The Local Impacts of Road Crossings on Puget Lowland Creeks

Christina Marie Avolio

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Abstract

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Christina Marie Avolio

Chair of the Supervisory Committee:
Professor, Derek B. Booth
Department of Civil and Environmental Engineering

Urbanization in the Puget Sound region continues to place mounting strain on natural fluvial systems. As one component of urbanization, the road network is commonly recognized to be a significant stressor of physical stream-channel processes. Several studies have considered the effects of forest roads on creeks in mountainous and/or logged areas, but few have examined the impacts of road crossings on lowland creeks, where most urban development is concentrated. This project provides an analysis of the local effects of road crossings on Puget Lowland creeks.

This analysis was conducted through three interrelated studies having four objectives: 1) developing methods for measuring local road-crossing impacts to physical channel conditions; 2) determining specific physical processes and conditions altered by road crossings; 3) determining what road-crossing characteristics contribute to downstream alterations; and 4) assessing the significance of local road-crossing impacts relative to basin-wide urbanization impacts. The first study, conducted in the summer of 2002, included reach and cross-sectional geomorphic assessments upstream and downstream of 8 selected road crossings. Road crossings reduced downstream channel sinuosity and channel complexity, and increased gravel embeddedness and cementation. Road-related alterations of the channel cross section depended on the type of road crossing, its confinement, and the amount of associated armoring. A second geomorphic study was conducted in the spring of 2003 for 33 road crossings to associate both local road-crossing design and overall basin urbanization to observed channel geomorphology. In general, culverts produced greater downstream geomorphic impacts than bridges, but urban reaches (>20% total impervious area in the contributing basin) were more sensitive to impacts from culverts than from bridges. A gravel entrainment study was conducted for two creeks during the winter/spring of 2002/2003 to explore road-crossing impacts and the influence of associated stormwater outfalls on sediment transport. Although the outfall contributions did not produce observable

upstream-downstream differences in entrainment for the storm flows experienced, road-altered channel cross sections downstream required different amounts of shear stress to produce similar magnitudes of gravel entrainment.

The results of this study affirm the negative influence of road crossings on the geomorphic conditions of lowland creeks, thereby emphasizing the importance of road network designs that minimize the magnitude and frequency of road-stream crossings. Densities of more than a few crossings per stream kilometer likely assure a fully impacted channel network. Road-crossing designs with less hydraulic confinement produce less geomorphic impact than more confining road crossings. In fact, the degree of road confinement appears to outweigh potential benefits of maintaining natural substrate within the crossing itself (e.g., confining arch culverts were connected to some of the most degraded downstream reaches). Other significant determinants of the net effect of a road crossing are both the overall watershed and adjacent riparian conditions. Less geomorphic degradation and better downstream recovery is found in downstream reaches having intact riparian corridors in low-urban watersheds, in comparison to those reaches with devegetated corridors or highly urbanized watersheds.

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DEDICATION

To my grandparents – for always believing in me.

1 INTRODUCTION

Since the industrial revolution, urbanization and land development have severely upset the hydrologic and geomorphic balances of creek ecosystems (Imhof 1991). However, quantifying urbanization's complex impacts on the naturally dynamic processes of streams can be challenging. Studies have shown that once watersheds become developed and surpass reference levels of impervious surface, impacts on stream water quality, biological condition, and physical habitat are ubiquitous (Center for Watershed Protection 1996). Yet understanding that urbanization leads to creek degradation and understanding how and why this degradation occurs are two different tasks. The transition between merely observing past disturbances and anticipating the degree and extent of future impacts has been difficult and slow. Best management practices and other mitigation and rehabilitation efforts could be better guided by an understanding of how the specific characteristics of different land-use changes and urban-development patterns affect the interrelated conditions of stream hydrology and geomorphology.

One of the most pervasive components of urban development is the road network. In the U.S., roads are necessary to cater to the principal mode of transportation – the car. As such, they are likely to be present for a long time, and mitigating their potential physical and biological impacts will be critical for reducing the net influence of urbanization in the future. This thesis considers the hydraulic and geomorphic impacts of road crossings on stream networks within the larger context of urban development's influence on natural systems.

1.1 Background on Urbanization-Induced Physical Changes

The stream condition that is perhaps best known to be influenced by urbanization is the hydrologic regime. Removal of vegetation, compaction of soils, and the installation of drainage networks associated with roads combine to transport water more

"efficiently" to the stream during storms (Konrad 2000, Booth 1991, Burges 1989, Hollis 1975). Such alterations made to stream discharge also affect the other components of the hydrologic cycle. While surface runoff experiences net increases during and immediately after storms, groundwater recharge, evapotranspiration, and throughflow typically suffer net reductions (Imhof 1991). This pattern commonly results in a flashy response (quick water level rise) to storms and decreased base flow during dry periods. Repetition of these patterns over multiple-year periods is likely to induce persistent physical and biological consequences (Booth et al. 2001, Moscrip and Montgomery 1997).

As hydrologic change influences the frequency and magnitude of stream discharges, the physical equilibrium of the channel is offset and the geomorphic form is changed (Imhof 1991). One such physical adjustment occurs with the alteration of channel-forming flows, or the discharges where sediment transport is regulated and the channel geometry is effectively maintained (Dunne and Leopold 1978). As impervious surfaces and ditches increase the rate and magnitude of the in-stream storm response, these channel-forming flows occur more frequently (Center for Watershed Protection 1996). Depending on geological conditions, this trend can promote downstream bank erosion, channel widening, and incision. Booth and Henshaw (2001) found that watershed urbanization and the annual rate of channel change were closely linked; their channels draining established neighborhoods exhibited lower rates of change than channels draining newly developing neighborhoods. These results suggested an ability of the channel to reestablish some sort of physical equilibrium, although such equilibrium is not necessarily an indicator of revised overall stream function or habitat quality (Booth and Henshaw 2001).

1.2 Research Emphasis on the Patterns of Urban Development

Although urban development has hydrologic impacts, little has been documented about the specific spatial characteristics of different development types that may influence the breadth and intensity of the effects to hydrologic systems. Do all urban

development types pose equivalent challenges to streams, or are the impacts more related to how the development is configured and how close and connected it is to stream networks? A recent interdisciplinary study (Alberti et al. in press) has linked both the magnitude of urban development and its spatial patterns to measures of creek ecological health. They developed geospatial metrics that quantified the landscape composition (land cover, percent total impervious area [%TIA]), the landscape configuration (aggregation and contagion of urban land, and the percent of adjacent pixels of identical classification), the land-use intensity (population density, road density, percent commercial land use), and the connectivity of urban land to the hydrologic network (the median flow distance from urban land to creeks, the number of road crossings per kilometer of stream upstream of the sample point). These metrics were applied to forty-two Puget Lowland sub-basins defined by stream locations where benthic macroinvertebrates had been previously sampled. The macroinvertebrate sample results were applied to the B-IBI (Benthic Index of Biological Integrity) developed by James Karr (Karr 1991, Karr and Chu 1999) to provide a measure of ecological stream health at each of these forty-two sites (Morley and Karr 2002). Higher B-IBI scores correspond to better stream macroinvertebrate species counts and diversity. These B-IBI values were then correlated in the present study to the geosptatial metric summaries of urban development in their respective sub-basins.

While the results of Alberti et al's urban patterns study confirmed that B-IBI was strongly correlated to aggregate measures of urbanization (i.e., %TIA; Figure 1.1), they also indicated that other measures of development configuration and connectivity could better predict B-IBI. For instance, both road density and the number of road crossings had better correlations to B-IBI than %TIA (Figure 1.2). In fact, the road-crossing metric was found to be the best individual predictor of declining B-IBI, with an R^2 value of 0.68 ($p < 0.001$). Multi-variable step-wise regression models also showed that any of these selected road metrics, in combination with metrics for the contagion of urban or forested land cover (percent of like adjacencies metric), significantly explained the B-IBI values ($R^2 > 0.7$), while measures of %TIA dropped out.

These results emphasize that clustered rather than dispersed parcels of urban or forested land may have a disproportionate influence on B-IBI relative to their overall

magnitude in a sub-basin. Road networks emerged as the component of urbanization that places the most stress on stream ecological health. Increasing the length of roads within a sub-basin (i.e. the road density) increases the amount of both impervious surface and channelized flow through roadside ditch and culvert drainage systems. Yet the road-crossing metric displayed the best correlation to B-IBI, suggesting that the connectivity of roads to streams matters more to stream biota than simply the total length or amount of roads within a watershed.

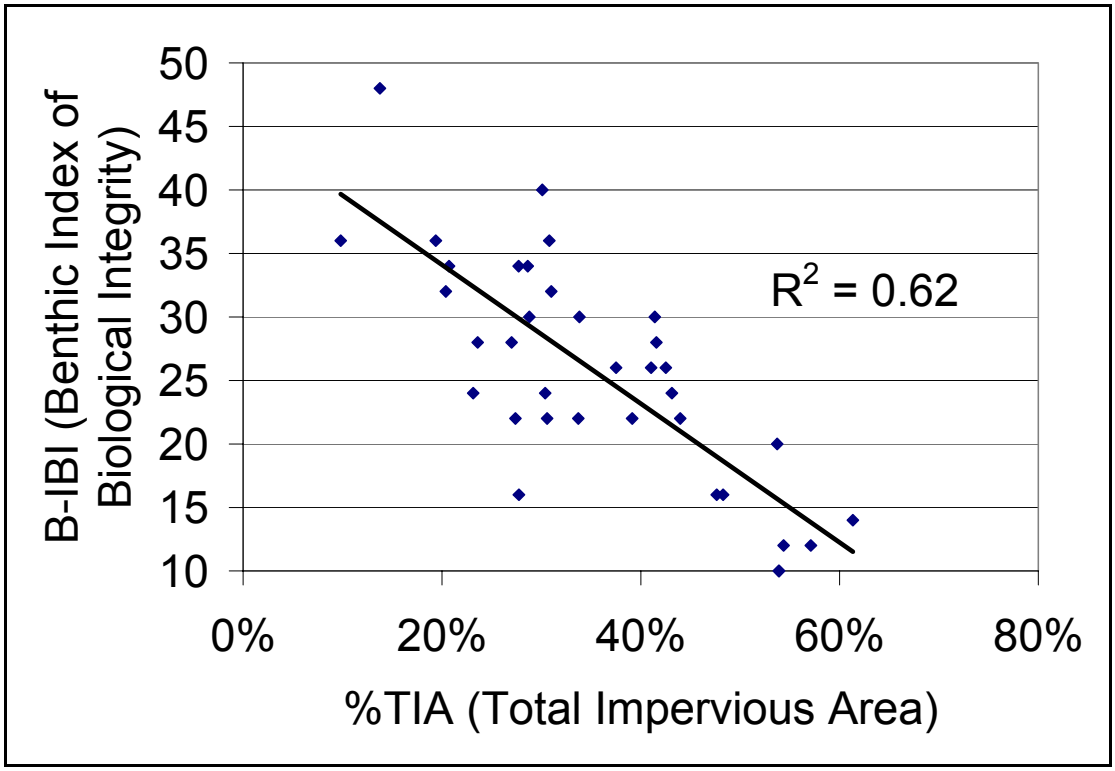

Figure 1.1: Urban Pattern Study correlation between %TIA and B-IBI (B-IBI data from Morley and Karr 2002)

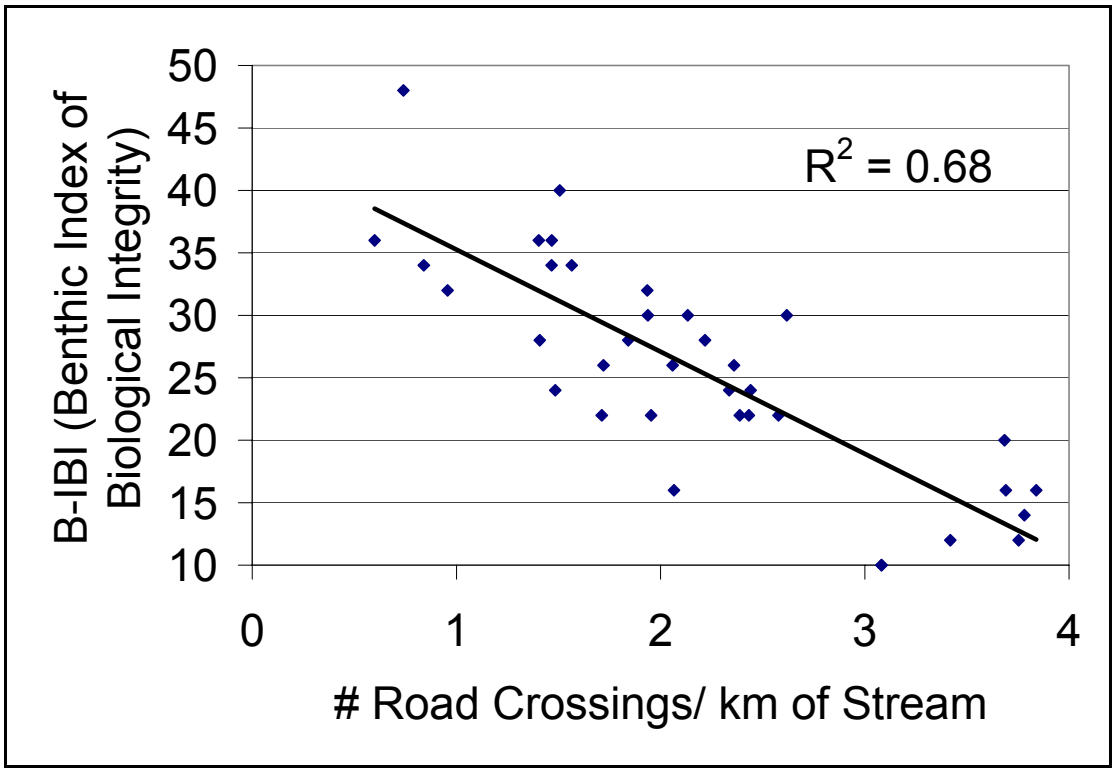

Figure 1.2: Urban Patterns study correlation between road connectivity (measured as the number of road crossings per kilometer of stream upstream of the sample point) and stream ecological health (Alberti et al. in press)

1.3 Background on Road-Related Creek Impacts

The Urban Patterns Study results confirmed that the density of road networks, and especially that of road-stream crossings, has significant relation to degraded in-stream biological health that is not explained by %TIA alone. Yet this correlation could be present for a variety of reasons. Roads contribute to impervious areas within a watershed and they correspond to concentrated drainage and runoff (Montgomery 1994). In addition, roads fragment riparian buffers (Luce and Wemple 2001) and are associated with outfall pipes, which can introduce contaminants directly to the creek. Roads alter hydraulics and intercept physical in-channel processes, such as meander migration and wood recruitment, that create habitat and refugia for macroinvertebrates

as well (King et al. 2001, Statzner 1986). It is likely that roads influence biological stream conditions for all these reasons, but it is difficult to evaluate every potential influence simultaneously. This thesis focuses on only one aspect of road impacts: the processes by which road crossings of stream channels impact the physical framework that supports biological conditions.

Several studies have considered the effects of roads and road crossings on stream hydrology and sedimentology (Anderson 1987, Reid et al. 1984, Montgomery 1994, Madej 2001, La Marche and Lettenmaier 2001, Jones et al. 2000, Weaver et al. 1995, Wemple 1998, Wemple et al. 2001). In general, these studies have found roads to alter creeks in the following ways:

- Increased magnitudes of storm flows
- Decreased downstream bank and hillslope stability
- Increased fine sediment production
- Altered sediment production and transport processes
- Trapped sediment and wood behind culverts
- Promotion of landsliding during storms
- Road/ditch/culvert interception of runoff
- Promotion of gullying and channel network expansion

Jones et al. (2000) developed a conceptual framework for how roads affect stream networks in mountainous regions, based on research from the H.J. Andrews Experimental Forest in Oregon. They suspected that road networks can both instigate and block debris flows, and can alter the balance between the intensity of flood peaks and the stream network's resilience to changes in discharge. They also considered those processes that are influenced by road usage (e.g., fine sediment production) as compared to those processes that are altered by the sheer physical presence of the road crossing (e.g., mass movement). They suggested that the location of roads and road crossings on the hillslope are significant considerations when anticipating road impacts on peak flow response, sediment production, and sediment transport. They support the idea that for mountainous watersheds, road crossings at perpendicular angles to

channels along middle to lower hillslope positions can directly affect peak flows and debris flow initiation and run-out, whereas valley-floor roads that run parallel to main-stem channels have their greatest impact by inhibiting lateral movement and meander migration. In conclusion, the authors propose that streams will experience the greatest effects from peak flows and debris flows just downstream of individual road-stream crossings, but they caution that observations must also be weighed within the context of the total road density to that point in the stream network.

LaMarche and Lettenmeier (2001) examined the effects of forest roads on peak flows in the Deschutes River Basin in Oregon. They hypothesized that roads altered 1) the volume of water converted to overland flow from the interception of road runoff, and 2) the rate of delivery of road runoff to the stream network. The effects of forest floods were found to increase with greater peak floods. Using a distributed hydrologic model to simulate road effects on peak flows in smaller subcatchments, they found forest roads to increase the magnitude of the mean annual flood from 2.2 to 9.5%, and the ten-year storm between 2.9 and 12.2%.

Madej (2001) studied the impacts of abandoned forest roads and road crossings to stream erosion and sediment delivery in the Redwood Creek Basin of Northern California. She separated the impacts of nearby road reaches and the influences of stream-road crossings, and found that mass movements were generally associated with hillslope road segments while channel incision and bank erosion were the most common effects of road crossings.

Montgomery (1994) also found that the surface drainage networks associated with roads had significant impacts on channel initiation and slope stability in mountainous regions. Results indicated that channels supported by road-related runoff required smaller drainage areas for initiation than undisturbed channels of similar slope. In addition, basins with greater basin area and greater slopes were found to be more prone to landsliding under the influence of road drainage. In conclusion, Montgomery found all roads, even ridgetop roads, to have significant influence on stream geomorphology, largely because of their association with drainage concentration. He proposed that adverse channel and slope impacts could be reduced if field data could be

gathered to support theoretical thresholds for erosion initiation and if road designs could make the necessary reductions in drainage concentrations.

1.4 Problem Statement and Research Questions

As populations increase and transportation networks spread, more streams will be increasingly subjected to watershed-wide and riparian alterations – of which some of the most significant will be induced by road crossings. There is a corresponding need to be able to identify which processes are intercepted by roads, not only to mitigate existing crossings, but also to promote more successful road, bridge, and culvert designs in the future. Although the literature provides significant evidence for how roads alter physical processes, there are clear gaps in the body of existing work to 1) describe these influences at the local scale, 2) discuss the relevance of these influences in alluvial, lowland, urbanizing stream systems, and 3) address the implications of different road crossing designs.

In terms of scale, the road literature's emphasis on watershed influences is consistent with the focus of most studies that consider urbanization's effects on creeks (May 1997, Konrad 2000, McBride 2001). These large studies enhance statistical power by broadly characterizing stream condition at various points throughout the watershed, but they fall short of explaining all of the variation in how urbanization and road networks change local hydrologic and sedimentologic processes in streams. Broader study designs are effective for identifying general trends, but they may be limited in their ability to discern local influences, such as the significance of local, riparian impacts.

Road infringement on riparian and floodplain areas can potentially influence several physical in-stream processes. Riparian and floodplain access allows the creek to develop its natural morphology, flood its banks, and create backwater areas for both water detention and fish habitat. Intact riparian buffers help to regulate the encroachment of invasive plant species while supplying woody debris for in-stream habitat quality and complexity. Riparian vegetation also aids in bank stability and provides greater flow resistance to runoff (Jacobson 2001). Road crossings can alter

these natural functions by fragmenting the riparian zone, providing opportunities for the introduction and encroachment of invasive plants, and preventing floodplain access throughout the length of the road crossing and its associated armoring. A more thorough understanding of the significance of roads to riparian alterations could help to guide stream rehabilitation efforts in best restoring some semblance of the natural hydrodynamic equilibrium.

Previous road research designs have focused on steep, mountainous landscapes (e.g., Montgomery 1994, Madej 2001). Although these study watersheds were not been completely forested, their dominant land use has typically been logging. Urbanization, however, is another primary land use that drives road-network development, and most urban areas are located within lowland regions instead of mountainous regions (Puget Sound Regional Council 2001). Stream morphologies within these alluvial lowland landscapes are drastically different from their steeper counterparts: channel processes, rather than hillslope processes, are largely responsible for sediment transport and recruitment. Therefore, road-crossing influences are likely quite different than in steeper watersheds. A complete analysis of road-crossing impacts to physical creek processes must consider these relationships for alluvial lowland channels.

Finally, there has not been adequate assessment of the implications of various road-crossing designs on the hydrologic and geomorphic processes that control physical habitat quality. Depending on the context of a road crossing's position within a channel network, the degree to which a certain road-crossing design isolates the channel from its floodplain or confines its bank full width can also influence the creek's natural morphologic functions. With this in mind, the explicit effects of a culvert could be quite different from those of a bridge placed at the same point in the stream network. Knowledge of these differences could better equip those making decisions regarding new road crossings or updating and restoring old ones.

The need to gain better understanding of the local influences of various road-crossing designs to lowland creek hydrology and geomorphology motivates the following questions:

1. How significant are road-crossing disruptions of the riparian zone to the local geomorphology and hydrology of creeks? Can better understanding of geomorphic and hydrologic change be developed from a study focused on riparian changes that can enhance the existing knowledge of watershed-wide changes?
2. Which metrics--field and GIS (Geographical Information System)--best measure the impacts of road crossings?
3. Does stream geomorphology respond differently to local road influence depending on the amount of watershed development?
4. What are the dominant processes that influence hydraulic and geomorphic responses?
5. What are the differences between road crossings that exert hydraulic controls on streamflow and road crossings that do not?
6. Can stormwater outfalls at road crossings lead to observable downstream differences in physical habitat and sediment transport?
7. Can riparian buffers help to mitigate the local impacts of road crossings?

1.5 Study Hypotheses and Thesis Framework

Given that roads are already known to have impacts on fluvial ecosystems but the processes associated with those impacts are only poorly understood, this study sought to accomplish the following four objectives: 1) to develop the best methods for measuring the local impacts of road crossings on physical creek conditions; 2) to determine the specific physical processes and conditions altered by road crossings; 3) to determine what characteristics of road crossings contribute to downstream alterations; and 4) to assess the significance of these local road-crossing impacts relative to basin-wide urbanization impacts.

This investigation has been organized around three sets of hypotheses, all of which consider impacts reflected by creek geomorphology. The first category includes those hypotheses related to road hydrologic alteration–-how the water is delivered to the

creek. The second group includes hydraulic alteration-–that is, how the structural geometry of road-crossings influence flow velocities and channel hydraulics downstream of the road. The third category includes direct impacts to stream geomorphology.

1.5.1 Directly Altered Geomorphology

1. Road-crossing structures and their associated bank armoring limit in-stream habitat diversity and variety of channel units by preventing the creek from accessing its floodplain and limiting lateral meander migration and sinuosity.
2. Reaches within more urbanized watersheds are less sensitive to the physical consequences of road crossings than reaches in more pristine watersheds.

1.5.2 Altered Hydraulics

3. Alluvial reaches downstream of channel-confining road crossings have more bank instability and downcutting.
4. The bank armoring associated with road crossings alters the natural morphology of the creek by preventing lateral adjustment and forcing the modification of channel slopes to maintain water and sediment transport downstream.

1.5.3 Altered Hydrology

5. Reaches downstream of road-related stormwater outfalls experience more bed entrainment, downcutting, and bank erosion due to the delivery of concentrated storm runoff.
6. Reaches downstream of stormwater outfalls experience increased embeddedness and cementation of gravels due to greater local bank erosion and wash-off of fine sediment from road surfaces.

1.5.4 Thesis Framework

Guided by these hypotheses, three interrelated studies were completed to understand the relationships between road crossings and stream channel geomorphology. During the summer of 2002, a hydraulic and geomorphic assessment was completed of 8 lowland creek reaches affected by nearby road crossings. This preliminary assessment was used to identify the principal geomorphic influences of road crossings so as to guide a second, but broader, geomorphic and hydraulic analysis. This follow-up study in spring 2003 employed a larger sample size (33) to explore the relative influences of road-crossing design and basin-wide urbanization. The third study conducted during the winter and early spring of 2002-2003, was a paired-basin sediment transport case study to address the impacts of stormwater outfalls and road-crossing geometry on local bedload entrainment.

2 METHODS

2.1 Study Area and Overall Site Selection Criteria

This study was conducted in the Puget Sound Lowland of Western Washington State. The area's last glacial advance, which occurred about 16,000 years ago (Booth et al. 2003), is largely responsible for creating the lowland. Because its elevation is mostly under 150m altitude, it is conducive to development. Its landscape now supports most of Washington's population and urban growth (Puget Sound Regional Council [PSRC] 2001). The Puget Sound's dense metropolitan region, in combination with the growing urban and suburban developments on the outskirts, conveniently provides a range of development types and ages that was needed for this study. These many development styles also provided a wide assortment of road-crossing designs that could be analyzed for their varying impacts to creek hydrology and geomorphology.

Stream-sampling strategies need to be careful in selecting locations that do not represent the muddled results of a variety of impacts. For this study, it was important to isolate the consequences of a specific road crossing. Sites were screened and stratified by channel type, reach slope, reach location within the channel network (i.e., sub-basin drainage area), and basin geology. Due to the time limitations of this study, other potentially important considerations, such as the temporal variability of impacts, the historic conditions, and the duration of impacts over time, were not assessed but were assumed to be little different between sites.

Stream sampling locations were dominantly alluvial, where the stream is able to erode banks, change channel form, and respond to various hydrologic and geologic impacts. Therefore, reaches that were completely armored or had bedrock geology, and so cannot reflect responses to watershed development, were removed from the sampling pool. Conversely, watershed geology characterized by erodible substrate is important to ensure that the channel has the ability to deposit and recruit sediment (Booth and Henshaw 2001). This condition is widely met across the Puget Lowland.

Secondly, it is important to compare sample sites with similar morphological functioning. Montgomery and Buffington (1997, 2001) developed a process-oriented stream classification system for Pacific Northwest streams. This classification groups streams according to similar morphologic functions, which tend to stratify by channel gradient. For alluvial stream classes, riffle-pool sequences have been found to be one of the channel classes most responsive to hydrologic and geomorphic changes. Riffle-pool morphology is generally found in stream reaches with less than 2% slope. To eliminate further sampling variance, only those reaches with riffle-pool morphology and slopes less than 2% were considered.

Thirdly, basin area is an important determinant of in-stream processes and therefore was also used as a criterion for sample site selection. The drainage area must be large enough that the channel surveyed is not dominated by the influx of hillslope deposits and the resulting colluvial morphology (Booth and Henshaw 2001). On the other hand, an upper bound must be established to ensure channel-type comparability while still encompassing a majority of the channels that are important to fish. These criteria helped narrow the sampling range to sub-basins (i.e. the area draining to the sampling locations, but not necessarily at the mouth) that had roughly between 15 and 30km^2 of surface area. Prior field experience supported the conclusion that reaches within this drainage-area range met the research criteria for alluvial function and sensitivity (Booth 1996).

Several GIS data sets were necessary to determine whether potential sample locations adequately met the above-stated criteria. A GIS road network layer for 1998 was obtained from the Puget Sound Regional Council. This data was used to help determine potential road-creek intersections that would be appropriate for sampling. A 10-m Digital Elevation Model (DEM) for the Puget Sound area was acquired from PRISM (Puget Sound Regional Integrated Synthesis Model). All geographical data sets used the UTM NAD27 projection. The original DEM data was derived from contour lines at 20 to 40ft intervals on USGS 7.5-minute maps. This elevation data was used to approximate reach slopes and delineate stream networks and sub-basins through developing Flow Direction and Flow Accumulation grids. The GIS-delineated sub-basins and stream networks were compared to USGS topographic quads to ensure accuracy. Once these

sub-catchments were delineated, drainage area could be calculated and the new watersheds could be used for spatial analysis of land cover and geology.

In order to determine the %TIA in each basin, Puget Sound land cover data was acquired from the University of Washington's Center for Water and Watershed Studies website (http://depts.washington.edu/cwws/Research/Projects/landsat.html). The land cover classification (Hill et al. 2003) was based on Landsat Thematic Mapper (TM) imagery from 1998, with a resolution of 30 m. The land cover was divided into seven classes: forested urban, grass/shrub urban, paved urban, forested, grass/shrub/crops, water, and bare soil. Sub-basin land cover could be determined by using GIS analyses to intersect the land cover with the sub-basins. The total area devoted to a specific land cover class was divided by the sub-basin area to determine the percent land cover for each sub-basin. The %TIA was then determined by summing each individual land cover class's contribution to the percent of impervious surface (Table 2.1).

Table 2.1: %TIA determined from different land cover classes (Hill et al. 2003)

Land Cover Class	% TIA
Forested Urban	39
Grass Urban	74
Paved Urban	92
Grass/Shrub/Crops	5
Water	0
Bare Soil	98
Forest	3

Finally, geologic maps (Booth et al. in press) were used to select sub-basins that were most dominantly characterized by erodible surface deposits that are necessary for alluvial stream functions. Basins dominated by glacial outwash, till, or fluvial deposits all qualified.

For each of the three studies, the above criteria were used to select sample sites with as many defining characteristics as possible in common. All the reaches are

impacted in some way, but to varying degrees, by road crossings and the total level of basin urbanization.

2.2 Initial Geomorphic Assessment of Local Road-Crossing Impacts to Eight Lowland Creek Reaches

For the summer 2002 study, the overall intention of physical sampling was to characterize the key physical processes that are locally influenced by road crossings and describe how these impacts could be observed in the geomorphology. More specifically, this study sought to address two of the hypotheses: 1) road crossings limit downstream habitat diversity and channel unit variety by preventing the creek from accessing its floodplain and by limiting lateral meander migration and sinuosity, and 2) confined channel reaches downstream of road crossings and bank armoring can have altered morphology and steeper slopes in order to maintain water and sediment transport downstream.

2.2.1 Site Selection

The eight stream reaches selected for this study were chosen for their ability to meet the primary sampling criteria. Additionally, they span a range of road crossing design types and total sub-basin levels of urbanization. The eight road crossing locations were selected from five different study watersheds (Figure 2.1). When possible, two sites were chosen from each study watershed to compare the effects of different road crossings within the same catchment. The Big Beef Creek sub-basin on the Kitsap Peninsula upstream of the Holly Road crossing, has an upper watershed that most closely resembles Puget Lowland reference conditions, and it is dominated by mature, second-growth forests. May Creek (Renton) and Big Bear Creek (Redmond) have sub-basins dominated by suburban and rural land use. Swamp Creek (Brier) and Thornton Creek (Seattle) have the most development and the most pervasive basin-wide urbanization. A second Thornton Creek site (at the 15th Ave. NE Crossing) has a

significantly smaller drainage area than the other sites. It was kept in the sample set, however, because it provided a second sample location on Thornton Creek, had similar reach morphology and slope to the other sites, and had a hillslope bridge without associated bank armor. This site's alluvial riffle-pool morphology made it consistent with the other sites in that it too should be sensitive to local road-crossing impacts. Table 2.2 lists the selected reaches and locations, as well as some of the defining characteristics used for site selection.

Table 2.2: Selected road-crossing reaches with important watershed characteristics for initial geomorphic study summer 2002

Basin	Site Location	Road Type	Drainage Area (km^2)	Sub-basin Geology	Reach-Average Slopes	%TIA
May Creek	I-405	Hillslope Bridge	30.5	Till, Outwash, Bedrock in Upper Watershed	0.8% - 1%	23
May Creek	Coal Creek Parkway	Hillslope Bridge	22.2	Till, Outwash, Bedrock in Upper Watershed	1.7% - 1.9%	17
Swamp Creek	Larch Way	Floodplain Bridge	29.7	Till, Outwash, Alluvium	0.5% - 1%	41
Swamp Creek	1-405, near Filbert Road	Double Concrete Box Culvert	27.5	Till, Outwash, Alluvium	1% - 1.7%	42
Big Bear Creek	NE 148th St.	Floodplain Bridge	20.9	Outwash, Till	0.6% - 1%	19
Thornton Creek	Sand Point Way Rd.	Double Concrete Box Culvert	27.8	Outwash, Till	0.6% - 0.7%	54
Thornton Creek	15th Ave. NE	Hillslope Bridge	3.2	Outwash, Till	1% - 1.2%	59
Big Beef Creek	Holly Road	Arch Culvert	18.4	Till, Outwash, Alluvium, some bedrock	0.5% - 1.7%	13

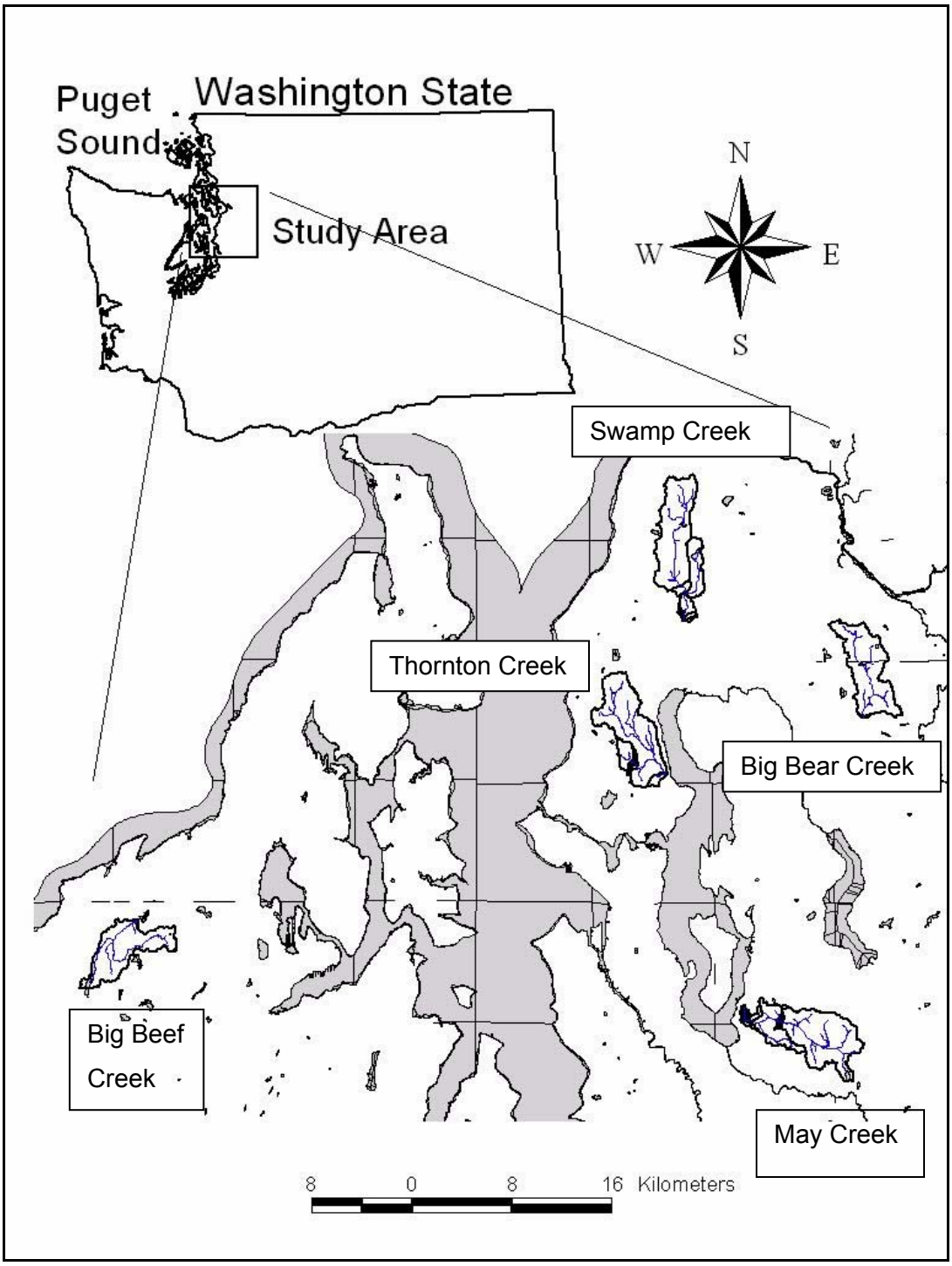

Figure 2.1: Locations of sample watersheds for the Summer 2002 study

2.2.2 Field Methods

To best observe the local effects implied by the hypotheses, 100m reaches were sampled upstream and immediately downstream of each road crossing. Upstream reaches served as local controls for how the creek might function without the influence of the road crossing, making sure to begin sampling beyond upstream effects of the road from armoring, backwater, canopy clearing, and dumping. The downstream reaches began downstream of any artificial bank armoring immediately associated with the road (generally less than 10m). These downstream reaches were expected to reflect any local influence of the road crossings.

A longitudinal survey assessed both physical in-stream conditions (channel morphology, hydraulic dimensions, and sediment attributes) and riparian conditions (the proximity and influence of both riparian vegetation and residential development). A hip chain was used to track distance; a Garmin 12XL Global Positioning System (GPS) receiver, with precision of about 10m, was used to record decimal degree coordinates for the downstream locations of each reach. The locations and dimensions of any stormwater outfall pipes or artificial drainage associated with the road crossings were noted along the profile with their GPS locations and diameters recorded. Channel morphology was described by:

- a surveyed creek bed and water surface profile,
- a surveyed representative riffle cross section,
- a reach assessment of the bank stability,
- a reach count of the number of large woody debris (LWD),
- aggregate measures of the lengths of gravel bars, bank erosion, and bank armoring in each reach,
- the sinuosity, and
- an assessment of the reach channel complexity (i.e. variety in riffle and pool channel units).

Standard surveying equipment (tripod, level, and stadia rod) was used to determine longitudinal and cross sectional creek-bed and water-surface elevations relative to benchmarks established in the field. Both the reach-averaged and local

slopes, the latter measured only for the riffle unit where the cross section was surveyed, were derived from the water-surface elevations. The stadia rod was also used to measure pool widths, lengths, and depths; the hip chain was used to determine gravel bar lengths. Pools were considered if they had a width or length of at least 10% of the channel width and a residual depth of at least 25% of the bank-full depth (Castro et al. 2002, Montgomery et al. 1995). Gravel bars were counted if their lengths were on the order of a channel width or greater (Knighton 1998).

For each reach, a cross section was chosen within a riffle that best represented the typical cross-sectional dimensions of the 100m reach. Each cross section was surveyed, and stream velocity was determined using a Marsh McBirney velocity probe. This information could then be used to determine hydraulic parameters such as the cross-sectional area, discharge, the wetted perimeter, the width-to-depth ratio (W/D), and the hydraulic radius. These hydraulic parameters could be compared both upstream and downstream of the road crossings and between different sites to determine if any patterns exist relative to the road crossings.

The bank stability assessment was used to indicate if and where road crossings could be causing channel enlargement or adjustment. To determine bank stability, a visual, categorical measure developed by Booth and Henshaw (2001) was used. The left and right banks along each reach were rated as stable, slightly unstable, moderately unstable, or unstable, and then an overall rating was applied to the reach. The guidelines for making the bank stability determination are described in Table 2.3. This assessment was only made along alluvial stream sections and was not applied to intermittent sections with bank armoring. A separate metric that tracked the percent of the bank armored was developed to test the related hypotheses. Erosion associated with meander bends was not included with the bank stability assessment, because naturally meandering channels without anthropogenic degradation are intrinsically characterized by bank erosion at channel bends (Knighton 1998).

LWD is known to be a key habitat-forming feature in lowland, alluvial channels (Fox et al. 2003), and was tallied as one indicator of habitat complexity. LWD pieces that were in the active bank-full channel and that satisfied a minimum diameter of 25cm and

minimum length of 1m (Montgomery et al. 1995, Swanson et al. 1976) were tallied for each reach.

A measure of sinuosity was also included in this study. GPS locations were recorded at the downstream and upstream ends of each reach, and the ArcView Measuring Tool was later used to calculate the straight-line distance between the two points. The hip chain distance was used to determine the stream distance and the sinuosity was then calculated by dividing the stream distance by the straight-line distance (Knighton 1998).

Channel complexity was another measure used to distinguish between a channel that is naturally diverse with riffles and pools and one that has become uniform and simplified through natural or anthropogenic influence. A quantitative field method that was both quick and comprehensive was not available for assessing stream channel complexity. Rather, a qualitative metric with specific guidelines for visible assessments of channel topography and habitat diversity (McBride 2001) was found to provide the most rapid and complete method. Although the metric is qualitative and subjective, the same observer applied the rank to all sites, therefore the results should be consistent for use in this analysis. The guidelines for this parameter estimate are shown in Table 2.4 (McBride 2001).

Table 2.3: Criteria for determining overall reach bank stability (Booth and Henshaw 2001)

Classification Category	Description
STABLE	perennial vegetation to waterline
	no raw or undercut banks (some erosion on outside of meander bends ok)
	no recently exposed roots
	no recent tree falls
SLIGHTLY UNSTABLE	perennial vegetation to waterline in most places
	small scalloping of banks
	minor erosion and/or bank undercutting
	recently exposed tree roots rare but present
MODERATELY UNSTABLE	perennial vegetation to waterline sparse (mainly scoured or stripped by lateral erosion)
	bank held by hard points (trees, boulders) and eroded back elsewhere
	extensive erosion and bank undercutting
	recently exposed tree roots and fine root hairs common
COMPLETELY UNSTABLE	no perennial vegetation at waterline
	banks held only by hard points
	severe erosion of both banks
	recently exposed tree roots common
	tree falls and/or severely undercut trees common

Table 2.4: Criteria for assessing stream channel complexity (McBride 2001)

Category	Description
EXCELLENT	Diverse and Complex Structure
	Variety in Channel Units (pools, riffles, glides)
	Side Channels and/or debris jams present
	Diverse Microtopography
	Variable Channel Geometry
GOOD	Less diverse and Complex structure
	Some Variety in Channel Units
	Side Channels and/or debris jams less frequent
	Some heterogeneity in microtopography and channel geometry
FAIR	Little diversity or complexity in structure
	Little variety in channel units
	Very few side channels and/or debris jams
	Little heterogeneity in microtopography and channel geometry
POOR	Simple Structure
	No variety in Channel Units
	No Side Channels or debris jams present
	homogeneous microtopography
	Very little variety in channel geometry

The reach sediment was assessed in three ways – sediment size, embeddedness, and cementation. At each established cross section, a pebble count was completed to provide an estimate of the gravel size distribution for each reach. The Wolman sampling method was used along with the Wentworth classification scheme (Wolman, 1954). The embeddedness of gravel in riffles is an indicator of the fine sediment that is present in the creek bed. Road crossings could promote fine sediment availability and transport if they contribute to bank instability and/or are associated with outfalls carrying fine sediments and dust off of roads. The embeddedness was determined by estimating the percent of the perimeters of random cobbles and gravels (located along the longitudinal profile) surrounded by fine sediment. The overall embeddedness for each reach was then grouped into one of four categories of embeddedness: 0-25%, 25-50%, 50-75% and 75-100% (Barbour et al. 1999, McBride 2001).

The final sediment metric measured in the field was the cementation of riffle gravels. This metric was used to quantify the hardening and compaction of the substrate that also often results from increased road runoff and erosion. Following a classification adapted by Comings et al. (2000) and McBride (2001), the cementation of each reach was qualitatively assessed. The specific descriptions of the cementation classes are shown in Table 2.5.

The quality of the riparian buffer was determined in the field by applying a qualitative metric for the width/integrity developed by May (1996) and later modified by McBride (2001). According to the riparian metric, a reach's riparian corridor could be classified as Optimal (wide/intact), Sub-Optimal (moderate/few breaks), Marginal (narrow/broken), or Poor (little/no buffer). Further guidelines for this classification are shown in Table 2.6. This metric provided a general description of the width of the riparian zone and an estimate of the disturbance from nearby residential development.

Table 2.5: Criteria used for determining riffle cementation

Classification Category	Description
EXCELLENT	Gravel and Cobbles are Loose throughout the riffle
	Very easy to penetrate riffle surface with heel pressure
	very little fine material released with heel pressure
GOOD	Gravel and Cobbles are tighter, but still loose at the downstream end of the riffle
	Some Effort needed to penetrate riffle surface
	Some fine material released with heel pressure
FAIR	Gravel and Cobbles are compacted and tight (perhaps loose only at the downstream end of a riffle)
	Considerable effort needed to penetrate the riffle surface
	Substantial fine material released with heel pressure
POOR	Gravel and cobbles are cemented throughout riffle (concrete-like)
	Very difficult to penetrate riffle surface
	Lots of Fine material released downstream with heel pressure (rich plume)

Table 2.6: Guidelines for the riparian classification (May 1996, McBride 2001)

Category	Description
OPTIMAL	Mature forest
	Wide/intact riparian buffer
	Continuous buffer along both stream banks for entire reach
	Closest development is at least 30m away from stream
SUB-OPTIMAL	Mature/young Forest
	Moderate width/few breaks to riparian buffer
	Buffer is not continuous along the entire reach
	Development may occur within 30m of the stream
MARGINAL	Young forest
	Narrow width/many breaks to the riparian buffer
	Only patches of buffer remain along the reach
	Development within 30m of the stream
POOR	No forest
	Little to no riparian buffer
	Development within the immediate riparian zone on both sides of the stream

Application of Survey Data to the Physical Stream Condition Index (PSCI)

Each measure of physical channel condition was used independently to test for the different downstream alterations of morphology and geomorphic condition observed due to road crossings. However, to compare the overall geomorphic health and function of each reach, the measures for riffle embeddedness, riffle cementation, bank stability, channel complexity, and large woody debris were applied to a mulitimetric index. Based on the PSCI (Physical Stream Conditions Index) developed by McBride (2001), this multimetric index offers a means of scoring each reach for comparing their physical quality and stability while providing the statistical power (Zar 1999) of a continuous variable.

This PSCI gives each of the physical measures equal weight. Each measure receives a rank between 1 and 4, with 4 being the best condition and 1 being the worst condition. These individual scores are then summed to provide a total PSCI score between 5 and 20. The PSCI was then computed for each reach by applying the ranks for each metric as shown in Table 2.7.

The ordinal score for LWD was determined by using the distribution of the LWD data results collected. Following the original PSCI methodology for grouping the LWD categories (McBride 2001), the mean of the data (25 pieces/100m reach) was used to establish the lower limit for the high score (4) of the metric. The three lower score categories were then divided equally (Table 2.7). These divisions were revisited later in the overall study.

Table 2.7: Guidelines for determining the PSCI index

Parameter	Description	Score			
		1	2	3	4
Bank Stability	Qualitative Rank (see Table 2.3)	Unstable	Moderately Unstable	Slightly Unstable	Stable
LWD Abundance	Rank Based on the quantity of LWD pieces per 100m of reach length	< 8	8 - 16	17 -25	>25
Channel Complexity	Qualitative Rank (see Table 2.4)	Poor	Fair	Good	Excellent
Embeddedness	Qualitative Rank	75 - 100%	50 - 75%	25 - 50%	< 25%
Cementation	(see Table 2.5)	Poor	Fair	Good	Excellent

2.2.3 Analytical Methods

Development of Spatial Metrics for Characterizing Urbanization

In addition to considering the local geomorphic effects of road crossings, GIS methodology was used to develop metrics for measuring both the magnitude of basin urbanization and the connectivity of the road network. The measure of basin urbanization used was %TIA. As described previously, %TIA was determined from the land cover classification of Hill et al. (2003). A road-crossing metric was developed to describe the connectivity of the road network to the stream networks. While partly correlated with %TIA, the road-crossing metric was employed to better describe the cumulative effect that multiple road crossings might have on downstream reaches. The Geoprocessing wizard in ArcView 3.2 was used to intersect the road line theme with the stream line theme. The number of clipped roads within each sub-basin was then summed to provide the total number of road crossings within that sub-basin. The total length of stream was also summarized for each basin. The road-crossing metric was then determined by dividing the number of road crossings by the total kilometers of stream upstream of the sample point.

Statistical Analyses

Geomorphic data and PSCI scores for reaches upstream and downstream of road crossings were compared using paired sample t-tests to determine which variables were the most sensitive to the presence of road crossings, regardless of road-crossing type. General upstream-downstream trends for how road crossings might alter slopes, the median sediment size, the hydraulic radius, the W/D ratio, the bank-full width, and the bank-full depth were also explored. The direction of the upstream-downstream change in these hydraulic parameters was stratified according to the road-crossing type (i.e. plain culvert vs. floodplain bridge) to explore how different road crossing designs with differing amounts of confinement could produce varying physical impacts. Simple linear regressions were used to compare the overall PSCI, the individual PSCI component metrics, and the other geomorphic variables (length of gravel bar/100m reach of stream, the percent of the bank eroded, and the W/D ratio) to plausible determinants of these conditions: basin urbanization (%TIA), the percent of the reach armored, the width/integrity of the riparian zone, the reach sinuosity, and the number of road crossings per km of stream.

2.3 Broader Geomorphic Analysis of Road-Crossing Influences

The preliminary geomorphic assessment was used to identify those geomorphic variables that are most sensitive to road-crossing impacts. Then, in the spring of 2003, a broader geomorphic analysis was conducted to better explore variation in those different variables due to two principal road-crossing types – bridges and culverts. Road crossings were further stratified according to their structural differences and various levels of confinement imposed on the creek. These specifications were tested across sites that spanned a gradient of urbanization, and with various amounts of stormwater contribution, to address the following hypotheses: 1) reaches downstream of stormwater outfalls experience more embedded and cemented gravels due to greater local erosion,

2) reaches downstream of channel-confining road crossings are more unstable and prone to downcutting, and 3) reaches within urbanized sub-basins are less sensitive to the physical impacts of road crossings than less urban reaches.

Bridges were grouped into two sub-categories, floodplain bridges and hillslope (or ridgetop-to-ridgetop) bridges. The floodplain-bridge category included bridges built directly over the lowland floodplain with or without much added fill or embankment to raise it above the stream channel. Although floodplain bridges are wider than culverts, they often do not have the space for natural banks to exist within their structures. Wood planks or concrete compose the side material under the road crossing. Hillslope bridges, on the other hand, are bridges where beams support a bridge farther above the creek, or the natural topography allows for a bridge to span the ridgetops without directly intersecting the channel floodplain. This bridge design may or may not be accompanied by a riprap trapezoidal channel design or bank armor underneath it.

The culvert road crossings were also grouped into two sub-categories, round or box culverts, called “plain” culverts here, and arch culverts. The main distinction here is that the plain culverts confine the creek on all sides (including the bottom), whereas the arch culvert has an open, sedimentary substrate bottom and is generally less confining. Both culvert designs can be associated with varying amounts of fill material adjacent to the channel.

2.3.1 Site Selection

Sample sites for the spring 2003 geomorphic survey were selected to include all four road-crossing types in addition to meeting the general site-selection criteria and representing a range of basin urbanization levels. For the purpose of this sample design, “urban” was classified as > 20% TIA, while “suburban” basins were classified as < 20% TIA. The selected sites were located throughout King, Pierce, Kitsap, and Snohomish counties. 17 culverts were surveyed, of which 10 were in urban and 7 were in suburban watersheds. 16 bridges were selected, including 9 urban sites and 7 suburban sites (Figure 2.2)

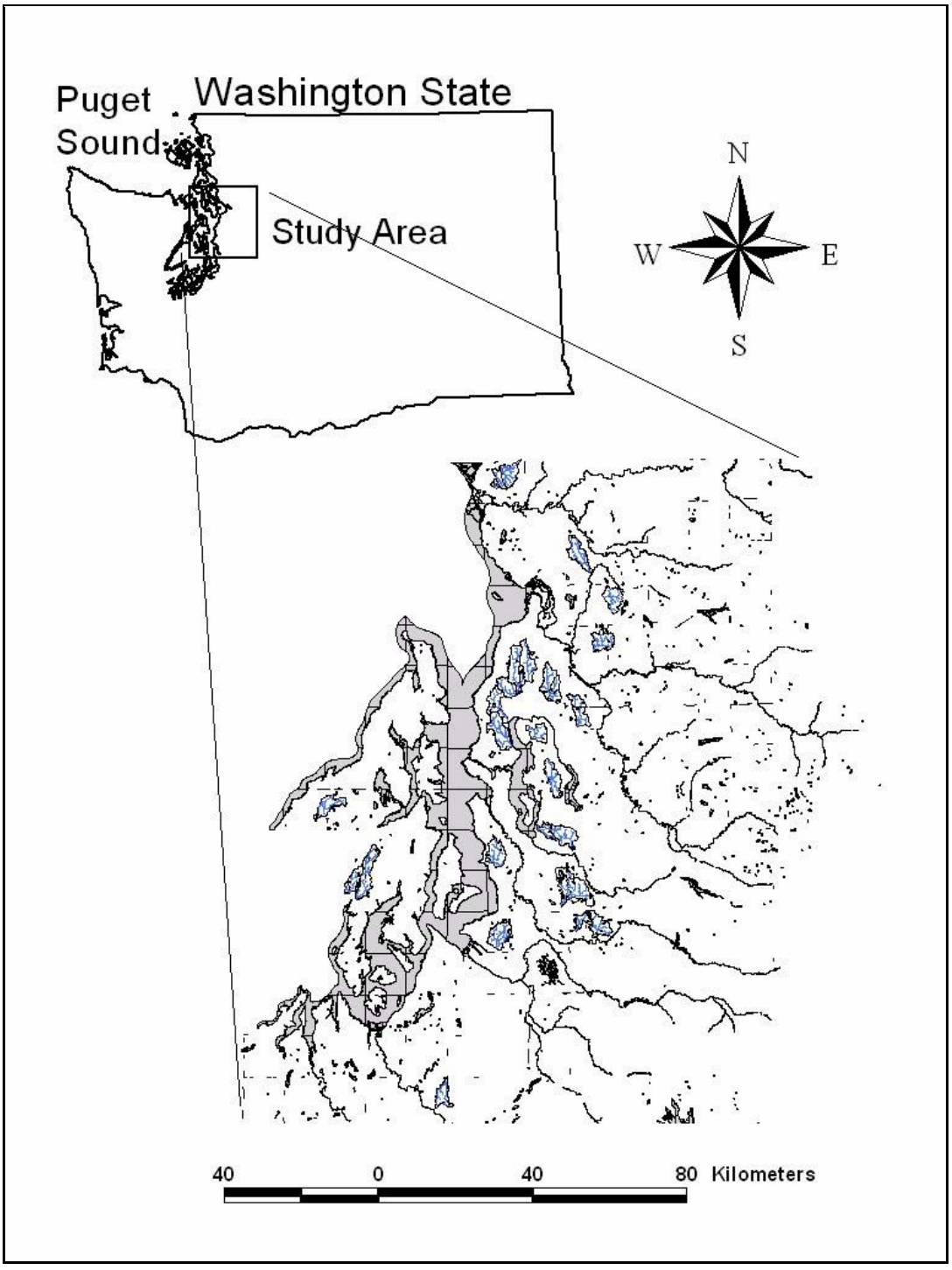

Figure 2.2: Locations of sample watersheds for the Spring 2003 study

2.3.2 Field Methods

Many of the field methods described for the preliminary summer 2002 survey were also employed for this survey. However, the intention here was to provide a more broad characterization of road-crossing impacts, increasing the sample size and thereby adding statistical power (Zar 1999). Therefore, the more detailed and time-consuming measurements, such as surveyed channel profiles and cross sections, velocity measurements, and pebble counts, were excluded from this survey. Instead, local slopes were checked with a clinometer and a stadia rod was used to measure pool, channel, road-crossing, and stormwater-outfall dimensions. To estimate the magnitude of the stormwater introduction at each road crossing, the sum of the outfall pipe areas were tabulated. This sum was used as a crude index of stormwater inputs, under the assumption that each outfall pipe was at least approximately sized to convey a certain volume of water to the creek. The bank-full dimensions (width and depth, Harrelson 1999) were measured at every riffle to determine reach averages for this study. The method used to determine reach sinuosity for the summer 2002 was also repeated for this analysis.

The summer 2002 methodology was used to quantify the total lengths of gravel bars, bank erosion, and bank armoring. The same criteria were used to tally LWD, and the same methods were also used for ranking the channel, bank stability, cementation, embeddedness, and riparian-zone conditions.

2.3.3 Application of Survey Data to a Modified PSCI

For this study, the original PSCI was modified to accommodate the new data collected for different sites during a different season. Therefore, the LWD Abundance metric scoring range was adjusted from that established for the summer 2002 study to reflect the ranges present in the new data set. This change, along with the original four other metric scoring criteria, are reiterated in Table 2.8. The total PSCI score had the same range between 5 and 20, with 5 representing the most degraded geomorphic conditions, and 20 representing the most pristine geomorphic conditions.

Table 2.8: New PSCI scoring criteria for the spring 2003 geomorphic study

Parameter	Description	Score			
		1	2	3	4
Bank Stability	Qualitative Rank (see Table 2.3)	Unstable	Moderately Unstable	Slightly Unstable	Stable
LWD Abundance	Rank Based on the quantity of LWD pieces in the reach	< 5	5 - 8	9 -14	>14
Complexity	Qualitative Rank (see Table 2.4)	Poor	Fair	Good	Excellent
Embeddedness	Qualitative Rank	75 - 100%	50 - 75%	25 - 50%	< 25%
Cementation	(See Table 2.5)	Poor	Fair	Good	Excellent

2.3.4 Analytical Methods

The road crossing and %TIA metrics were determined for the spring sample reaches using the same methodology described for the summer data. Pool volume was calculated from the measured pool dimensions such that:

$$V = (1/3)(0.8*W*L*RD),$$

where W is the maximum pool width, L is the pool length, and RD is the pool residual depth. This equation approximates the volume of an ovular cone, where the area of an oval is about 0.8* (length *width), and the volume of a cone would be (1/3)*(area of an oval)*(maximum height). The total pool volume for each reach was then summed and divided by 100 to create a standard metric of pool volume per 100m of channel.

To estimate the degree of confinement that each road crossing imposes on the creek, the maximum creek width underneath the road crossing was divided by the average bank-full width of the upstream reach. This confinement metric created a

continuous variable that was regressed against geomorphic variables to determine the relative influences of road crossings with varying amounts of confinement.

Paired t-tests were used to denote differences in upstream-downstream geomorphic trends. Boxplots were then completed to show graphical illustrations of these differences. The box in the boxplot incorporates the middle 50% of the data, with the line in the middle indicating the median, with the upper and lower horizontal lines of the box indicating the 75^{th} and 25^{th} percentiles, respectively, and with the outer vertical lines extending to the most extreme observations within 1.5 times the difference between the 25^{th} and 75^{th} percentiles. Data points beyond this range are indicated as outliers, or independent points on the graph. Analysis of variance (ANOVA) tests were used to signify the presence of significant differences ($p < 0.05$) when more than two data sets were being compared. If ANOVA tests found significant differences to be present, the Student-Newman-Keuls test was then completed to discern the categories between which the difference was present.

Linear regression analyses were used to compare PSCI trends to the road-crossing metric for reaches both upstream and downstream of roads. Linear regression models were also developed to describe relationships between stormwater outfall area, road confinement, reach sinuosity, and channel complexity as well as the differences in upstream minus downstream PSCI values (ΔPSCI). Multi-variable stepwise regression models were used to determine how different combinations of forcing variables (sinuosity, outfall area, riparian rank, length of bank armoring) predicted overall PSCI and geomorphic values as well as upstream-downstream differences in PSCI (ΔPSCI) values.

2.4 Road-Crossing Influences on Channel Hydraulics and Sediment Transport – a Paired-Basin Case Study

A third element of this work, a paired-basin case study, considered two different road crossings and their alteration of sediment transport processes between upstream and downstream reaches. Specifically, this study focused on the following hypotheses:

1) reaches downstream of stormwater outfalls experience more bed entrainment due to the delivery of concentrated runoff, and 2) the confinement and armoring associated with road crossings alter the ability of the channel to recruit and transport sediment, as measured by the amount of gravel bed entrainment.

2.4.1 Site Selection

The two basins chosen were Big Bear Creek in Redmond, Washington and May Creek in Renton, Washington (Figure 2.3). The two basins have similar sub-basin drainage areas (between 20 and 30 km^2) and similar amounts of development and impervious surface within their catchment areas (around 20% TIA). The specific road crossings selected both have bridge designs that do not appear to significantly alter the conveyance of water downstream. However, the May Creek site is a hillslope bridge that creates a riprap-lined trapezoidal channel under the road, whereas the Big Bear Creek site is a floodplain bridge that is characterized by wood planks along the sides, which protect the piers that support the bridge. The two sites both have similar amounts of outfall-pipe stormwater contribution at the road crossings. Although total contributing watershed TIA and the sub-catchment areas drained to the two stormwater outfalls were similar in the two streams, these outfalls drained different amounts of impervious surface. The May Creek outfall pipe contributes drainage mostly from I-405, while the Big Bear Creek outfall pipe contributes drainage mostly from nearby residences. Table 2.9 summarizes the important basin and site characteristics for the paired study.

While similar in many aspects (drainage area, watershed geology, reach slope, upstream number of road crossings, sub-basin %TIA, and km^2 of outfall contributing area), the two selected study sites have two variables that are different – the road-crossing type, and the %TIA of the outfall contributing area. Therefore, although the impacts of the road design and the type of outfall contributing area cannot be isolated, this study still offers opportunities to test any influences that road design type and outfall contribution might have on sediment transport. But both of these sites have bridges that separate the channels from their floodplains, but that also appear to be well-sized for adequate water passage downstream. Thus road design influences should not be as

drastically different as if a bridge and a culvert were being compared. For both sites, study reaches were established both upstream and downstream of the road crossing so that the upstream reaches could serve as the local controls before the influence of stormwater introduction. Comparing upstream to downstream reaches for each site can yield information regarding the relationships between the shear stress and sediment transport that are subject to basin influences before the impacts of the road crossings and their associated stormwater contributions.

Table 2.9: Summary of basin characteristics for the paired basin sediment transport case study

	May Creek	Big Bear Creek
Site Location	I-405 Crossing, near 44th St Exit and Jones Rd	NE148th St.
Sub-basin Drainage Area (km^2)	30.5	20.7
Geology	Till, Outwash, Bedrock in Upper Watershed	Outwash, Till
%TIA	22.7	19.0
Road Crossings/ km of stream, upstream of site	1.55	1.75
Road-crossing type	Hillslope Bridge	Floodplain Bridge
Ratio of cross-stream width beneath road to the average upstream bank-full width	1.24	0.97
Outfall Contributing area (at site, km^2)	0.03	0.03
%Drainage Area Contributed at Outfall	0.11	0.12
%TIA in Outfall Contributing Area	45	21

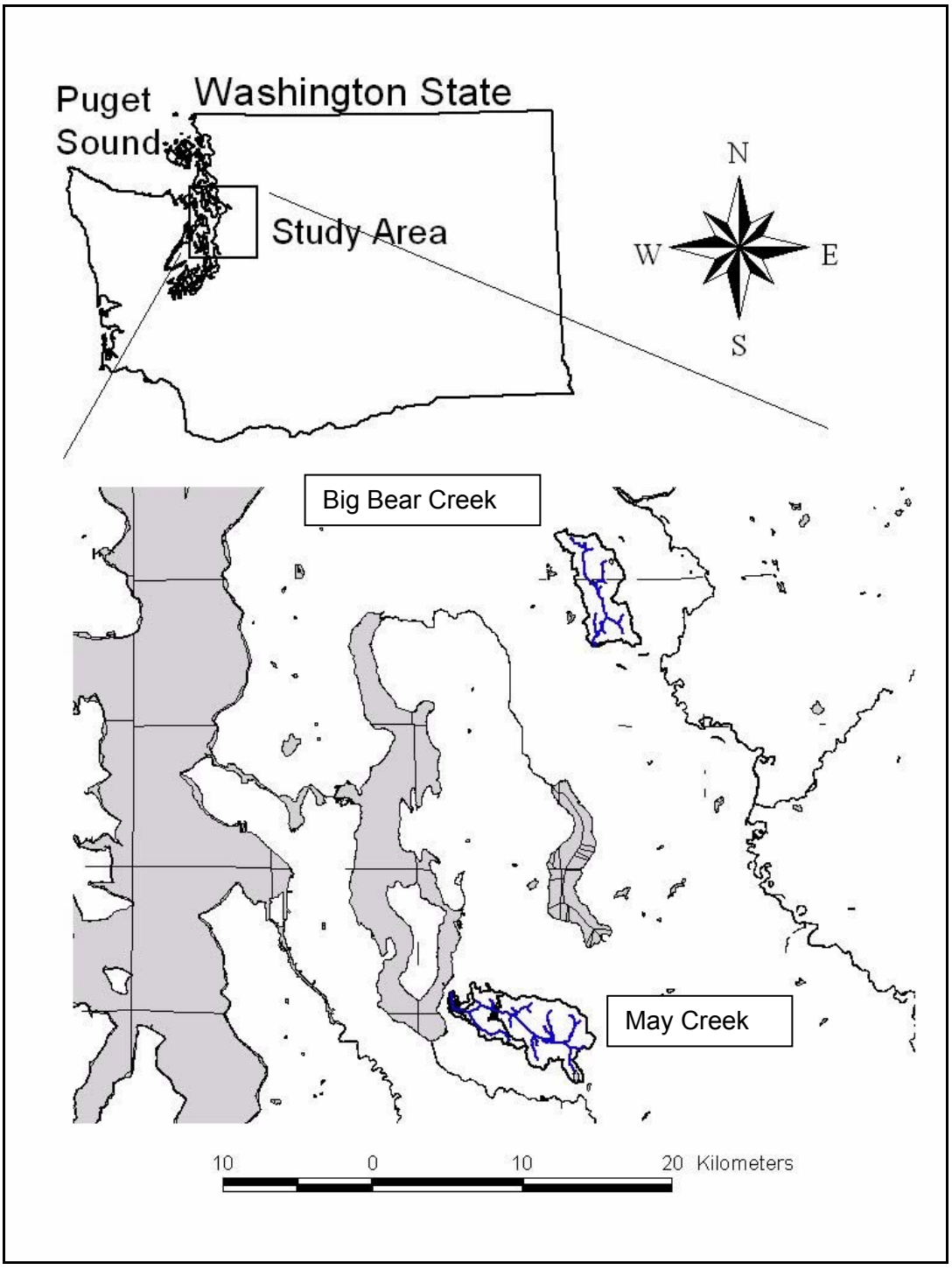

Figure 2.3: Locations of sample watersheds for the sediment transport study

2.4.2 Field Methods

Bed-tag Monitoring

Adapting a protocol developed by Konrad et al. (2002), steel washer bed tags (38mm diameter, 2mm thick) were used to track bed material entrainment at cross sections established upstream and downstream of both road crossings. The cross sections were located in riffles that had fairly consistent flow-depth throughout the section, and also had the most similarity to their upstream-downstream counterpart (see Figure 3.1 and Appendix A, respectively, for the locations of the Big Bear Creek and May Creek bed tag cross sections within the channel). Three rows of bed tags were placed at each cross section, with one row at the cross section, one row one meter upstream of the cross section, and one row one meter downstream of the cross section. The washers were located at 0.5m intervals across each row. The tags were set up so close enough along the cross section so that each tag would hypothetically have an equal probability of entrainment. Entrainment theory (White 1940, Einstein 1942, Komar and Li 1986) and empirical data from flume experiments (Little and Mayer 1976, Ikeda and Iseya 1988, Kirchner et al. 1990) have yet to adequately support extrapolation of the results regarding the spatial distribution of τ_{cr} and τ for gravel bed streams (Konrad 2002). Therefore, for this study, the probability of gravel entrainment was assumed to be spatially uniform across the cross section, as benchmarked by the median grain-size diameter of the cross section's sediment.

A short piece of flagging was tied to each washer to increase its visibility for subsequent field observations. Washers were placed vertically between the stream surface sediments, with their axes oriented cross-stream, until their tops were even with the surface of the bed material. This bed tag washer set-up was designed so that the tags would be displaced when the surface sediment surrounding them also became dislodged. In this way, the washers could be monitored for presence/absence after different storm flows and thereby serve as benchmarks for bed-surface entrainment.

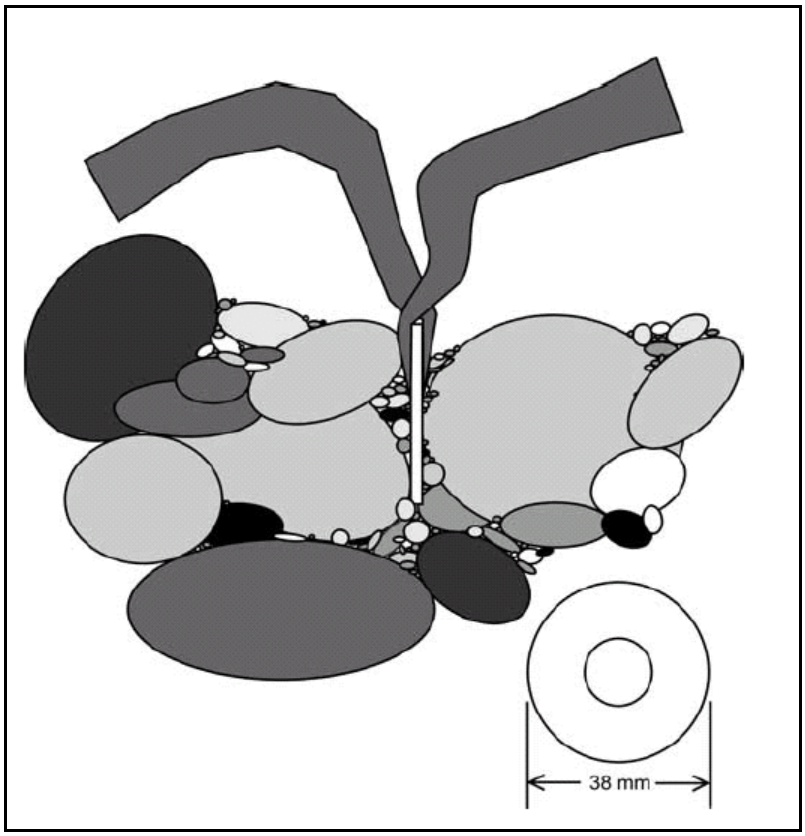

Figure 2.4: Diagram of bed-tag placement in a stream bed (Konrad 2002)

Bed-tag cross sections were established on 11/8/2002 for the May Creek site and on 11/17/2002 for the Big Bear Creek site. They were monitored throughout the winter and spring of water year 2003. Sites were inventoried after each individual flood peak and at least twice each month. When tags were missing, their locations were recorded and new washers were placed at the location. Therefore, for each inventory, the percent of the number of tags missing for each row and for each site served as the measure of partial entrainment (PE). Cross-sectional PE was then compared for sites upstream and downstream of the road crossings to test the hypothesis that reaches downstream of stormwater outfalls experience increased frequencies and magnitudes of gravel bed entrainment.

Channel thalweg profiles were surveyed in the summer before the entrainment study. Pebble counts (Wolman 1954) were also collected at the beginning of the

entrainment study to estimate the particle size distribution for each cross section. In addition, cross-sectional surveys and flow measurements were taken at each site before, during, and after the entrainment sample period. In this way, the cross sections could be monitored for changes with time, and associations and rating curves between discharge, water-surface slope, and hydraulic radius could be made.

Hydrologic Data

Discharge information for the water year prior to the entrainment study (water year 2002) was available from King County. The closest gauge (02f) to the Big Bear Creek site was located at the next road crossing upstream of the NE 148th St. sample location. The closest stream gauge (37a) to the May Creek site was located at the next road crossing downstream of the I-405 sample location. Daily maximum discharge summaries are shown in Figure 2.5 and Figure 2.6 below.

Gauge discharge information for water year 2003 was also collected from King County. This data was used to compare dates with peak discharges to dates with observed entrainment.

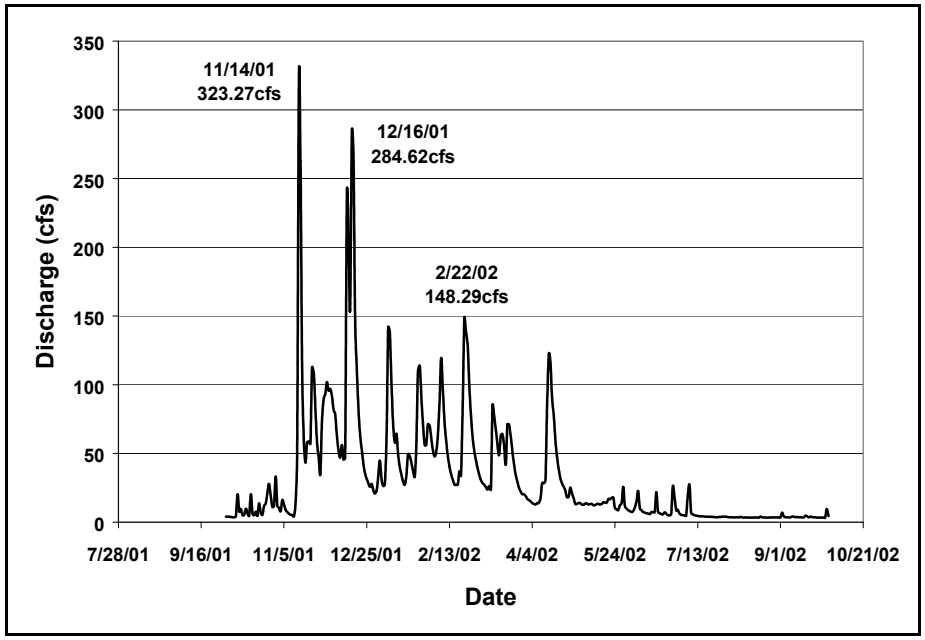

Figure 2.5: Maximum daily flow record for the May Creek gauge in water year 2002

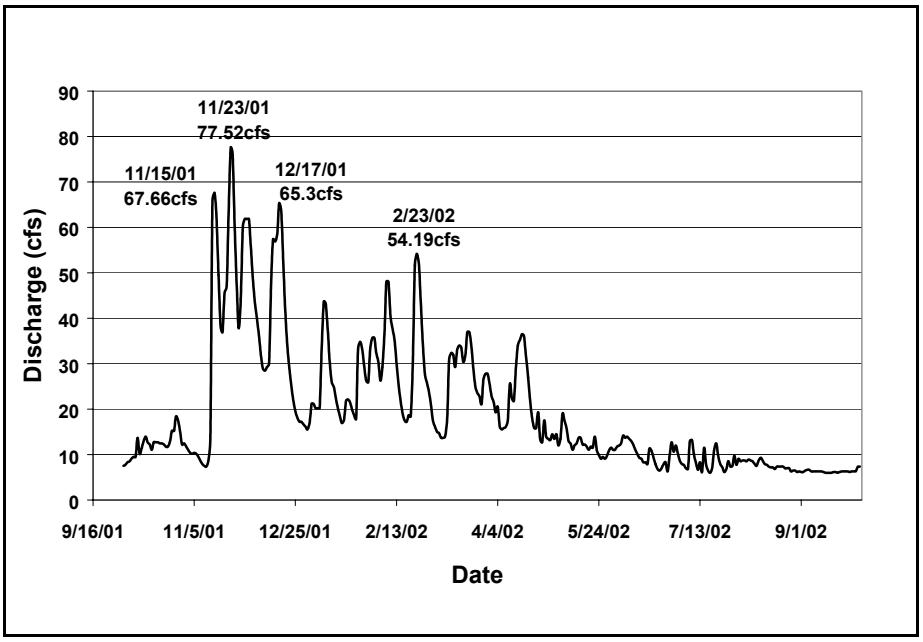

Figure 2.6: Maximum daily flow record for the Big Bear Creek gauge in water year 2002

2.4.3 Analytical Methods

The total calculated boundary shear stress was used to estimate the average applied shear stress acting across each cross section. Assuming that the highest discharge between each inventory was responsible for any entrainment that would have occurred, the total boundary shear stress was calculated for the peak flow between each inventory using the following uniform flow equation:

$$\tau_0 = \gamma_w RS,$$

where γ_w is the specific weight of water (taken as 9,800 N/m^3), R is the hydraulic radius (m), and S is the water surface slope, or the energy gradient, of the stream flow across the cross section. τ_0 is dependent on the variations of hydraulic radius and slope that correspond to different peak stages or discharges. Therefore, calculations of τ_0 for particular storms of known peak flows were based on rating curves that related field-measured values of hydraulic radius to known gauge-recorded discharges. Rating

curves between discharge and hydraulic radius are shown in Table 2.10. Local slopes did not show systematic differences relative to measured discharge. Thus, the average field-measured local slope was used for the shear stress calculations. The average upstream and downstream local slopes were 0.0036 and 0.0110, respectively for May Creek, and 0.0034 and 00110, respectively for Big Bear Creek.

Table 2.10: Rating Curves for predicting hydraulic radius (R) from discharge (Q), extrapolated from field measurements of corresponding R and Q

Section	Rating Curve [Hydraulic radius (R) predicted by discharge (Q)]
Downstream May	$R = 0.16*Q^{0.20}$
Upstream May	$R = 0.25*Q^{0.24}$
Downstream Big Bear	$R = 0.23*Q^{0.43}$
Upstream Big Bear	$R = 0.35*Q^{0.52}$

In order to compare sites, the dimensionless shear stress, τ^*_0, was also calculated using the following equation:

$$\tau^*_0 = \tau_0/(\gamma_s - \gamma_w)D_{50},$$

where γ_s is the specific weight of the sediment, estimated to be 2.7 (estimated from bulk samples collected in similar creeks nearby; Konrad 2002) multiplied by γ_w, and the D_{50} is the median particle size at the cross section, as measured by pebble counts.

In order to use the uniform flow equations for the shear stress calculations it was assumed that the road crossings would not cause any backwater effects. For May Creek, the upstream cross section was 50 m upstream of the nearest road-related armor. This distance was considered to be beyond any potential backwater effects, especially since the road-crossing design, a hillslope bridge, was not very confining. However, for Big Bear Creek, the upstream cross section was only 22 m upstream of the road crossing, which is a slightly more confining floodplain bridge. This cross section could therefore potentially experience local effects of backwater under higher discharges. The net effect of ignoring the potential of backwater influence would be to possibly overestimate the shear stress upstream and underestimate the shear stress downstream, but, because there was not adequate field data for water surface slopes to make the necessary backwater adjustments, only the uniform flow equations were used.

The resulting inherent errors in the shear stress calculations for the Big Bear site could not be quantitatively assessed.

Once the dimensionless shear stress calculations were completed, comparisons of these values to different upstream and downstream channel morphologies and different road crossing designs could be made. Linear regressions were carried out to correlate dimensionless shear stress values to observed PE using SPSS. Any differences in the relationships between PE and dimensionless shear stress would be indicative of both the influences of the road crossing design on the channel hydraulics and the subsequent abilities of the channel to transport sediment. Therefore, these shear stress and partial-entrainment relationships were explored relative to reach and cross-sectional measures of channel morphologic structure.

3 RESULTS

This section is divided into three major parts that are congruent with the three separate field studies: 1) an initial geomorphic assessment of local road impacts, 2) a broader geomorphic analysis of road crossing design and urbanization impacts, and 3) a paired-basin case study of road-crossing influences to hydraulics and sediment transport. The first section describes those hydraulic and geomorphic variables that were found to be the most sensitive to road-crossing impacts. It specifically examines the relationships between road crossings, sinuosity, and habitat complexity, and it compares the ability of different road crossings to have different impacts on channel morphology. In the second section relationships between reach geomorphology and both the road-crossing type and the total basin urbanization are described. Relationships between outfall pipes and increased downstream embeddedness and cementation are tested as well. The third section describes the differences in entrainment and shear stress that are experienced as a result of road-altered channel hydraulics, in addition to tracking the magnitude of entrainment relative to the delivery of concentrated runoff from outfalls.

3.1 Summer 2002 Initial Geomorphic Study Results

The summer 2002 data was analyzed for relationships between road crossings and their influences on hydraulic and geomorphic patterns.

3.1.1 Trends in Channel Hydraulics and Geometry by Road-Crossing Type

Alterations to channel hydraulics and geometries were quite variable. Figure 3.1 and Figure 3.2 show examples of the surveyed reach longitudinal profile, along with the surveyed cross sections and hydraulic parameters particular to each of those cross sections. Arrows indicate where the cross sections were surveyed along the longitudinal

profiles. Where the creeks could not be surveyed through the road crossing to create a continuous profile, there are two separate profile graphs – one each for the upstream and the downstream reaches (similar graphs are shown for the remaining sites in Appendix A).

Paired t-tests were not able to determine any significant differences in upstream-downstream hydraulic parameters across all sites ($p > 0.05$). Some patterns, however, emerged relative to how road crossings might relate to upstream-downstream changes of the hydraulic parameters based on consistent trends among a very limited sample population. Table 3.1 summarizes these changes by using arrows to signify the direction of the upstream-downstream change, where noted downstream changes had more than 10% (positive or negative) difference from the upstream reach value. The actual percent differences are also shown in the table. This table shows that the D_{50} values generally decreased or remained constant when transitioning from upstream to downstream for all the sites except for the floodplain bridges (FPbr), which saw increases in D_{50} values from upstream to downstream. The local slopes were also found to decrease from upstream to downstream reaches, except for two of the hillslope bridges (MA02 and MA01) and the Big Bear floodplain bridge (BB01). The reach-averaged slopes followed a similar trend, with decreases in the downstream direction. However, SW02 (double-box culvert) and MA02 and TH02 (two of the hillslope bridges) had higher reach-averaged downstream slopes. The reach slope estimate for SW02 included an upper section of the reach that had five concrete weirs. If this human-modified section of the channel was not included, the downstream reach slope was only 0.007, producing a –30% change relative to upstream. The increases in reach-average slope for MA02 and TH02, on the other hand, were minimal, with only about 10% differences.

More trends were identified when road crossings of similar design type were compared. BB01 and SW01, both floodplain bridges, were characterized by downstream decreases in hydraulic radius and reach-averaged slopes, and downstream increases in bank-full widths (BFW), width-to-depth ratios (W/D), and median particle size (D_{50}). In other words, reaches downstream of floodplain bridges became wider, shallower, and coarser with overall flatter slopes. The two double-box culverts, TH01

and SW02, also showed similar hydraulic patterns relative to each other. In both situations, moving from upstream to downstream related to increases to the hydraulic radius, decreases to the local slope and median particle size, and increases to both the width and the depth. Thus channels downstream of box culverts were larger, deeper, flatter, and finer. BE01 – the arch culvert – experienced some of the same trends of the other culverts. It too had a larger, flatter, downstream reach; but unlike the box culverts, there was no significant downstream change in sediment size.

The hillslope bridges did not exhibit distinct trends for downstream channel geometry. The two May Creek hillslope bridges had the most similar downstream changes, with decreases in hydraulic radius, increases in local slope, and similar bank-full widths. But the Thornton Creek hillslope bridge exhibited opposite trends, with a downstream increase in hydraulic radius, a decrease in local slope, and a decrease in bank-full width. The downstream reach for the Thornton Creek hillslope bridge was also impacted by intermittent patches of bank armoring from nearby residential development, however, which may have contributed to overall alterations in hydraulic geometry. In general, the hillslope bridges produced the most variable results of the different road types surveyed, and also the most common occurrences of less than 10% downstream changes in the channel parameters.

Table 3.1: Summary of upstream to downstream trends in channel hydraulic geometry for the different road crossings

Creek	Site	Road Type	Hydraulic Radius (m)	W/D Ratio	D50	Local Slope	Reach Averaged Slope	Bankfull Width (m)	Bankfull Depth (m)
Thornton	TH02	Hillbr	66.7 ↑	-45.9 ↓	-41.7 ↓	-41.7 ↓	9.1 =	-55.2 ↓	-17.1 ↓
May	MA02	Hillbr	-25.0 ↓	-34.7 ↓	2.2 =	22.2 ↑	11.8 ↑	-2.5 =	49.2 ↑
May	MA01	Hillbr	-30.8 ↓	0.8 =	-18.8 ↓	150.0 ↑	-38.5 ↓	-4.3 =	-5.1 =
Big Bear	BB01	FPbr	-33.3 ↓	52.1 ↑	108.7 ↑	120.0 ↑	-40.0 ↓	30.7 ↑	-14.0 ↓
Swamp	SW01	FPbr	-12.5 ↓	78.9 ↑	25.0 ↑	-46.7 ↓	-54.5 ↓	73.3 ↑	-3.1 =
Big Beef	BE01	Arch	125.0 ↑	-40.5 ↓	8.8 =	-70.0 ↓	-70.6 ↓	-22.9 ↓	29.5 ↑
Thornton	TH01	Culvert	50.0 ↑	39.1 ↑	-65.6 ↓	-85.7 ↓	-14.3 ↓	58.9 ↑	14.3 ↑
Swamp	SW02	Culvert	40.0 ↑	-27.9 ↓	-48.8 ↓	-87.5 ↓	70.0 ↑	31.6 ↑	82.6 ↑

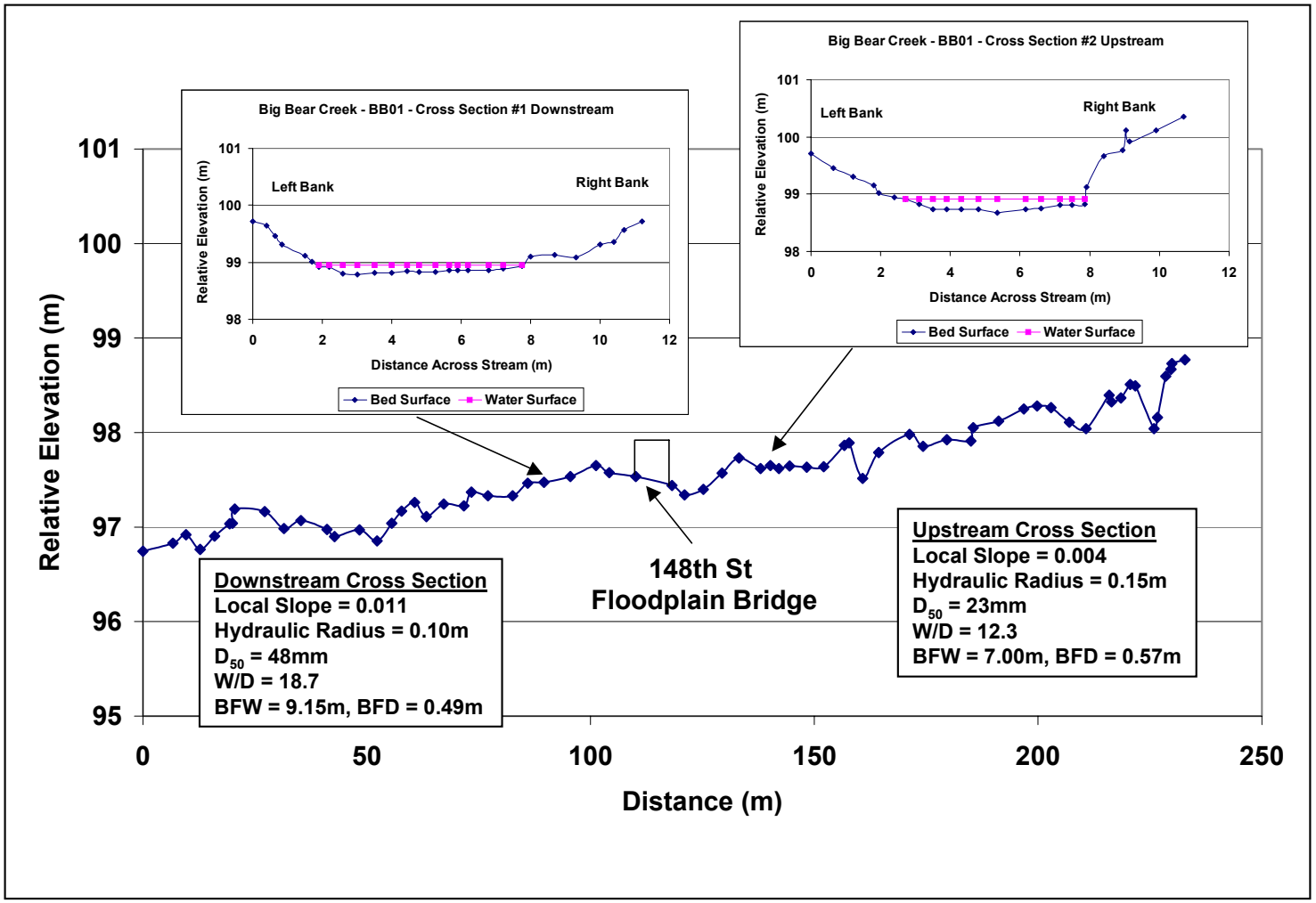

Figure 3.1: Surveyed profile and cross sections, and hydraulic data for Big Bear Creek (BB01) on 8/26/02

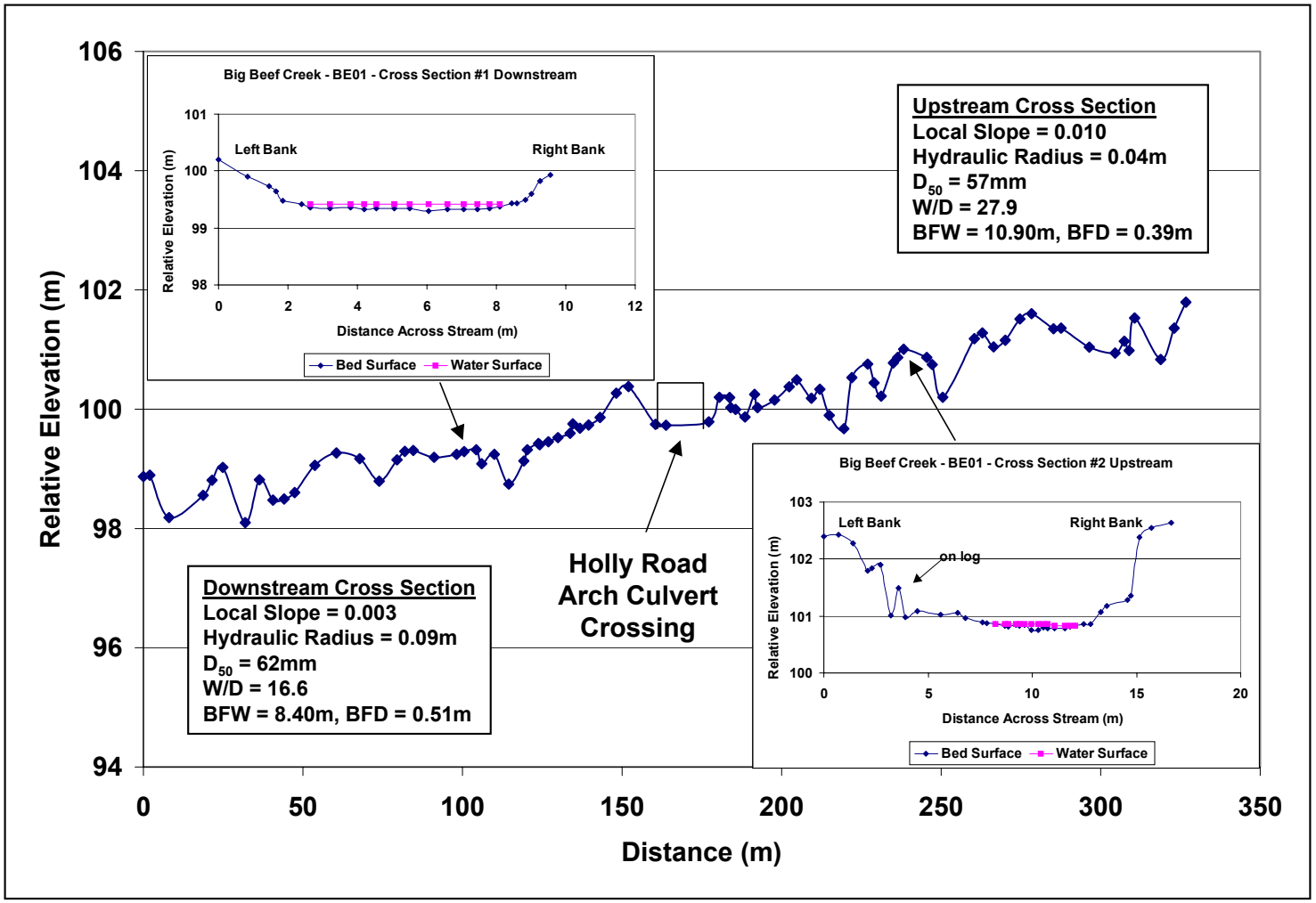

Figure 3.2: Surveyed profile and cross sections, and hydraulic data for Big Beef Creek (BE01) on 8/26/02

3.1.2 Geomorphic Relationships

Significant Upstream-Downstream Trends

Several of the geomorphic variables were found to have significant upstream-downstream differences ($p < 0.05$). Road crossings, regardless of type or level of basin urbanization, were associated with lower downstream channel complexity ($p = 0.019$), LWD ($p = 0.007$), embeddedness ($p = 0.007$), and cementation ($p = 0.002$) rankings; less sinuosity ($p = 0.002$); and lower overall PSCI scores ($p = 0.001$). Downstream reaches had significantly higher percentages of bank armoring ($p = 0.043$) and significantly lower values of riparian width/integrity rankings ($p = 0.005$). Other variables, such as the bank stability, the percent of the reach with bank erosion, the pool frequency, and length of gravel bars/100m did not show significant upstream-downstream differences.

Relationships Among Geomorphic Variables

Correlations between PSCI and other variables were explored to understand the potential processes through which road crossings alter downstream physical conditions (Table 3.2). In other words, by correlating the PSCI and PSCI sub-metrics with other geomorphic variables that were shown by t-tests to be significantly different downstream of roads, the reasons that road crossings lead to degraded physical conditions can be better evaluated. Two such variables were the sinuosity and the riparian rank. Both the sinuosity and the riparian rank had significantly lower values downstream of road crossings. These metrics are also significantly correlated to increasing PSCI scores ($R^2 = 0.74$, $p < 0.001$ for the sinuosity and $R^2 = 0.45$, $p = 0.005$ for the riparian rank). Therefore, lower PSCI scores downstream of roads could also be a symptom of road-related decreases of the sinuosity and the riparian zone width and integrity.

To test the hypothesis that road-related bank armoring can alter the downstream morphology of alluvial reaches, relationships between PSCI and the percent bank armor metric were explored. Paired t-tests had already found that road crossings were

associated with significantly more bank armoring downstream of them than upstream. Linear regression results also found that the percent of reach armored had a negative correlation to the PSCI scores ($R^2 = 0.55$, $p = 0.001$). Bank armoring was also negatively correlated to the bank stability rank ($R^2 = 0.65$, $p = 0.000$), the LWD rank ($R^2 = 0.36$, $p = 0.013$), the sinuosity ($R^2 = 0.57$, $p = 0.001$), and the length of gravel bars/100m ($R^2 = 0.33$, $p = 0.021$). Therefore roads with more armoring have more straightened and unstable downstream alluvial reaches with less LWD or gravel bars.

The width-to-depth (W/D) ratio was also positively correlated to PSCI ($R^2 = 0.37$, $p = 0.013$). This relationship was further explored by considering the regression results of the W/D ratio with specific sub-metrics of the PSCI. The W/D ratio was significantly correlated with metrics for bank stability ($R^2 = 0.49$, $p = 0.003$) and the number of LWD/100m ($R^2 = 0.60$, $p < 0.001$). Therefore, higher PSCI scores are related to higher W/D ratios, or wider, shallower channels, because these channels have more bank stability and are characterized by higher numbers of LWD. Yet because paired sample t-tests did not find a significant change in the downstream W/D ratio across all road crossings, more analysis would be needed to determine which road-crossing types produce downstream decreases in W/D and thereby less bank stability and LWD.

Table 3.2: Simple linear regression relationships for geomorphic and urbanization variables tested

		R	D50	W/D	Stability	LWD rank	LWD/ 100m	Comp lexity	Embedd edness	Cement ation	%TIA	Rd xs/km of stream	pool frequency (#/10m)	Rip Width/ Integ. Rank	% reach armor	% bank erosion	Gravel Bar/100m	PSCI	Sinuosity
R	R	1.000	-0.150	-0.090	0.153	0.104	-0.193	-0.052	0.116	0.119	-0.396	-0.428	0.030	-0.133	0.024	-0.367	-0.160	0.098	0.187
	p (2-tail)	.	0.579	0.739	0.572	0.700	0.474	0.848	0.668	0.660	0.129	0.098	0.912	0.622	0.928	0.162	0.555	0.719	0.489
D50	R	-0.150	1.000	0.749	0.605	0.695	0.593	0.551	0.718	0.286	-0.610	-0.592	0.290	0.682	-0.438	-0.412	0.470	0.686	0.448
	p (2-tail)	0.579	.	0.001	0.013	0.003	0.015	0.027	0.002	0.282	0.012	0.016	0.276	0.004	0.090	0.113	0.066	0.003	0.082
W/D	R	-0.090	0.749	1.000	0.697	0.432	0.777	0.525	0.532	0.419	-0.473	-0.483	0.404	0.427	-0.349	-0.376	0.165	0.606	0.311
	p (2-tail)	0.739	0.001	.	0.003	0.095	0.000	0.037	0.034	0.106	0.064	0.058	0.120	0.099	0.185	0.151	0.540	0.013	0.241
Stability	R	0.153	0.605	0.697	1.000	0.619	0.558	0.619	0.583	0.643	-0.487	-0.506	0.497	0.438	-0.805	-0.221	0.385	0.795	0.643
	p (2-tail)	0.572	0.013	0.003	.	0.011	0.025	0.011	0.018	0.007	0.056	0.046	0.050	0.089	0.000	0.410	0.141	0.000	0.007
LWD rank	R	0.104	0.695	0.432	0.619	1.000	0.602	0.803	0.774	0.570	-0.632	-0.599	0.446	0.748	-0.603	-0.388	0.516	0.899	0.777
	p (2-tail)	0.700	0.003	0.095	0.011	.	0.014	0.000	0.000	0.021	0.009	0.014	0.083	0.001	0.013	0.137	0.041	0.000	0.000
LWD/100m	R	-0.193	0.593	0.777	0.558	0.602	1.000	0.603	0.581	0.576	-0.520	-0.501	0.466	0.649	-0.350	-0.256	0.093	0.683	0.461
	p (2-tail)	0.474	0.015	0.000	0.025	0.014	.	0.013	0.018	0.020	0.039	0.048	0.069	0.006	0.184	0.339	0.731	0.004	0.073
Complexity	R	-0.052	0.551	0.525	0.619	0.803	0.603	1.000	0.814	0.550	-0.398	-0.424	0.531	0.582	-0.558	-0.432	0.529	0.906	0.746
	p (2-tail)	0.848	0.027	0.037	0.011	0.000	0.013	.	0.000	0.027	0.126	0.102	0.034	0.018	0.025	0.094	0.035	0.000	0.001
Embeddedness	R	0.116	0.718	0.532	0.583	0.774	0.581	0.814	1.000	0.549	-0.616	-0.663	0.460	0.643	-0.528	-0.512	0.534	0.893	0.788
	p (2-tail)	0.668	0.002	0.034	0.018	0.000	0.018	0.000	.	0.028	0.011	0.005	0.073	0.007	0.036	0.042	0.033	0.000	0.000
Cementation	R	0.119	0.286	0.419	0.643	0.570	0.576	0.550	0.549	1.000	-0.175	-0.192	0.355	0.376	-0.763	0.000	0.277	0.749	0.678
	p (2-tail)	0.660	0.282	0.106	0.007	0.021	0.020	0.027	0.028	.	0.516	0.477	0.177	0.151	0.001	0.999	0.299	0.001	0.004
%TIA	R	-0.396	-0.610	-0.473	-0.487	-0.632	-0.520	-0.398	-0.616	-0.175	1.000	0.976	-0.355	-0.624	0.207	0.392	-0.177	-0.559	-0.387
	p (2-tail)	0.129	0.012	0.064	0.056	0.009	0.039	0.126	0.011	0.516	.	0.000	0.177	0.010	0.443	0.134	0.512	0.024	0.138
Rd xs/km of stream	R	-0.428	-0.592	-0.483	-0.506	-0.599	-0.501	-0.424	-0.663	-0.192	0.976	1.000	-0.434	-0.522	0.209	0.408	-0.232	-0.577	-0.413
	p (2-tail)	0.098	0.016	0.058	0.046	0.014	0.048	0.102	0.005	0.477	0.000	.	0.093	0.038	0.437	0.117	0.387	0.019	0.112
pool frequency	R	0.030	0.290	0.404	0.497	0.446	0.466	0.531	0.460	0.355	-0.355	-0.434	1.000	0.155	-0.266	-0.441	0.510	0.539	0.434
	p (2-tail)	0.912	0.276	0.120	0.050	0.083	0.069	0.034	0.073	0.177	0.177	0.093	.	0.567	0.320	0.087	0.044	0.031	0.093
Rip Width/ Integ. Rank	R	-0.133	0.682	0.427	0.438	0.748	0.649	0.582	0.643	0.376	-0.624	-0.522	0.155	1.000	-0.389	-0.254	0.252	0.670	0.436
	p (2-tail)	0.622	0.004	0.099	0.089	0.001	0.006	0.018	0.007	0.151	0.010	0.038	0.567	.	0.137	0.342	0.347	0.005	0.092
% reach armor	R	0.024	-0.438	-0.349	-0.805	-0.603	-0.350	-0.558	-0.528	-0.763	0.207	0.209	-0.266	-0.389	1.000	-0.149	-0.571	-0.743	-0.755
	p (2-tail)	0.928	0.090	0.185	0.000	0.013	0.184	0.025	0.036	0.001	0.443	0.437	0.320	0.137	.	0.581	0.021	0.001	0.001
% bank erosion	R	-0.367	-0.412	-0.376	-0.221	-0.388	-0.256	-0.432	-0.512	0.000	0.392	0.408	-0.441	-0.254	-0.149	1.000	-0.097	-0.391	-0.325
	p (2-tail)	0.162	0.113	0.151	0.410	0.137	0.339	0.094	0.042	0.999	0.134	0.117	0.087	0.342	0.581	.	0.720	0.134	0.219
Gravel Bar /100m	R	-0.160	0.470	0.165	0.385	0.516	0.093	0.529	0.534	0.277	-0.177	-0.232	0.510	0.252	-0.571	-0.097	1.000	0.539	0.551
	p (2-tail)	0.555	0.066	0.540	0.141	0.041	0.731	0.035	0.033	0.299	0.512	0.387	0.044	0.347	0.021	0.720	.	0.031	0.027
PSCI	R	0.098	0.686	0.606	0.795	0.899	0.683	0.906	0.893	0.749	-0.559	-0.577	0.539	0.670	-0.743	-0.391	0.539	1.000	0.856
	p (2-tail)	0.719	0.003	0.013	0.000	0.000	0.004	0.000	0.000	0.001	0.024	0.019	0.031	0.005	0.001	0.134	0.031	.	0.000
Sinuosity	R	0.187	0.448	0.311	0.643	0.777	0.461	0.746	0.788	0.678	-0.387	-0.413	0.434	0.436	-0.755	-0.325	0.551	0.856	1.000
	p (2-tail)	0.489	0.082	0.241	0.007	0.000	0.073	0.001	0.000	0.004	0.138	0.112	0.093	0.092	0.001	0.219	0.027	0.000	.

Local Road-Crossing Impacts Relative to Cumulative Road Influence

Correlation results explored many interrelationships among the geomorphic variables to better explain some of the significant upstream-downstream trends implied by the paired t-test results. Yet the cumulative influences of the entire road network, and specifically the connectivity of that road network, must also be considered to adequately understand the local significance of an individual road crossing's impacts. Regression of the PSCI metric against the number of road crossings per km of stream illustrates that the increasing number of road crossings upstream of a sample reach contributes to a downward trend in physical condition ($R^2 = 0.33$, $p = 0.019$). Although there is substantial variability for any given number of road crossings, regressing the upstream and downstream data separately (Figure 3.3) significantly reduces the PSCI variability ($R^2 = 0.52$ for upstream reaches, $R^2 = 0.53$ for downstream reaches). Reaches upstream of road crossings have distinctly higher PSCI scores than reaches downstream of road crossings (according to paired t-test results), but because the two regression lines are almost parallel, both upstream and downstream reaches appear to be similarly impacted by the increasing number of road crossings upstream.

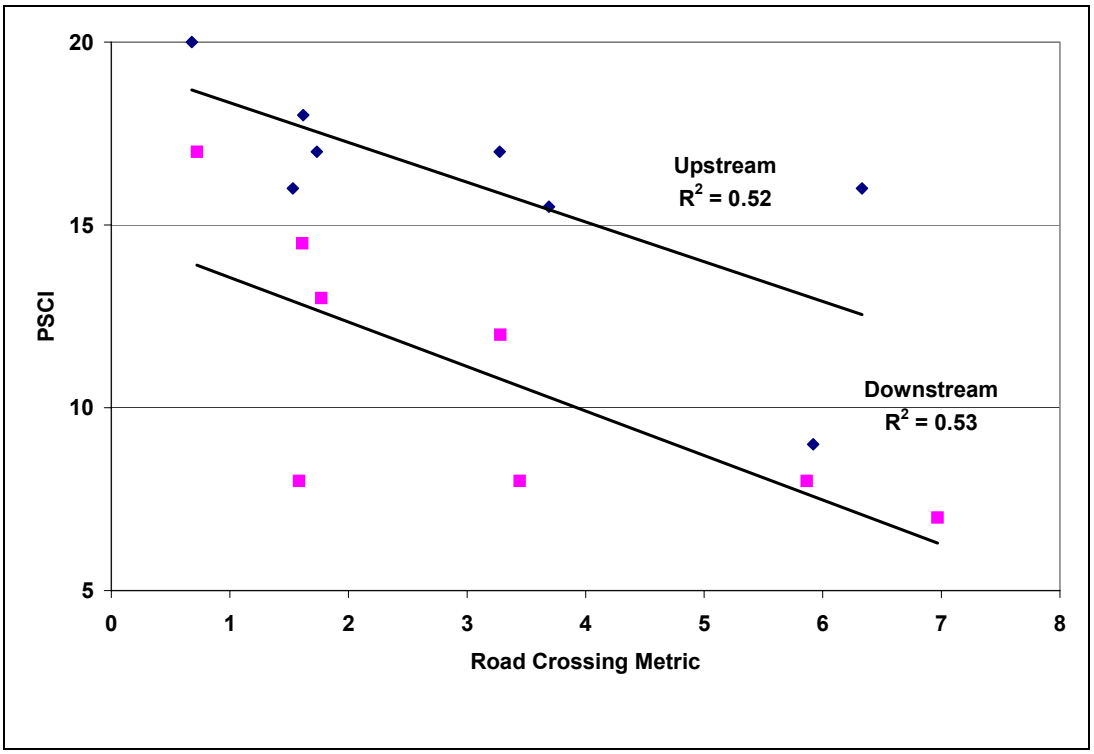

Figure 3.3: Upstream-downstream trends in PSCI relative to the road-crossing metric

3.2 Broader Geomorphic Analysis Results

The spring 2003 geomorphic data were used to explore the relationships between overall sub-basin urbanization and various road-crossing types on physical in-stream conditions. This analysis was motivated by the preliminary results of the previous year that demonstrated some statistically significant upstream-downstream relationships, even with a very small sample set.

3.2.1 Significant Upstream-Downstream Geomorphic Trends

Paired sample t-test analyses were once again carried out across the entire sample set to determine which geomorphic variables exhibited significant ($p < 0.05$)

upstream-downstream trends relative to road crossings. Spring 2003 data characterized reaches downstream of road crossings as having:

- Less sinuosity ($p = 0.002$)
- Higher percent bank armoring ($p = 0.022$)
- Less LWD/100m ($p = 0.045$)
- Lower pool frequency ($p = 0.013$), lower pool volume/100m ($p = 0.029$)
- Less gravel bar storage ($p = 0.034$), lower habitat complexity ranks ($p < 0.001$)
- More bank erosion ($p = 0.002$), lower bank stability ranks ($p < 0.001$)
- More cemented ($p < 0.001$) and embedded ($p < 0.001$) gravels
- Lower overall PSCI scores ($p < 0.001$)

In contrast to the summer 2002 results, the riparian rank did not show a significant upstream-downstream difference ($p = 0.809$).

3.2.2 Comparison of PSCI and ΔPSCI to Road Types

With the data set divided between two road-crossing types, bridges and culverts, culverts correlated with lower values of downstream PSCI scores and larger differences in the upstream minus the downstream PSCI value (ΔPSCI). The average PSCI score downstream of culverts is about 10, while the average score downstream of bridges is closer to 14 (Figure 3.4). This result applies to the entire data set, for sites with all levels of watershed urbanization. T-tests found these road-crossing type differences to be significant ($p = 0.011$). The two culvert-category outliers in the graph with much higher downstream PSCI scores (one of the Rocky/Muck creek sites and one of the Church Creek sites) are both within low-urban basins, and they both have wide and generally intact riparian buffers. The low-scoring bridge outlier is one of the May Creek sites, directly downstream of a large stormwater outfall.

Culverts tend to be associated with greater upstream-downstream differences in PSCI. As shown in Figure 3.5, the average culvert-related ΔPSCI was about 4.7, while the average bridge-related ΔPSCI was found to be about 2.6. One-tail t-test results confirm that ΔPSCI is significantly larger for culverts than it is for bridges (p = 0.044). Two-tail t-tests, however, did not find the ΔPSCI scores to be significantly different between the two road groupings (p = 0.087).

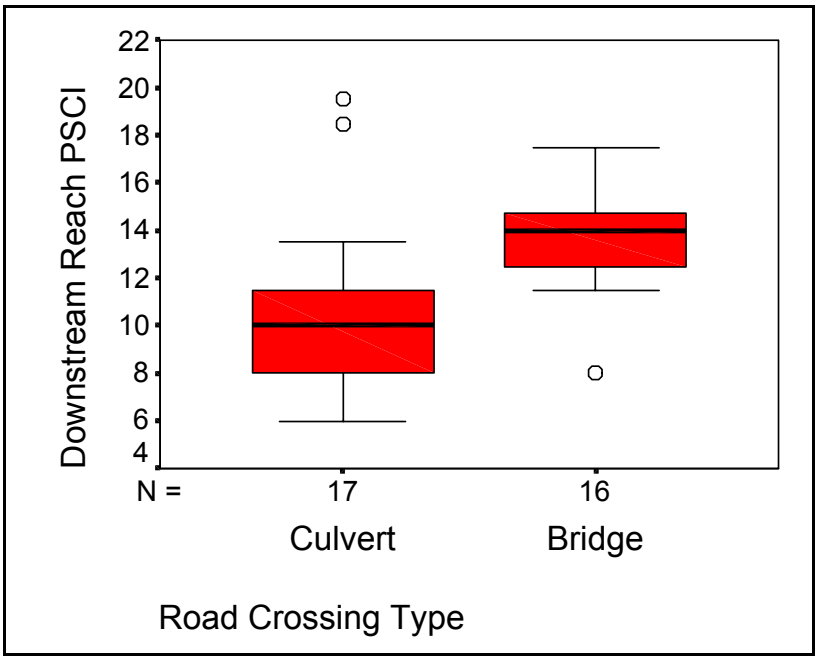

Figure 3.4: Comparison of PSCI scores downstream of culverts vs. downstream of bridges

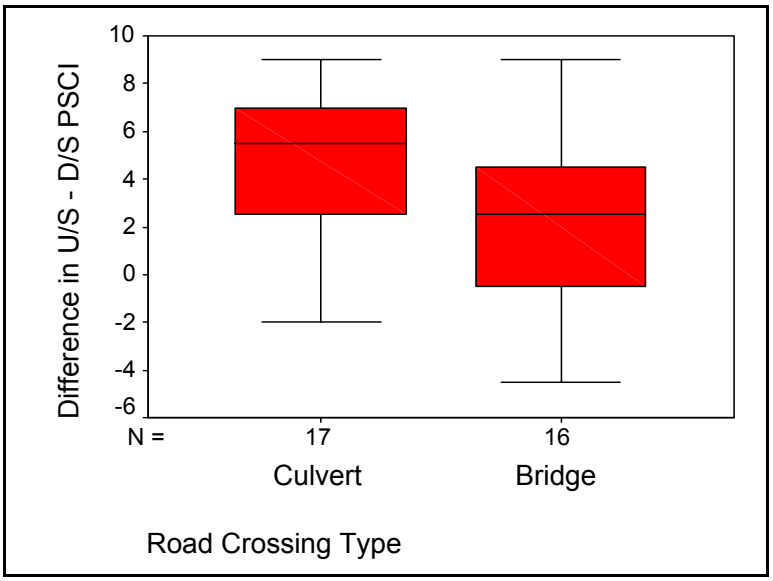

Figure 3.5: Comparison of ΔPSCI scores relative to bridges vs. culverts

When the sites are grouped by the four different road-crossing types, each of the two culvert types are associated with lower downstream PSCI values than either of the two bridge types. Floodplain bridges have the highest mean downstream PSCI values while the plain culverts have the lowest mean downstream PSCI values. The arch culverts have mean downstream PSCI values similar to that of plain culverts, but the arch culverts have more variance possibly related to their smaller sample size. Only four hillslope bridge road crossings were surveyed, but their mean downstream PSCI value was not as high as that of the floodplain bridges. A Student Newman Keuls test found the arch culvert and the floodplain bridge to be the only two road crossing types to be significantly different

Examining the ΔPSCI values relative to the four road crossing categories illustrates that arch culverts are associated with the largest mean differences in upstream minus downstream PSCI values (ΔPSCI), while floodplain bridges are associated with the smallest mean differences in ΔPSCI. Both the culvert and hillslope bridge categories have intermediate ΔPSCI values, which generally range between 2 and 6. However, ANOVA tests did not find a significant difference between the ΔPSCI values for the four different road-crossing types ($p = 0.123$).

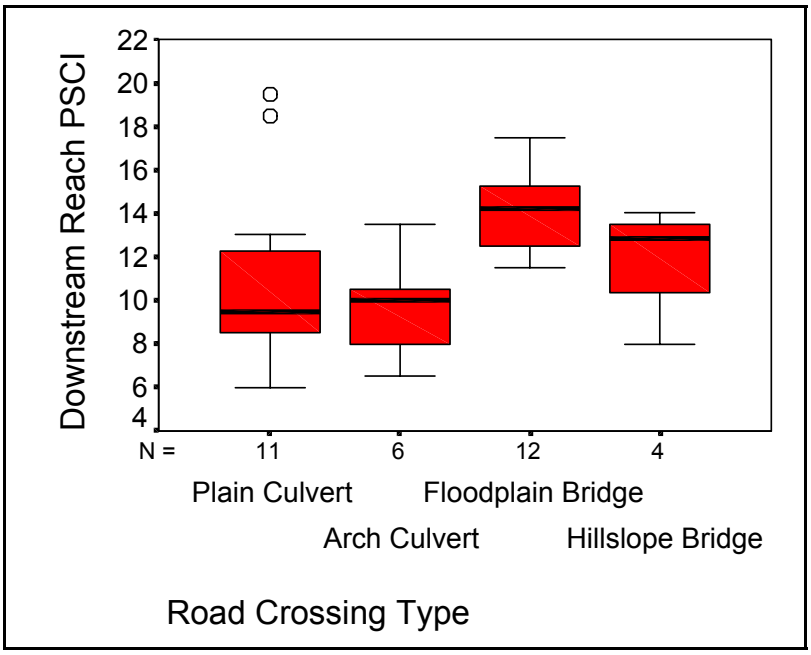

Figure 3.6: Downstream reach PSCI scores for the four road-crossing types

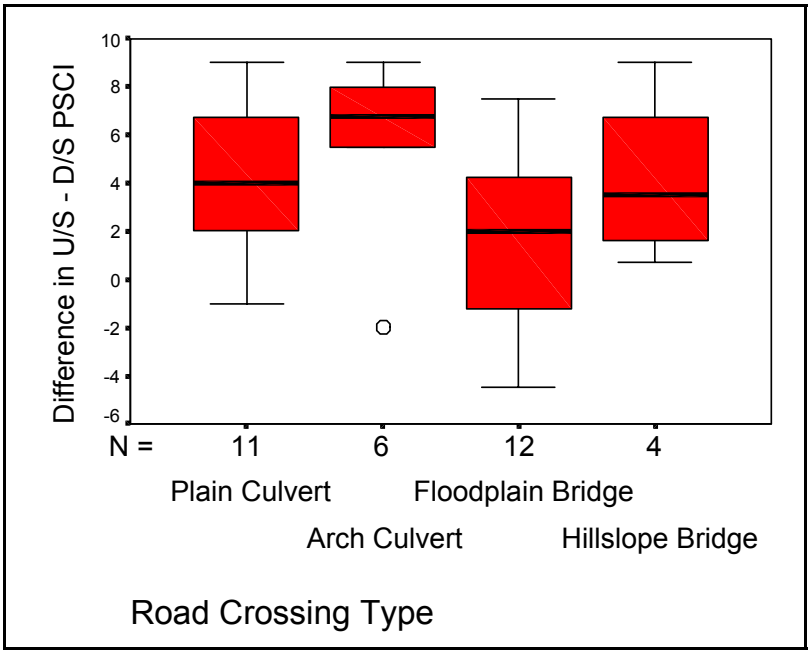

Figure 3.7: Comparison of ΔPSCI scores for the four road-crossing categories

3.2.3 Relation of PSCI to Combinations of Road-Crossing Type and Watershed Urbanization Level

Upstream-to-downstream PSCI values fall along different trends when grouped by the level of urbanization. When considering only the low-urban (i.e. <20% TIA) culvert and bridge categories, there is no significant difference between culverts and bridges ($p = 0.659$). However, the more urban reaches (>20% TIA) do experience significantly higher PSCI values downstream of bridges than downstream of culverts (Figure 3.8; $p < 0.001$).

Similar results are found when considering urbanization relative to the ΔPSCI. There is no significant difference between culverts and bridges for the <20% TIA category ($p = 0.683$), but the two road types relate to significantly different ΔPSCI scores for the >20% TIA category ($p = 0.014$). Culverts present in basins with >20% TIA were found to produce the largest ΔPSCI. These results suggest that urban reaches are more sensitive to the type of road-crossing impacts than less urban reaches.

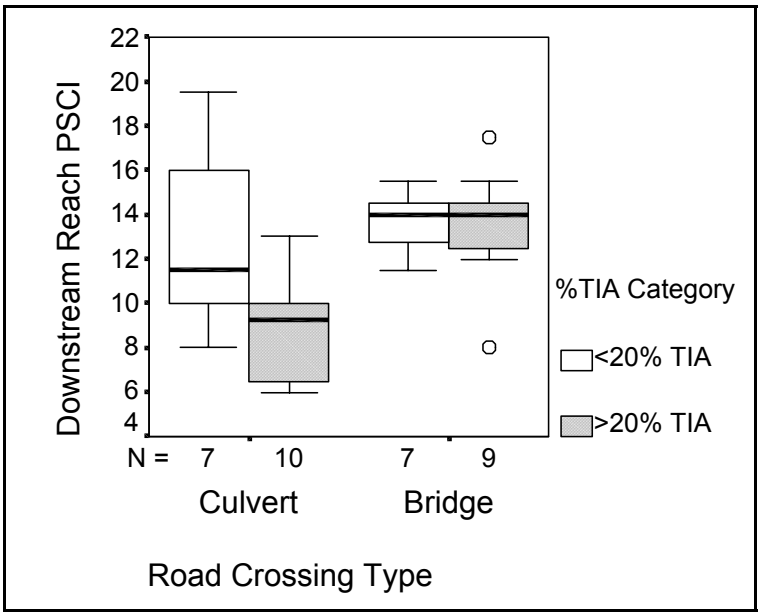

Figure 3.8: Downstream PSCI values for two road-crossing categories and two urbanization categories

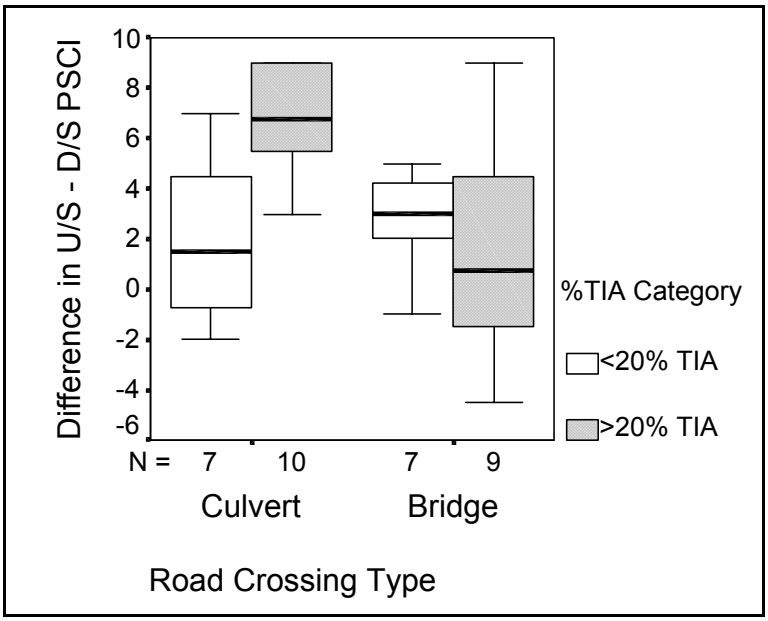

Figure 3.9: Comparisons of the ΔPSCI scores for two road-crossing categories and two urbanization categories

3.2.4 Regression Model Results

Several linear simple regression relationships were explored to better understand why different road types and different magnitudes of urbanization combine to impose different impacts on in-stream conditions (Table 3.3). One of the hypothesized causes for upstream-downstream changes in physical condition is the introduction of stormwater via outfall pipes at road crossings. For those reaches with outfall stormwater delivery, a simple linear regression produced a moderate correlation between the log of the total outfall area and the ΔPSCI (R^2 = 0.46, p = 0.007; Figure 3.10). To better understand this relationship between outfall contribution and overall decline in PSCI, both the total outfall area (including all data points) and the log of the total outfall area (including only those reaches with outfalls) were regressed against the PSCI sub-metrics. The only sub-metric that was significantly correlated to the log of the outfall area was the ΔChannel Complexity rank (R^2 = 0.54, p = 0.003), although a moderate correlation was found with

the metric for the differences in LWD/100m in upstream and downstream reaches (R^2 = 0.36, $p < 0.001$).

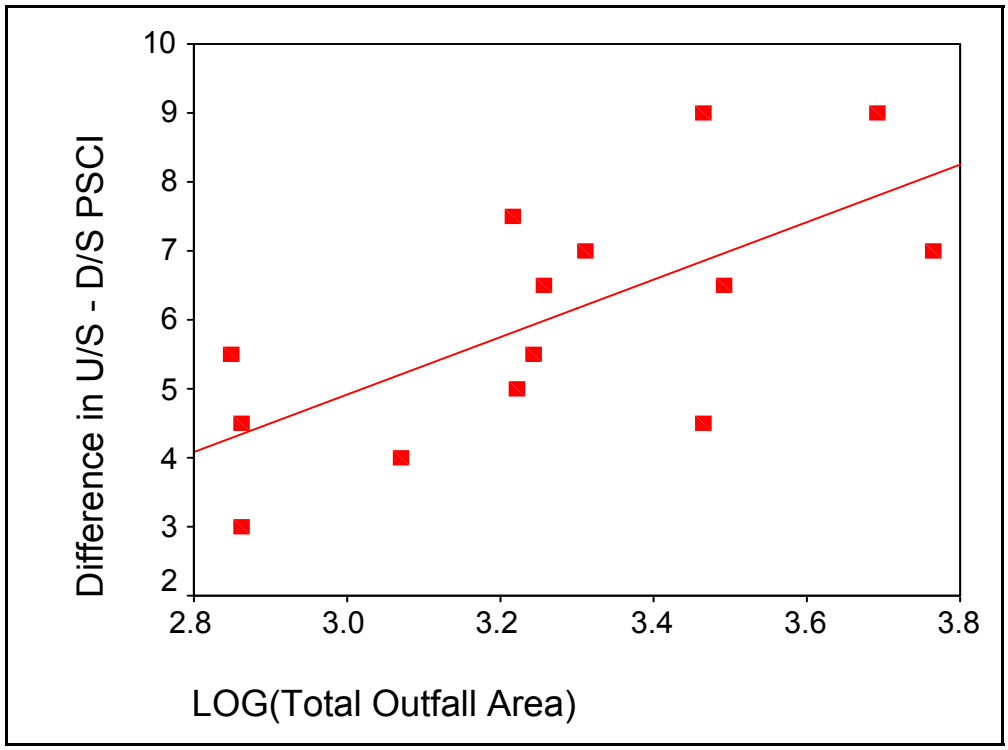

Figure 3.10: Relationship between the log of total outfall area per reach and the difference in upstream minus downstream PSCI

Table 3.3: Simple linear regression results for road metrics and upstream-downstream geomorphic change

		ΔPSCI	Δcomplexity	Δstability	Δcementation	Δembeddedness	ΔLWD rank	%Dif U/S - D/S Sinuosity	%Dif U/S - D/S Pool Vol	%Dif U/S - D/S Pool Freq	%Dif U/S - D/S Bank Erosion	%Dif U/S - D/S g-bar/100m	%Dif U/S - D/S LWD	%Dif U/S - D/S PSCI
ΔPSCI	R	1	0.814	0.529	0.646	0.625	0.778	0.326	0.398	0.485	0.071	0.401	0.739	0.965
	p (2-tail)	.	0	0.002	0	0	0	0.064	0.022	0.004	0.693	0.021	0	0
Δcomplexity	R	0.814	1	0.378	0.349	0.387	0.583	0.553	0.517	0.669	0.019	0.541	0.512	0.759
	p (2-tail)	0	.	0.03	0.046	0.026	0	0.001	0.002	0	0.915	0.001	0.002	0
Δstability	R	0.529	0.378	1	0.269	0.069	0.262	-0.041	0.193	0.238	-0.068	0.105	0.253	0.536
	p (2-tail)	0.002	0.03	.	0.13	0.704	0.14	0.819	0.281	0.183	0.706	0.561	0.156	0.001
Δcementation	R	0.646	0.349	0.269	1	0.517	0.237	0.034	0.14	0.118	0.011	0.091	0.492	0.643
	p (2-tail)	0	0.046	0.13	.	0.002	0.185	0.85	0.436	0.514	0.95	0.616	0.004	0
Δembeddedness	R	0.625	0.387	0.069	0.517	1	0.304	0.151	0.213	0.171	0.019	0.214	0.433	0.623
	p (2-tail)	0	0.026	0.704	0.002	.	0.086	0.401	0.234	0.342	0.916	0.232	0.012	0
ΔLWD rank	R	0.778	0.583	0.262	0.237	0.304	1	0.288	0.265	0.377	0.179	0.333	0.724	0.734
	p (2-tail)	0	0	0.14	0.185	0.086	.	0.104	0.136	0.031	0.319	0.058	0	0
%Dif U/S - D/S Sinuosity	R	0.326	0.553	-0.041	0.034	0.151	0.288	1	0.344	0.35	-0.103	0.508	0.288	0.339
	p (2-tail)	0.064	0.001	0.819	0.85	0.401	0.104	.	0.05	0.046	0.567	0.003	0.105	0.054
%Dif U/S - D/S Pool Vol	R	0.398	0.517	0.193	0.14	0.213	0.265	0.344	1	0.378	-0.18	0.367	0.358	0.404
	p (2-tail)	0.022	0.002	0.281	0.436	0.234	0.136	0.05	.	0.03	0.317	0.036	0.041	0.02
%Dif U/S - D/S Pool Freq	R	0.485	0.669	0.238	0.118	0.171	0.377	0.35	0.378	1	0.358	0.271	0.167	0.494
	p (2-tail)	0.004	0	0.183	0.514	0.342	0.031	0.046	0.03	.	0.041	0.127	0.352	0.004
%Dif U/S - D/S Bank Erosion	R	0.071	0.019	-0.068	0.011	0.019	0.179	-0.103	-0.18	0.358	1	0.072	0.226	0.192
	p (2-tail)	0.693	0.915	0.706	0.95	0.916	0.319	0.567	0.317	0.041	.	0.692	0.206	0.285
%Dif U/S - D/S g-bar/100m	R	0.401	0.541	0.105	0.091	0.214	0.333	0.508	0.367	0.271	0.072	1	0.352	0.455
	p (2-tail)	0.021	0.001	0.561	0.616	0.232	0.058	0.003	0.036	0.127	0.692	.	0.045	0.008
%Dif U/S - D/S LWD	R	0.739	0.512	0.253	0.492	0.433	0.724	0.288	0.358	0.167	0.226	0.352	1	0.769
	p (2-tail)	0	0.002	0.156	0.004	0.012	0	0.105	0.041	0.352	0.206	0.045	.	0
%Dif U/S - D/S PSCI	R	0.965	0.759	0.536	0.643	0.623	0.734	0.339	0.404	0.494	0.192	0.455	0.769	1
	p (2-tail)	0	0	0.001	0	0	0	0.054	0.02	0.004	0.285	0.008	0	.
Rd XS/km of Stream	R	0.168	0.062	0.216	0.061	0.02	0.2	0.006	-0.237	0.055	0.235	0.216	-0.082	0.201
	p (2-tail)	0.35	0.731	0.228	0.736	0.911	0.266	0.972	0.183	0.761	0.188	0.228	0.651	0.261
TIA	R	0.135	0.058	0.254	0.095	0.049	0.062	-0.047	-0.275	-0.029	0.106	0.13	-0.156	0.155
	p (2-tail)	0.455	0.75	0.153	0.6	0.786	0.731	0.794	0.122	0.872	0.558	0.47	0.386	0.388
Rd Armor Length	R	0.424	0.348	0.221	0.001	0.321	0.476	0.218	0.197	0.33	0.099	0.251	0.328	0.439
	p (2-tail)	0.014	0.047	0.216	0.995	0.068	0.005	0.224	0.271	0.061	0.582	0.159	0.062	0.011
%Reach Armor	R	0.056	-0.153	0.293	0.298	0.075	-0.135	-0.348	-0.054	0.024	0.38	0.086	-0.018	0.153
	p (2-tail)	0.756	0.395	0.098	0.092	0.679	0.455	0.047	0.766	0.895	0.029	0.634	0.922	0.394
#outfalls	R	0.251	0.073	0.169	0.2	0.177	0.241	0.07	0.034	-0.207	-0.096	0.2	0.309	0.213
	p (2-tail)	0.16	0.688	0.348	0.264	0.323	0.176	0.698	0.849	0.247	0.594	0.265	0.08	0.233
Total Outfall Area	R	0.566	0.403	0.298	0.23	0.5	0.492	0.209	0.202	0.251	-0.099	0.279	0.421	0.556
	p (2-tail)	0.001	0.02	0.092	0.198	0.003	0.004	0.244	0.26	0.159	0.583	0.116	0.015	0.001
Log(total outfall area)	R	0.68	0.737	-0.028	-0.159	0.438	0.326	0.496	0.578	0.707	-0.354	0.18	0.545	0.521
	p (2-tail)	0.007	0.003	0.925	0.586	0.118	0.256	0.072	0.03	0.005	0.214	0.538	0.044	0.056
Rd W/ upstream BFW	R	-0.381	-0.221	-0.274	-0.421	-0.191	-0.239	0.018	-0.157	-0.118	-0.168	-0.385	-0.422	-0.434
	p (2-tail)	0.029	0.217	0.122	0.015	0.286	0.18	0.922	0.384	0.512	0.35	0.027	0.014	0.012

In addition to the amount of stormwater introduced at road crossings, the amount of confinement imposed by the road crossing was also tested for its relation to increased degradation of physical stream condition. However, regressions of the road-confinement metric (ratio of creek width beneath road to upstream average bank-full width) with ΔPSCI showed little correlation (R^2 = 0.15, p = 0.029). Yet a step-wise multiple regression to predict ΔPSCI included only the road confinement metric and the total outfall area (R^2_{adj} = 0.44, p <0.001). This model excluded other variables which measured basin urbanization (%TIA, road crossings per km of stream) and road impact (road armor length, %of reach armored, the number of outfalls, the total outfall area, the cross-sectional area below the road, and the ratio of the road area to the upstream bank-full cross-sectional area).

In order to determine which variables could be combined to best predict reach PSCI values, another step-wise multiple-regression was completed that included all geomorphic variables that could serve as drivers of physical condition (sinuosity, riparian rank) and the urbanization and road-impact variables. The best predictive model (R^2_{adj}= 0.54, p < 0.001) used sinuosity, the riparian rank, the road armor length (length of armoring associated with the road crossing), and the number of outfall pipes. The corresponding model equation is as follows:

PSCI = -10.5 +18.89(Sinuosity) + 1.44(Riparian rank) – 0.014(Length of road-related armoring) – 0.711(Number of outfalls).

As this model suggests, it was necessary to explore the combinations of several contributing factors in order to provide the best regression estimate for predicted PSCI. Even so, the model only explained 54% of the variation in PSCI.

3.3 Sediment Transport and Hydraulics Results

The summer 2002 and spring 2003 geomorphic studies indicated that road crossings and outfall pipes relate to decreased downstream channel complexity and stability and lower overall PSCI scores. The sediment transport study was intended to focus on one potential aspect of downstream channel change – the mobility of the bed. The data collected for the sediment transport study were therefore used to determine if downstream reaches were still responding to the influence of road crossings and their associated outfall pipes, and if that response could be observed by tracking gravel bed entrainment.

3.3.1 Partial Entrainment Results

The May Creek and Big Bear Creek cross sections were monitored for entrainment between November of 2002 and May of 2003. The May Creek reaches experienced levels of entrainment that ranged between zero and 100%, whereas the Big Bear Creek reaches experienced very little entrainment with the highest percentage being 29% (Appendix C). However, paired t-test results show that there is no significant difference between the magnitude or the frequency of entrainment between upstream and downstream cross sections for either of the sites. In fact, the upstream reach for May Creek consistently had higher entrainment than the downstream site for the largest peak flows (212.4 cfs and 172.6 cfs). Yet, the downstream reach experienced more entrainment for some of the intermediate storms (50 cfs and 40.5 cfs). This trend of downstream reaches experiencing higher PE for the intermediate storm events was not present for Big Bear Creek, although the highest flow experienced during the period was only 49 cfs, and there was therefore very little entrainment data to consider.

The relationship between the partial entrainment for the overall sections and individual rows is shown in Figure 3.13. Overall, the variability was evenly distributed about a 1:1 line.

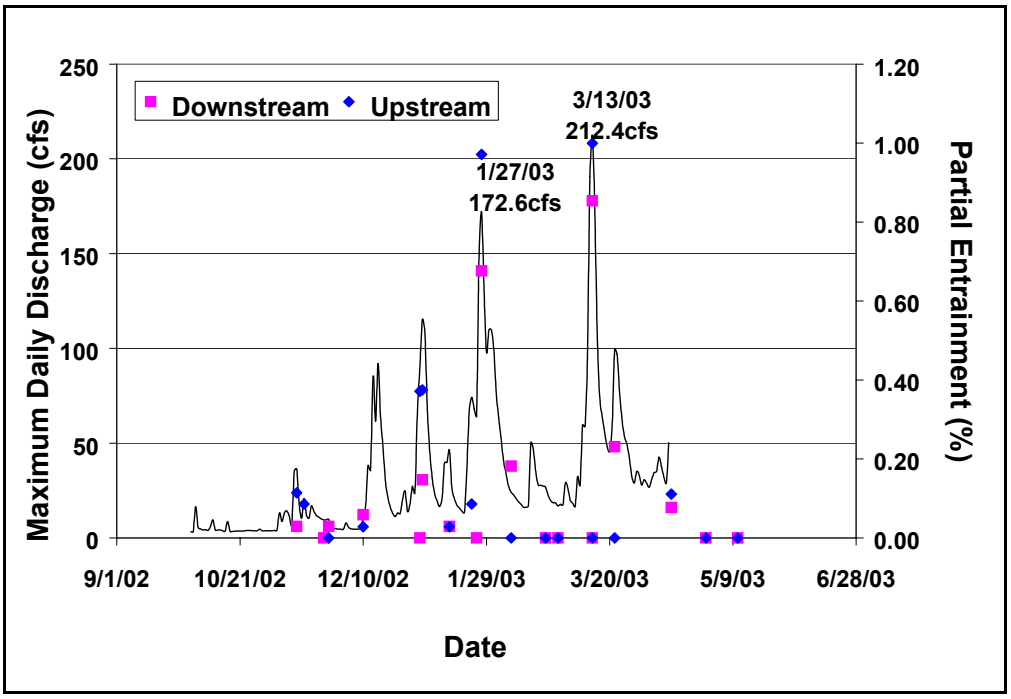

Figure 3.11: Partial entrainment results for May Creek

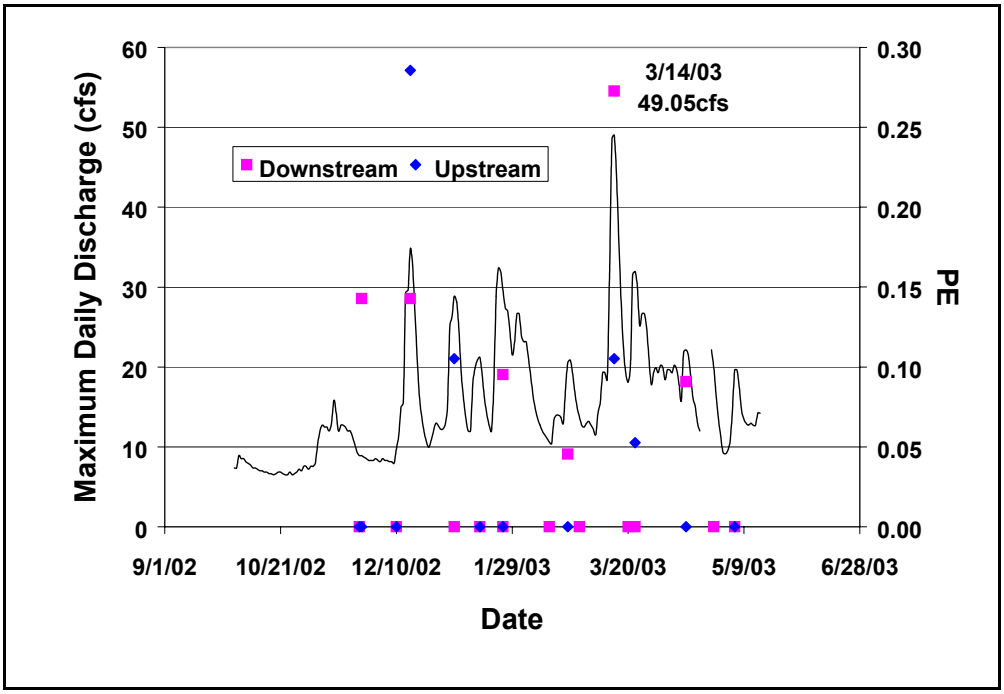

Figure 3.12: Partial entrainment results for Big Bear Creek

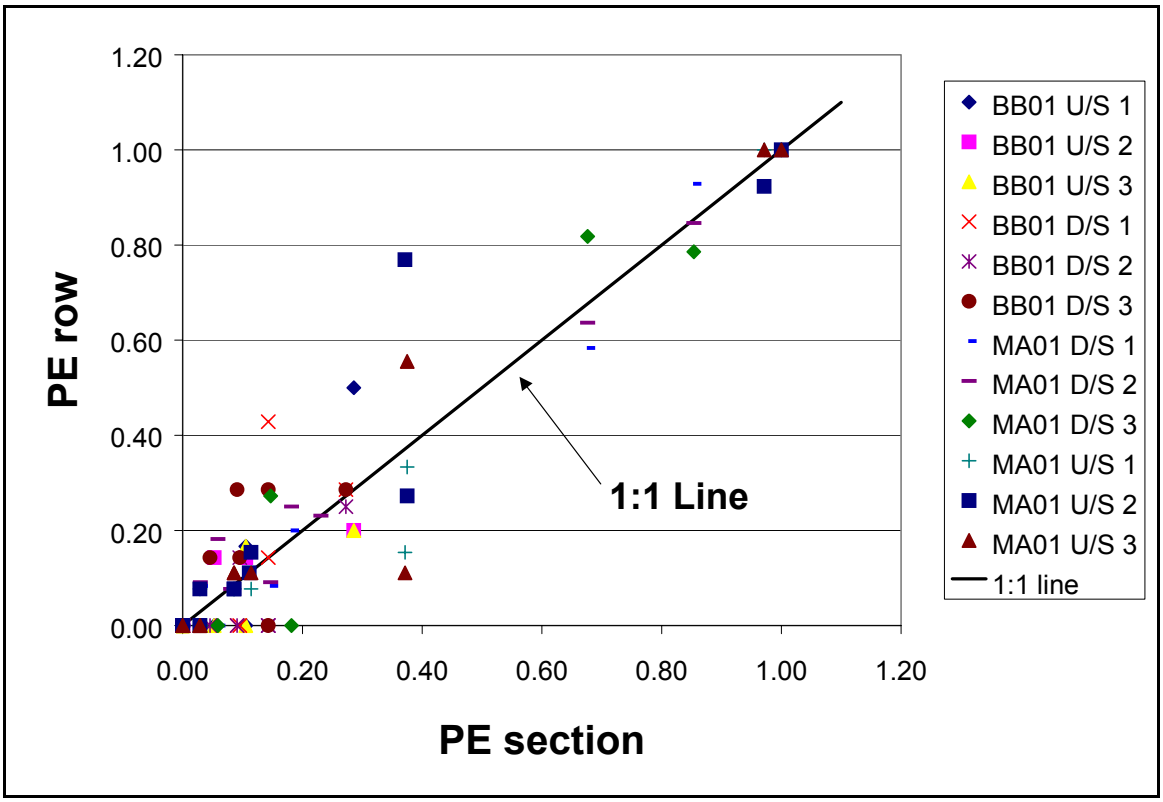

Figure 3.13: Comparison of PE for individual rows and overall section

3.3.2 Comparisons between upstream and downstream Shear Stress and Partial Entrainment

The downstream dimensionless shear stress was significantly different from upstream values for both the May Creek site (paired t-test $p < 0.001$) and the Big Bear Creek site (paired t-test $p = 0.004$). These differences resulted in distinct relationships between the amount of shear stress necessary to produce similar levels of partial entrainment for the upstream and downstream reaches. Plotting PE vs. dimensionless shear stress for all the sections (both upstream and downstream) at both sites does not produce an overall trend (Figure 3.14). Grouping the data by upstream and downstream reach explains a significant amount of the variation for the downstream PE, but not the upstream PE, indicating that there are important site influences as well (Figure 3.15).

Comparison between the upstream and downstream data for May Creek exhibits strong trends, highlighting the significant difference between the upstream and downstream shear stresses (Figure 3.16). Thus for May Creek, the downstream reach experienced significantly higher shear stress than the upstream reach for the same PE.

The reverse trend was experienced at the Big Bear Creek site, as evidenced by the trend lines in Figure 3.17. In general a certain value of PE correlated to higher shear stress at the upstream section than the downstream section. However, there were several days when no entrainment was observed for both the sites, and again, the maximum partial entrainment did not exceed 30%. Additionally, the two Big Bear Creek trend lines are so close to one another that if backwater effects actually were occurring, the Big Bear Creek cross sections could follow the same trend as the May Creek cross sections. The collected data is inadequate to resolve this uncertainty.

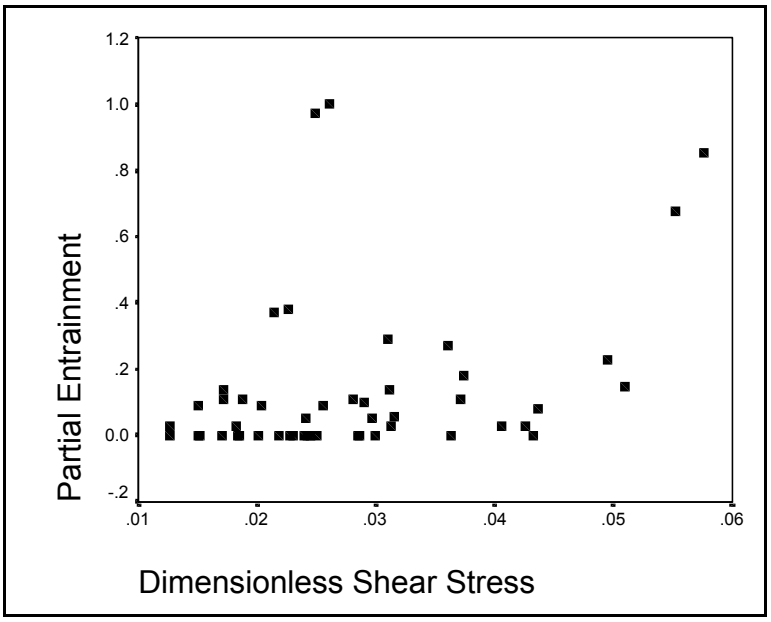

Figure 3.14: Relationship between dimensionless shear stress and PE

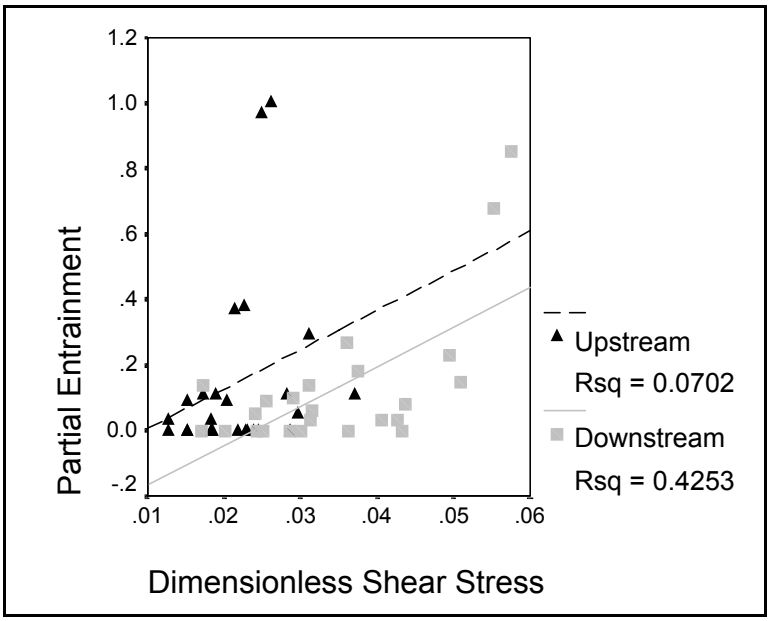

Figure 3.15: Dimensionless shear stress and PE relationships for upstream vs. downstream reaches

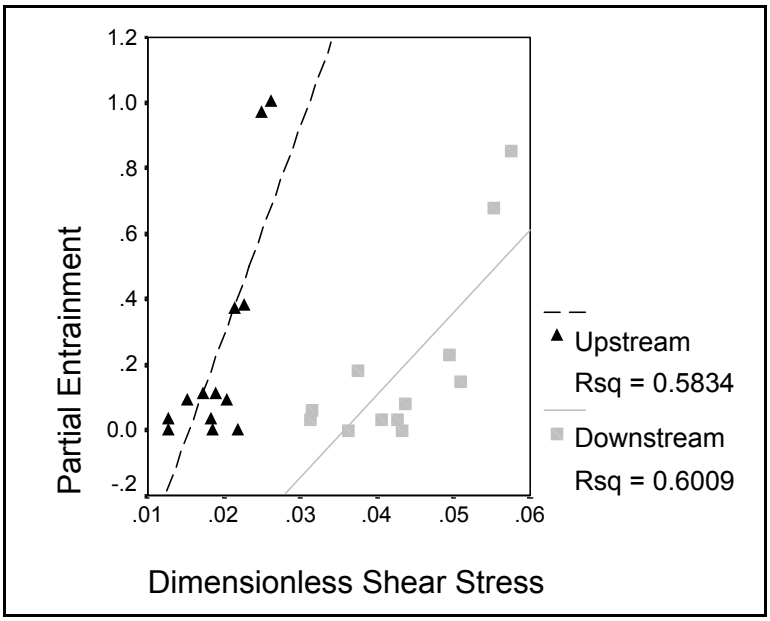

Figure 3.16: Dimensionless shear stress and PE relationships for upstream vs. downstream reaches of May Creek

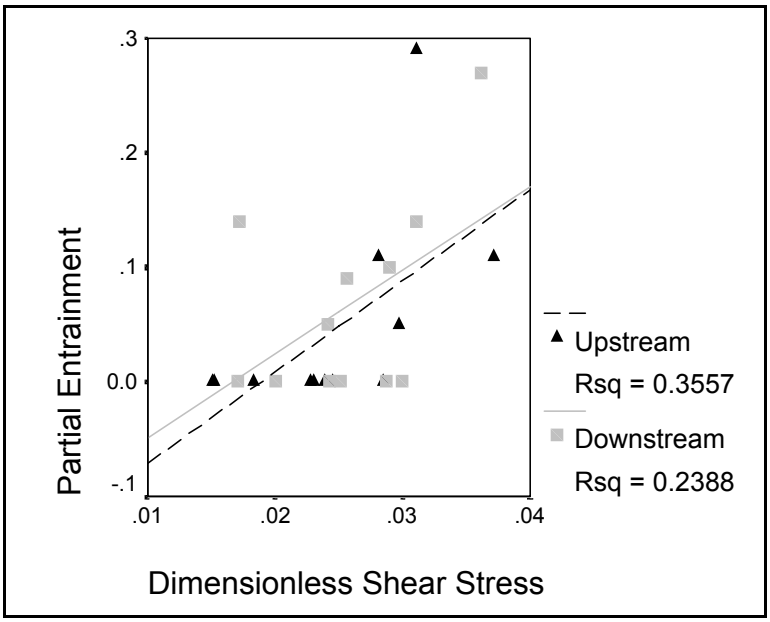

Figure 3.17: Dimensionless shear stress and PE relationships for upstream vs. downstream reaches of Big Bear Creek

3.3.3 Relationships Between Reach altered Morphology and Effects on Critical Shear Stress

Differences between upstream and downstream shear stresses are directly related to the differences in channel geometry for the upstream and downstream reaches, as shear stress calculations include values for the hydraulic radius, energy gradient (water surface slope for uniform flow), and the median grain size diameter. Therefore, the thalweg and water surface profile, in addition to the geomorphic characterization data, contribute added insight into how the channels may have adjusted to the presence and influence of the road-crossings and their outfall contributions.

Firstly, the May Creek profile data show that the water-surface slope is greater downstream (S = 0.011) than upstream (S = 0.0036) of the road. In addition, the pebble count results show that the upstream reach has a coarser D_{50} (32 mm) than the downstream reach (26 mm), and the hydraulic radius of the upstream site (0.13 m) was larger than the downstream site (0.09 m), as measured on July 31st 2002.

Similar to May Creek, the upstream reach of Bear Creek has a slightly greater hydraulic radius (0.15 m) than the downstream reach (0.10 m). But unlike May Creek, the Bear Creek upstream reach also has smaller median sediment size (D_{50} = 23 mm upstream, D_{50} = 48 mm downstream) and flatter slopes (S = 0.004 upstream, S = 0.011 downstream), as measured on August 26th 2002.

4 DISCUSSION

The results of the three studies confirm that road crossings impose significant local impacts on channel geomorphology and hydraulics, and they suggest potential impacts on hydrology. In this section, the key results are organized by overall hypothesis category; their consequences are also reviewed with respect to the overall research objectives.

4.1 The Local Impacts of Road Crossings

4.1.1 Direct Geomorphic Impacts

Both the summer 2002 and the spring 2003 assessments found road crossings to induce significant upstream-downstream alterations to overall geomorphic condition. In particular, road crossings reduced downstream channel complexity and degraded overall physical condition. Reaches downstream of road crossings are typically characterized by:

- less sinuosity and fewer meander bends
- less LWD
- less channel complexity/diversity of channel units
- lower channel stability and more bank erosion
- lower pool volume and pool frequency
- less gravel bar sediment storage
- more cemented and embedded gravels
- lower overall geomorphic conditions (PSCI).

Reaches downstream of road crossings tend to be straightened, hydraulically simple yet unstable channels that can neither maintain as much LWD nor gravel storage

as their upstream counterparts. These geomorphic trends were generally observed across all sites, regardless of road type or level of watershed urbanization. Such relationships indicate, then, that the passage of a stream through a road crossing is enough to almost always alter the fluvial processes that control the formation of complex channel geomorphology.

Sinuosity is related to the formation of point bars on the inside of meander bends and scour pools on the outside of bends (Knighton 1998), and it is the primary driver of habitat diversity in low-gradient riffle-pool creek systems. The data showed significant correlations between reach sinuosity and both the channel complexity and the length of gravel bars per 100m of stream reach. Sinuosity is also related to the recruitment of LWD into the system, with significant correlations between sinuosity and the LWD per 100m. Road crossings that prevent or alter channel sinuosity create simplified downstream channels that lack the ability to deposit sediment and recruit LWD.

Road crossings structurally limit meander migration and the development of sinuosity. The summer 2002 results showed that the percent of reach armored was significantly and negatively correlated to the reach sinuosity. Bank armoring, whether it be riprap below a bridge or simply the sides of a culvert, may be effective for protecting the road crossing structures and transmitting water more efficiently downstream, but it fails to provide streams the flexibility they require to develop diverse topography and complex channel geomorphology.

4.1.2 Hydraulic Impacts

As hypothesized, the degree to which road crossings alter local creek hydraulics depends on the geometries and specific design characteristics of the road crossings. Culvert crossings (both plain and arch), which typically impose more confinement upon creeks than bridge crossings, correlate with larger, deeper, and flatter downstream channels. Plain culverts with concrete bottoms also correlate with finer downstream sediment, whereas arch culverts with open bottoms impose no significant change on sediment size. Floodplain bridges, which confine the creeks' floodplains but are not as directly confining to the bank-full channel as culverts, gave rise to downstream channels

that were wider, shallower, and coarser. Hillslope bridges, which have the least amount of direct interaction with the channel, produced no strong downstream trends.

These results suggest that more confined road-crossing designs with more flow constriction produce downstream reaches that express the effects of flow expansion as the flow passes from more confined (through the road crossing) to less confined (alluvial) cross sections. Channel adjustment apparently occurs primarily through bank erosion and enlargement. Additionally, study reaches with greater W/D ratios (i.e. those downstream of floodplain bridges) were more stable and were characterized by more LWD pieces per 100m. Thus road crossings that decrease the downstream W/D ratios can also be expected to contribute more to downstream bank instability and channel complexity.

Predicting the degree and extent of hydraulic impacts from road crossings also requires an assessment of the creek geomorphology above the road crossing, in addition to the actual hydraulic designs of the road-related structures. Data from both the summer 2002 and the spring 2003 surveys indicate that for alluvial riffle-pool channels, not only the road-crossing design but also the amount of bank armor associated with that road-crossing design can have serious implications for downstream geomorphic conditions. Reaches that were more confined by both the road-crossing design and downstream bank armoring displayed more unstable downstream alluvial sections with less LWD and less gravel deposition. Bank armoring thus displays many of the same types of impacts as confined road-crossing designs.

For the sediment transport study, paired t-test results dispelled the hypothesis that outfall contributions could alter the magnitude of observed entrainment under the experienced discharges. On May Creek, however, the different relationships between the upstream and downstream dimensionless shear stress and the observed partial entrainment did appear to be related to the road crossing's physical alterations of reach hydraulics. The reach downstream of the May Creek bridge crossing required higher shear stress to produce the same level of partial entrainment that an upstream cross section would experience. Physically, the upstream reach is deeper and flatter, with coarser gravel, and the downstream reach is shallower, steeper, and with finer gravel. This characterization complements field geomorphic observations that found the

upstream reach to be much more sinuous with a higher frequency of gravel bars relative to the downstream reach. The smaller sediment sizes and increased slopes in the downstream May Creek reach require a more resistant bed in order to maintain overall equilibrium of sediment transport at both upstream and downstream reaches under nearly identical discharges but different shear stresses. At this site, the stream channel and its sediment size have apparently adjusted to the road crossing and any associated drainage contribution. Road-crossing alterations to the hydraulics, and subsequently the geomorphology, thus have resulted in different shear stress requirements to produce the same amount of upstream and downstream entrainment.

4.1.3 Hydrologic Impacts

Although basin-wide roadway drainage systems might influence the hydrologic regime enough to cause overall in-stream geomorphic degradation, any given outfall may not contribute enough drainage to cause observable downstream impacts. Not surprisingly, outfall contributions of only 0.1% of the drainage area for 20-30km^2 sub-basins were not enough to cause more visible bed entrainment downstream at the observed storm flows. More entrainment data would be useful for explaining the relationships between road crossings, their associated drainage alterations, and any possible relationships to sediment transport patterns.

Although these sediment-transport data do not demonstrate any differences in erosive potential of reaches upstream and downstream of stormwater outfalls, the geomorphic data suggests that stormwater outfalls do have some significance to local geomorphic conditions. The presence of more stormwater outfalls, or more outfall contributing areas (as a proxy for the relative magnitude of pipe-conveyed discharge) correlate to downstream decreases in overall PSCI scores and to individual LWD, channel complexity, and embeddedness ranks. The best multivariable predictive models for both PSCI and ΔPSCI included variables related to outfalls, in preference to those relating to several metrics related to road confinement, or measures of the overall watershed development (%TIA and the number of road crossings per km of stream).

Reconciling these apparently contradictory results requires that the influence of stormwater outfalls be disproportionate to their mere drainage area or to their contribution at relatively modest storm flows. Depending on the amount of impervious surface drained by the stormwater outfalls, they have the potential not only to contribute significant inputs of drainage at a point in a creek system but also to significantly alter the time-to-peak that downstream reaches experience during those storms. For different intensities and durations of storms, such alterations to the timing of flood peaks might also cause bed entrainment to occur at different times in a storm than would be experienced naturally. More entrainment data and field observations are needed, however, to support this speculation.

4.2 An Analysis of Scale – Local Effects Relative to Basin-Wide Urbanization

This study originally hypothesized that creeks within more urban basins are less sensitive to the local impacts of road crossings, or that these local impacts are too difficult to distinguish, given the variety of other potential urban stressors. Relationships between the metrics of overall basin urbanization and many of the measured geomorphic variables confound many of the potential effects of road crossings. For example, increasing numbers of upstream road crossings per kilometer of stream (thus increasing the overall connectivity of the road network to the stream network upstream of a sample reach) correlates with overall declines in PSCI, for reaches both upstream and downstream of road crossings. This road-crossing metric also correlates to decreases in the D_{50}, tallies of LWD, and bank stability, while correlating to significant increases in riffle embeddedness. Another whole-basin metric, %TIA, is also correlated with PSCI, several of the PSCI sub-metrics, the riparian rank, and the median grain size. Any creek assessment investigating the local significance of road crossings to these geomorphic variables must also note the role of basin-wide urbanization influences.

Yet the results of this study do show significant differences between the urban (> 20% TIA) and suburban (<20% TIA) channels investigated here, and they indicate that urban creeks actually experience larger upstream-downstream changes in geomorphic

condition than their less developed suburban counterparts. Culverts placed in urban reaches produced significantly larger decreases in physical condition than culverts in suburban reaches.

This trend could be due to a variety of reasons. Firstly, as culverts are more confining than bridges and therefore have increased potential for direct and severe interference with the creek's hydraulic and geomorphic processes, culverts produce greater changes in urban creek geomorphology than bridges. Secondly, urban reaches may be more sensitive to culverts than suburban reaches because urban systems have such little forested protection within their basins. Riparian corridors might be the only remaining forested areas in urban basins and therefore the only remaining locations where hydrologic processes of infiltration and subsurface-runoff, and geomorphic processes of sediment transport and LWD recruitment can continue in a more natural state. Yet even these remaining riparian corridors are not able to provide the full level of resiliency that a reach might need to counteract the impacts of a road crossing. Results indicate that more urban basins generally had lower riparian rankings. In other words, reaches downstream of road crossings in urban watersheds were more likely to be impacted by local residential development. Streamside landowners frequently arm their banks to prevent "damage" to their private property. This additional armoring would be expected to produce more degraded downstream geomorphic conditions as well.

Suburban creeks were also affected by local road-crossing impacts to geomorphology. However, in contradiction to hypotheses that suburban reaches are more sensitive to the type of road-crossing influences, there was no significant difference for these systems between the magnitude of culvert impacts and the magnitude of bridge impacts. This could be due to the fact that suburban creeks with more intact riparian corridors, as well as less developed basins, are more likely to recover quickly from the local effects of a road crossing (i.e. somewhere within the 100m-long sample reach). In fact the riparian rank was a variable with one of the strongest correlations to PSCI (R^2 = 0.45, p =0.005), which incorporates significant correlations to the LWD rank (R^2 = 0.56, p =0.001) and lower embeddedness (R^2 = 0.41, p =0.007). This could explain why suburban reaches experienced less downstream geomorphic degradation from culverts than did urban reaches. These suburban reaches

have the space to regain meander migration, they tend to be less armored downstream because of that available space, and therefore the processes that contribute to increased habitat complexity are allowed to recover in a shorter distance.

4.3 Discussion of Error

4.3.1 Errors Associated With Collection Of Qualitative Geomorphic Data

Because the geomorphic data was collected in the field by the same person, variability from different people making qualitative measurements (channel complexity rank, bank stability rank, etc.) was avoided (Hannaford et al. 1997). In addition, before field sampling began, sites that represented the extremes of different overall basin urbanization were visited. Upstream reaches of Big Beef Creek of the Kitsap Peninsula were used to guide later field judgments and to set the standard for physical conditions. Although errors associated with qualitative measurements can never be completely avoided. Often, determining whether a specific geomorphic parameter meets qualifications for the "good" or the "fair" category is ambiguous. It is easier to determine when the extreme conditions are being met (i.e. when a variable receives an "excellent" score or a "poor" score). Establishing one middle category might lead to more consistent results, although doing so would also alter the distribution of the data.

4.3.2 Variance in Regression Relationships for Spring 2003

Because the spring 2003 study used a larger sample size than the 2002 study, its results have greater statistical power (Zar 1999). Yet the increased sample size of the spring survey also made it more difficult to avoid other confounding variables, such as local residential impacts, that had been more carefully stratified for in the earlier survey. Because the spring data set also happened to be characterized by more variance, some correlations were less significant than those found between the same variables for the summer 2002 study. At this broader scale of analysis, however, it is

extremely difficult to detect any systematic alterations of the PSCI or other geomorphic variables because of the many potentially confounding forcing functions. For example, the effect of a particular road crossing incorporates not only the hydraulic influence due to the level of confinement imposed by that road crossing, but several other characteristics of that road crossing can be reflected in the downstream geomorphology as well. The relationship of the road geometry to the typical upstream cross-sectional geometry must be considered. Additionally, the length of the road crossing, the amount of armoring associated with it, and the number of and discharge contributions from outfall pipes near road crossings must all be considered. Although multiple regression analysis can be used to begin to identify the additive impacts of these interrelated factors, they are so overlapped that regression relationships could never be expected to describe an overwhelming amount of the variance unless more variables could be controlled for. Nonetheless, what these locally interrelated variables do convey is a true understanding of the many local influences that significantly contribute to observed stream geomorphology.

4.3.3 Field Limitations to Data Collection for the Sediment Transport Study

Several limitations of field measurements taken at the sediment-transport reaches likely affected the accuracy of the shear stress calculations. In order to determine the shear stress corresponding to the maximum discharges between each inventory, the water surface slope (energy gradient) and hydraulic radius that correspond to that known discharge must be determined. However, field personnel could not be present in the field for every peak discharge to manually measure these parameters. Instead, rating curves were established between the times when field measurements for slope and hydraulic radius were determined, and the gauge-recorded discharge corresponding to the time of measurement. Yet there was not enough systematic variation in the slopes for all sites to warrant applying a rating-curve relationship. Thus an average local slope, based on the different field visits, was used consistently for each site. In regards to the hydraulic radius, linear discharge-related trends were observed and so rating curves were established based on the available

data. However, in the case of the May Creek sites the largest field-determined hydraulic radius was an entire order of magnitude less than the maximum-predicted hydraulic radius from the rating curve. Because over-bank flow may result from these high discharges, the rating curve may not have been appropriate for the discharges on the higher end of the curve.

5 CONCLUSIONS AND MANAGEMENT IMPLICATIONS

This study has shown that road crossings can impose significant alterations to the geomorphology, hydraulics, and hydrology of downstream channels in lowland, fluvial systems. Results confirmed the hypothesis that road structures and related bank armoring can degrade downstream channel complexity and decrease the variety of channel units through alterations of sinuosity and meander migration. As hypothesized, altered hydraulics through road crossings that confine the creek are associated with more downstream bank instability. Additionally, the armoring downstream of and associated with the different road-crossing design types did induce downstream channels to alter morphologies and channel slopes to overcome the inability to adjust laterally, while maintaining downstream water and sediment transport. Entrainment results could not confirm the hypothesis that individual stormwater outfalls could contribute to increased downstream erosion; however, stormwater outfalls were found to correlate to altered downstream physical conditions, including increased embeddedness. Contrary to the initial hypothesis that reaches in urbanized watersheds would not be as sensitive to road-crossings impacts, urban reaches generally experienced even more downstream effects than suburban reaches, especially downstream of culverts. These findings have many implications for management, especially those related to future road-crossing designs and riparian corridor protection.

5.1 Significant Road-Crossing Characteristics and Design Considerations

Geomorphic results implicate all road crossings; that is, for almost every road crossing, geomorphic condition was found to locally degrade in the downstream direction. These local road-crossing impacts were experienced across the entire gradient of urbanization. Therefore, to avoid impacts to natural fluvial systems, the number of road-creek crossings should be minimized. Ensuring efficient transportation networks might supersede the need to avoid physical alterations of creeks; therefore, it

is important to understand which road-crossing designs might best minimize their downstream impacts.

The observed impacts to local creek geomorphology, hydrology, and hydraulics imply that there are explicit road crossing attributes that cause the observed degradation of physical conditions downstream. Culverts generally have larger impacts to overall geomorphic condition than their less confining counterpart, bridges. Bridges are generally associated with a downstream channel geometry (i.e. larger W/D ratios) that correlates to in-stream channel complexity and greater overall physical condition (PSCI). In addition, road crossings that related to downstream reaches that had higher W/D ratios, coarser sediment, and smaller hydraulic radii also had greater PSCI scores because those channels were also more stable and had the lateral space to support both gravel bars and LWD. Therefore, to allow for more stable and complex geomorphology downstream, culverts should be avoided, and road crossings should be designed with wider widths to minimize the confinement imposed on the channel.

To the same extent that the confinement related to the road design should be minimized, so the confinement imposed by bank armoring should be avoided. The longer the road crossing imposes artificial banks (whether through the road crossing itself or with riprapped banks downstream), the longer will be the lengths of downstream physical degradation. The key factor here is allowing the naturally meandering creek to reestablish its sinuosity. This requires both erodible banks and the physical space needed to make lateral channel adjustments. A lack of space is often the vital issue for urban reaches abutted by private property. To protect private property, creek banks along residences are often lined with concrete and riprap. If some downstream bank reinforcement is necessary, natural vegetation or placed LWD could be used to diffuse some of the stream power associated with discharge coming out of the road-crossing outlets. Such measures are unlikely to substitute for the loss of an unconfined planform, however.

5.2 Local Means of Supporting Downstream Recovery from Road Crossings

Protecting and restoring riparian buffers along creeks can help to mitigate the local effects of road crossings on channel morphology. The results have indicated that suburban creeks with better riparian buffers are more resilient to the local impacts of a culvert than urban creeks. For example, one of the Rocky/Muck Creek sites with a wide riparian buffer and only about 16% basin TIA, had an overall downstream reach PSCI score of 19.5 even though it was downstream of a narrow culvert. Measures of the riparian zone width and integrity were shown to significantly relate to more LWD, greater channel complexity, and higher reach sinuosity. Therefore, wide and intact riparian corridors can successfully support complex geomorphic structure, even in some of the most urbanized basins. The upstream reach of TH02 (summer 2002 survey) and the upstream reach for the Miller Creek site (spring 2003 survey) both had relatively wide riparian buffers. Although the Thornton Creek sub-basin is characterized by 59% TIA it had a PSCI score of 16. Similarly, the Miller Creek sub-basin has 59% TIA but a PSCI value of 19. In these cases, wide riparian buffers apparently counteract the magnitude of basin development and provide an effective support for high-quality channel morphology. These results must be tempered, however, by earlier findings by others that biological health does not necessarily follow from good physical habitat alone.

5.3 Summary

Field evidence strongly indicates that road-stream crossings promote local downstream geomorphic degradation. However, a particular reach's susceptibility to change relies on the road crossing's confinement, and the integrity of both the riparian buffer and the watershed as a whole. Although less-confining road crossings can potentially minimize the degree of road impacts, the effectiveness of such designs will likely be reduced if the entire watershed is characterized by a high frequency of road-stream intersections. Watersheds with road networks that exceed four or five road crossings per stream kilometer (e.g., a crossing every 200 to 250 m) will probably

negate the stream's ability to achieve downstream recovery from the local impacts of one road crossing before encountering the influence of the next. Protected riparian corridors within these watersheds can be expected to provide greater resiliency, but they cannot eliminate the compounding road-crossing effects because they too would be fragmented at the same frequency as the stream. Therefore, it is important to consider both the condition of the entire watershed and the overall connectivity of the road network to the stream network before the potential impacts of a new road-stream crossing design can be assessed.

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APPENDIX A: Summer 2002 Channel Geometry and Hydraulic Parameters

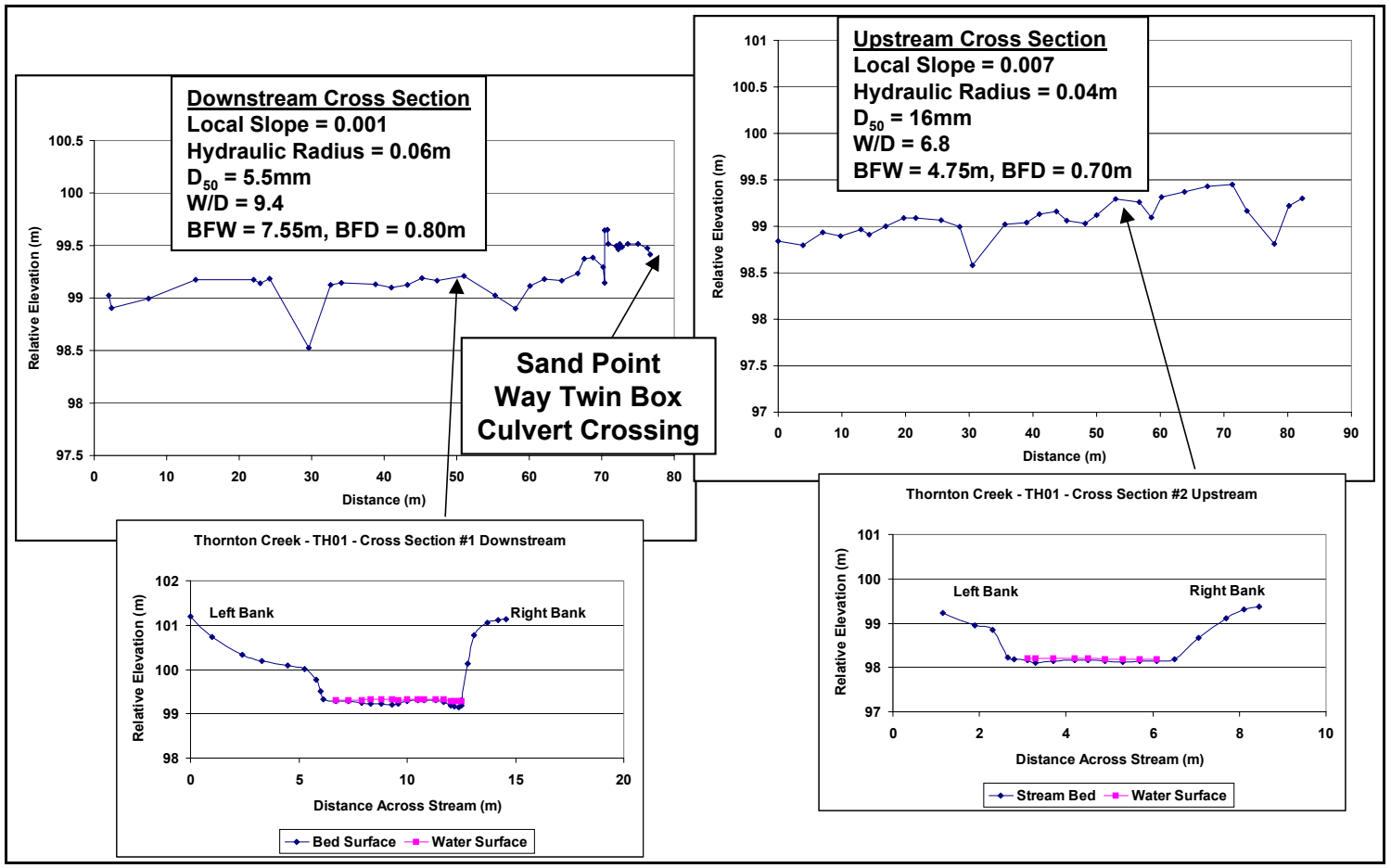

Figure A1: Surveyed profile and cross sections, and hydraulic data for Thornton Creek (TH01) on 8/15/02

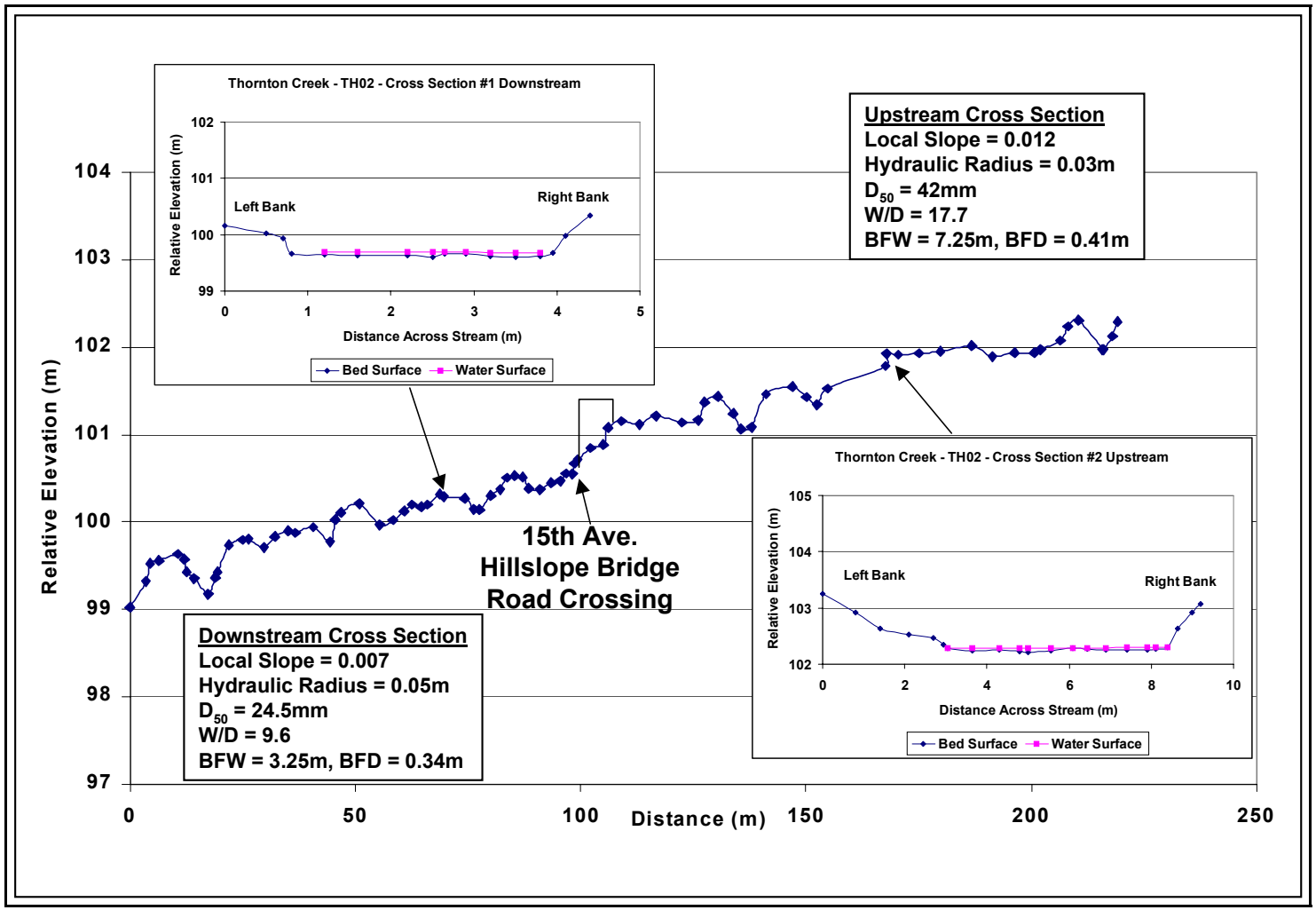

Figure A2: Surveyed profile and cross sections, and hydraulic data for Thornton Creek (TH02) on 8/16/02

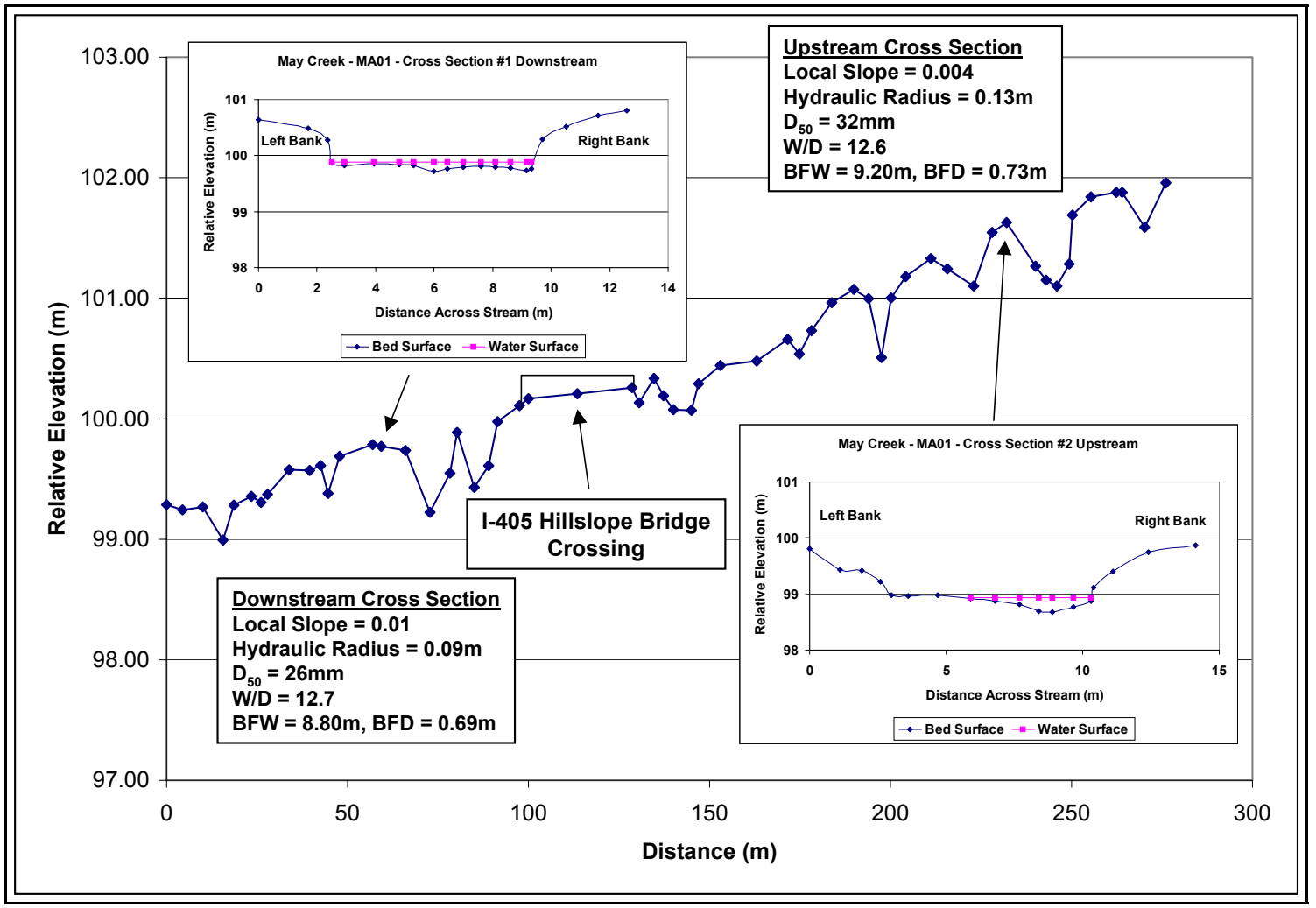

Figure A3: Surveyed profile and cross sections, and hydraulic data for May Creek (MA01) on 7/31/02

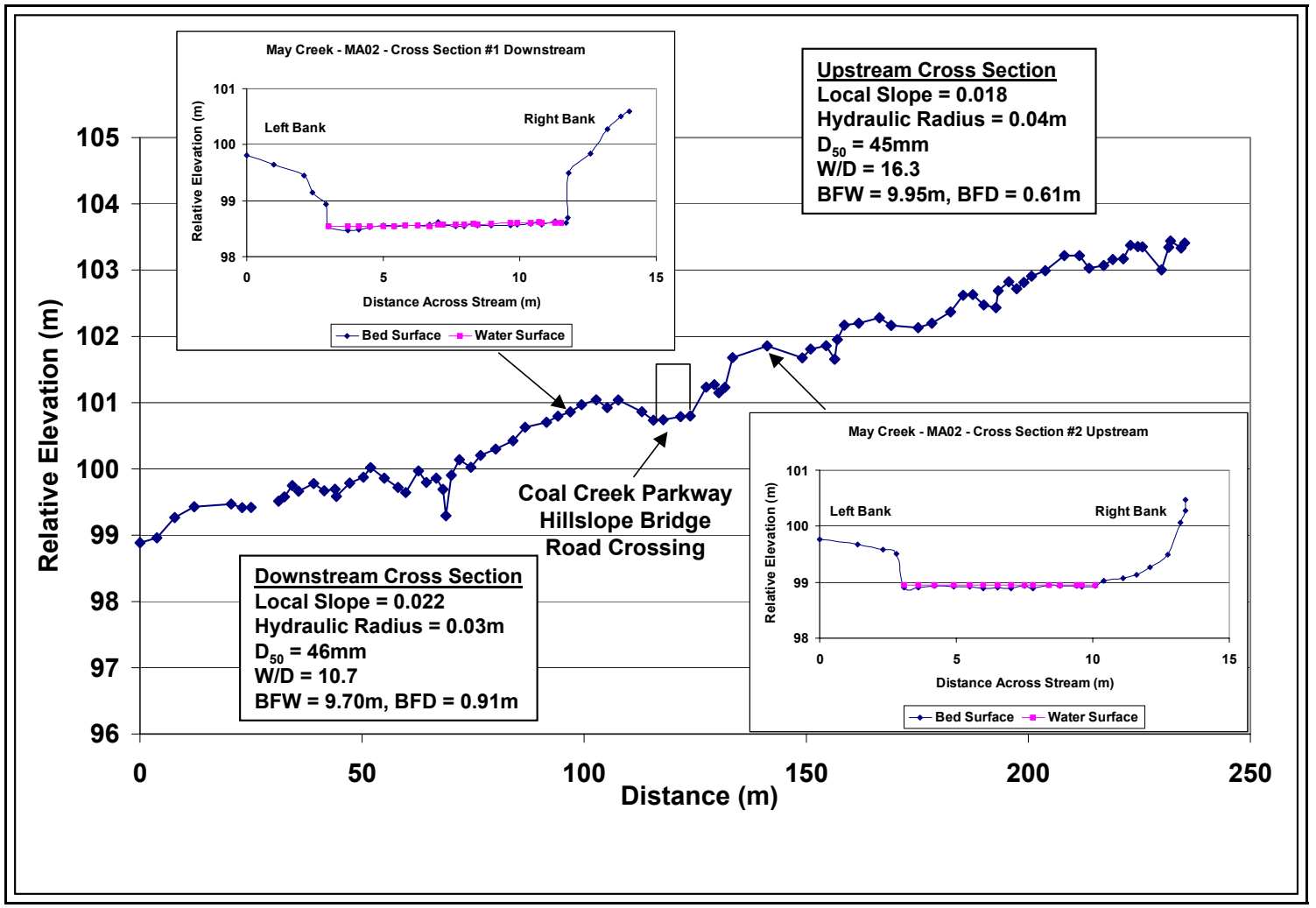

Figure A4: Surveyed profile and cross sections, and hydraulic data for May Creek (MA02) on 7/3/02

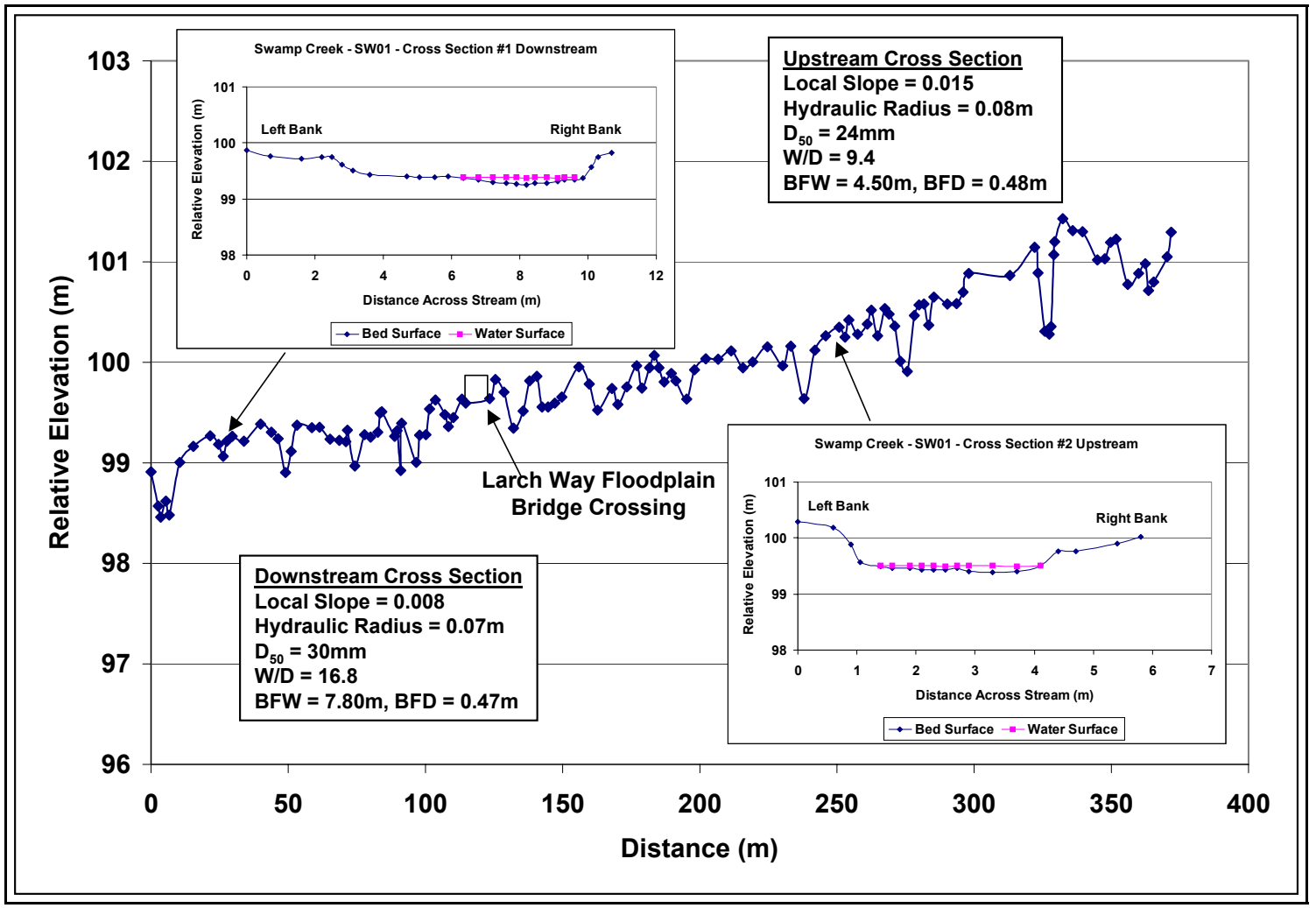

Figure A5: Surveyed profile and cross sections, and hydraulic data for Swamp Creek (SW01) on 8/22/02

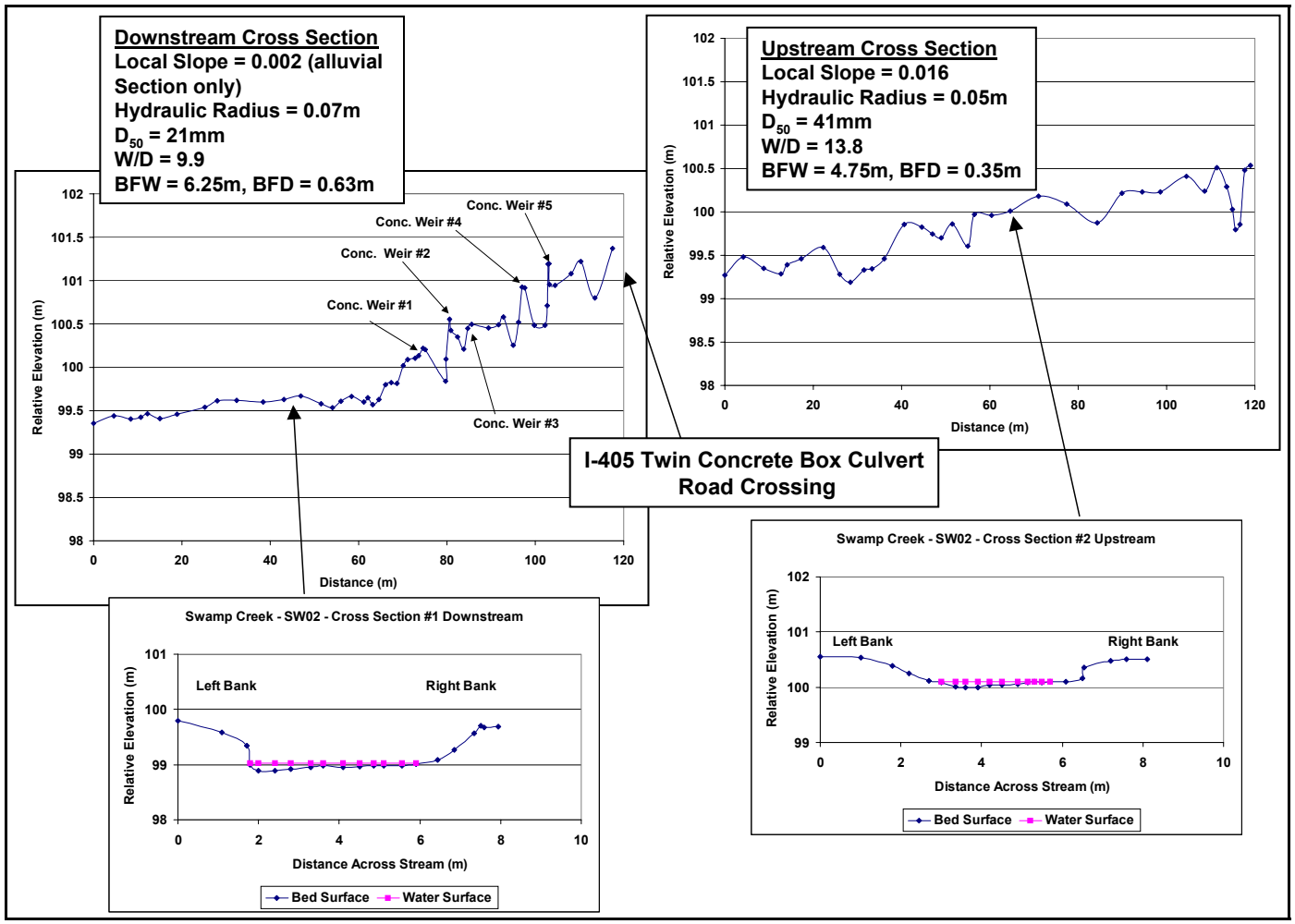

Figure A6: Surveyed profile and cross sections, and hydraulic data for Swamp Creek (SW02) on 8/21/02

APPENDIX B: Distributions of the PSCI Data

Distribution of Summer 2002 PSCI Data

The data for the geomorphic rankings that were used to develop the PSCI showed variable results. The data included both upstream and downstream reaches, and so normal distributions were not necessarily expected. Most study reaches had slightly unstable banks with the score of 3 being the most common for the bank stability rank (Figure B1). More reaches received LWD scores of 4 (excellent) than for any other score (Figure B2). This result is driven by the fact that some of the upstream reaches had extremely high LWD counts. For instance, the upstream reach for Big Beef Creek, also the least urban system, averaged 120 pieces of LWD per 100m. Embeddedness did not vary much between the sites (Figure B3), with a fairly even distribution of rankings for 2 (50-75% embedded), 3 (25-50% embedded), and 4 (<25% embedded). The modal cementation rank was a 3 (good), which was defined to apply to reaches that have slightly tighter cobbles and gravels at riffle heads, but looser gravels at ends of riffles (Figure B4). There was also a fairly even distribution of channel complexity rankings, with no single score being applied to more than 5 sites or less than 3 sites (Figure B5). Values for the total PSCI ranged from 7 to 20, with a bimodal distribution (Figure B6) indicating increased frequencies of either very low scores (PSCI = 8) or very high scores (PSCI = 18).

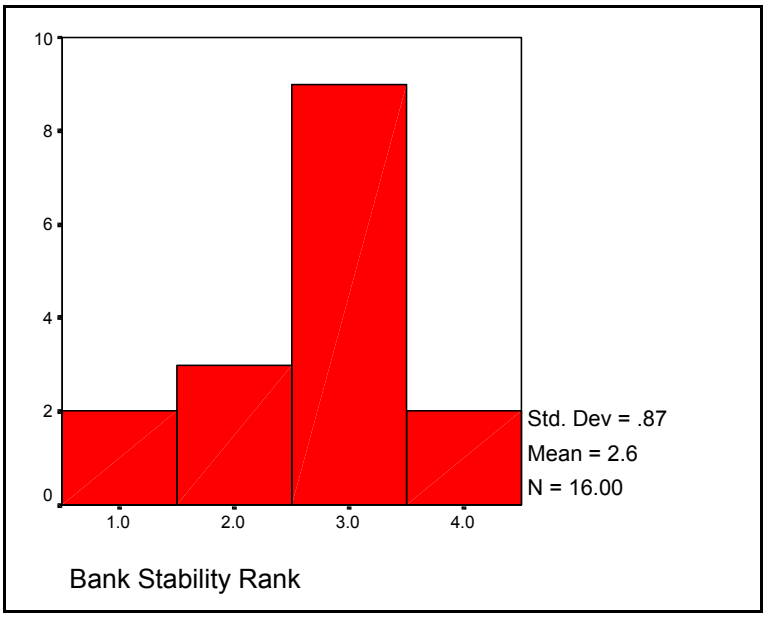

Figure B1: Summer 2002 distribution of bank stability rankings

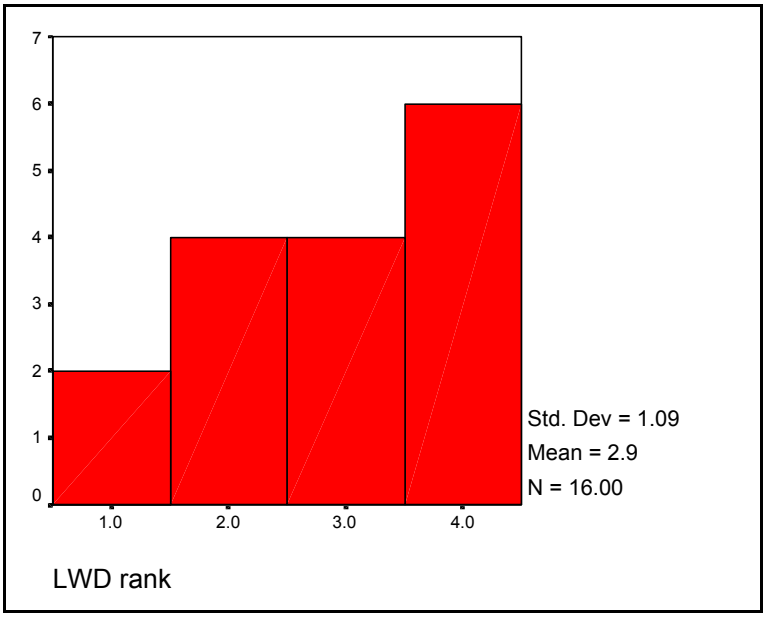

Figure B2: Summer 2002 distribution of LWD rankings

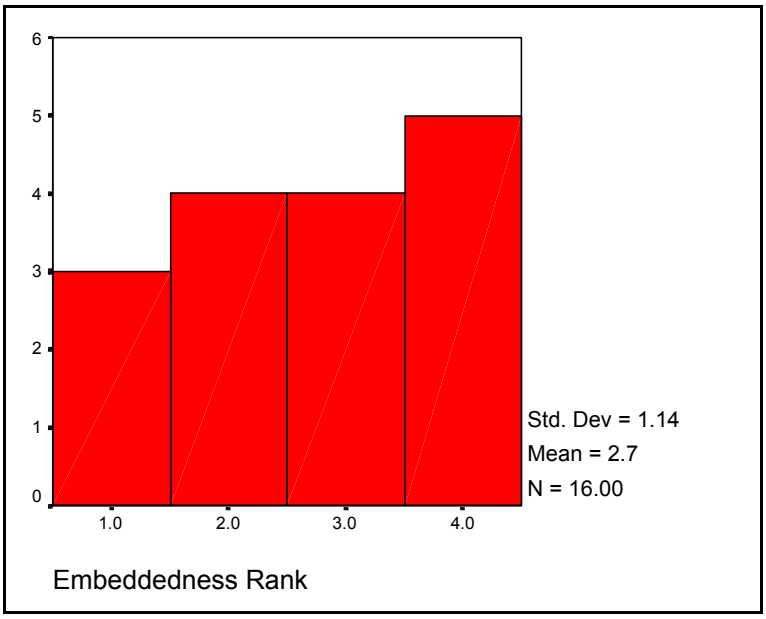

Figure B3: Summer 2002 distribution of embeddedness rankings

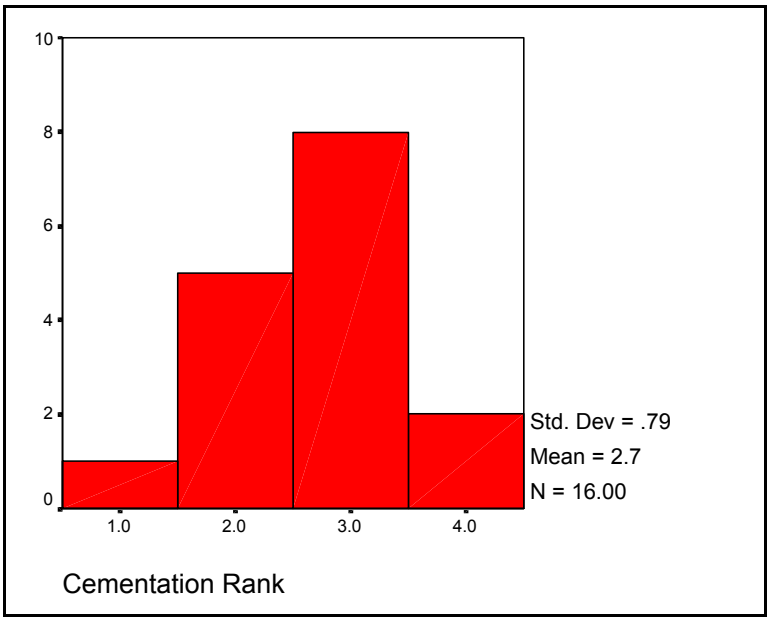

Figure B4: Summer 2002 distribution of cementation rankings

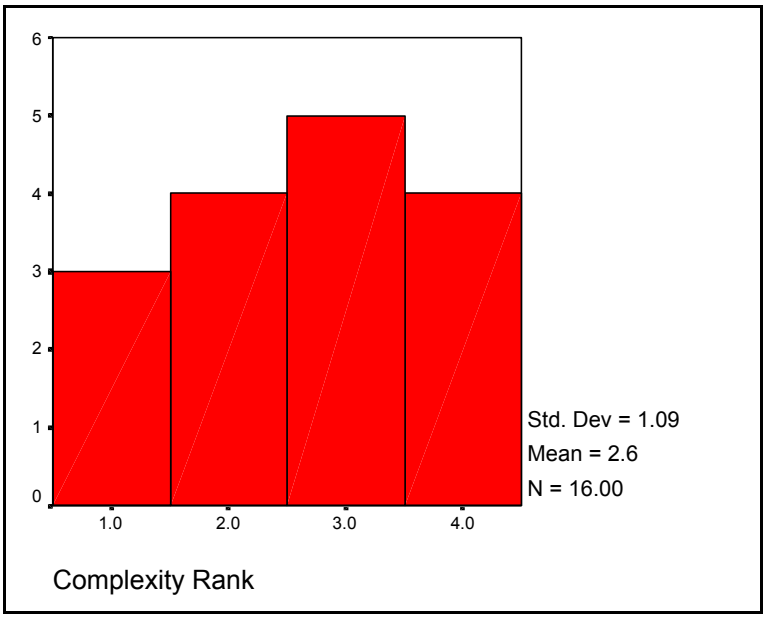

Figure B5: Summer 2002 distribution of channel complexity rankings

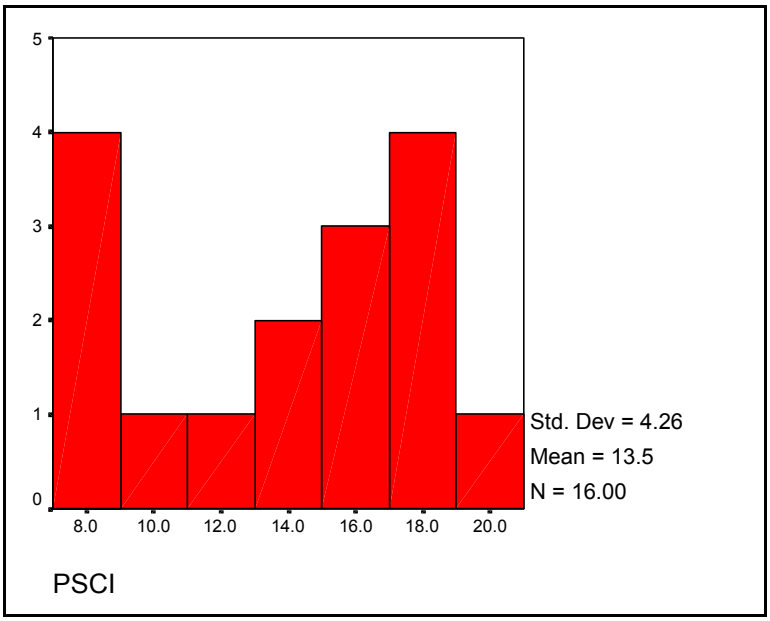

Figure B6: Summer 2002 distribution of PSCI scores

Distribution of Spring 2003 PSCI Data

The spring 2003 PSCI data reiterated many of the trends present in the summer 2002 data. Once again, the bank stability metric had a modal score of 3, meaning that more reaches were characterized as slightly unstable than for any other category (Figure B7). The LWD rankings were fairly evenly spread throughout the four categories. However, the category for the highest score (score of 4) had slightly more reaches than the other categories (Figure B8). The embeddedness rankings were negatively skewed, indicating that more reaches tended to receive higher scores than lower scores for embeddedness (Figure B9). The cementation results also showed a modal score of 4 (excellent) but a mean of 2.8 that was closer to the center of the potential scoring range (Figure B10). The complexity rankings were more normally distributed with a mean of 2.7 and a modal score of 2 (fair; Figure B11). The PSCI data, based on a continuous variable, showed a fairly normal distribution, with a mean of 13.8 and most of the data clumped in the middle scores (Figure B12).

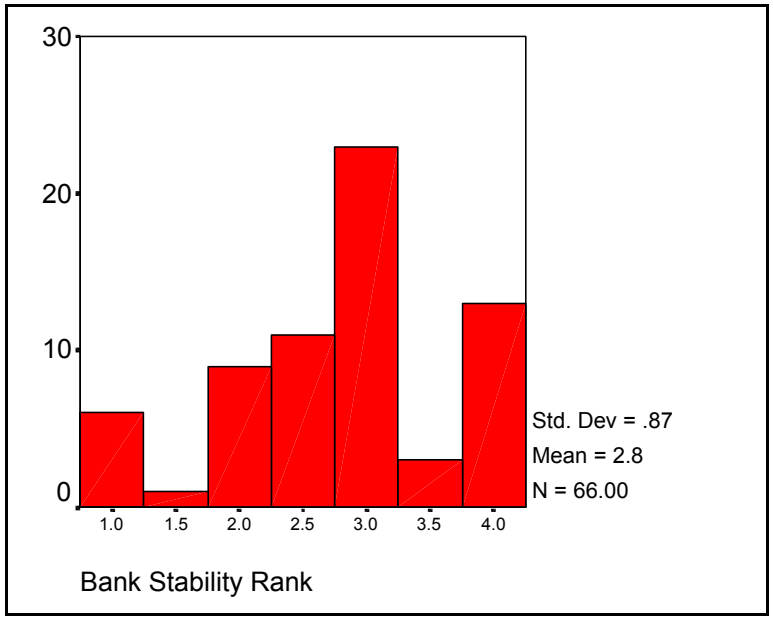

Figure B7: Spring 2003 distribution of bank stability rankings

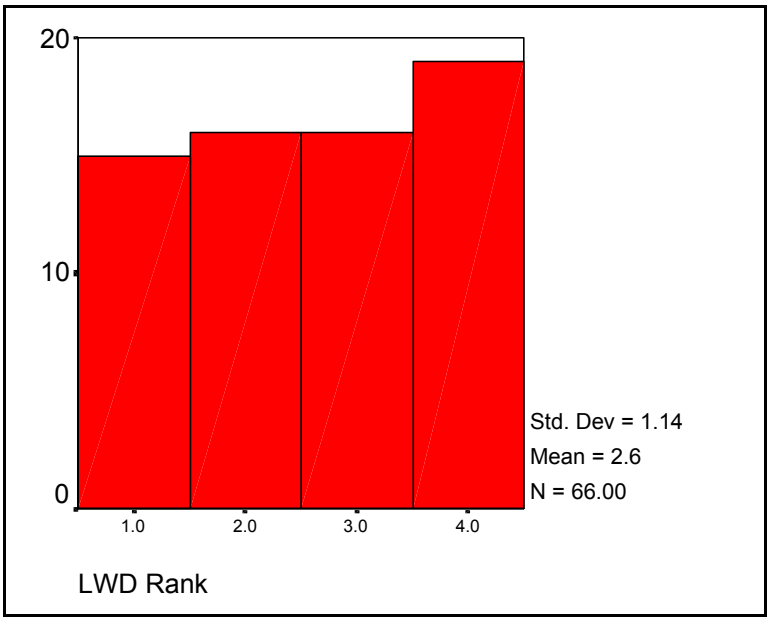

Figure B8: Spring 2003 distribution of LWD rankings

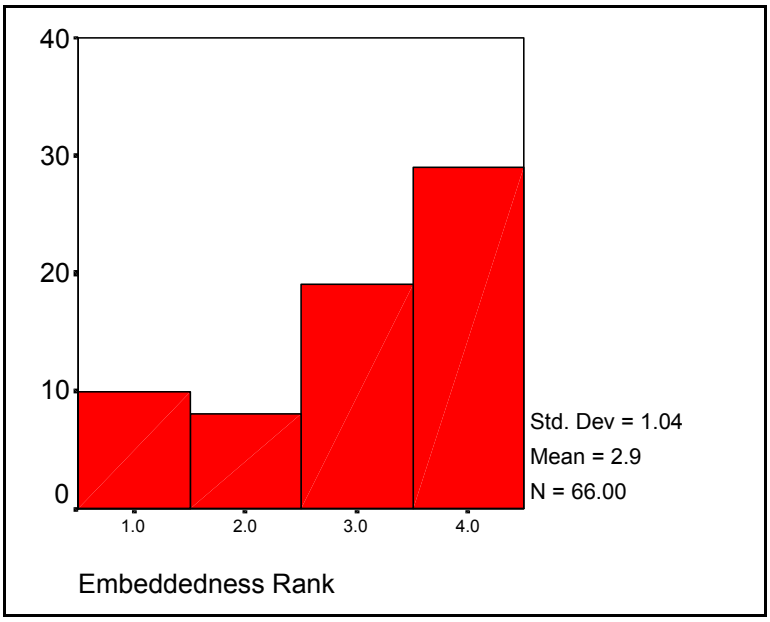

Figure B9: Spring 2003 distribution of embeddedness rankings

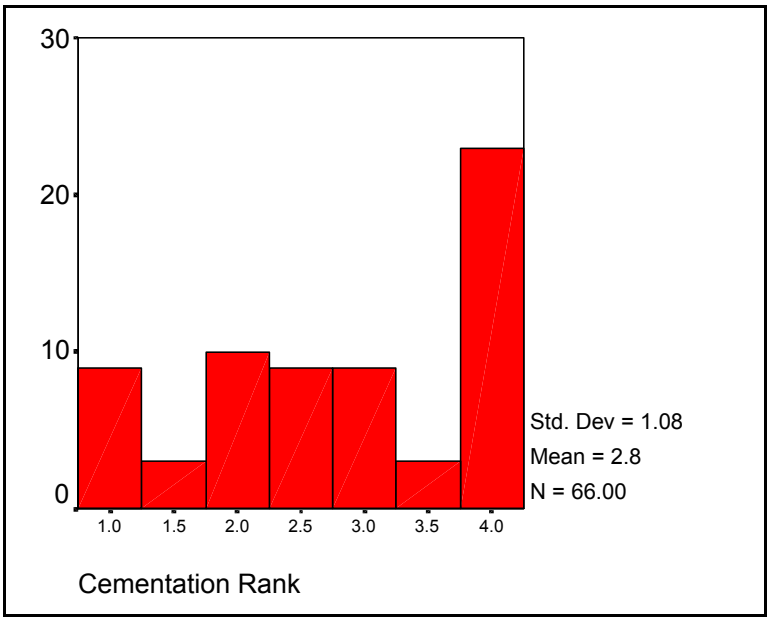

Figure B10: Spring 2003 distribution of cementation rankings

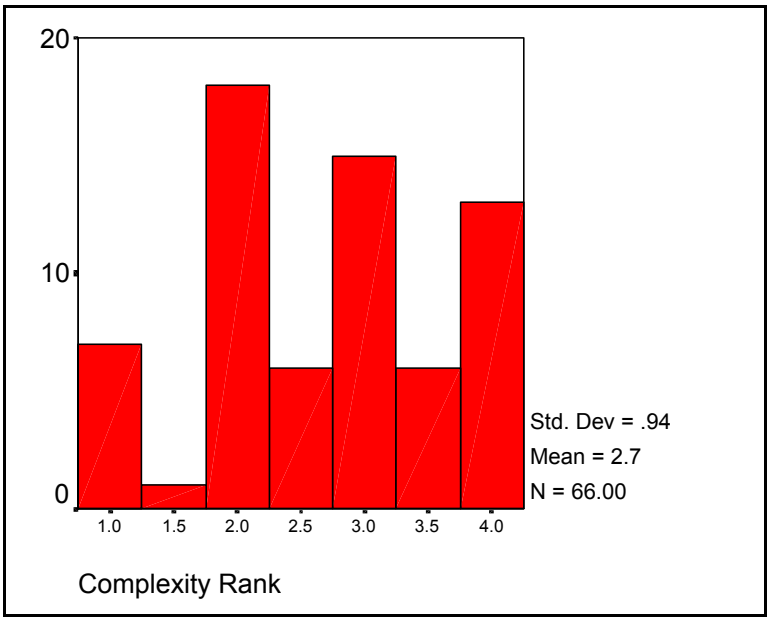

Figure B11: Spring 2003 distribution of channel complexity rankings

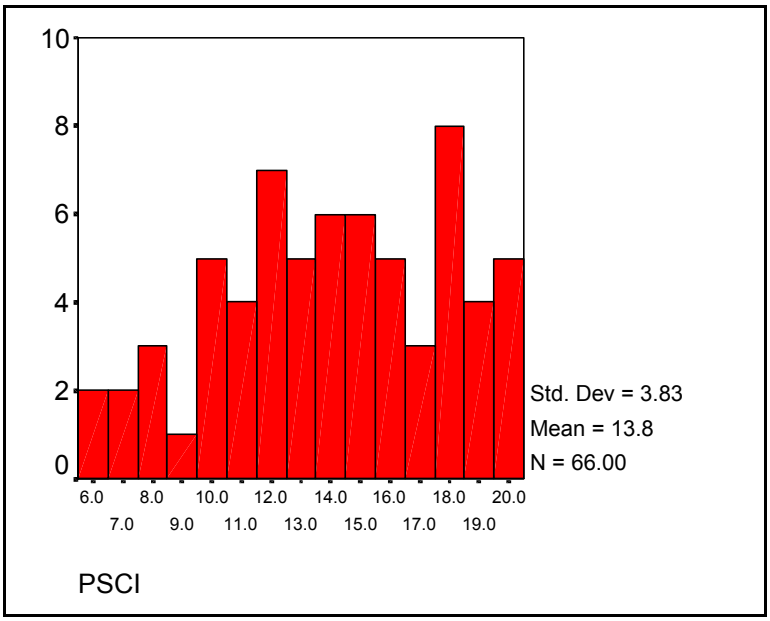

Figure B12: Spring 2003 distribution of PSCI data

APPENDIX C: Sediment Transport Study Data

Monitored Cross Sections with Time:

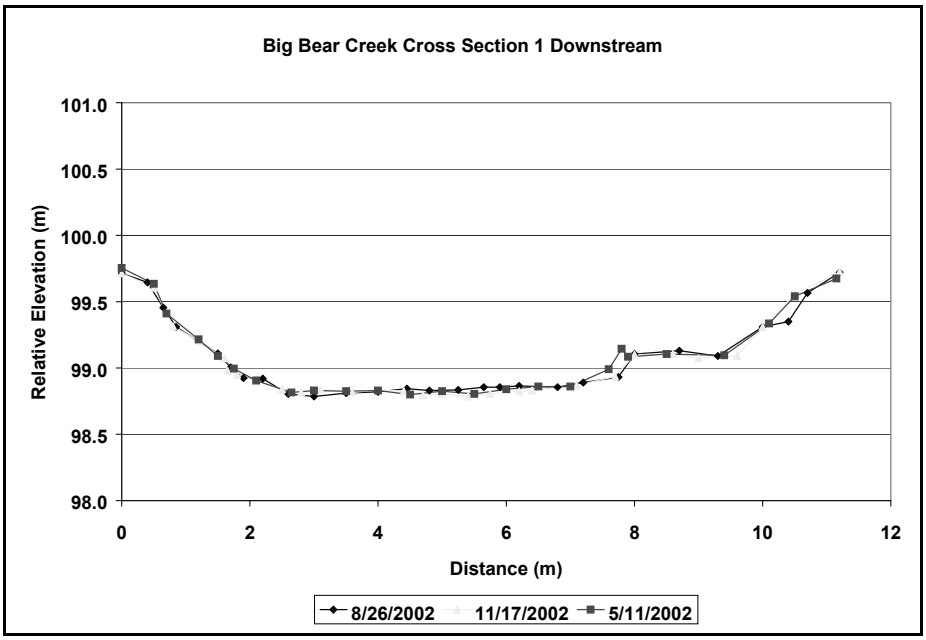

Figure C1: Big Bear Creek downstream cross section surveys

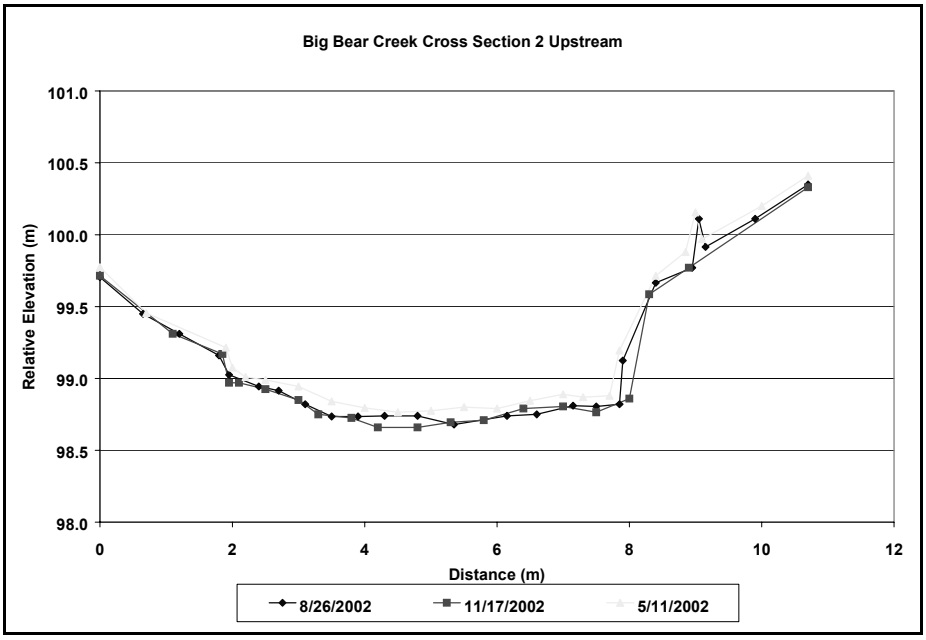

Figure C2: Big Bear Creek upstream cross section surveys

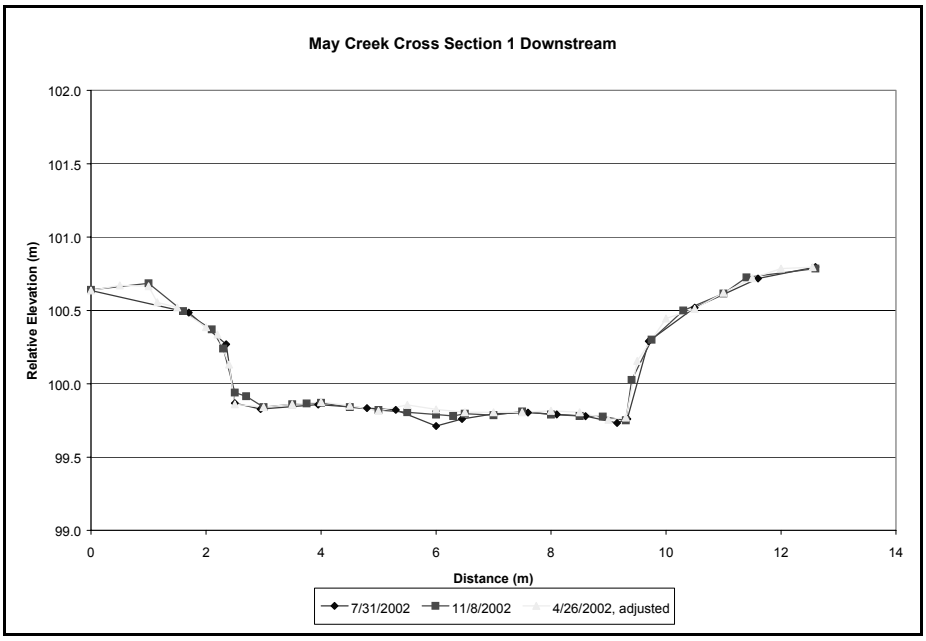

Figure C3: May Creek downstream cross section surveys

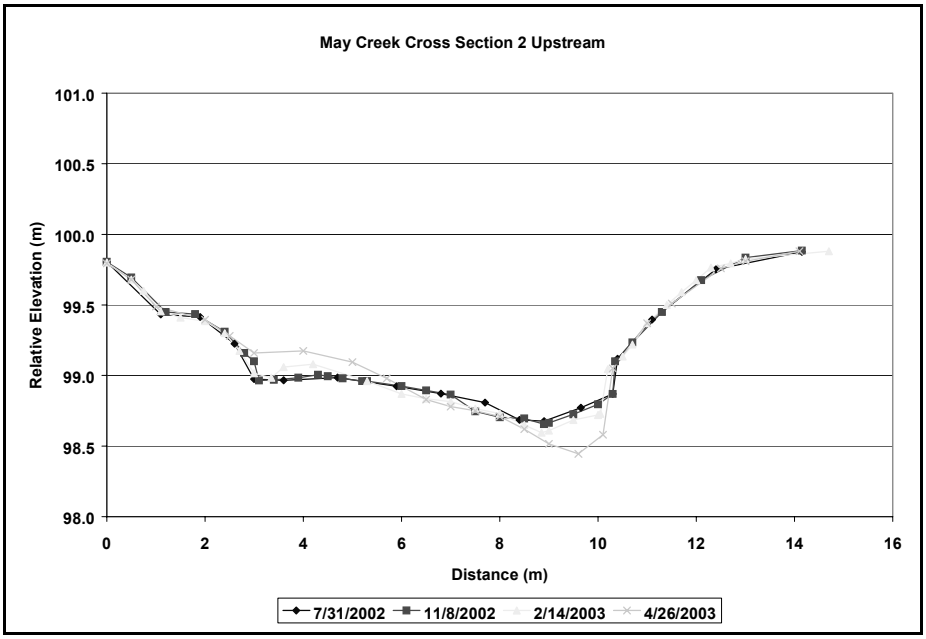

Figure C4: May Creek Upstream Cross Section Surveys

Gravel Size Distribution Results:

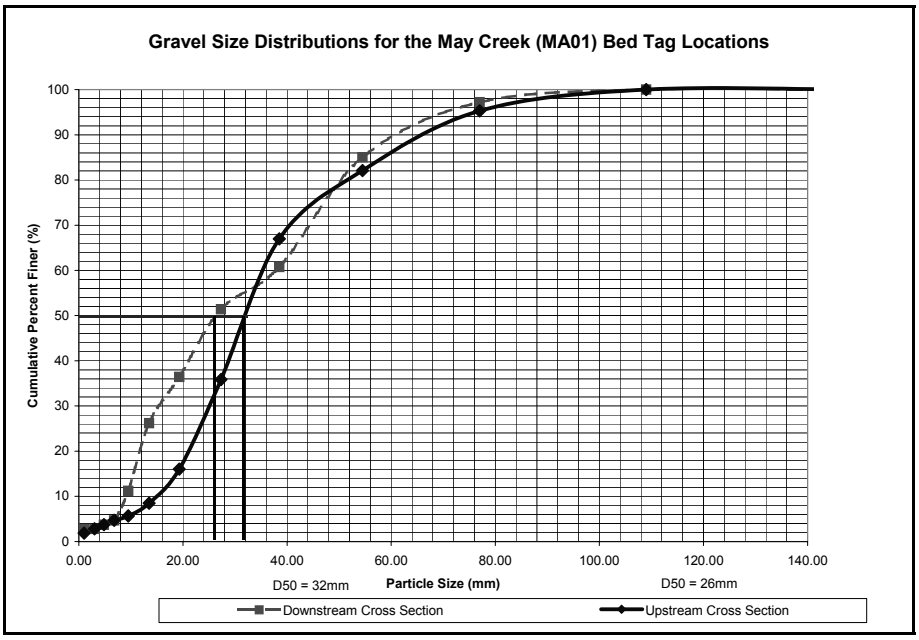

Figure C5: Pebble Count Results for May Creek Cross Sections

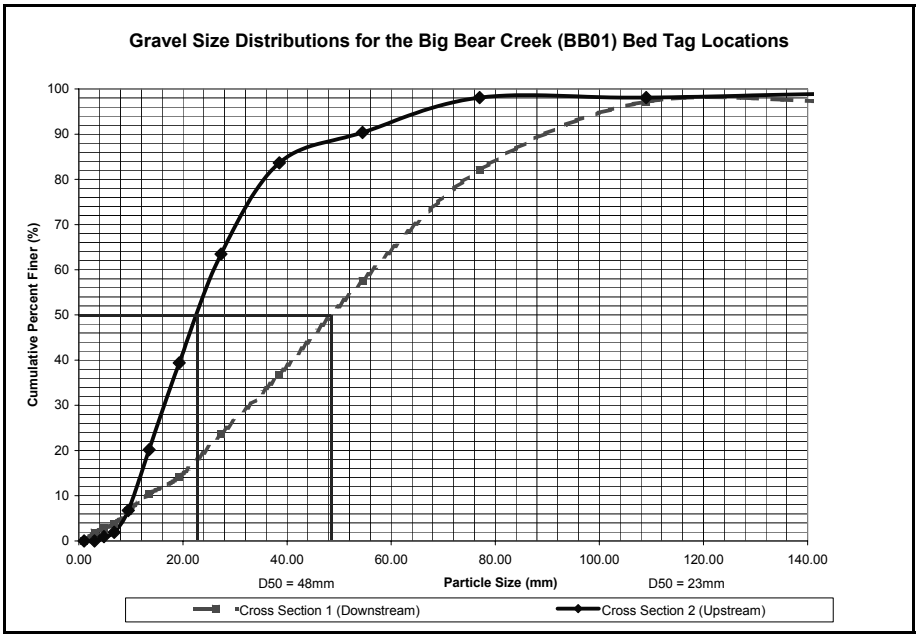

Figure C6: Pebble Count Results for Big Bear Creek Cross Sections

Observed Partial Entrainment:

Table C1: Observed entrainment (PE) for May Creek downstream site

Date Set-up	11/8/2002				
# of Rows	3				
# of tags	34				
Inventory Date	**Expected Entrainment Date**	**PE (row 1)**	**PE (row 2)**	**PE (row 3)**	**PE (entire cross section)**
11/13/2002	11/13/2002	0.08	0.00	0.00	0.03
11/24/2002	11/24/2002	0.00	0.00	0.00	0.00
12/3/2002	11/26/2002	0.00	0.09	0.00	0.03
12/10/2002	12/10/2002	0.00	0.18	0.00	0.06
1/2/2003	1/2/2003	N/A	N/A	N/A	N/A
1/9/2003	1/3/2003	0.08	0.09	0.27	0.15
1/15/2003	1/14/2003	0.08	0.00	0.00	0.03
1/25/2003	1/25/2003	N/A	N/A	N/A	N/A
2/8/2003	1/27/2003	0.58	0.64	0.82	0.68
2/14/2003	2/8/2003	0.20	0.25	0.00	0.18
2/27/2003	2/27/2003	0.00	0.00	0.00	0.00
3/20/2003	3/13/2003	0.93	0.85	0.79	0.85
4/6/2003	3/22/2003	N/A	0.23	N/A	0.23
4/26/2003	4/14/2003	N/A	0.08	N/A	0.08

N/A, or “Not Applicable” means that there was no data collection for that day

Table C2: Observed entrainment for May Creek upstream site

Date Set-up	11/8/2002				
# of Rows	3				
# of tags	35				
Inventory Date	**Expected Entrainment Date**	**PE (row 1)**	**PE (row 2)**	**PE (row 3)**	**PE (entire cross section)**
11/13/2002	11/13/2002	0.08	0.15	0.11	0.11
11/24/2002	11/24/2002	0.08	0.08	0.11	0.09
12/3/2002	11/26/2002	0.00	0.00	0.00	0.00
12/10/2002	12/10/2002	0.08	0.00	0.00	0.03
1/2/2003	1/2/2003	0.15	0.77	0.11	0.37
1/9/2003	1/3/2003	0.33	0.27	0.56	0.38
1/15/2003	1/14/2003	0.00	0.08	0.00	0.03
1/25/2003	1/25/2003	0.08	0.08	0.11	0.09
2/8/2003	1/27/2003	1.00	0.92	1.00	0.97
2/14/2003	2/8/2003	N/A	N/A	N/A	N/A
2/27/2003	2/27/2003	0.00	0.00	0.00	0.00
3/20/2003	3/13/2003	1.00	1.00	1.00	1.00
4/6/2003	3/22/2003	N/A	0.00	N/A	0.00
4/26/2003	4/14/2003	N/A	0.11	N/A	0.11

N/A, or “Not Applicable” means that there was no data collection for that day

Table C3: Observed entrainment for Big Bear Creek downstream site

Date Set-up	11/17/2002				
# of Rows	3				
# of tags	21				
Inventory Date	**Expected Entrainment Date**	**PE (row 1)**	**PE (row 2)**	**PE (row 3)**	**PE (entire cross section)**
11/24/2002	11/24/2002	0.00	0.00	0.00	0.00
12/3/2002	11/25/2002	0.43	0.00	0.00	0.14
12/10/2002	12/10/2002	0.00	0.00	0.00	0.00
1/2/2003	12/16/2002	0.14	0.00	0.29	0.14
1/9/2003	1/4/2003	0.00	0.00	0.00	0.00
1/15/2003	1/15/2003	0.00	0.00	0.00	0.00
2/8/2003	1/25/2003	0.00	0.14	0.14	0.10
2/22/2003	2/22/2003	0.00	0.00	0.14	0.05
3/19/2003	3/14/2003	0.29	0.25	0.29	0.27
4/6/2003	3/23/2003	0.00	0.00	0.00	0.00
4/28/2003	4/14/2003	0.00	0.00	0.29	0.09
5/11/2003	5/5/2003	0.00	0.00	0.00	0.00

N/A, or “Not Applicable” means that there was no data collection for that day

Table C4: Observed entrainment for Big Bear Creek upstream site

Date Set-up	11/17/2002				
# of Rows	3				
# of tags	14				
Inventory Date	**Expected Entrainment Date**	**PE (row 1)**	**PE (row 2)**	**PE (row 3)**	**PE (entire cross section)**
11/24/2002	11/24/2002	0.00	0.00	0.00	0.00
12/3/2002	11/25/2002	0.00	0.00	0.00	0.00
12/10/2002	12/10/2002	0.00	0.00	0.00	0.00
1/2/2003	12/16/2002	0.50	0.20	0.20	0.29
1/9/2003	1/4/2003	0.00	0.14	0.17	0.11
1/15/2003	1/15/2003	0.00	0.00	0.00	0.00
2/8/2003	1/25/2003	0.00	0.00	0.00	0.00
2/22/2003	2/22/2003	0.00	0.00	0.00	0.00
3/19/2003	3/14/2003	0.17	0.14	0.00	0.11
4/6/2003	3/23/2003	0.00	0.14	0.00	0.05
4/28/2003	4/14/2003	0.00	0.00	0.00	0.00
5/11/2003	5/5/2003	0.00	0.00	0.00	0.00

N/A, or “Not Applicable” means that there was no data collection for that day