	0.0		1.8				2.6	14.4%
Wildcat	52				1.0				1.0	3.0%

Table A-3 (continued)

CREEK	ID*	Forest urban	Grass shrub urban	Paved urban	Forested	Grass shrub crops	Water	Bare soil	Total area (Ha)	TIA (%)
Wildcat	53				0.9				0.9	3.0%
Wildcat	54				1.1				1.1	3.0%
Wildcat	55				0.9				0.9	3.0%
Wildcat	56	0.0			1.0				1.0	4.1%
Wildcat	57	0.0			1.0				1.0	3.4%
Wildcat	58	0.2			0.6				0.8	11.3%

Appendix B: Basic data Chapter 2

Table B-1: Channel geomorphic assessment results by each rapid assessment methodology

Table B-1: Channel geomorphic assessment results by each rapid assessment methodology

REACH No.	Channel type	CEM*	CS*	COMP*	RC*	TOTAL*	CEM**	BS**	LWD**	POOL**	TOTAL**	LWD/100 ** (m)	LWD/100 ***(m)	D16*** (mm)
1	FPR	3.0	2.0	3.0	3.0	11.0	4.0	4.0	1.5	2.5	12	10.4	7.2	17.9
2	FPR	3.0	4.0	4.0	4.0	15.0	4.0	4.0	2.5	3.5	14	22.5	29.7	7.7
3	FPR	3.0	3.0	4.0	3.0	13.0	3.0	3.0	3.0	4.0	13	28.8		
4	FPR*	3.0	3.0	4.0	3.0	13.0	3.0	3.0	2.0	3.0	11	19.8		
5	FPR	3.0	4.0	4.0	4.0	15.0	3.0	4.0	4.0	3.0	14	37.8		
6	FPR	3.0	4.0	4.0	4.0	15.0	4.0	4.0	4.0	3.0	15	76.5		
7	FPR	4.0	4.0	4.0	3.0	15.0	3.8	4.0	4.0	3.3	15	49.8		
8	FPR*	3.0	4.0	4.0	3.0	14.0	4.0	4.0	3.0	3.0	14	25.6	42.4	11.6
9	FPR	3.0	4.0	4.0	3.0	14.0	4.0	4.0	2.0	4.0	14	16.5		
10	PB	3.0	3.0	3.0	3.0	12.0	3.0	4.0	3.0	2.0	12	21.1	29.0	17.5
11	FPR*	3.0	3.0	3.0	3.0	12.0	3.0	3.0	2.0	2.0	10	14.9		
12	FPR	3.0	2.0	3.0	4.0	12.0	4.0	3.3	3.7	3.0	14	37.5	36.0	12.4
13	PB	3.0	4.0	3.0	4.0	14.0	4.0	3.0	3.0	2.0	12	21.9	39.8	9.2
14	PB	2.0	2.0	2.0	3.0	9.0	4.0	2.0	1.0	1.0	8	4.0		
15	PBc	2.0	1.0	2.0	3.0	8.0	3.0	1.0*	1.0	1.0	6	1.5		
16	PB	2.0	1.0	2.0	3.0	8.0	3.0	2.0	2.0	3.0	10	16.0	61.5	
17	FPR	3.0	3.0	3.0	3.0	12.0	3.0	3.0	3.0	4.0	13	31.3		
18	FPR*	3.0	4.0	4.0	4.0	15.0	4.0	4.0	4.0	4.0	16	46.1	61.5	9.3
19	C	4.0	4.0	4.0	4.0	16.0	1.0	4.0	3.0	4.0	12	28.1		
20	PB	2.0	3.0	2.0	3.0	10.0	3.0	3.0	3.0	4.0	13	22.5	10.3	
21	FPR*	2.0	2.0	1.0	2.0	7.0	3.0	2.0	2.0	4.0	11	8.5	11.8	
22	SP	2.0	2.0	1.0	2.0	7.0	3.0	2.0	1.0	1.0	7	4.7		
23	FPR*	2.0	2.0	2.0	3.0	9.0	4.0	3.0	4.0	4.0	15	33.9	26.3	
24	C	2.0	2.0	2.0	3.0	9.0	3.0	2.0	2.0	4.0	11	14.2		
25	PR	1.0	2.0	1.0	2.0	6.0	2.0	1.0*	2.0	3.0	8	10.5	0.7	34.1
26	PR	2.0	1.0	2.0	1.0	6.0	3.0	1.0*	2.0	2.0	8	7.5		39.0
27	PR	2.0	1.0	2.0	1.0	6.0	3.0	1.0*	2.0	2.0	8	7.5		
28	PB	2.0	1.0	1.0	1.0	5.0	2.0	2.0	1.0	2.0	7	3.9	12.2	16.6
29	PBc	2.0	1.0	1.0	1.0	5.0	2.0	1.0*	1.0	1.0	5	0.0	3.1	21.5
30	PB	2.0	2.0	2.0	2.0	8.0	2.0	2.0	2.0	2.0	8	8.3		

Table B-1 (continued)

REACH No.	Channel type	CEM*	CS*	COMP*	RC*	TOTAL*	CEM**	BS**	LWD**	POOL**	TOTAL**	LWD/100 ** (m)	LWD/100 ***(m)	D_{16} ***
31	PBc	3.0	2.0	2.0	2.0	9.0	2.0	1.0*	1.0	1.0	5	1.1		
32	PBc	3.0	2.0	2.0	2.0	9.0	3.0	1.0*	2.0	1.0	7	8.4		
33	PB	3.0	2.0	2.0	2.0	9.0	3.0	2.0	1.0	1.0	7	2.0		
34	FPR	3.0	2.0	2.0	2.0	9.0	3.0	2.0	1.0	2.0	8	6.4		
35	FPR	3.0	2.0	2.0	2.0	9.0	3.0	2.0	1.0	2.0	8	6.4		
36	PB	2.0	2.0	2.0	3.0	9.0	2.0	1.0	2.0	1.0	6	8.4	7.7	11.3
37	PB	2.0	1.0	1.0	1.0	5.0	3.0	1.0	2.0	1.0	7	7.4	7.7	15.7
38	FPR	3.0	2.0	2.0	2.0	9.0	2.0	2.0	2.0	2.0	8	12.6		
39	FPR	3.0	3.0	4.0	4.0	14.0	3.0	3.0	2.0	1.0	9	10.9	45.8	8.1
40	FPR	3.0	3.0	4.0	4.0	14.0	3.0	3.0	3.0	2.0	11	32.8		
41	FPR	3.0	3.0	4.0	4.0	14.0	2.0	3.0	4.0	2.0	11	36.3		

Channel type: PBc: Constrained plane-bed; FPR: Forced pool-riffle; FPR*: Forced pool-riffle at gradients above 0.02; PB: Plane-bed; SP: Step-pool; C: Cascade.
Scores "rapid 1" assessment: CEM* (cementation), CS* (channel stability), COMP* (channel complexity), RC* (riparian condition), TOTAL* (total score)
Scores "rapid 2" assessment: CEM**(cementation), BS** (bank stability), LWD** (large woody debris counts), POOL** (pools counts), TOTAL ** (total score), LWD/100** (large woody debris per 100m)
Detailed geomorphic surveys: LWD/100*** (large woody debris per 100m), D_{16}***

Appendix C: Basic data Chapter 3

Table C-1: Geomorphologic data by reach

Table C-2: Coefficient of determination between riparian zone variables expected to anticipate LWD, pool, and bar frequency, volume in bars, LWD distribution, and bank erosion. Coefficients of determination for complete data set N=32

Figure C-1: Basal area versus LWD/100m in reaches surveyed in the Chico Creek watershed and in the Eastside reaches

Table C-3: Total number of trees and basal area per landform in reaches surveyed in Chico

Table C-4: Total number of trees and basal area per landform in reaches surveyed in the Eastside

Table C-1: Morphologic results per reach. Slope, channel type, channel size, confinement, channel size, LWD, pools, sediment storage, and bank erosion.

ID	Slope (%)	Channel type	Confinement		Channel size		LWD				Pools						Sediment storage		Bank erosion ***		
								Distribution of LWD				Pool forming agent (%) **					Bars		(% bank length)		
			1*	2*	BFD	BFW	LWD/100 m	jams with >10 pieces	jams with >5 pieces	jams with <2 pieces	pool/100 m	LWD	MEAD	BED	BOL	ANT	#/ 100 m	Volume /100m	LS+BA	LS	BA
1	1.5	PB	0.5	0.50	0.6	8	20.7	6	26	32	5.7	60	20	20	0	0	2.6	33.2	5	5	0
2	2.3	FPR*	0	0.25	0.45	9	63.9	15	37	30	7.3	94	6	13	0	0	0.9	43.6	4	4	0
3	2	FPR	0	0.40	1	11	55.8	21	35	26	8.6	85	5	15	10	0	0.9	16	2	2	0
4	1.9	FPR	0	0.30	0.6	11	37.8	10	24	57	5.6	85	15	15	0	0	1.7	55.8	5	5	0
5	2.7	SP	0	0.50	0.75	8	59.2	23	45	41	5.9	87	13	7	27	0	5.1	165.6	21	21	0
6	2.2	FPR*	0	0.50	0.7	8	42.5	29	14	0	8.5	47	29	0	24	0	4.5	136.9	1	1	0
7	2	FPR	0.5	0.50	0.6	8	25.3	15	31	23	7.6	82	36.4	0	0	0	3.4	125	0	0	0
8	2.2	FPR*	0	0.00	0.8	8	44.8	20	35	40	7.7	74	11	32	5	0	3.2	106	6	6	0
+	5	C	0.5	0.38	0.55	6	30.1	22	39	33	6.9	55	36	18	0	0	1.9	26.3	3	3	0
9	2.7	FPR*	0.5	0.60	0.6	8	46.5	24	28	40	6.9	65	29	41	0	0	0.4	6.2	2	2	0
+	1.6	FPR	0	0.50	0.5	8	28.3	9	13	48	8.7	52	57	22	0	0	2.3	67.9	12	12	0
+	0.3	PBc	0.25	0.63	1	7	1.38	0	0	100	6.2	0	89	0	0	11	2.1	56.5	14	3	10
10	2.5	PB	0.5	0.70	1	7	7.27	0	10	60	4	27	82	0	0	0	2.2	54.7	47	17	30
+	9.3	C	1	1.00	1	5	18.3	0	8	67	12.5	27	7	27	67	33	0.8	15.8	17	5	12
+	3.5	FPR*	0.75	0.75	1	8	42.4	4	22	43	9.7	81	13	6	44	6	0.6	16.7	35	15	20
+	2	SP	0.75	0.80	0.6	5	7.55	0	17	33	4.7	50	30	10	10	40	0.9	11.3	42	3	39
11	1.8	FPR	0	0.13	0.65	9	38.8	0	20	40	7.2	91	27	9	9	0	2	79.4	4	4	0
12	1.8	PB	0	0.00	0.5	8	5	0	0	50	5	0	16.7	50	33	0	3.3	37.1	7	7	0
13	2	FPR	0	0.10	0.5	9	51.4	12	31	38	7.7	100	6	0	0	0	1	16.2	5	5	0
14	1.4	PB	0	0.25	0.6	5	28.6	0	28	44	7.6	25	75	0	0	0	6.7	60.8	0	0	0
15	2.4	FPR*	0	0.00	0.6	6	54.3	7	29	36	9.5	70	40	20	0	0	4.8	35.7	0	0	0
16	3.3	FPR*	0	0.38	0.6	6	49.1	13	27	47	13.6	53	33	20	0	0	5.5	38.9	0	0	0
+	2	SPc	0.5		0.6	5.0	4.2	0	0	83	4.8	0	50	13	0	50	1.2	4.4	93	18	74

Table C-1 (continued)

ID	Slope (%)	Channel type	Confinement		Channel size		LWD				Pools							Sediment storage		Bank erosion ***		
								Distribution of LWD				Pool forming agent (%) **						Bars		(% bank length)		
			1*	2*	BFD	BFW	LWD/100 m	jams with >10 pieces	jams with >5 pieces	jams with <2 pieces	pool/100 m	LWD	MEAD	BED	BOL	ANT	#/ 100 m	Volume /100m	LS+BA	LS	BA
17	2.5	SPc	0.5	0.75	0.7	8.0	3.6	0	0	83	6.2	33	17	17	17	25	0.5	2.6	49	4	46
18	1.9	PBc	0.25	0.63	0.8	8.0	4.1	0	0	86	6.2	8	50	25	8	17	2.1	7.6	32	4	28
19	1.5	PBc	0.5	0.38	0.7	7.0	4.9	0	0	86	6.5	33	17	8	8	50	1.1	9.3	76	0	76
20	1.5	FPR	0.25	0.60	0.8	8.0	11.4	0	0	65	8.6	26	37	32	0	11	4.5	39.9	25	8	18
+	0.7	PBc	0.75		0.7	4.0	0.0	0	0	0	6.5	15	23	38	8	31	1.5	5.5	54	2	52
21	1.3	PBc	0.5	0.75	0.7	8.0	3.5	0	0	50	5.0	20	30	30	0	30	1.0	7.3	57	4	53
22	3.1	SP	0.75	0.88	0.8	7.5	5.1	0	17	83	6.6	15	23	31	23	31	2.0	21.0	27	23	4
23	1.2	PBc	0.25	0.63	1.0	5.0	2.7	0	0	75	5.4	20	20	20	20	40	0.5	3.2	63	4	59
24	0.7	PB	0.25	0.63	0.6	5.0	20.8	0	9	64	6.9	29	43	14	0	14	5.0	10.4	17	9	8
25	1.5	PB	0	0.38	0.6	4.0	7.5	0	0	60	8.5	11	67	11	11	22	5.7	12.4	37	19	18
26	2.0	PBc	0.75	0.88	0.7	4.0	18.8	0	8	75	6.0	0	14	43	0	57	2.6	5.5	47	8	39
27	1.3	PBc	0.75	0.75	0.7	5.0	15.4	0	22	56	7.1	33	0	25	25	42	4.1	17.5	50	7	42
28	1.3	PB	0.25	0.63	0.8	7.5	25.0	7	13	73	5.0	38	38	13	13	0	5.0	31.1	14	12	2
29	1.8	PBc	0.5	0.63	0.6	8.0	4.5	0	0	67	6.4	20	10	25	0	50	2.9	29.3	44	3	42
30	1.6	PB	0.75	0.88	0.7	5.0	6.1	0	0	100	3.7	33	33	17	0	33	2.5	9.7	31	7	23
+	2.2	SPc	0.5		0.8	4.0	0.8	0	0	100	3.3	25	25	25	25	0	0.0	0.0	73	0	73
+	3.8	SPc	0.75		0.5	1.1	0.0	0	0	0	5.8	0	0	0	83	17	0.0	0.0	70	0	70
+	3.7	SPc	0.75		0.7	4.0	6.3	0	0	89	4.4	86	0	0	0	14	0.0	0.0	26	0	26
+	2.0	PB	0.25		0.8	8.0	18.7	10	20	40	4.7	50	38	25	13	0	3.5	33.9	20	17	4
31	3.0	SP	0.5	0.50	0.8	5.0	28.4	13	31	44	7.2	57	43	7	0	14	2.6	15.2	21	21	0
32	2.4	SPc	0.25	0.50	0.7	7.0	8.0	0	11	22	5.6	29	14	14	7	50	2.8	14.7	52	4	48

* Two different confinement variables were calculated. “Confinement (1)” scored unconfined and partially confined intervals with a value of 0 and confined intervals with a value of 1. By “confinement (2)” confined intervals received a score of 1, partially confined a score of 0.5 and unconfined a score of 0.

**: Pool forming agent: LWD, meandering (MEA), scour (BED), behind a boulder (BOL), or anthropogenic influence (ANT)

***: Bank erosion, either (Landslide or bank-armoring)

+: Reaches not include in the combined data set

Table C-1: Coefficient of determination between riparian zone variables and channel morphology including the complete data set (N = 32)

Channel morphology	# trees	Basal area (m^2)	% trees located in HS	Channel Confinement
LWD/100m	**0.36**	**0.38**	0.06	**0.32**
Single piece wood jams	**0.41**	**0.30**	0.06	**0.23**
LWD jams with >5 pieces	**0.39**	**0.46**	0.006	0.05
LWD jams with >10 pieces	**0.17**	**0.14**	0.005	0.09
Pool frequency	**0.11**	0.08	**0.22**	**0.22**
Bar frequency (#/100m)	-0.02	-0.02	0.02	0.02
Log Sediment storage (bar volume/100m)	**0.24**	**0.13**	**0.18**	**0.19**
Squared-root% of bank length eroded	**0.34**	**0.33**	**0.37**	**0.29**

Note: Highlighted values are statistically significant (considering alpha of 0.05). FP: Flood plain; HS: Hill slope.

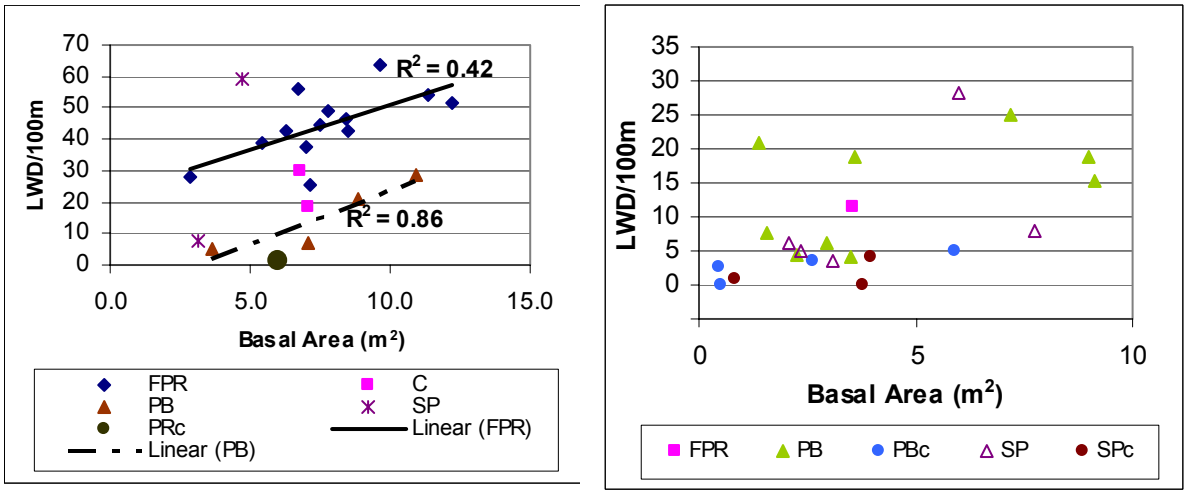

Figure C-1: Basal area versus LWD/100m a) Chico Creek watershed (n = 22) and b) eastside watersheds (n = 22)

Table C-2: Total number of trees and basal area per landform in reaches surveyed in the Chico Creek watershed

Species	Floodplain		Hillslope		Terrace	
	#	Basal area (m^2)	#	Basal area (m^2)	#	Basal area (m^2)
Red Alder	214	24.4	147	14.7	95	10.4
Apple	2	0.1				
Conifer not identified	3	0.4	15	2.3		
Douglas Fir	5	1.6	76	16.6	18	3.7
Bigleaf Maple	54	12.4	117	22.2	25	5.6
Red Cedar	47	21.4	194	26.3	33	13.3
Western Hemlock	39	2.8	127	13.7	42	3.5
Total	**364**	**63.1**	**676**	**95.7**	**213**	**36.4**

Table C-3: Total number of trees and basal area per landform in reaches surveyed in the Eastside

Species	Floodplain		Floodplain*		Terrace		Top of armoring		Hillslope		Hillslope*	
	#	Basal area (m^2)	#	Basal area (m^2)	#	Basal area (m^2)	#	Basal area (m^2)	#	Basal area (m^2)	#	Basal area (m^2)
Red Alder	35	2.8	2	0.1			19	4.1	48	3.9	10	1.1
Red Cedar	16	3.9	6	2.4	0	0.0	31	5.5	39	8.2	4	0.5
Conifer no identified	1	0.0	4	0.1			7	0.8	9	1.1	5	0.8
Douglas Fir	31	4.1	19	3.1	0	0.0	45	6.1	49	8.8	9	0.5
Bigleaf maple	18	1.8	11	2.2	1	0.1	14	2.5	86	11.4	6	2.3
Other deciduous	2	0.1										
Western hemlock	4	1.1	1	0.2			8	1.6	18	2.7	1	0.1
Total	**107**	**14**	**43**	**8**	**1**	**0.1**	**124**	**21**	**249**	**36**	**35**	**5.3**

(*) In a residence back yard.