THE IMPACT OF URBANIZATION ON STREAM HABITAT IN LOWER MAINLAND BRITISH COLUMBIA

by

JENNIFER FINKENBINE

B.Eng., McGill University, 1995

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF

THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF APPLIED SCIENCE

in

THE FACULTY OF GRADUATE STUDIES

(Department of Civil Engineering)

We accept this thesis as conforming
to the required standard

THE UNIVERSITY OF BRITISH COLUMBIA

June 1998

ABSTRACT

Low-order streams in Lower Mainland British Columbia have been surveyed in order to determine their response to urbanization, and to attempt to define limit levels of watershed development. The study watersheds span a gradient of percent total impervious area (%TIA). It was hypothesized that the quality of the following physical elements of fish habitat would be dependent on the %TIA: base flow, cross-sectional geometry, bed particle composition, intragravel dissolved oxygen, riparian integrity, instream cover (large woody debris and rooted cutbanks), bank stability, and temperature.

Some of the fish habitat conditions studied were found to improve with increasing urbanization. The urban streams had less fine material and larger coarse material in their beds. Bed coarsening was accompanied with a slight increase in the levels of intragravel dissolved oxygen. The absence of fine material indicates that the study streams, developed approximately 20 years ago, have recovered from the construction and channel adjustment phases of urbanization.

The degradation of other elements of fish habitat indicates that the most severe damage is done to streams at low levels of urbanization. Base flow became uniformly low between 20-40% TIA, and caused a decrease in velocity, rather than in wetted depth. The high-gradient study streams widened when the TIA increased to 10-15%. Large woody debris abundance was low in all streams with > 20% TIA. The loss of riparian integrity and large woody debris with increasing urbanization also played a role - stream erosion increased

when the buffer strip was less than 30 m wide, and when there were fewer than 5-10 pieces of LWD per 100 m.

Since stream degradation takes place at low levels of imperviousness, it is recommended that the Land Development Guidelines increase the required buffer strip width to 30 m, even for low-density development. As well, stormwater detention ponds should be constructed before urbanization is begun, with the aim of keeping cumulative excess shear stress to a minimum.

TABLE OF CONTENTS

Abstract ii
Table of Contents iv
List of Tables vi
List of Figures vii
List of Symbols viii
Acknowledgements ix

1 Introduction 1

2 Literature Review 3
- 2.1 Introduction 3
- 2.2 Impervious Area 3
- 2.3 Peak Flow 5
- 2.4 Base Flow 6
- 2.5 Sediment Loads 7
- 2.6 Bed Composition 9
- 2.7 Effect of Sediment Loads on Salmonid Incubation 10
- 2.8 Bankfull Flow and the Shifting Equilibrium 11
- 2.9 Stream Morphology at the New Equilibrium 16
  - 2.9.1 Sediment Discharge vs. Width and Depth 16
  - 2.9.2 Water Discharge vs. Width and Depth 17
- 2.10 Riparian Zone 19
- 2.11 Large Woody Debris and Instream Cover 22
- 2.12 Temperature 25
- 2.13 Management Alternatives 27
- 2.14 Summary of Present Knowledge 28

3 Project Scope 30
- 3.1 General 30
- 3.2 Hypotheses 30

4 Methodology 33
- 4.1 Study Sites 33
- 4.2 Total Impervious Area 35
- 4.3 Riparian Buffer Width 38
- 4.4 Stream Surveys 38
- 4.5 Base Flow 39
- 4.6 Cross-Sectional Geometry 39
- 4.7 Stream Bed Composition 40
- 4.8 Intragravel Dissolved Oxygen 42
- 4.9 Slope 43
- 4.10 Instream Cover 44
- 4.11 Bank Erosion 45
- 4.12 Temperature 45

5 Results and Discussion 46
5.1 Total Impervious Area and Buffer Width 46
5.2 Surficial Geology 48
5.3 Base Flow 49
5.4 Substrate Composition 53
5.4.1 Fine Material 53
5.4.2 Coarse Material 55
5.5 Intragravel Dissolved Oxygen 57
5.6 Channel Dimensions 59
5.7 Large Woody Debris 67
5.8 Bank Erosion 70
5.9 Channel Modeling 72
5.10 Hydrologic Analysis 76
5.11 Temperature 78
5.12 Summary 84

6 Evaluation of the Land Development Guidelines 88
6.1 General 88
6.2 Leave Strips 88
6.3 Stormwater Detention Ponds 91

7 Conclusions and Recommendations 94
7.1 Conclusions 94
7.2 Recommendations 97

8 References 99

Appendix A: Raw Data 106

LIST OF TABLES

Table 4.1: Study stream reaches 34
Table 4.2: Total impervious areas of various land uses 36

Table 5.1: Percent impervious area and buffer characteristics of study watersheds 46

Table A-1: Land uses in study watersheds 107
Table A-2: Drainage characteristics of the study watersheds' surficial geology 109
Table A-3: Measured base flow and stream geometry, calculated bankfull flow 110
Table A-4: Sieving results 111
Table A-5: Pebble count results 112
Table A-6: Intragravel / water column dissolved oxygen 113
Table A-7: Large woody debris, rooted cutbanks, and bank erosion data 114
Table A-8: Temperature measurements 115

LIST OF FIGURES

Figure 2.1: Land use, sediment yield, and channel response from a fixed area 8
Figure 2.2: Relations between rate of transport, applied stress, and frequency of stress applications 13
Figure 2.3: Riparian forest effect on streams as a function of buffer width 21

Figure 4.1: Random bed sampling locations 41
Figure 4.2: Well point for IGDO measurements 42

Figure 5.1: Removal of riparian vegetation during urbanization 47
Figure 5.2: Runoff curve number vs. %TIA 49
Figure 5.3: Effect of imperviousness on summer base flow 50
Figure 5.4: Summer base flow vs. runoff curve number 50
Figure 5.5: Effect of watershed imperviousness on summer stream velocity 52
Figure 5.6: Loss of fine material in urban streams 54
Figure 5.7: Bed coarsening in low-gradient urban streams 56
Figure 5.8: Increase in IGDO with increased %TIA 57
Figure 5.9: Decrease in IGDO with increased fine material 58
Figure 5.10: Channel dimensions 59
Figure 5.11: Channel bankfull cross-sectional area vs. catchment area 60
Figure 5.12: Width vs. catchment area 62
Figure 5.13: Corrected bankfull width vs. %TIA (high-gradient channels) 63
Figure 5.14: Widening of Surrey streams 64
Figure 5.15: Depth vs. catchment area 65
Figure 5.16: Corrected bankfull depth vs. %TIA 66
Figure 5.17: Effect of impervious area on instream cover 68
Figure 5.18: Instream cover vs. buffer width 69
Figure 5.19: Effect of buffer width on bank erosion 71
Figure 5.20: Stabilizing effect of large woody debris 72
Figure 5.21: Calculated bankfull flow vs. catchment area 74
Figure 5.22: Observed bank erosion vs. calculated bank critical shear stress 75
Figure 5.23: Comparison of hydraulically calculated bankfull discharge and hydrologically calculated two-year discharge 77
Figure 5.24: Reference stream temperature records 78
Figure 5.25: Temperature increase in urban streams (four days of measurement) 80
Figure 5.26: Stream delta-T vs. 30 m buffer 81
Figure 5.27: Stream delta-T vs. 100 m buffer 82

Figure 6.1: Simulated post-development discharge in Enver Creek with and without stormwater detention 92

LIST OF SYMBOLS

A	channel cross-sectional area (m^2)
A	catchment area (rational method)
A_{bf}	bankfull channel cross-sectional area (m^2)
C	catchment area (ha)
C	runoff coefficient (rational method)
c_u	undrained bank cohesion
d	water depth (m)
D_{84}	diameter of 84th percentile bed particle
E	percent survival to the eyed stage
F	width-to-depth ratio
f	Darcy-Weisbach roughness
I	rainfall intensity (mm/hr)
k_s	roughness coefficient
K_2	reaeration rate ($days^{-1}$)
K	land cover factor (rational method)
LWD	large woody debris
M	percentage of silt and clay (< 0.074 mm) forming channel perimeter
n	Jarrett's roughness coefficient
Q	water discharge (m^3/s)
Q_{bf}	bankfull water discharge (m^3/s)
R_{bf}	bankfull hydraulic radius (m)
RCB	rooted cutbank
S	channel gradient (%)
%TIA	percent total impervious area
t	time to hatching (days)
t_c	time of concentration
T_1	temperature from fertilization to the eyed stage (^oC)
T_2	temperature from the eyed stage to hatching (^oC)
v	velocity (m/s)
w	channel width (m)
τ	shear stress (kPa)
τ_{crit}	critical shear stress (Pa)
τ_{bank}	bank shear stress
γ_t	saturated weight of bank material

ACKNOWLEDGEMENTS

I would like to thank Prof. Jim Atwater at the University of British Columbia for his guidance throughout this study. Dr. Don Mavinic, Dr. Rob Millar, and Dr. Ken Hall of UBC also provided valuable input, and their help is much appreciated.

I would like to express my gratitude to Barry Chilibeck of the Government of Canada Department of Fisheries and Oceans for giving this thesis its initial direction, and providing much of the necessary equipment.

The Langley Environmental Partners Society was extremely helpful in teaching me methods of stream surveying, and in providing information about the Salmon River Watershed.

I would also like to thank Paul Zandbergen, Ph.D. student at the Institute for Resources and Environment at UBC, for all his help with impervious area calculations, and for information regarding the Burnaby and Langley streams.

Richard Boase of the Corporation of the District of North Vancouver, Stephen Lan of Langley Township, Henry Wong of the City of Coquitlam, Harry Long of the City of Surrey, and Bruce Smiley of the Greater Vancouver Regional District all provided indispensable information about the study watersheds, and their help is appreciated.

All of those in the Rusty Hut (UBC) are thanked for their input regarding field equipment.

I would also like to thank the many UBC students who spent time helping and entertaining me in the field: Carlos Barrera, Bob Devlin, Kristy Dziver, Stephanie Ebelt, Sue Greco, Kristina Laretei, Abyartha Sharma, and Shane Uren.

Finally, a big thank-you to Andrew Griezic for all his support and encouragement.

1 INTRODUCTION

Towards the end of the 19th century, European settlement of the Vancouver area transformed Lower Mainland British Columbia from a forested wetland into urban and agricultural zones. Since that time, rapid population growth has pushed the urban boundaries further and further into agricultural land. Most of the numerous streams that previously flowed through the City of Vancouver have been culverted, removing valuable fish habitat. Those which have remained above ground in the Greater Vancouver Regional District (GVRD) have been affected physically, by the alteration of flow regimes and removal of riparian vegetation, and chemically, by the introduction of pollutants. Salmon habitat degradation has been significant in these streams over the past 100 years (Rood et al., 1994). As a result, stocks of wild British Columbian coho, chinook, and steelhead have declined, with the salmon returns dropping to the lowest levels in history in 1996 (Fresh Outlook, 1998).

An attempt is now being made to restore these damaged systems, and to improve salmon stocks. The Land Development Guidelines (Chilibeck, 1993) set out new recommendations for the protection of fish and fish habitat. Strategies such as the maintenance of a forested buffer strip and the construction of stormwater detention ponds have been implemented to mitigate the effects of development. Low-order streams, as well as providing important spawning and rearing habitat, are the most sensitive to changes in land use (Church, 1992). It is therefore critical to determine how much harm has been done to them under past development practices, both so that appropriate restorative measures may be applied, and so that the same mistakes are not made in the future. To this end, this study will measure the degradation of physical elements of fish habitat in several Lower Mainland streams which have been impacted, to varying degrees, by urbanization. The extent to which the current Land Development Guidelines protect fish habitat will then be reviewed.

2 LITERATURE REVIEW

2.1 Introduction

Streams in urbanizing watersheds undergo many changes which are detrimental to fish populations. In the first phase of development, construction sites deliver a large sediment load to streams. In the second stage, impervious surfaces generate high peak flow rates, and increased frequency of bankfull flows. Streams that were once able to return to equilibrium after each channel disturbing flow become subjected to a greatly increased frequency of such flows. The loss of riparian cover during urbanization accelerates the damage to aquatic habitat. Once equilibrium is reached, the new urban stream has changed to a larger, wider, shallower channel, with lower complexity, less woody debris, and an altered temperature regime. In order to effectively mitigate the effects of urbanization, it is important to determine at which level of urbanization fish habitat becomes degraded.

2.2 Impervious Area

In the urbanization process, pervious forest land is replaced by impervious surfaces such as rooftops and roads, and less permeable surfaces such as compacted lawns and parks (Beyerlein, 1996). Increased imperviousness results in larger and more frequent floods, greater total surface runoff, and decreased time to produce runoff (Morisawa et al., 1979; Neller, 1988). The percent total impervious area (%TIA) has been identified as a good means to quantify the level of watershed development (Arnold, 1996), as it indicates the amount of rainfall that is converted to direct runoff.

An attempt has been made to identify the threshold at which a stream becomes degraded. Arnold et al. (1996) review research showing that degradation first occurs at 10% TIA, and becomes severe at 30% TIA. Schueler (1994) cites studies, conducted in a variety of geographical areas and focusing on different variables, which consistently find that degradation takes place at 10-20% TIA. Schueler et al. (1997) classify a stream with TIA < 10% as "sensitive," 11 to 25% as "impacted," and > 25% as "non-supporting." Fish sampling has shown that two sensitive species of fish disappeared when imperviousness increased from 10 to 12%, and four more were lost when %TIA increased to 25%; only two species remained at 55% TIA (Schueler, 1994). Such impacts on the fish community are attributed to changes in substrate composition, temperature, pollution, flow, and other elements of fish habitat (Schueler, 1994). According to Horner et al. (1997), the decreases in benthic communities and in the sensitive coho salmon population that result from increased %TIA are linked more to the changes in physical habitat than to impairment of water quality. He found that change occurs most rapidly in the beginning stages, when TIA increases to 5-8%, and slows with greater urbanization. For Puget Sound streams, it is recommended that the TIA be kept below 5% to protect benthic communities, unless the stream has a good riparian zone or is protected by other management (Horner et al., 1997).

Percent effective impervious area (%EIA), if known, is a better means of quantifying the impact of watershed development on runoff. Total impervious area includes all surfaces that do not allow infiltration, such as streets, sidewalks, and rooftops. However, not all of these surfaces are connected directly to the storm drainage system. Some runoff from a house's rooftop infiltrates into the surrounding lawn, and the rooftop is therefore partially ineffective. Effective impervious area describes those surfaces directly connected to a conveyance system, and is a fraction of the TIA. Robinson (1976) identified percentage impervious area and percentage of area serviced by storm sewers as the two main factors affecting discharge and channel size. Hammer (1972) found that streams enlarged more in watersheds with sewered streets than in areas unconnected to the drainage system. Typical values of %EIA have been developed for different land uses (Beyerlein, 1996; Dinicola, 1990) using study areas in the state of Washington, but these numbers have not yet been verified for British Columbia.

2.3 Peak Flow

Streams with higher %TIA experience flashier flows with higher peaks (Robinson, 1976). In Western Washington, frequently occurring discharges in urban streams can be from 10 to 100 times as large as for pre-development conditions (Sovern et al., 1997). These increased peak flows affect stream structure and the quality of fish habitat. Fish mortalities occur when high current velocities wash salmonid eggs from the redds (Sidle, 1988; Vronskii et al., 1991). Severe high flows have been correlated with pre-emergence mortality of coho salmon (Scrivener, 1987). According to May (1996) the timing of floods has important impacts on fish populations, as newly emergent alevins and fry are most likely to be displaced by high flows. Coho salmon, which hatch earlier in the spring than cutthroat, are particularly at risk (May, 1996). Increased flooding can cause mortalities for another reason: during flood periods, new areas of the streambed develop sufficient intragravel circulation to provide suitable spawning ground, and spawners dig redds outside of the usual sites. Once the water level returns to normal levels, however, these areas suffer from reduced infiltration, and eggs and embryos are lost (Vronskii et al., 1991). High flows are signals to fish to begin upstream migration - earlier peak flows may therefore encourage early migration. Flows that are too high, however, may temporarily hinder the upstream journey (Jonsson, 1991).

2.4 Base Flow

Urbanization causes an increase in storm runoff, and a corresponding decrease in groundwater recharge, as impervious surfaces prevent infiltration of rainwater (Pawlow et al., 1977; Klein, 1979). A study conducted in Puget Sound found that the ratio of 2-year peak flow to winter base flow increased from under 20 in streams with < 10% total impervious area (TIA) to over 50 in streams with > 50% TIA (Horner et al., 1997). However, it is principally the effective impervious area that impacts base flows. On Long Island, New York, approximately 95% of flow in a rural stream is baseflow; urbanization accompanied by storm and sanitary sewerage lowered the baseflow contribution to 20%, while increased imperviousness without sewerage reduced the baseflow contribution to 84% (Simmons et al., 1982).

Lower flows in the summer season can cause losses in fish rearing habitat. When irrigation demands placed on the Trinity River in northern California reduced yearly average streamflows to 10% their original value, salmon and steelhead production declined by at least 80% (Williamson et al., 1993). The reduced flows caused mortalities due to reductions in velocity, cross-sectional area, and water depth - pre-smolt chinook salmon were found to prefer water depths greater than 0.3 m (Williamson et al., 1993).

2.5 Sediment Loads

In the early stages of urbanization, streams experience an increase in sediment load from two different sources (Sovern et al., 1997). First, terrestrial sources are magnified due to both construction in the watershed and the loss of vegetation which slows overland flow and filters sediments (Yorke et al., 1978). The amount of sediment generated in just a year from areas cleared for construction can match that yielded by untouched and agricultural land over many decades (Wolman et al., 1967). Land use effects can be seen by comparing data from Maryland river basins. Forested and grassy areas produced just 0.03 to 0.2 ton of suspended sediment per acre annually, as compared to the 7 to 100 tons per acre from construction sites (Yorke et al., 1978).

The stream channel itself represents a second source, as higher peak flows generate sediments from increased erosion of stream beds and banks (Sovern et al., 1997). Increased velocities lead to increased competence, defined as "a measure of the ability of the stream to transport debris in terms of particle size" (Mackin, 1948). The weight of the largest particle moved is typically proportional to the sixth power of the velocity (Mackin, 1948). In recently urbanized areas of Maryland, sediment yields were estimated at 3.7 tons per acre, primarily influenced by stream-channel erosion (Yorke et al., 1978). During a stream's adjustment period (estimated at 15 years), a total of 2,300 m^3/km^2 of sediment are estimated to be generated from bank erosion (Klein, 1979).

After urbanization is complete, sediment loads are expected to fall to pre-development levels. This is because both terrestrial sources disappear (construction is completed) and channel erosion will no longer generate significant quantities of sediment (the new channel area is in equilibrium with the new flow regime) (Yorke et al., 1978). Figure 2.1 illustrates the changes in sediment load with progressing development (Wolman, 1967). As shown, sediment loads increase sharply during the construction phase, but post-construction loads are expected to fall to, or below, those generated from forest lands.

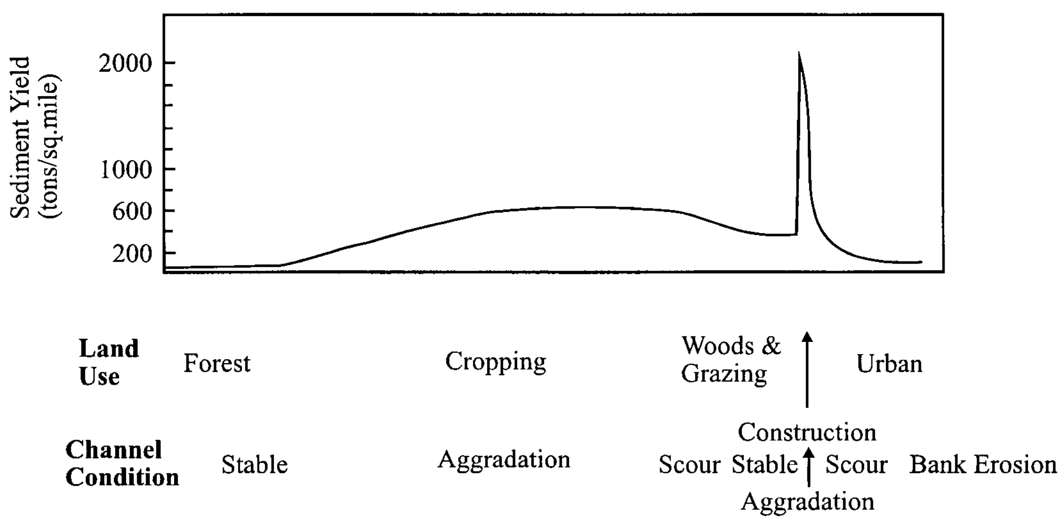

Figure 2.1:
Land use, sediment yield, and channel response from a fixed area (Wolman, 1967)

2.6 Bed Composition

Bed composition is an important element of habitat assessment – in fact, streambed instability has been identified as the critical factor impacting fish populations in urban streams (Sovern et al., 1997). As a stream adjusts to a new flow regime, the influx of sediment will affect the streambed composition. Observations made in several studies indicate that the urbanization process increases the percentage of fines on the bed (Arnold et al., 1996). In as short a period as 2 to 3 months, fines from construction can cover an entire streambed (Klein, 1979). This results in a decrease in the porosity of the gravel (Sovern et al., 1997), creating unsuitable conditions for incubating fish eggs. It also creates a more mobile streambed (Olthof, 1994; Wolman et al., 1967), which detrimentally increases benthic drift (Culp, 1987). As well, pools become infilled with fine particles (Lisle et al., 1992), which reduces their volume and removes available fish rearing habitat. The percentage of fines in the bed increases when the imposed sediment load is greater than the transport capacity, and the effect is seen even when there is no change in the size distribution of the imposed sediment (Lisle et al., 1992). The impervious area in a watershed has been found to explain 75% of the variance in the bed fine sediment content during summer low flows (Olthof, 1994), likely a result of overland and channel erosion during the previous high flow season.

Although a streambed will no longer be subjected to increased sediment loads once equilibrium is reached, it can take at least 15 years (Robinson, 1976) and up to 50 years (Klein, 1979) for a stream to recover. According to Scrivener (1987), a stream can recover from sudden pulses of sediment within a few years, but chronic sediment sources lead to deeper intrusion of fines into the bed, making a rapid return to pre-disturbance conditions difficult. However, more frequent high flows clean gravel faster (Scrivener, 1987). Therefore, in an urban situation, increased peak flows due to impervious surfaces could remove fine particles relatively quickly. The change from high sediment loads to high flows is evidenced in the morphology of a Colorado stream. The extensive floodplain developed from excessive deposition in the early phase of urbanization was subsequently incised by high peak flows, revealing layers of construction sediments (Graf, 1975). The new equilibrium involves a reverse shift in bed composition, indicated by research which found that the beds of urban streams are coarser than their rural counterparts. Robinson (1976) found that the D_{84} (84% of the sample was finer than this size) of urban streams was approximately four times higher than in the rural case. He also reports finding lower percentages of silt and fines in urban streams. This coarsening is attributed to increased flow competence following urbanization, accompanied by reduced sediment loads after construction is completed. His findings are supported by the field studies of Lisle et al. (1992).

2.7 Effect of Sediment Loads on Salmonid Incubation

A high percentage of fines in a streambed creates unfavourable incubation conditions for salmonid eggs. This layer of low permeability separates the surface from the subsurface flow. The resulting loss of water exchange causes decreases in the oxygen content in the intragravel water (Vronskii et al., 1991) and prevents the removal of metabolic waste products from the eggs (Havis et al., 1993). For these reasons, spawning chinook salmon prefer substrates with 0-10% embedded fines, and usually less than 40% embedded (Williamson et al., 1993). In

Carnation Creek, British Columbia, egg to fry mortality increased as the fraction of pea gravel and sand increased (Scrivener, 1987). Horner et al. (1997) discovered that the ratio of intragravel dissolved oxygen (IGDO) to water column DO decreased from over 80% for most streams with a %TIA below 5%, to below 70% and as low as 30% for streams with a %TIA above 40%. Measures of IGDO are a good indicator of the extent of clogging due to fine material. Vronskii et al (1991) found that in pools with an 80% content of material less than 2 mm in diameter, the intragravel dissolved oxygen was approximately half the value in adjacent coarse riffles. An excessive load of coarser material is detrimental to salmon eggs for another reason – while there is sufficient intragravel flow for egg survival, the coarse materials create a seal through which the fry cannot emerge (Havis et al., 1993; Sidle, 1988).

Although high flows help to clean fines from spawning gravels (Sidle, 1988; Williamson et al., 1993), flows that are too high can also remove gravel from 5 to 15 cm in diameter – the ideal size for spawning (Williamson et al., 1993).

2.8 Bankfull Flow and the Shifting Equilibrium

There is some disagreement as to the frequency of the dominant discharge. Carling (1988) defines the dominant discharge as "that discharge which transports the most bed sediment in a stream that is close to steady-state conditions." It is this flow which influences the size and shape of the channel (Leopold, 1994). Many authors have considered bankfull flow, occurring approximately every 1 to 2 years, to be the dominant discharge (Hammer, 1972; Leopold, 1994; Leopold et al., 1964; MacRae, 1997; Sovern et al., 1997; Wolman et al., 1960).

According to Hammer (1972), a channel adjusts its cross-sectional area so that there is a constant frequency of overbank flow; therefore, the amount of channel enlargement after urbanization is proportional to the increase in magnitude of the 1.5 year flood. Flume experiments performed by Barishnikov (1967) have shown that flow which remains within the channel carries more sediment than does overbank flow, especially when the adjacent floodplain is rough. The roughness provided by the floodplain slows the water flowing overbank, and the friction between the overbank and within bank portions of the flow decreases the sediment transporting energy (Barishnikov, 1967).

The consensus of many authors is that, while overbank flow carries more sediment than bankfull flow, it does not occur often enough to be the channel maintaining flow. In Figure 2.2, the work curves generated by Wolman et al. (1960) illustrate how more frequent events of moderate intensity carry more sediment than less frequent, catastrophic events. The excess stress (stress greater than critical) has been found to follow a log-normal distribution (Figure 2.2b), while the rate of movement is proportional to some power of the stress (Figure 2.2a). The product of the rate and frequency (Figure 2.2c) reaches a maximum, indicating the flood frequency for which, over time, the most sediment is moved (Wolman et al., 1960). Measurements of sediment transport rates and frequencies have confirmed that, in many basins, 90% of the sediment load is moved in floods of frequency of 5 years or less (Wolman et al., 1960).

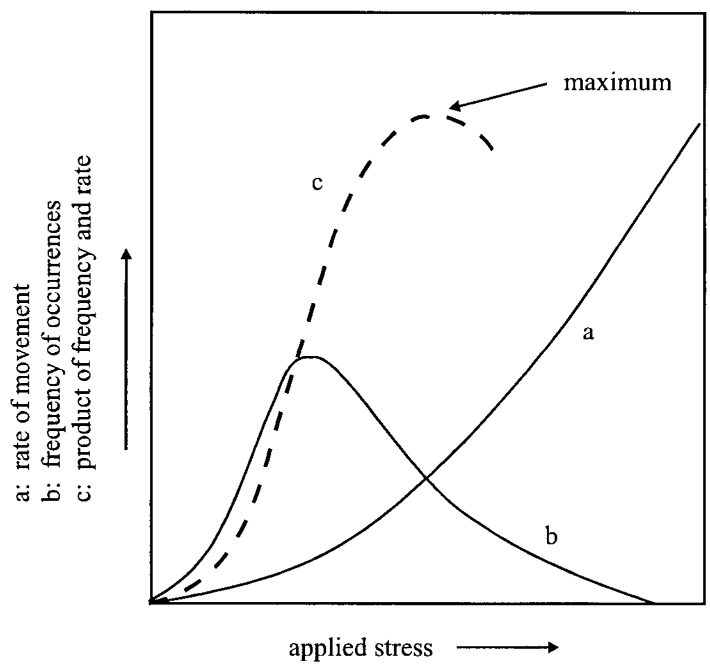

Figure 2.2:
Relations between rate of transport, applied stress, and frequency of stress application (Wolman et al., 1960)

Leopold et al. (1967) point to channel form as evidence of the importance of bankfull flow. In a meandering river, overbank flows flow down valley, across the meander pattern, rather than within the channel, and therefore do not contribute to the erosion and deposition at channel bends (Leopold et al., 1967).

There is, however, some doubt as to whether the 2-year flood moves the most sediment. Wolman et al. (1960) found that for small drainage basins with more variable flow regimes, more of the sediment is carried by less frequent, larger floods. Mountainous streams with large boulders can only be shaped by larger, less frequent events (Church, 1992; Leopold et al., 1964). Sidle's (1988) research on an Alaskan gravel bed stream showed that while fine bed load sediment is scoured and deposited several times within a storm season, coarse material is scoured only during high storm flows with a return period greater than approximately 5 years. A comparative study of two gravel-bed streams showed that the bankfull discharge was effective in maintaining equilibrium transport (phase 2 transport) in the alluvial stream. However, phase 3 transport – which mobilized most of the bed, and changed the channel shape – only occurred with overbank flows. The other stream studied, which had more resistant cohesive till-banks and a heavily compacted bed, experienced minimal bed movement even at the highest discharges (Carling, 1988). While the two streams experienced different modes of transport at bankfull flow, it is important to note that in both streams this flow occurred with a recurrence interval of 0.9 years on the partial duration series (Carling, 1988). This means that, for both streams, the bankfull cross-sectional areas indicate the magnitudes of equally frequent discharges.

Impervious area contributes direct runoff to stream flow in all types of storms; however its effect is most obvious in smaller storms, when pervious areas have not reached saturation (Yorke et al., 1978; Booth, 1990; Hollis, 1975). Floods with a recurrence interval of 100 years or more are not likely to increase more than 2 to 3 times in magnitude. Therefore, floods that are catastrophic at the human level do not increase appreciably after development (Hollis, 1975). It is the less noticeable, but morphologically significant, high in-bank flows that cause the most damage. The increase in frequency and duration of flows near bankfull disrupts stream equilibrium in urbanizing watersheds. According to MacRae (1997), because urbanization causes a greater increase in frequency of smaller floods, the maximum sediment transporting work is done by mid-bankfull flows in urban streams. Channel disturbing flows cause bank erosion, movement of large cobbles and boulders, movement of large woody debris, infilling of pools, and scouring of bars (Booth, 1991). In a natural system, these flows help to maintain stream health by scouring and cleansing (Klein, 1979); the low flows that follow extreme events serve to rebuild the stream and return it equilibrium (Booth, 1991). Under fully urbanized conditions, however, such flows can occur 3 (Klein, 1979) to 5 (Booth, 1991) times per year. Urbanization can cause the frequency of sediment transporting flows to increase by as much as 50 times (Booth et al., 1997). The stream therefore does not have time to return to equilibrium before being stressed again (Klein, 1979), and the result is a stream with a uniform bed (few pools and riffles), an incised bed, steep and eroding banks, and small and infrequent woody debris (Booth, 1991).

Although stream equilibrium may be delayed for several decades following urbanization, a stream will eventually enlarge until the velocity drops to a stable level (Morisawa et al., 1979). The enlargement process may be delayed when urbanization first begins, as Hammer (1972) found that developed areas less than 4 years old do not significantly affect the channel's cross-sectional area. Morisawa et al. (1979) showed that channel enlargement is a secondary response after the initial response of increased velocities. Therefore, a stream's response to urbanization is delayed until about 25% of the watershed has > 5% impermeability. Streams then enlarge gradually until about 30-40% of the watershed reaches this level of development, after which a threshold is reached and the rate of enlargement greatly increases. Neller (1988) found that, five years after urbanization, a stream continued to enlarge at a rate greater than that of a rural channel. However, because the bank retreat could be explained by the larger flows in the urban channel, there was no evidence of channel instability, and the urban channel was considered to be at equilibrium (Neller, 1988). Regardless of the rates of change, eventually a new equilibrium will be reached, where bankfull flows again occur approximately every 1.5 years, and channel erosion has returned to pre-development levels. It is reported to take at least 15 years for a stream to adjust to a new equilibrium (Robinson, 1976). At the new equilibrium, not only the channel size, but its shape will have changed.

2.9 Stream Morphology at the New Equilibrium

The following stream responses are reported to accompany hydrologic changes (Sovern et al., 1997):

1) Increased sediment discharge increases the width to depth ratio.
2) Increased water and sediment discharge both cause an increase in bankfull width.
3) Increased water discharge increases the bankfull depth.

The process by which these changes take place will be described, and reasons given for the transformations.

2.9.1 Sediment Discharge vs. Width and Depth

When sediment discharge increases, it is deposited on the streambed as the storm hydrograph recedes (Lisle et al., 1992). This results in a shallower channel with a lower cross-sectional area. When higher flows resume, the stream is required to erode its banks to accomodate these flows (Wolman et al., 1967). While the depth decreases due to deposition, the width increases due to bank erosion, resulting in a stream with a high width-to-depth ratio. The construction phase of urbanization would cause a stream to take this shape.

2.9.2 Water Discharge vs. Width and Depth

A stream's capability of transporting sediment is reflected by the mean shear stress (τ_o). When its flow increases initially, unaccompanied by a change in width or slope(S), its depth (d) will increase as explained by Manning's equation (Henderson, 1966):

$$Q = \frac{A}{n} d^{2/3} S^{1/2}$$

The shear stress will also increase, as it is directly proportional to the flow depth (Henderson, 1966):

$$\tau_o = \gamma d S$$

The transporting capacity of the stream will therefore be greater, and if it is not accompanied by an increase in the imposed sediment load (as in the post-construction phase), it will remove sediment from the bed and banks, enlarging the stream's cross-sectional area.

Channel enlargement can take place in one of two ways: first, expansion is a continuous enlargement of both width (by bank erosion) and depth (by stream-bed degradation), closely proportional to the increase in discharge (Booth, 1990). In a Maryland stream, the channel cross-sectional area and width increased when the basin impervious area increased from 5.6% to 13.5% over an eight-year period (Yorke et al., 1978). Another study conducted in the same area showed that urban streams had channel areas approximately twice the size of rural streams (Robinson, 1976). Streams in the Piedmont region were found to enlarge in relation to the amount of sewered, impervious surfaces in their watersheds (Hammer, 1972); as well, for a given level of urbanization, a steeper sloped basin was found to enlarge more. Empirical equations have been established by several authors to explain a stream's widening and deepening with a downstream increase in flow. They are as follows (Leopold et al., 1964):

$$w = aQ^b$$

$$d = cQ^f$$

The values of the constants *a* and *c* vary according to the bank stability (Morisawa et al. 1979). The values of the exponents *b* and *f* are closer between studies, and generally $b > f$, indicating that the width-to-depth ratio typically increases as flow increases (Leopold et al., 1964). Schumm (1969) identifies the type of sediment load as the most important factor influencing width to depth ratio. He found that the width to depth ratio (*F*) was proportional to the percentage of silt and clay (< 0.074 mm) in the sediments forming the perimeter of the channel (*M*) according to the following relationship:

$$F = 255M^{1.08}$$

However, not all channels enlarge in this quasi-equilibrium fashion. Some experience drastic change as channel incision takes place greatly out of proportion of the increase in discharge. Others expand gradually until a threshold is reached, then suddenly begin to incise. A stream is likely to incise when the transporting capacity of the flow exceeds the sediment supply due to increased flowrates, and streams with steep slopes and fine-grained non-cohesive sediments are particularly susceptible to this catastrophic change (Booth, 1990). This would cause the depth to increase at a faster rate than the width. If stream deepening causes the bank height to exceed the critical value for stability, then mass failure will occur (Millar et al., in press). This sudden change will cause the channel to become wider and shallower, and the width-to-depth ratio will increase.

The regime equations described above are likely to have been developed for streams with shallow slopes and larger sediment sizes, not prone to incision. Hammer (1972) found that the width to depth ratio was correlated with the channel slope and watershed area, but not to the degree of urbanization, indicating that all channels enlarge in different ways. Local hydrologic regimes and the relative resistance of bed and bank materials play a role in determining the width and depth adjustments (Morisawa et al., 1979). A new England stream was observed to undergo an increase in width due to bank erosion, and a decrease in depth, due to deposition of bank sediments, after the construction phase of urbanization was completed (Arnold et al., 1982). For streams having similar geology, Robinson (1976) found that the width-to-depth ratio in urban streams was approximately 1.7 times that of their rural counterparts. He also showed that urban channels had lower ratios of low flow wetted width to bankfull width. This low ratio is due to both increased channel width and reduced base flow. For both reasons, summer flow depths may be insufficient for fish in urban streams.

2.10 Riparian Zone

A study of the impacts of urbanization cannot focus on TIA alone. The removal of riparian vegetation is an important consequence of urbanization, and itself exerts influences on stream habitat. As forest land is cleared during urbanization, the width and quality of the riparian buffer zone diminish. A stream's buffer width is negatively correlated with the %TIA (May et al., 1996). Maintenance of a buffer strip helps to mitigate the impacts of urbanization in many ways. The vegetation in the buffer zone slows overland flow, and enhances the deposition and filtering of sediment and nutrients which would otherwise be carried into the stream (Belt et al., 1994). Shade provided by riparian vegetation also serves to regulate stream temperature (Belt et al., 1994, LeBlanc et al., 1996). Schueler (1994) reports research showing that, for the same level of urbanization, streams with intact riparian forests have higher levels of macroinvertebrate diversity than those without buffers.

Forested riparian zones are important sources of large woody debris. Research performed in western Oregon and Washington found that with a 30 m wide buffer strip, large woody debris counts were 85% of what would occur naturally, whereas with a 10 m strip, less than half of the naturally occurring debris was found (Belt et al., 1994). Buffer zones also provide leaf litter as food for benthic invertebrates, which are themselves important fish food (Belt et al., 1994). Culp (1987) observed that a 10 m buffer strip provided insufficient amounts of benthic detritus, resulting in declines in macroinvertebrate biomass and density. The buffer strip serves another purpose – as spawning gravel is carried from the stream by high flows, it is replenished by landslides and debris flows into the stream from forested areas (O'Laughlin et al., 1995).

The loss of wide streamside buffers of natural vegetation is highly correlated with increased bank erosion (Whipple et al., 1981). However, these have difficulty in isolating the effect of the buffer zone on erosion rates, as the streams with poor buffers also tend to be highly developed, thus generating erosive flows from impervious surfaces. Keller et al. (1979) report research showing that a healthy root system can retard bank erosion much more effectively than does unvegetated soil. Vegetated streams are therefore expected to be narrower than unvegetated streams carrying the same water and sediment discharges, particularly in streams with small drainage areas (Keller et al., 1979). Similarly, Gurnell et al. (1984) cite research showing that channels with grassy banks are 30% wider and those with tree-lined banks are 30% narrower than average.

A consensus on the ideal buffer strip width has not been reached. Whipple et al. (1981) classify a naturally wooded strip greater than 50 ft (15 m) as excellent, and one less than 10 ft (3 m) as poor. A buffer strip should be wider in zones with low infiltration rates and steep land slopes (Belt et al., 1994). Figure 2.3 shows the approach used by FEMAT (O'Laughlin, 1995) to determine the required buffer strip width.

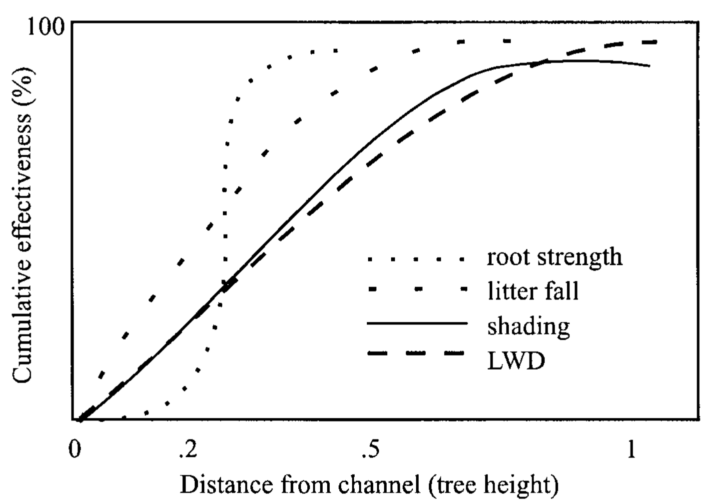

Figure 2.3:
Riparian forest effect on streams as a function of buffer width
(O'Laughlin et al., 1995)

Here, the increase in effectiveness of various leave strip functions is plotted against increasing strip width. To be conservative, FEMAT prescribes a buffer width of twice the height of a site-potential tree, or 300 ft (90 m), whichever is greater (O'Laughlin et al., 1995). Booth's (1991) estimation of the required buffer width is less conservative, as he suggests that the benefits of LWD recruitment, shading, and leaf detritus do not increase beyond a width of 100 ft (30 m). Other research has found that a 30 m buffer strip was sufficient to protect salmonids and benthic communities (Brown et al., 1997). According to the Land Development Guidelines (Chilibeck, 1993), the buffer strip width should be measured from the stream's high water mark; or, if the stream is surrounded by steep slopes susceptible to erosion, from the break in slope at the top of the ravine. The width should be at least 15 m in a residential or low density area, and 30 m in a commercial or high density area.

2.11 Large Woody Debris and Instream Cover

Large woody debris (LWD) is beneficial to streams in many ways. On a physical level, it provides channel roughness. This serves to dissipate flow energy, thereby stabilizing stream beds and banks (Scrivener, 1987; Smith et al., 1993). LWD plays a significant role in shaping a stream, by obstructing flow and trapping sediment (Ralph et al, 1994). On a biological level, it creates habitat diversity (Crispin, 1993). By slowing flow, LWD slows the flushing of fines and gravel during winter freshets (House et al., 1986). By improving the stability of sediment deposition sites and by providing nutrients, LWD helps to maintain a healthy benthic community (Keller et al., 1979). May et al. (1996) found that with an increase in watershed imperviousness area, a decline in the Benthic Index of Biotic Integrity accompanied a decrease in the volume of large woody debris. In a study performed on an Oregon stream, a reach rich in LWD had about 10 times more spawning gravel than a downstream section lacking LWD, while the downstream section had larger percentages of boulders and cobble (House et al., 1986). As well, LWD provides instream cover necessary to shield fish from predators. LWD also improves instream cover indirectly. By causing local lateral erosion, it leads to the development of side channels and meanders that undercut banks (House et al., 1986). These rooted cutbanks are an important element of instream cover (Bjornn et al., 1991), and help to dissipate flow energy, creating areas of slower velocity used by juvenile salmonids (Martin et al., 1986).

Perhaps most importantly, LWD leads to the formation of pools (Keller et al., 1979), which are an important element of fish rearing habitat. Gurnell et al. (1984) refer to a study which showed that, in a coastal California stream, at least 50% of the pools were influenced by LWD. Crispin et al (1993) found that the addition of LWD to a stream increased the volume of dammed, plunge, and lateral scour pools. This improvement in rearing habitat was accompanied by a marked increase in the number of coho salmon spawners in subsequent years, relative to untreated streams. Likewise, House et al. (1986) found a good positive correlation between the number of large woody debris per surveyed station and the number of coho salmon. Large coho salmon, in particular, were 12 times more abundant in the LWD rich section. This study attributed the increased productivity to the more numerous and larger volume pools created by LWD. Lack of LWD is most critical in the winter, when fish need refuge from high flows (Martin et al., 1986).

Loss of LWD is both a result of increased peak flows, and itself responsible for a great deal of the morphological changes to streams after urbanization. When watershed imperviousness is increased, LWD is washed out by higher peak flows, stranded by stream downcutting, and removed in attempts to "beautify" the stream (Booth et al., 1997). While occasional washout of LWD is normal in pristine streams, it is constantly replaced by new wood from the riparian zone. Additions of LWD are largely caused by bank failure due to stream erosion, and windthrow (Smith et al., 1993), and in steeper gradient forested streams there is the added cause of soil mass movement (Keller et al., 1979). In urbanized streams, however, both the increased frequency of channel altering flows, and riparian clearing preclude the addition of new LWD to the system. Horner et al. (1997) found that LWD frequency never exceeded 300 pieces/km in streams with > 9% TIA. The frequency dropped to below 100 pieces/km when the TIA increased to > 40%.

This loss is detrimental for several reasons. In the short term, it can increase the bedload transport at bankfull discharge up to four times the original rate, which causes deposition in pools in the downstream sections (Smith et al., 1993). This increased transport could also induce scour or burial of salmonid eggs, and impede fry escapement (Smith et al., 1993). Lack of cover, which exposes fish to predators and forces them to migrate in search of suitable habitat, is an important cause of fish mortality (Williamson et al., 1993). As well, LWD is crucial for preventing incision. Because it provides additional roughness, it allows a stream to remain stable at a slope greater than the equilibrium slope dictated by the grain size alone. Therefore, if it is removed by one of the above mechanisms, the stream's high slope makes it susceptible to sudden incision. As this incision lowers the water surface, stranding tree trunks, it renders the remaining LWD in the system ineffective (Booth, 1990).

2.12 Temperature

Many studies have examined the effects of urbanization on summer temperatures. Research reported by Schueler (1994) shows that while a lack of riparian cover and ponds contributed to higher summer temperatures, the increase was most affected by the percentage of impervious cover. LeBlanc et al. (1996) created a stream temperature model which demonstrated that summer stream temperatures are most affected by riparian shading, stream width, and groundwater discharge - all factors which are typically affected by urbanization. A wider stream exchanges heat with the air more rapidly, and a high groundwater influx helps to moderate temperature extremes (LeBlanc et al., 1996). Temperature increases reduce the dissolved oxygen content of the water, thereby impacting fish populations (DFO, 1996). Martin et al. (1986) discovered that the magnitude of the diel temperature fluctuation was closely correlated with the summer mortality of coho fry.

There are, however, few results available for the effects on winter temperatures. According to Arnold et al., (1996), loss of tree cover over streams creates temperature extremes, making urban streams warmer in the summer and colder in the winter. Because rainwater is typically at the same temperature as the air, which in wintertime is colder than groundwater, an urban stream with greater surface runoff could be expected to be colder than a rural stream in the winter.

The winter temperature regime of a stream has important implications for fish egg incubation. Alteration of incubation temperature may change the order of appearance of body structures, as it affects the various developmental rates of metabolism differently. As a result, embryos may die of starvation, normal hatching may be hindered, or hatched embryos may be deformed (Hayes et al, 1953). Higher temperatures speed the development of the hatching gland, and therefore salmonids hatch before they are completely developed (Marten, 1992). By studying brook trout, Marten (1992) has developed a regression equation to explain the time to hatching (t) relative to the temperature (°C) from fertilization to the eyed stage (T_1) and the temperature from the eyed stage to hatching (T_2): $t = 176 - 14.7T_1 - 9.67T_2 + 0.800T_1^2 + 0.367T_2^2$. The percent survival to hatching was found to depend only on T_1, and the percent survival to the eyed stage (E) related to T_1 as follows: $E = 52.7 + 10.1T_1 - 0.682T_1^2$. A maximum survival rate was obtained at 7.4°C. This relation indicates that it is the temperature at the beginning of the winter that affects egg survival.

Alterations in temperature may change salmonids' migration patterns. Salmon use temperature changes as one of their cues to begin upstream and downstream migration (Jonsson, 1991). Warmer summer stream temperatures may therefore delay upstream migration in the fall, and colder winter temperatures could delay downstream migration in the spring.

2.13 Management Alternatives

Many different strategies have been suggested to mitigate the impacts of impervious area. For transport related TIA, alternatives include narrower roads, smaller parking lots and vertical parking garages, vegetated islands in parking lots, porous pavement, grass swales rather than curbs (Arnold et al., 1996), and sidewalks only on one side of the street (Schueler, 1994). For residential and industrial areas, options include open space requirements, cluster-type housing (Schueler, 1994), and sloping of impervious surfaces towards vegetated strips (Beyerlein, 1996). It has been suggested that, because it is not feasible to keep all development below the identified threshold of 10% TIA, development should be concentrated in high-density areas (Schueler, 1994). Rather than impacting all streams, some would be protected at the expense of others. In stressed streams (< 10% TIA), the focus is on stream protection using buffer strips and green spaces. The effect on impacted streams (11-25% TIA) can be mitigated using some of the impervious surface reduction techniques described above. In degraded streams (26-100% TIA), habitat diversity cannot be maintained, and the focus turns to removal of urban pollutants (Schueler, 1994). For streams already impacted by high levels of imperviousness, stormwater detention and the implementation of habitat structures could help to restore a stream's quality (Schueler, 1994). As seen above, large woody debris plays many roles in maintaining habitat diversity. Introduction of wood structures could therefore be a first step in stream improvement.

2.14 Summary of Present Knowledge

The extensive research already performed has determined that watershed urbanization increases peak flows in a stream, and hinders groundwater recharge. Increases in sediment loads during the construction phase of urbanization, and the subsequent flushing of fine material by high peak flows have also been documented. There is still disagreement, however, as to the period of time required for a stream to recover from the construction phase of urbanization. The literature indicates that a streambed can cleanse itself from fine material due to construction and to stream enlargement in 15 to 50 years.

While the exact frequency of bankfull flow has not been confirmed, it is generally agreed that the dimensions of the bankfull channel are good indicators of the magnitude of peak flows. However, local differences in the extent of channel widening and deepening exist due to differences in geology and riparian vegetation. It is therefore necessary to develop new regime equations to suit specific geographical areas. The stage in the development process again comes into play when predicting a channel's enlargement process, as the magnitude and distribution of water and sediment discharge affect the width and depth. A channel that is more resistant to widening may better preserve fish habitat by preventing low-flow water depths from becoming too shallow, and by preventing an influx of too much fine material from bank erosion.

Although the riparian zone is known to regulate stream temperatures, improve benthic habitat, protect stream banks, and provide large woody debris, an optimum buffer width has not been determined. Different authors have recommended widths from 15 to 90 m, depending on the purpose the buffer zone is expected to serve. It is difficult to relate stream quality to buffer strip width alone, since streams with little riparian vegetation are often also situated in urban watersheds, and have suffered the consequences of an altered flow regime.

The mechanisms by which urbanization increases stream summer temperatures are well understood. Few studies have looked at its effects on winter temperatures, however. The temperature throughout this period affects the incubation time and survival rate of salmonids, and the changes in the winter temperature regime should be quantified.

Degradation of physical habitat has been identified as more critical than the effects on water quality. The many different elements of fish habitat respond differently to urbanization, however. While degradation has consistently been found to occur when TIA < 20%, differences in climate and geology are likely to cause some elements of fish habitat to degrade more quickly than others.

3 PROJECT SCOPE

3.1 General

It is desired to determine the response of streams in Lower Mainland British Columbia to urbanization, in order to identify limits for future development. The ideal study would follow a stream's response throughout the development process. Such a study would span decades, however. Instead, several streams, spanning a gradient of percent total impervious area, were chosen. Eleven stream reaches have been surveyed, and an additional three streams have been monitored for temperature.

3.2 Hypotheses

It is hypothesized that the deterioration of stream habitat is related to the increase in percent total impervious area (%TIA) of a watershed. In order to verify this, various parameters have been measured in the study streams, with the following expectations:

- Base flow
  - ➢ A decrease in groundwater recharge is expected to produce decreasing summer low flow (relative to catchment area) with increasing %TIA.
- Cross-sectional geometry
  - ➢ Increased peak flows due to urbanization are expected to increase the bankfull cross-sectional area and width (relative to catchment area). The individual responses of

width and depth to increased imperviousness will be determined. These are of interest particularly because increased channel width, along with reduced base flow are expected to decrease water depth at summer low flow.

- Bed composition
  - Construction activity and channel enlargement are assumed to increase the fine material in the bed, while increased flow competence, combined with decreased post-construction sediment loads, cause a decrease in the percentage of fine material. The study streams are in areas which were developed approximately 20 years ago – the measurements taken will determine whether they have recovered from the initial phase of development.
  - Increased flow competence after urbanization is expected to produce a coarser stream bed.
- Intragravel dissolved oxygen (IGDO)
  - To further analyze gravel quality, IGDO will be measured. It is expected that streambeds with higher percentages of fine material have lower IGDO concentrations.
- Riparian buffer zone
  - The width of the buffer zone is expected to diminish with increasing %TIA. The widths of the study streams' riparian zones will be compared to some elements of fish habitat, in an effort to identify the ideal buffer width.
- Instream cover
  - Streams with higher %TIA and smaller buffer widths are expected to have fewer and smaller pieces of large woody debris (LWD). The loss of protective bank vegetation and of LWD is likely to reduce the number of rooted cutbanks.

- Bank erosion
  - It is expected that increased peak flows due to increased %TIA, as well as reduced bank strength due to riparian clearing, will be reflected in the incidences of visible bank erosion, slumping, and protective measures such as rip rap.
- Winter temperature
  - Increased runoff and decreased groundwater recharge, as well as reduced riparian canopy, are expected to decrease winter water temperatures in urban streams.

4 METHODOLOGY

4.1 Study Sites

The study streams are all located near the city of Vancouver, in Southwest British Columbia. Those in Burnaby, Langley, and Surrey are in the Fraser Lowland, while those in North Vancouver and Coquitlam drain into the Fraser Lowland but have their headwaters in the Coast Mountains to the North. The Surrey streams form part of the Bear (or Mahood) Creek system; they flow into the Serpentine River, which drains into Boundary Bay. Anderson Creek is a tributary of the Nicomekl River, also draining into Boundary Bay. Union Creek joins the Salmon River, a tributary of the lower Fraser River; Hyde Creek drains into Pitt River, also a tributary of the lower Fraser River; The North Vancouver streams flow into the Burrard Inlet. All of the study watersheds receive about 75% of their precipitation in the six month period from October to March (Armstrong, 1984), with the higher elevation watersheds receiving more frequent and intense storms than the others.

The study streams were chosen using percent impervious area calculations performed by Rood et al. (1994, 1995) for larger watersheds. The study streams are described in Table 4.1. The reaches encompass a range of contributing catchment areas, slopes, and surficial geology. Analysis of the data collected will take into account such variations, and will allow for the determination of the relative sensitivity of different types of streams to urbanization. Although the high-gradient streams (slope $\geq$ 4.5%) are generally too steep to support fish populations, they are important areas for the production of benthic invertebrates and

Table 4.1: Study stream reaches

Stream	TIA (%)	Reach	Catchment area (ha)	Stream gradient (%)	Surficial geology*
Langley:					
Anderson Creek	5	East of Surrey/Langley border	2680	1.5	Sumas Drift and Fort Langley Formation
Union Creek	5	Junction with Salmon River	91	1.5	Fort Langley Formation
Surrey:					
Bear Creek (u/s)	77	West of 132 St.	199	2.0	Capilano Sediments
Bear Creek (d/s)	57	Bear Creek Provincial Park	1658	0.5	Capilano Sediments
Enver Creek	32	North of 82A Ave.	103	1.5	Capilano Sediments
Quibble Creek	54	North of 88 Ave.	591	1.0	Capilano Sediments
Coquitlam:					
Hyde Creek (u/s)	7	North of David Ave.	281	4.5	Vachon Drift, Capilano Sediments, and Bedrock
Hyde Creek (d/s)	16	Lincoln Park	498	1.0	Vachon Drift, Capilano Sediments, and Bedrock
North Vancouver:					
Big John's Creek	19	Burrard Inlet Indian Reserve 3	215	17.5	Vachon Drift, Capilano Sediments, and Bedrock
McCartney Creek	15	North of Dollarton Highway	285	7.5	Vachon Drift and Capilano Sediments
Roche Point Creek	4	North of Dollarton Highway	55	10.0	Vachon Drift and Capilano Sediments
Burnaby:**					
Eagle Creek	33	Burnaby Lake Nature House	566	n/a	Vachon Drift and Capilano Sediments
Still Creek	52	Burnaby Lake Sports Complex	3028	n/a	Vachon Drift, Capilano Sediments, and Bog Deposits
Stoney Creek	34	Junction with Brunette River	787	n/a	Vachon Drift, Capilano Sediments, and Pre-Vashon Deposits

*Armstrong et al., 1980a,b

**Monitored for temperature only

(u/s) = upstream, (d/s) = downstream

recruitment of organic material which may be transported downstream (Church, 1992). As well, erosion of their beds and banks transports sediment into the lower-gradient spawning ground downstream. It is therefore necessary to consider these streams when analyzing the impact of urbanization on fish habitat.

Development in these watersheds was carried out under guidelines which are different from those presently in place. Portions of some of the streams lack sufficient riparian cover. The Bear Creek watershed is the only one with stormwater detention facilities. These facilities were designed in order to control a five-year flow of two hour duration, which has since been deemed insufficient (Harry Long, City of Surrey, personal communication).

4.2 Total Impervious Area

The percent total impervious area (%TIA) was calculated for each watershed upstream of the surveyed reach, using orthophotos obtained from the municipalities. Orthophotos are aerial photos which have been corrected, so that the photo is to scale with the landscape. Watershed boundaries were first determined using storm sewer maps of the urbanized areas, and from contour lines in the undeveloped areas. The watershed boundaries for Union Creek and the Burnaby streams were obtained from Zandbergen (1998, as calculated by Wernick, 1996 and McCallum, 1995), and the boundaries of the Anderson Creek watershed were obtained from the Township of Langley. The watersheds were then divided into land use areas, and each area assigned a %TIA. The photos were then overlaid with tracing paper, and the outlines of the land use areas were drawn. The tracing paper was cut and the different portions weighed, in order to give the relative areas of each land use. Using the scale, a piece of tracing paper of a known area was also cut and weighed, to obtain the absolute area of each land use. The contributing areas were then multiplied by their %TIA to give a %TIA for the watershed. The following values were used (Table 4.2):

Table 4.2:
Total impervious areas of various land uses

Land Use	% Impervious
Lake or water reservoir	0%
Forest	2%
Cleared areas, playing fields, golf courses	5%
Agricultural	5%
Low-density single family residential (< 3 units/ha)	10%
Medium-density single family residential (7-15 units/ha)	25%
High-density single family residential (7-15 units/ha)	50%
Multi-family residential (> 15 units/ha)	80%
Institutional	30-95%
Industrial	75-90%
Commercial	80-95%

These values have been taken and adapted from several other studies (Olthof, 1994; Soil Conservation Service, 1975; Zandbergen, 1998). For forested land, the value of 2% takes all roads into account. The value of 5% for playing fields and golf courses takes into account both soil compaction and roads passing through the area. This value could be quite a bit higher for playing fields underlain by drainage systems. Agricultural areas have been assigned a value of 5% to take into account roads, and runoff from farm buildings and green houses transported by ditches. The percent impervious values for residential areas differ from those used by Olthof (1994), and have been changed to match the results of detailed calculations performed by Zandbergen (1998) for certain communities in lower mainland British Columbia. The imperviousness of institutional, industrial, and commercial areas varies a great deal, and values were assigned on a case-by-case basis.

As described in Section 2.2, effective impervious area (EIA) is a more useful tool to describe the impact of development on runoff. However, %TIA was chosen for this study, for two reasons. First, most past studies have used %TIA as the independent variable causing stream degradation, and it was desired to compare their results with those obtained in this research. Second, the %EIA values given by Dinicola (1990) and by Beyerlein (1996) have been developed using land development patterns in areas of Washington state, and the additional time required to check these values for the British Columbia watersheds was not felt to be warranted for this study. The residential areas in the Anderson Creek and Union Creek watersheds are known to be unsewered, and in these cases only %EIA values of 5% for low and medium-density, and 10% for high-density single family residential areas were used.

4.3 Riparian Buffer Width

Using orthophotos, the riparian buffer width was measured both upstream of, and over the length of the surveyed reach. The upstream buffer integrity was expressed as the percent of total stream length with a buffer width greater than 30 m and 100 m on each side of the stream. An average buffer width within the reach was obtained by measuring the forested area adjacent to the stream (m^2), and dividing it by the reach length (m).

4.4 Stream Surveys

Field surveys were conducted in each of the chosen stream reaches, according to Department of Fisheries and Oceans guidelines (DFO, 1996), following a procedure similar to that used by Olthof (1994). Each survey began at the downstream end of the reach, and progressed upstream for a distance of approximately 400 m. In an effort to keep the local riparian conditions homogeneous throughout the reach, it was sometimes necessary to make the reach shorter. Accessible locations such as bridge crossings were chosen as starting points; however, the surveys were begun a sufficient distance upstream of the crossings to avoid measuring local anomalies. Base flow was measured at the downstream end of each reach. Upstream distance was measured along the stream using a hip chain. Every 50 m, a transect was set up and the cross-sectional geometry, pebble sizes, and slope were measured. A 400 m survey, therefore, included nine transects. Random locations were chosen for bed sampling, and intragravel dissolved oxygen was measured in riffles, as near as possible to these random locations. Large woody debris and rooted cutbanks, as well as bank characteristics, were noted along the reach.

4.5 Base Flow

A one-time base flow measurement was made in each stream. Measurements were taken during the dry period between August 1st and September 12th. At the downstream end of each reach, a tape was stretched perpendicular to the stream, spanning its wetted width. The width was divided into ten sections, then the depth and velocity were measured in the centre of each section. If the stream was wider than 5 m, the width was divided into 0.5 m sections. The velocity was measured using a Swoffer Instruments Model 2100 Current Velocity Meter, at a distance of 0.4 times the depth from the streambed. This location was chosen because, for a logarithmic velocity profile, the average velocity is found at a distance of 0.37 of the depth from the bed (Leopold et al., 1964). For each of the ten sections, the measured velocity was multiplied by the cross-sectional area to obtain the discharge contribution of the section; the total discharge was the sum of the ten smaller discharges.

4.6 Cross-Sectional Geometry

During the stream surveys, a transect was set up every 50 m to measure the cross-sectional geometry of the stream. The dimensions of the low flow wetted channel were measured, as this area is the aquatic habitat channel: that containing the food web, fish, and fish habitat (Sovern et al., 1997). First, the wetted width was measured by stretching a tape across the stream, perpendicular to the flow. The wetted widths for all the transects were then averaged to obtain a wetted width for the reach. The wetted depth was measured at intervals of 1/10 the wetted width, for a total of 11 measurements per section. The measurements of wetted depth from all the transects were averaged to obtain a representative water depth for the reach. The bankfull channel dimensions were also measured, as they are good indicators of the magnitude of the 1 to 2-year flow (discussed in section 2.8). The bankfull width was measured by stretching a tape horizontally from one bank to the other. According to Johnston (1996), the bankfull channel boundaries can be identified by a break in slope from the vertical stream bank to the adjacent floodplain, or where perennial rooted vegetation begins. The distance from the bankfull height to the water surface was also measured; the measured wetted depth was then added to this value to obtain the bankfull depth. Both bankfull width and depth were averaged to give the representative dimensions of the reach.

4.7 Stream Bed Composition

To determine the bed particle composition, a pebble count of the type described by Wolman (1954) was conducted in each stream reach. These counts were based on a grid system. At each transect, beginning at the water's edge, the pebbles that fell at intervals of 1/10 the stream width were picked up, for a total of 11 particles per transect. The b-axis (intermediate axis) of each particle was measured using a small ruler, and the bed particle gradation was then determined from these measurements. Since it was difficult to measure diameters smaller than 2 mm, sand or clay particles were assigned a diameter of 2 mm. Although this method has been found to be biased towards larger particles (Wolman, 1954), it is a quick way to characterize the stream bed, and is particularly useful when dealing with cobbles and boulders.

One composite bed sample was taken from each reach in order to characterize the smaller size fractions of the sediment. The sample was composed of up to 8 shovel samples along the reach. These samples were taken by pushing a bottomless plastic 5 gallon bucket into the sediment to create an area of still water. Sediment was then collected from inside the bucket using a small trowel, and an effort made to consistently collect material from the top 10 cm of the bed. The sample locations were chosen randomly. Before beginning the fieldwork, a grid representative of the stream reach was constructed, a number assigned to each section of the grid, and the sampling locations chosen from a random number table. The following locations were used (Figure 4.1):

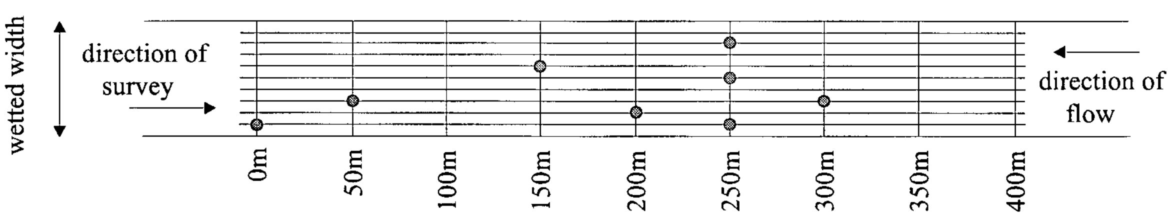

Figure 4.1:
Random bed sampling locations

The sample was returned to the lab, oven dried, and separated using sieves of the following sizes: 38.1 mm, 25.4 mm, 18.85 mm, 9.52 mm, 6.35 mm, 2.00 mm, 0.833 mm, 0.500 mm, 0.250 mm, 0.125 mm, and 0.063 mm. All bed material larger than 38.1 mm was discarded so that the small number of cobbles collected would not bias the sample.

4.8 Intragravel Dissolved Oxygen

A consequence of increased fine material is a decrease in intragravel dissolved oxygen (IGDO). The IGDO was measured using a steel well point. This instrument has the advantage of being portable, therefore allowing for many measurements of IGDO in a single reach. This type of instrument has been used before (Wickett, 1954) for simple assessments of pore water dissolved oxygen. Figure 4.2 shows the dimensions of the well point.

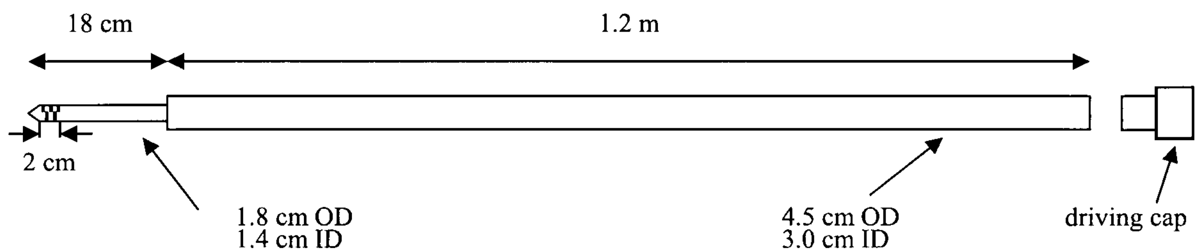

Figure 4.2:
Well point for IGDO measurements

The well point was driven into the gravel by hammering on the driving cap. The cap fit snugly into the well point, thereby preventing surface water from entering through the perforations. Once the smaller diameter section of the well point had completely entered the gravel, the cap was removed and a DO probe was lowered down into the well point. When the water inside the tube rose to cover the membrane of the probe, and the DO reading stabilized, it was then recorded. Each reading took from one to five minutes, depending on how rapidly the water entered through the perforations.

Modifications to this simple method exist, however the chosen method was deemed sufficient for the purpose of comparing streams. Wickett (1954) buried a standpipe in the gravel, and Havis (1993) buried plastic well screens – both then took water samples by suction for analysis. Terhune (1958) used a portable well point; he first lowered the water level in the pipe, then measured the inflow rate to determine the permeability of the gravel. Another method exists for long term analysis at a single location. A perforated pipe may be buried horizontally in the gravel, with a tube connected to a pump above the water surface. According to Hoffman (1986), this method is particularly useful when large quantities of intragravel water are required for analysis. As well, it allows for integrated samples across the width of the artificial redd, which is quite useful as the permeability can vary greatly within a single redd (Terhune, 1958). Olthof (1994) used a similar procedure, with the added benefit of being able to bury the pipe in a fashion that imitated the gravel-cleaning actions of adult fish, hence yielding a DO reading more indicative of what would be found in a natural redd. The aim of this study was not to reproduce the DO conditions in a redd, but to give an indication of the relative gravel permeability from one stream to another.

4.9 Slope

The slope was measured at each transect using a Suunto PM-5 Optical Reading Clinometer. One field worker first noted the height of his/her eye level on the clothing of the second field worker. The first worker then walked upstream as far as possible without losing sight of the other person, and sighted back to the eye level marking. As the purpose was to measure the slope of the water surface, both people stood either next to the stream, or on a rock, with the bottom of their feet at the level of the water surface. The clinometer gave a reading of the stream slope in percent. The slopes at all the transects were then averaged over the reach.

4.10 Instream Cover

Large woody debris (LWD) and rooted cutbanks (RCB's) were counted and measured along the reach. The classification of large woody debris has not been standardized from one agency to another, and the MOELP procedures (Johnston, 1996) were chosen. Every piece of dead wood greater than 2 m in length and 10 cm in diameter was measured, and was characterized as "w" (within the wetted channel) or "bf" (within the bankfull channel). Both the volume and the total number of LWD per 100 m were calculated for each reach. Large woody debris within the bankfull channel but above the low water level does not affect the flow patterns for most flows, however it still provides cover for fish, supplies nutrients to the system, and provides bank stability and roughness during the channel forming, bankfull flows. In the final tally, therefore, it was decided to consider all large woody debris within the bankfull channel.

Rooted cutbanks were also counted. These are areas where the lower section of the bank is eroded, but the upper sections are stabilized by roots, providing a sheltering overhang. The number of rooted cutbanks has also been expressed per 100 m of stream length.

4.11 Bank Erosion

Along the survey reach, the state of the banks was noted. Any signs of bank sloughing and of vegetation removal by streamflow were recorded, as they are indicative of fluvial erosion and bank mass failure. Human modification of the banks in the form of channelization or rip-rap was also recorded as indicators of bank erosion in the past. Both were recorded as a percentage of the total reach length.

4.12 Temperature

Temperatures were measured in each stream on several occasions, and compared to a relatively undeveloped reference stream. Since North Vancouver and Coquitlam's climates are influenced by the Coast Mountains to the North, they experience different rainfall patterns from the Fraser Lowland. Two reference streams were therefore used: Roche Point Creek (TIA = 4%) was chosen as a reference for the North Vancouver and Coquitlam streams, and Anderson Creek (TIA = 5%) as a reference for the Fraser Lowland streams. An Onset Optic StowAway Temp logger was placed in a sheltered area of each reference stream. The loggers were fixed inside protective stainless steel tubes that were themselves connected to long metal cables. These cables were wrapped around tree roots or trunks that projected over the stream surface, allowing the loggers to hang, unnoticed, in the water. The loggers recorded temperature every thirty minutes in the reference streams. On each occasion that temperature was measured, all the temperatures were measured in a single day, and each then compared to that of the reference stream at the same time of day.

5 RESULTS AND DISCUSSION

5.1 Total Impervious Area and Buffer Width

The study streams are listed in Table 5.1 in order of increasing percent total impervious area (%TIA). Details of the land uses within each watershed are given in Table A-1. Also listed in Table 5.1 are the percentages of total stream length upstream of the study site with 30 m and 100 m wide forested buffer strips on each side. In the final column, the average buffer width for the study reach is given.

Table 5.1:
Percent impervious area and buffer characteristics of study watersheds

Stream	%TIA	% of stream length with buffer > 30 m	% of stream length with buffer > 100 m	Average buffer width within reach (m)
Roche Point Creek	4	86	86	167
Union Creek	5	-	-	50*
Anderson Creek	5	47	12	62
Hyde Creek (u/s)	7	97	81	43
McCartney Creek	15	95	55	37
Hyde Creek (d/s)	16	85	62	60**
Big John's Creek	19	66	47	300
Enver Creek	32	44	16	100
Eagle Creek	33	17	0	n/a
Stoney Creek	34	31	0	n/a
Still Creek	52	8	0	n/a
Quibble Creek	54	61	0	27
Bear Creek (d/s)	57	57	3	30**
Bear Creek (u/s)	77	40	0	15

*estimate only
**width close to zero along one bank

The urbanization process has caused a reduction in the buffer width of streams, as illustrated in Figure 5.1. The percentage of total stream length with a 100 m or wider forested riparian zone decreases linearly as the %TIA increases (R^2 = 0.98), until it reaches zero at a TIA of approximately 35%. Anderson Creek is considered an outlier, because its watershed is primarily agricultural, and it would not be expected to follow the same patterns as in a watershed where urbanization is taking place. The percentage of stream length with a 30 m buffer also decreases with increasing %TIA, but the relationship is more scattered - the %TIA explains only 40% of the decrease in buffer width.

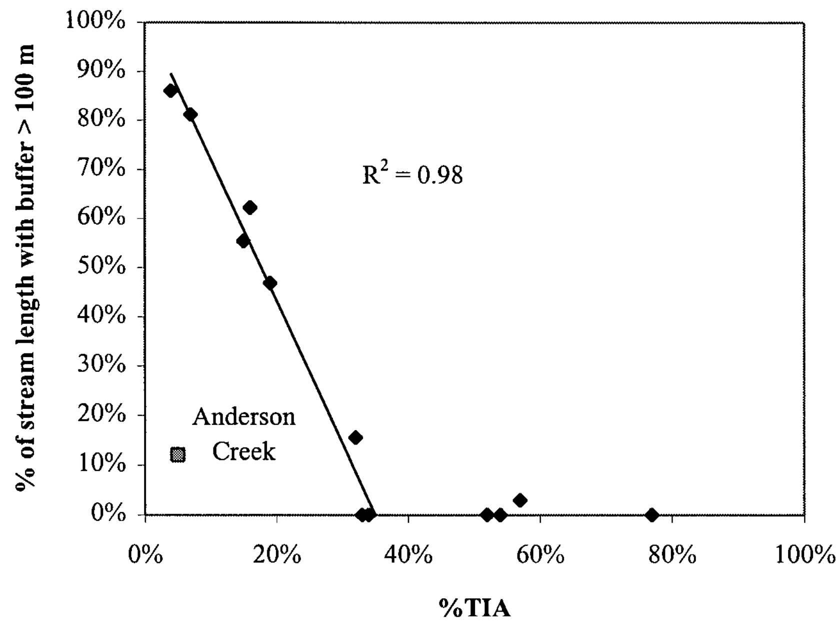

Figure 5.1:
Removal of riparian vegetation during urbanization

The loss of riparian vegetation acts, along with the increase in %TIA, to degrade stream health. When comparing the study streams, therefore, it will be important to distinguish between the effects of the two parameters.

5.2 Surficial Geology

Impervious area is not the only factor affecting infiltration and runoff - the geological materials in a watershed also influence the infiltration pattern. For example, sands and gravels have a high infiltration rate and low runoff potential, while clays have a low infiltration rate, and a correspondingly high runoff potential (SCS, 1975). As described in Section 4.1, the surficial geology varies among the study watersheds. In order to determine the importance of these differences, a composite runoff curve number (CN) was determined for each watershed for antecedent moisture conditions II, using the drainage characteristics of the surficial geology (Table A-2). As described by the SCS (1975), soils with higher CN's have lower infiltration rates and higher runoff depths. A watershed's CN is determined by taking into account both the drainage characteristics of the surficial geology and the type of land use. As seen in Figure 5.2, there is a good linear relationship between %TIA and CN (R^2 = 0.90 when Union Creek is excluded). The calculation of the CN takes %TIA into account, and so it is expected that the two will correlate perfectly for watersheds with equally pervious geological types. Because most of the watersheds under consideration are relatively poorly drained, the CN's increase in proportion to the %TIA. The one outlier, the Union Creek watershed, is composed of very well-drained gravel and sand. Had the watersheds' geological cover been more heterogeneous, Figure 5.2 would have displayed a wide scatter. Excluding Union Creek, the %TIA adequately describes the runoff pattern for the study watersheds, and the variations in soil type need not be considered when analyzing the data.

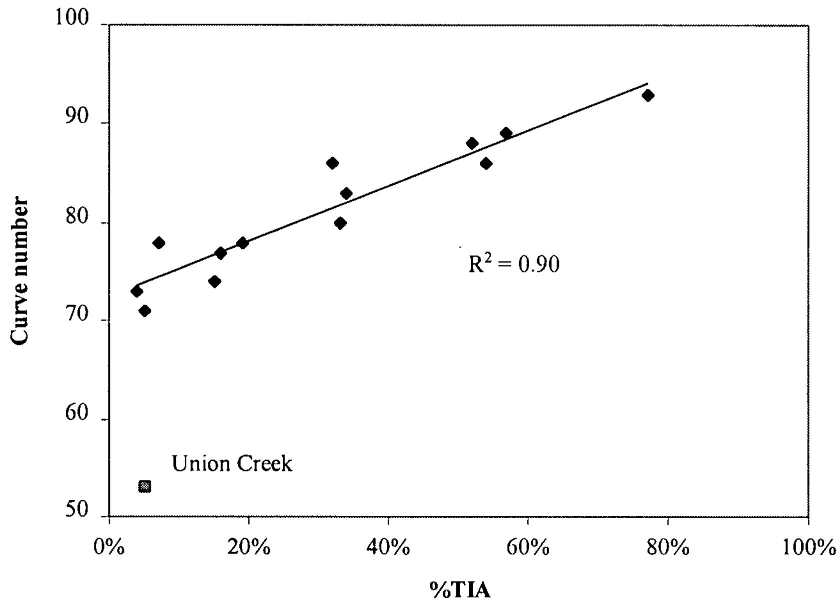

Figure 5.2:
Runoff curve number vs. %TIA

5.3 Base Flow

Base flow measurements, when corrected for catchment area, yield results similar to expectations (see Figure 5.3, raw data in Table A-3). Increased total impervious area is seen to decrease the summer base flow, due to decreased groundwater recharge. The flow in Enver Creek is included for comparative reasons only, as its watershed received over 25 mm of rain in the 24-hour period preceding the survey. Base flow was not measured in either Roche Point or Big John's Creek, due to the difficulty of measuring water velocity in their cascade structure. There is quite a bit of variability in the < 20% TIA range, particularly in the case of the two Hyde Creek reaches. Their recorded flows were quite low, close to those recorded for the more urbanized streams. Although relating base flow to CN (Figure 5.4) produces a slightly better relationship ($R^2 = 0.80$ when Enver Creek is excluded), the flows

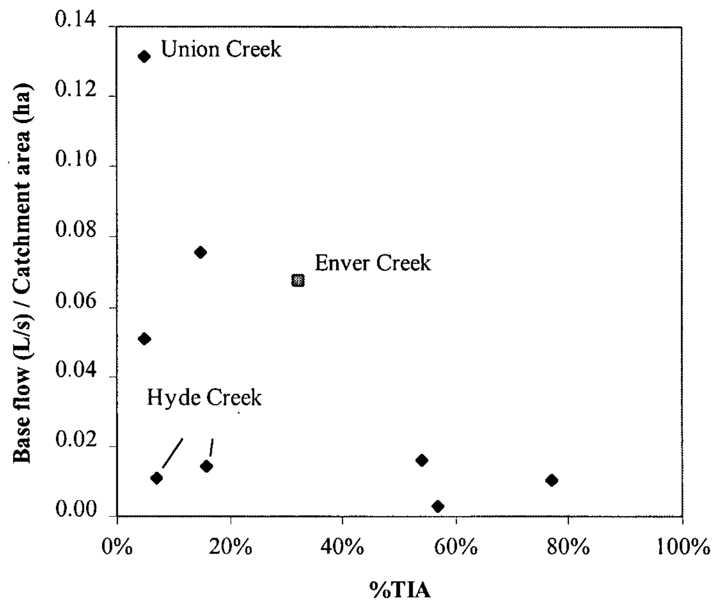

Figure 5.3:
Effect of imperviousness on summer base flow

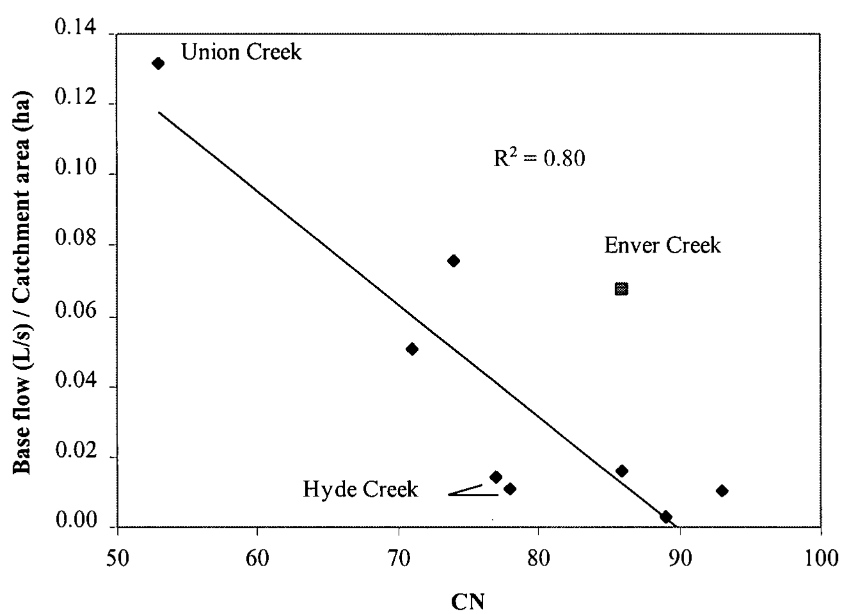

Figure 5.4:
Summer base flow vs. runoff curve number

in the Hyde Creek reaches are still low. As expected, the well-drained Union Creek watershed has high storage potential, and is able to maintain relatively high flows in the summer dry season. While there is a lot of variability in the low %TIA range, the three streams with TIA > 40% all experience very low flows in the summer. This reduced flow has serious implications for fish habitat. Streams with low summer flow typically have shallower water and reduced pool volume. There is less physical space available as rearing habitat, and the number and size of resident fish decreases as a consequence. If flow decreases sufficiently, creeks may dry up in the springtime, thereby stranding juvenile fish – a phenomenon observed in Hyde Creek in the spring of 1998.

The average velocity at each flow measurement site has been calculated (Table A-3), and is plotted against %TIA in Figure 5.5 below. Although the velocity changes along the reach depending on the local channel geometry, the velocity at the measurement site is indicative of conditions throughout the reach. The velocity for the upstream reach of Hyde Creek (0.30 m/s) is excluded, because its discharge was measured in a narrow area where the flow converged between two boulders. The measured velocity is therefore likely higher than would be expected for a more representative cross-section. When Enver Creek is excluded, the decrease in velocity is quite well related to the increase in %TIA ($R^2 = 0.75$). This may cause a drop in dissolved oxygen values in the urban streams, both because the slower flow is more quickly heated in the daytime, and because reaeration rates are lower in slow-moving water.

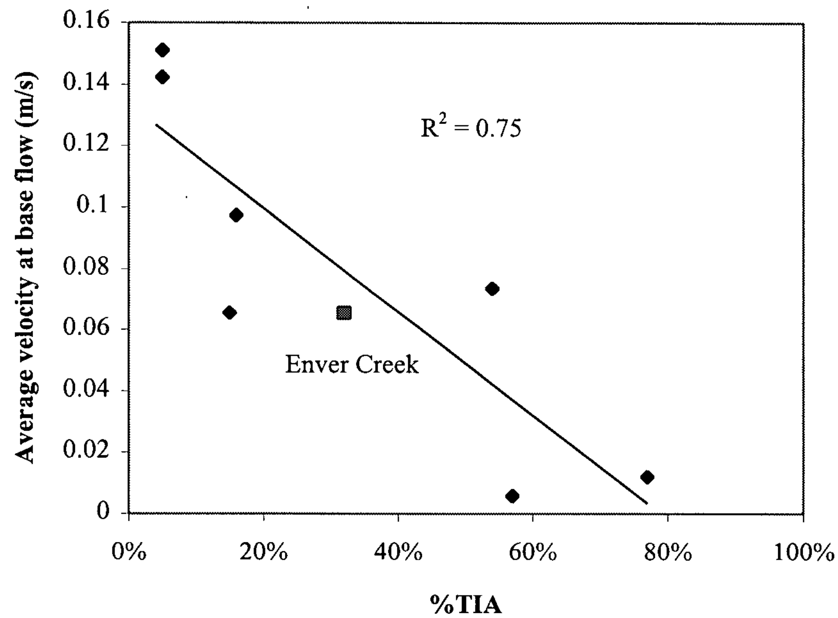

Figure 5.5:
Effect of watershed imperviousness on summer stream velocity

In order to identify streams that are likely to experience low oxygen contents in the summertime, the reaeration rates (K_2, base e, days^{-1}) have been calculated using the following equation (Clover, 1976):

$$K_2 = \frac{21.7v^{0.67}}{d^{1.85}}$$

where v is the average velocity (ft/s) and d is the average wetted depth at the discharge measurement site (ft) (Table A-3). Although the velocities are low in the urban streams, the depths are also very low, and in all the study streams the calculated K_2 at 20°C is greater than 1.15, or the typical value for white water (Lindeburg, 1994). The lowest calculated K_2 was 5.8 days^{-1} in the downstream reach of Bear Creek. This indicates that, in terms of reaeration, the velocity in the study streams has not reached critical levels.

5.4 Substrate Composition

5.4.1 Fine Material

Results from the bed sampling and pebble counts indicate that the amount of fine material (less than 2 mm in diameter) in the bed is lower in the urban streams (Figure 5.6, raw data in Tables A-4, A-5). Both methods of sediment analysis have produced similar results. The percent imperviousness explains 70% of the variation in the percent fines using the pebble count data, and 60% of the variation using the results from sieve analysis. It is interesting to note, however, that although the pebble count method is said to be biased towards larger particles (Wolman, 1954), in all cases the pebble count yields a higher percentage of fines than does the sieve analysis. This result is likely a reflection of the bed sampling procedure. The sample was collected using a shovel, and it is quite possible that fine material was lost in the process. While an exact value has not been obtained for the percentage of fine material in each stream, the sampling method was consistent among streams, and the relative results are considered reliable.

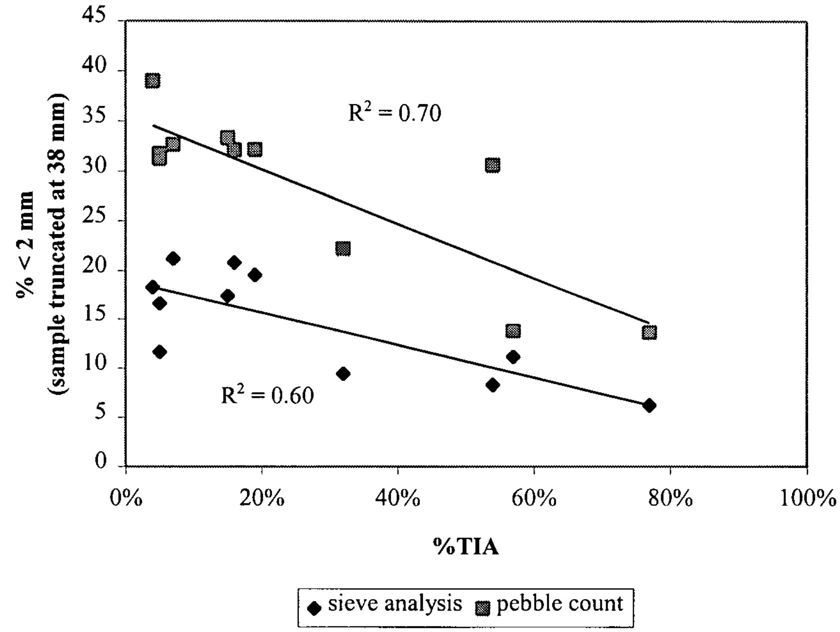

Figure 5.6:
Loss of fine material in urban streams

The observed decrease in fine material in the urban streams is likely due to the higher and more frequent peak flows they experience in the winter, which winnow away fine material. As discussed in Section 2.5, it is the latter stage of urbanization that causes a decrease in fine material. After the construction phase is finished, and once a stream's cross-sectional area has reached equilibrium, the input of fine material diminishes to near pre-development levels. There has been some disagreement as to how long a stream requires to recover from the construction phase of development. In most of the study watersheds, the development is at least 20 years old. Some development has taken place in the McCartney Creek (15% TIA) and Big John's Creek (19% TIA) watersheds within the past 20 years. However, when these points are excluded, the overall trend remains the same (R^2 = 0.61 for the sieve analysis and 0.69 for the pebble count). The results given here indicate that, within a 20-year period, not only will the newly introduced fines be removed, but the streambed will have less fine material than before development. Therefore, it appears that urbanization improves the quality of the spawning gravel. It is interesting that the two watersheds that have land used for agriculture (Anderson and Union Creeks) have percentages of fine material equivalent to, or less than, the other streams with low %TIA. Much of the Anderson Creek watershed is used for grazing, a possible reason why its load of fine material is lower than what would be expected in a watershed used for cropping only (see Section 2.5).

It was thought that the amount of fine material would be dependent on the slope of the stream and the size of the catchment area, and that a correction would have to be made for both. However, neither exerted a significant influence on the data. The stream slope and catchment area explained less than 30% and 10%, respectively, of the variation in percentage fines.

5.4.2 Coarse Material

An abundance of large particles in a stream bed is evidence of higher flow competence (Robinson, 1976). Coarse material is expected to predominate in urban streams first, because higher flows remove smaller particles, and second, because the higher flows are capable of transporting more large particles into the stream. The D_{84} (84% of the material is finer than this size) of each stream has been determined using the pebble count data (Table A-5). A relationship was found between stream slope and the D_{84} ($R^2 = 0.70$). This is to be expected, as a higher sloped stream has a greater competence to transport coarse material. This relationship is not considered meaningful, however, since it is primarily a reflection of the geology of the watersheds. The four high gradient reaches either flow through, or just downstream of bouldery gravel (Armstrong et al., 1980a,b). For this reason, only the low-gradient streams will be compared for coarse material. When these streams are considered, no relationship is found between the stream slope or catchment area and the D_{84} ($R^2 < 0.01$ in both cases). The D_{84} is therefore plotted directly against the %TIA (Figure 5.7). As expected, bed coarsening is observed in the urban streams ($R^2 = 0.66$). The stormwater detention ponds located in the Surrey watersheds (32-77% TIA) have evidently not slowed flows sufficiently to prevent the winnowing away of fine material and the transport of large particles. Large cobbles and boulders help to shelter fish predators. The relationship below indicates that, as far as large particles are concerned, the urban streams provide better rearing habitat than do the rural streams.

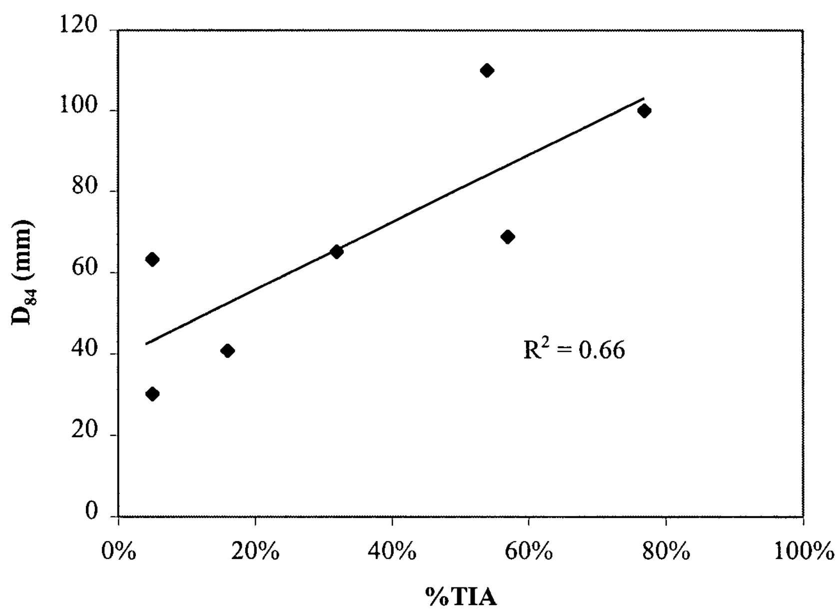

Figure 5.7:
Bed coarsening in low-gradient urban streams

5.5 Intragravel Dissolved Oxygen

Intragravel dissolved oxygen (IGDO) was measured in all the study streams except Enver Creek (raw data in Table A-6). The gravel in this stream overlaid soft clay, and the gravel layer was not deep enough to allow for an IGDO measurement. It is the low gradient streams – those which are most likely to be used for spawning – for which the IGDO is of interest. The results indicate that the urban streams have better intragravel circulation, and hence better replenishment of dissolved oxygen, than do the rural streams. In Figure 5.8, the IGDO relative to the water column dissolved oxygen (WCDO) is plotted vs. the %TIA. The increase in IGDO is attributed to the lower percentage of fine material in the urban streams, as discussed above. In Figure 5.9, it is illustrated that the stream beds with more fines do, in fact, have lower IGDO concentrations.

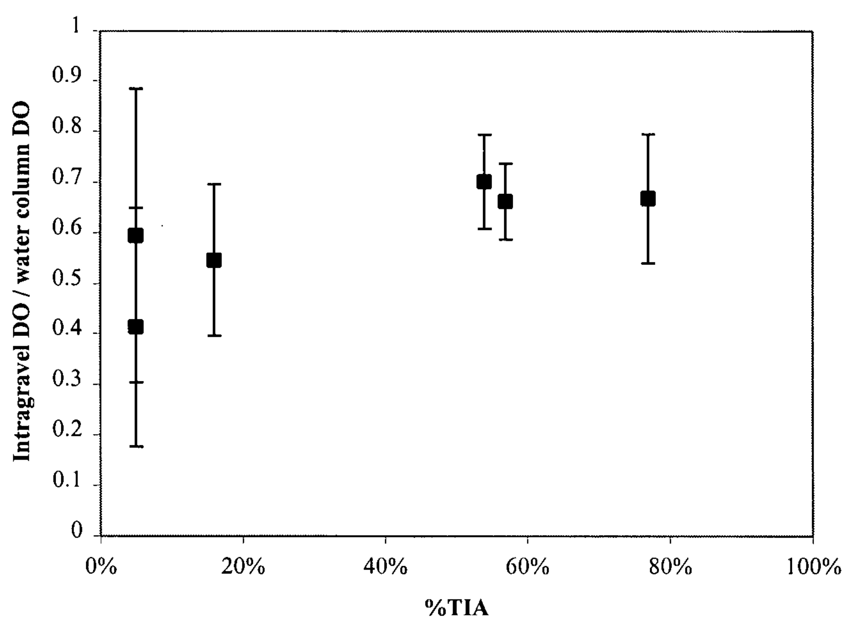

Figure 5.8:
Increase in IGDO with increased %TIA

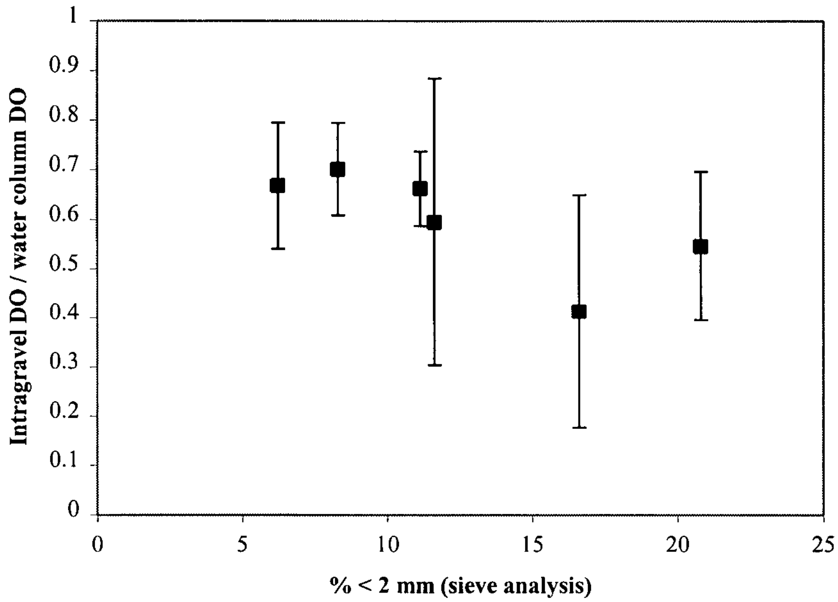

Figure 5.9:
Decrease in IGDO with increased fine material

The error bars in the two figures above represent the standard deviation of the IGDO reading, as several readings were taken in each stream. One can see that there is great variability within a single stream. In practice, it was observed that two IGDO measurements taken in adjacent areas of the same riffle could yield quite different results. This agrees with the results of Terhune (1958). In order to determine whether the measurements taken in the urban streams were significantly different from those taken in the rural streams, an ANOVA (analysis of variance) was performed on the data (Zar, 1996). The streams were lumped into two categories: rural (Union and Anderson Creeks, and the downstream reach of Hyde Creek) and urban (Quibble Creek and both reaches of Bear Creek). It was found that the IGDO readings in the urban streams were significantly different from those in the rural streams ($P = 0.006$). It appears, therefore, that the increased flows in the urban streams have served to clean spawning gravel, creating better incubation conditions.

5.6 Channel dimensions

The bankfull channel dimensions are assumed to indicate the magnitude of the two-year flood (discussed in Section 5.10 below). From the channel dimensions measured at the transects, an average bankfull cross-sectional area has been calculated for each reach (Table A-3). The channel was assumed to be trapezoidal, and the bottom width was assumed equal to the measured wetted width (Figure 5.10). It was expected that the cross-sectional area, when corrected for the catchment area, would be larger in the urban channels. In order to make the correction, the channel cross-sectional area was plotted against the catchment area (Figure 5.11).

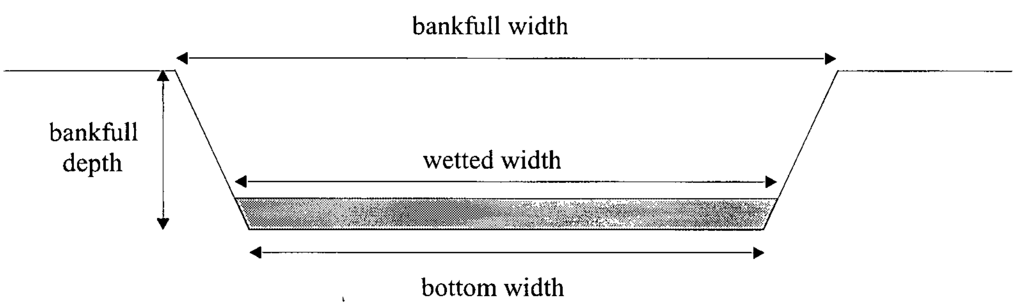

Figure 5.10:
Channel dimensions

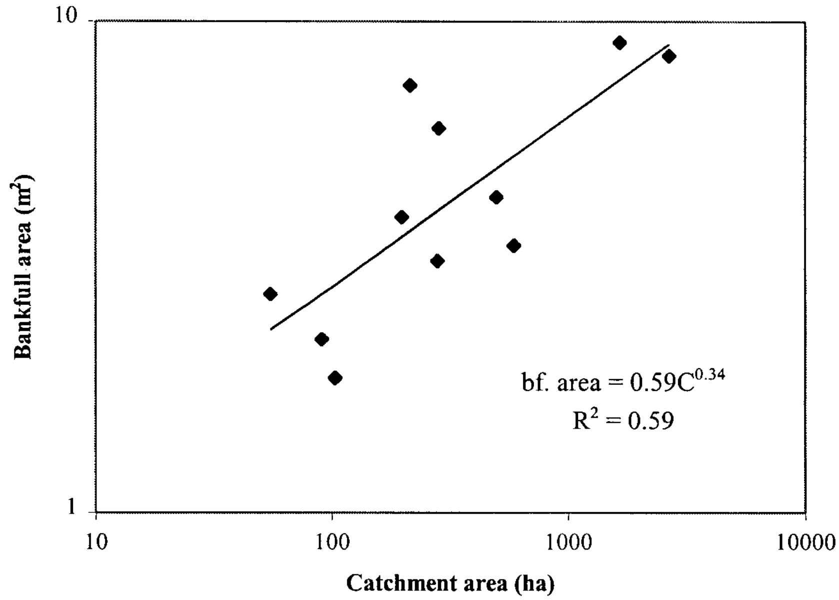

Figure 5.11:
Channel bankfull cross-sectional area vs. catchment area

The bankfull cross-sectional area was corrected for the catchment area by dividing by the regression equation, a method similar to that used by Ralph et al. (1994). When the high-gradient channels were considered, the %TIA explained 70% of the variation in the bankfull area. The relationship was quite poor for the low-gradient channels, with the %TIA explaining only 22% of the variation in bankfull area. This is in agreement with Hammer's results (1972) – he found that steeper gradient channels enlarge more than shallow gradient channels for the same level of urbanization. In addition to channel slope, the strength of riparian vegetation, bed particle size and the geologic material making up the stream banks can all affect the manner in which a channel enlarges.

To further investigate the type of enlargement experienced by the different streams, width was first considered. Again, to correct for catchment area, the wetted and bankfull widths were plotted against the catchment area (Figure 5.12). The equations are of the form $w = aQ^b$ as presented by Leopold et al. (1964). The research these authors summarized showed that an approximate value for b was 0.5. The value of 0.25 found in this study for the bankfull width is reasonable, since catchment area (C), rather than discharge (Q), is the independent variable. The discharge typically increases less rapidly than the watershed area (LeBlanc et al., 1996). The correlation seen is not very high, mainly because the high-gradient channels (slope $\geq$ 4.5%) are wider than the low gradient channels (slope $\leq$ 2.0%) with the same contributing area. This is consistent with equations presented by Millar et al. (in press). A bank-shear constrained channel will continue to widen, therefore dissipating flow energy over its bed, until the bank shear stress (τ_{bank}) is lower than the critical value (τ_{crit}). Since τ_{bank} is proportional to the channel gradient (S), higher gradient channels must widen more to bring τ_{bank} below critical. Observations made by Ferguson (1986) indicate that steeper channels are wider and shallower than lower-gradient channels.

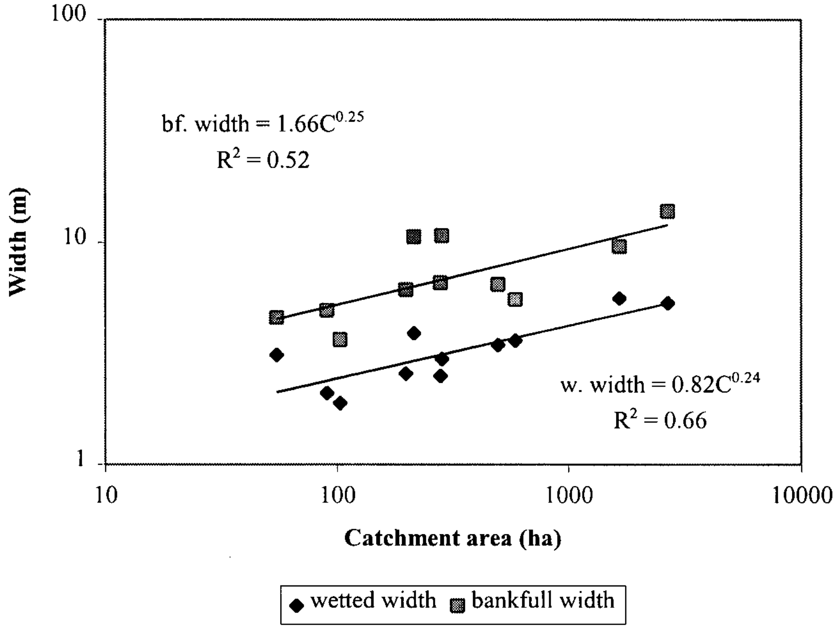

Figure 5.12:
Width vs. catchment area

When only the high-gradient channels are considered, the corrected bankfull width is found to be related to the %TIA (Figure 5.13). The high correlation ($R^2 = 0.93$) is slightly deceiving since only four data points are available, spanning a small range of %TIA. Also of concern is the fact that the stream slopes, shown on the chart below, are related to the %TIA ($R^2 = 0.39$). This means that the more urbanized channels are more prone to widening partly because their gradients, and therefore their bank shear stresses, are higher. In order to determine which factors most highly affect the bankfull width, a multiple regression was carried out. For the high-gradient channels, the independent variables: *TIA* (total impervious area, in percent), *C* (catchment area, in km^2) and *S* (slope, in percent) were related to the bankfull width by the following equation ($R^2 = 1.00$):

$$\textit{Bankfull width} = 0.64(\textit{TIA}) - 0.75(C) - 0.33(S) + 5.69$$

According to this equation, the %TIA is the only variable positively correlated with the bankfull channel width. It can be concluded, therefore, that urbanization has widened these high-gradient channels. The increase in width may not be linear, as shown. The width noticeably increases in the 10-15% TIA range. This is consistent with the claim of Morisawa et al. (1979) that channel enlargement is delayed in the initial stages of urbanization.

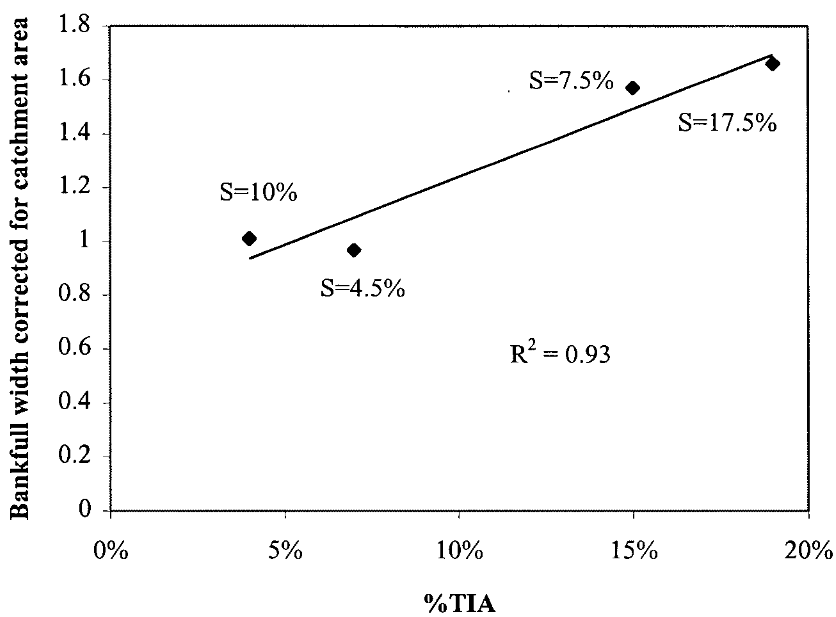

Figure 5.13:
Corrected bankfull width vs. %TIA (high-gradient channels)

When all of the low-gradient channels were compared with each other, they were not found to widen with increasing levels of urbanization. The most urbanized streams (Surrey) had corrected bankfull widths close to, or lower than those of the least urbanized streams (Coquitlam and Langley). The low width values in the Surrey streams may be due in part to the presence of stormwater detention ponds. These ponds were designed to keep the five-year flow at the pre-development level, whereas control of the two-year flood is now recognized as being more beneficial (Chilibeck, 1993; Lee et al., 1988). Lee et al. (1988) surveyed Surrey streams and found that developed streams with detention facilities were wider than undeveloped streams, but narrower than developed streams without detention. Differences in bank material strength may also have caused the Surrey streams to remain narrower than the others. When the Surrey streams, all situated in Capilano sediments, are compared to each other, the heavily urbanized streams are wider than those which are moderately urbanized (Figure 5.14). Widening is therefore a concern in the low-gradient streams, even when detention facilities are provided, although to a lesser extent than in the high-gradient channels.

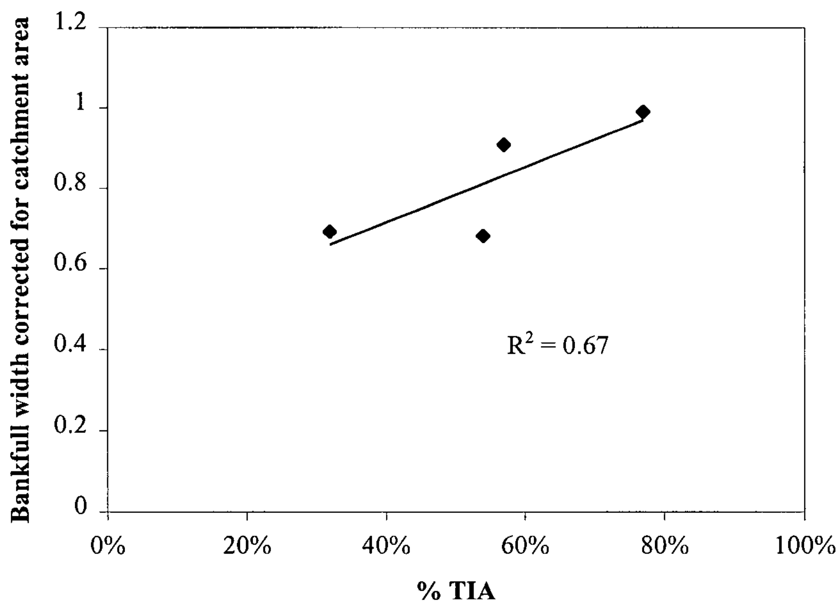

Figure 5.14:
Widening of Surrey streams

When examining the increase in depth with increasing %TIA, there is less of a distinction between the high and low gradient channels. The relationships in Figure 5.15

below have been developed in order to correct the depth measurements for catchment area. As with bankfull width, the exponent in the bankfull depth regression equation (0.10) is lower than the typical *f* value of approximately 0.4 in the equation $d = cQ^f$ (Leopold et al., 1964).

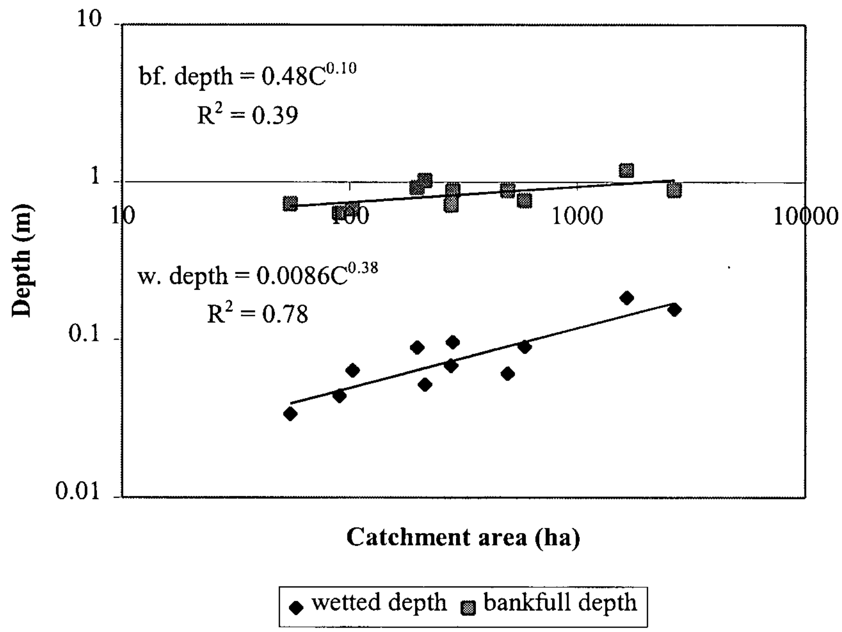

Figure 5.15:
Depth vs. catchment area

The bankfull depth was corrected for catchment area, and found to increase slightly with an increase in %TIA (Figure 5.16). For the high gradient channels, the %TIA explained 61% of the increase in corrected bankfull depth. Their response to urbanization is therefore evidenced more by widening than by deepening. Although the low gradient channels did not consistently widen with increasing urbanization, the increase in their corrected depth was slightly related to %TIA ($R^2 = 0.45$). The Surrey streams are deeper than the undeveloped streams despite the existence of stormwater detention, suggesting that the detention has not reduced shear stresses a great deal. Having drawn this conclusion, the low widths in the

Surrey streams are therefore likely due more to bank strength, than to stormwater detention ponds. When all of the low-gradient channels are considered together, is appears that the necessary channel enlargement has taken place more by deepening than by widening.

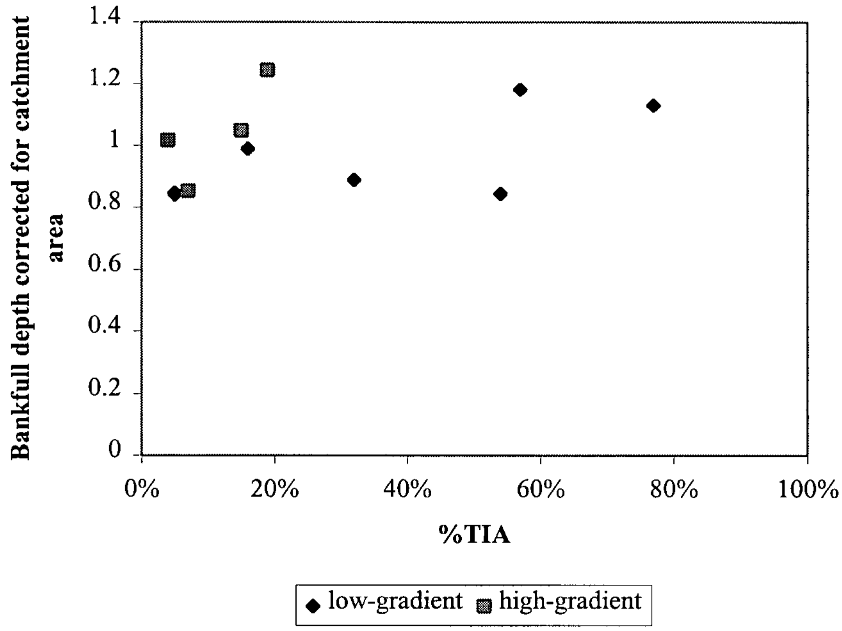

Figure 5.16:
Corrected bankfull depth vs. %TIA

The patterns of enlargement seen in the study channels have implications for the quality of fish habitat. Channel widening is detrimental: first, because it decreases the water depth at summer low flow. Second, as the width-to-depth ratio increases, more heat exchange can take place with the atmosphere, causing the stream to have greater temperature extremes (LeBlanc et al., 1996). Because of the differences in mode of enlargement, the change in bankfull width-to-depth ratio with urbanization is different in the two types of channels. While the ratio does not change with %TIA in the low-gradient channels, the high-gradient channels experience a linear increase in bankfull width-to-depth ratio (R^2 = 0.64) with increasing %TIA. Unfortunately a wide enough range of data is not available to determine if the ratio would level off after a certain %TIA. Because the low-gradient channels (slope ≤ 2%) are the most likely to be productive, it is their dimensions that are of most interest. In these channels, the wetted depth (corrected for catchment area) was found to increase with %TIA ($R^2 = 0.53$), indicating that although the urban streams have lower summer flows per hectare of watershed area, their resistance to widening helps maintain the low flow depths experienced before urbanization.

5.7 Large Woody Debris

As discussed in Section 2.11, several mechanisms are responsible for the loss of large woody debris (LWD) in urban streams. The higher peak flows due to increased watershed imperviousness are expected to wash out the smaller pieces of large woody debris. Loss of large woody debris itself can lead to more uniform flow patterns and a resulting loss in the number of rooted cutbanks (RCB's). Figure 5.17 shows the relationship between instream cover and %TIA (raw data in Table A-7). The total volume of large woody debris per 100 m, and the number of pieces of LWD plus number of RCB's are shown below.

As shown in Figure 5.17, while there is a large amount of scatter in the < 20% TIA range, above this value the abundance of instream cover is uniformly low. Some of this scatter can be explained. Both McCartney and Big John's Creeks have a higher LWD frequency and volume than expected for their level of imperviousness. Both streams,

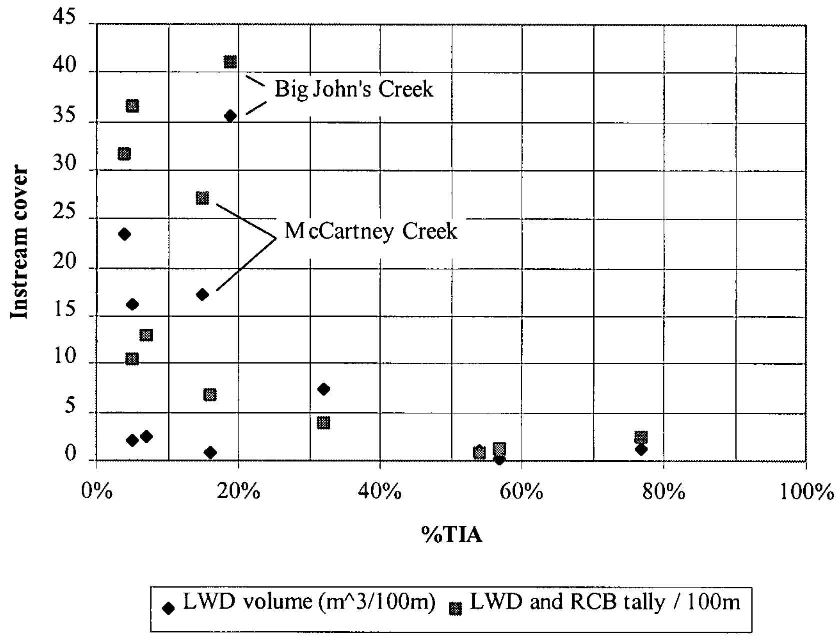

Figure 5.17:
Effect of impervious area on instream cover

however, are located in North Vancouver, where there is a healthy population of mature second growth trees. The higher slope of their catchments is also expected to slightly increase LWD recruitment by aiding windfall. It can be seen, then, that without an exceptionally good buffer zone, minimal quantities of large woody debris exist above 10% imperviousness. It should be noted that LWD values are extremely low in the most urbanized streams, despite the presence of stormwater detention ponds. Assuming that LWD was not purposely removed from these streams, the design of a pond based on control of the five-year flow is therefore not sufficient to prevent LWD washout.

To further examine the relationship between local buffer conditions and instream cover, the LWD volume and instream cover tally have been plotted against the buffer strip width within the study reach (Figure 5.18). While both parameters generally increase along with the buffer strip width, LWD volume shows a stronger relationship ($R^2 = 0.75$). The lack of accessibility to Roche Point and Big John's Creeks due to their wide buffer zones have probably helped these systems to keep their woody debris. As no homes are nearby, it is unlikely that people would clear wood from the stream in an attempt at beautification. Another important factor to consider is that the leave strip width is indicative of its quality – a 300 m wide zone is likely to be undisturbed forest, while a 15 m wide zone would tend to be comprised of young trees, planted after urbanization began. Beyond a certain buffer strip width, it is more likely the type and age of the riparian vegetation that exerts the greatest influence on the abundance and quality of LWD. When the three streams in North Vancouver are removed from the picture, the relationship below no longer holds.

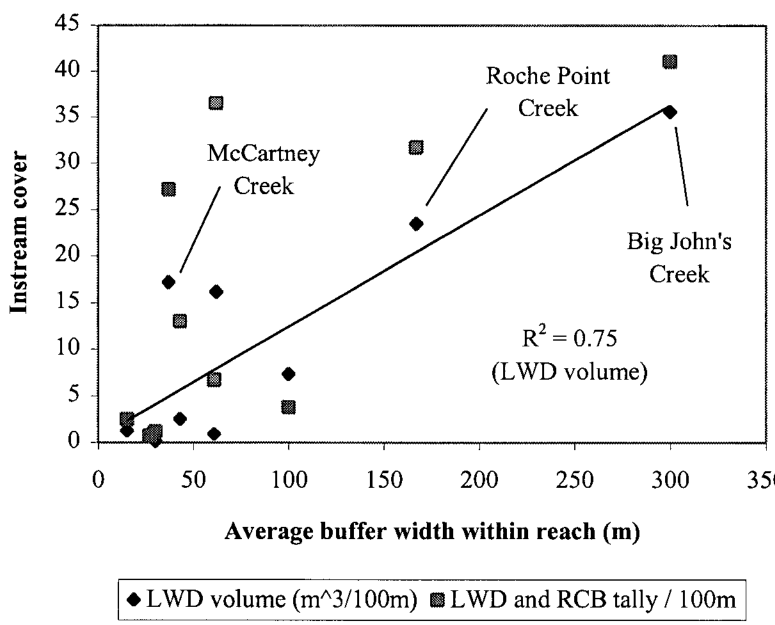

Figure 5.18:
Instream cover vs. buffer width

As seen, both impervious area and buffer strip width affect the abundance of LWD. Washout due to peak flows has already been discussed. However, other elements, not related to flow, are likely to cause a reduction in LWD. First, a stream with a higher percentage impervious area is likely to have more crossings (i.e. bridges and culverts) where LWD accumulates and is removed. Second, watersheds with more impervious areas are more highly populated. Streams in these watersheds run through parks and near homes, where wood is more likely to be removed by residents.

5.8 Bank Erosion

As a stream enlarges to accommodate higher flows after urbanization, banks become unstable. Erosive flows remove particles from stream banks, causing widening, and beds, causing deepening. Excessive stream deepening will cause bank mass failure if the bank height exceeds the critical value (Millar et al., in press). Stream banks which have been stabilized with rip rap or concrete walls are likely to have undergone erosion in the past. A forested riparian zone helps to mitigate the effects of urbanization by stabilizing stream banks. This study found no significant relationship between the %TIA and bank erosion (raw data in Table A-7). However, the extent of visible bank erosion and protection was found to decrease as the width of the buffer zone increases (Figure 5.19). The two streams with the highest amount of bank erosion, Bear Creek (d/s) and Hyde Creek (d/s), had at most two metres of small bushes along one bank of the stream, for most of the reach. Their average buffer width, calculated from orthophotos, is only representative of the conditions along the intact bank, and their buffer strip width is effectively zero (indicated by arrows in Figure 5.19).

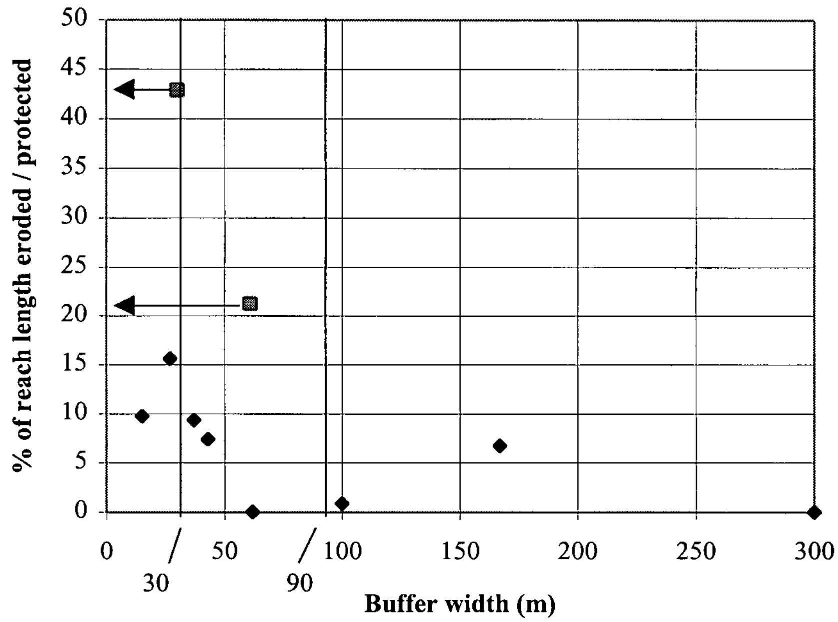

Figure 5.19:
Effect of buffer width on bank erosion

Different authors have recommended a buffer width of either 30 or 90 m for adequate stream protection. As shown here, all of the streams with forested leave strips wider than 30 m have eroded or protected banks over less than 10% of their length. With buffer zones wider than 30 m, however, not much difference is seen in the extent of bank erosion, indicating that 30 m is a critical value. It must be recognized, however, that the quality of vegetation in the buffer zone exerts a large influence on the extent of bank stabilization. It is likely the size and strength of tree roots and of large woody debris on the immediate banks that dictate the rate of bank erosion. As indicated in Figure 5.20, this expectation is justified. The relationship given below indicates that between 5 and 10 pieces of large woody debris per 100 m are sufficient to stabilize 90% or more of the stream banks.

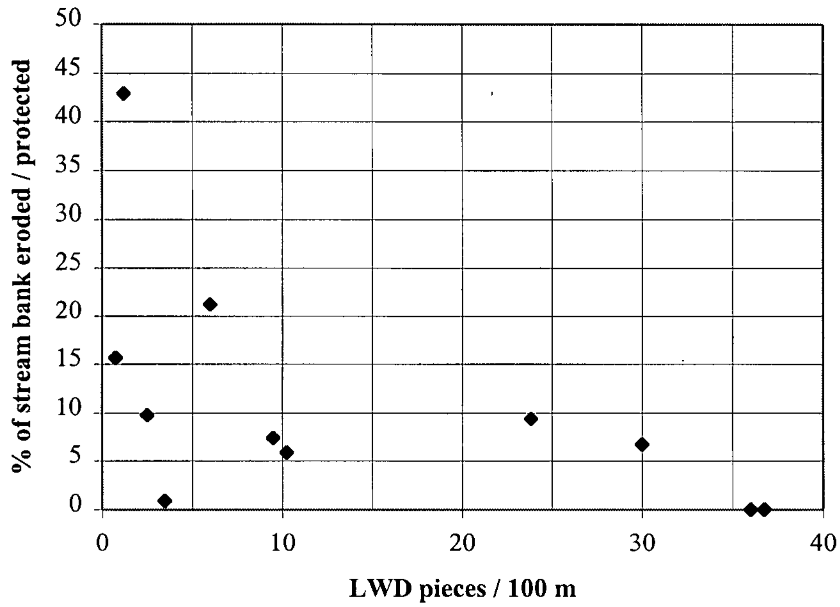

Figure 5.20:
Stabilizing effect of large woody debris

Stream bank erosion is difficult to quantify. While it is easy to identify banks which have undergone mass failure, the signs of bank retreat may disappear quickly. The values given in this study are merely indicators of the overall stability of the banks.

5.9 Channel modeling

The analytical model developed by Millar et al. (in press) for gravel-bed rivers with cohesive banks has been used in order to determine the bank stability in the studied channels. This model determines the stable width and depth of a channel given its bankfull flow (Q_{bf}), gradient (S), roughness height (k_s), median grain diameter of the bed material (D_{50}), the saturated weight of the bank material (γ_t), undrained bank cohesion (c_u), and the bank critical shear stress (τ_{crit}). Since the flow in the high-gradient streams was typically cascading, the model was applied only to the more easily modeled low-gradient streams. The bankfull flow was calculated from Manning's equation:

$$Q_{bf} = \frac{A_{bf}}{n} R_{bf}^{2/3} S^{1/2}$$

A rectangular channel was assumed, taking the bankfull width as equal to the average between the measured wetted and bankfull widths. According to Jarrett (1994), Manning's coefficient n underestimates the roughness in streams with gradients higher than 0.02%. The alternative equation that he proposes was used to calculate the roughness:

$$n = 0.32 S^{0.38} R^{-0.16}$$

The calculated bankfull flow (Table A-3) was found to be related to the catchment area (Figure 5.21). As expected, the data follow a power relationship (R^2 = 0.85), with the discharge increasing less rapidly than the catchment area (LeBlanc et al., 1996). The relationship is unsatisfactory, however, because the data points representing the more developed watersheds do not consistently lie above the line of best fit.

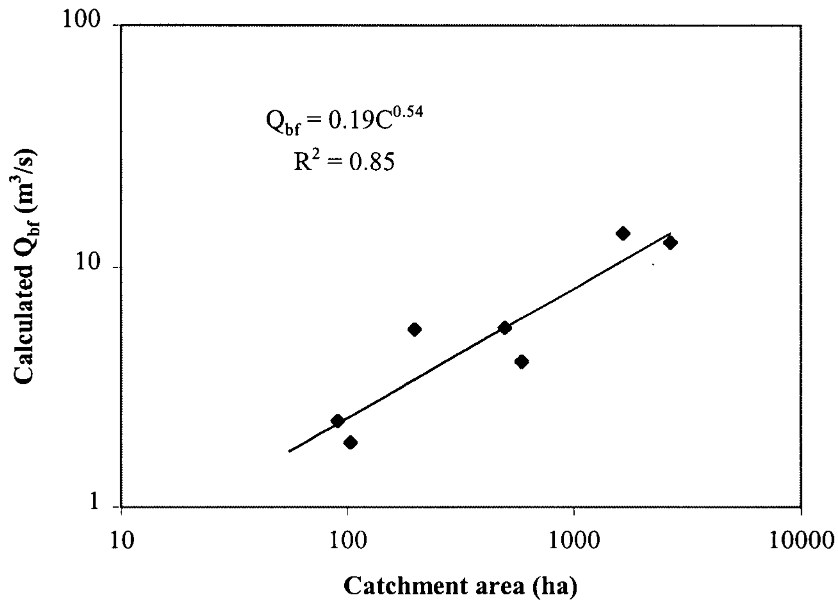

Figure 5.21:
Calculated bankfull flow vs. catchment area

The variables S and D_{50} were determined from the field data. The roughness k_s was calculated using the Keulegan equation (Millar et al., in press):

$$\frac{1}{\sqrt{f}} = 2.03\log\left(\frac{12.2R}{k_s}\right)$$

where the roughness f was determined from the Darcy-Weisbach equation (Millar et al., in press):

$$v = \sqrt{\frac{8gRS}{f}}$$

The bank saturated unit weight was not known, and a value of 20 kN/m^3 was assumed for all the channels. Since the channels are small, they are more likely to enlarge due to fluvial erosion than from mass failure. The undrained bank cohesion was therefore overestimated at 25 kPa. The critical bank shear stress was not known, but was determined by a trial and error process. For each study reach, the model was run using the calculated Q_{bf} and trial values of τ_{crit} until the width and depth in the model output matched those measured in the field as closely as possible. As expected, there is a relationship between the observed amount of erosion and the bank critical shear stress (Figure 5.22). The downstream reach of Bear Creek had the lowest τ_{crit} and the most noticeable bank erosion. The streams with a τ_{crit} between 50 and 60 Pa had less than approximately 20% of their length eroded or protected, while those with the most resistant banks had 10% or less of their banks affected by erosion.

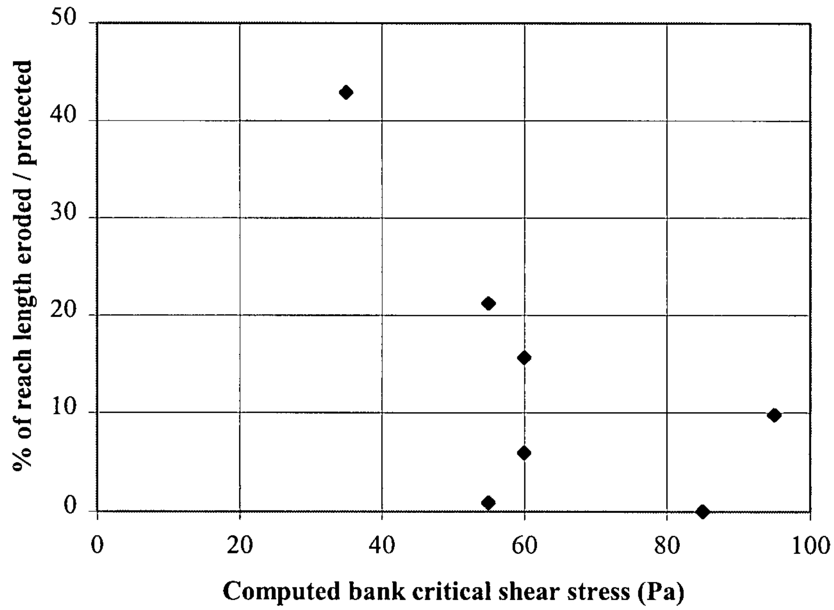

Figure 5.22:
Observed bank erosion vs. calculated bank critical shear stress

5.10 Hydrologic Analysis

The channel dimensions have been considered indicative of the magnitude of the two-year discharge. In order to verify the validity of this assumption, the two-year discharge has been calculated for each of the low-gradient channels under present development conditions using the rational method. The following equation was used (Chilibeck, 1993):

$$Q_{peak} = \frac{CIA}{360}$$

where C is the runoff coefficient (Lindeburg, 1994), I is the intensity of rainfall (mm/hr) for a given time of concentration (t_c), and A is the catchment area (ha). The time of concentration was determined for each watershed, from the equation:

$$t_c = \frac{L}{60K\sqrt{S}}$$

where L is the distance of overland flow (m), K is the land cover factor, and S is the slope (m/m). The water velocity was assumed to be 1.5 m/s in storm sewers, and 0.75 m/s in stream channels. Rainfall intensities corresponding to the two-year storm and the calculated t_c were determined from IDF (intensity-duration-frequency) curves for the study sites. As shown in Figure 5.23, although the hydrologically calculated two-year flows and hydraulically calculated bankfull flows do not fall along the 1:1 line, they are of the same order of magnitude. Considering that both methods of calculating the channel-forming flow are based on assumptions – of channel roughness, time of concentration, runoff coefficient, etc. – the relationship between the two flow values is quite good. It is therefore not unreasonable to assume that the bankfull flow calculated from the channel's cross-sectional dimensions approximates the two-year flow. The hydrologically calculated two-year flows did not take detention ponds into account, and the calculated values for Quibble Creek and the downstream reach of Bear Creek are noticeably higher than the hydraulically calculated bankfull flow. Stormwater detention ponds may have reduced erosion in these streams, keeping their widths and depths smaller than without detention. Errors may also have been incurred by applying the rational method to large watersheds without dividing them into sub-basins. The flow values for the three largest watersheds considered: Anderson Creek, the downstream reach of Bear Creek, and Quibble Creek fall furthest from the 1:1 line.

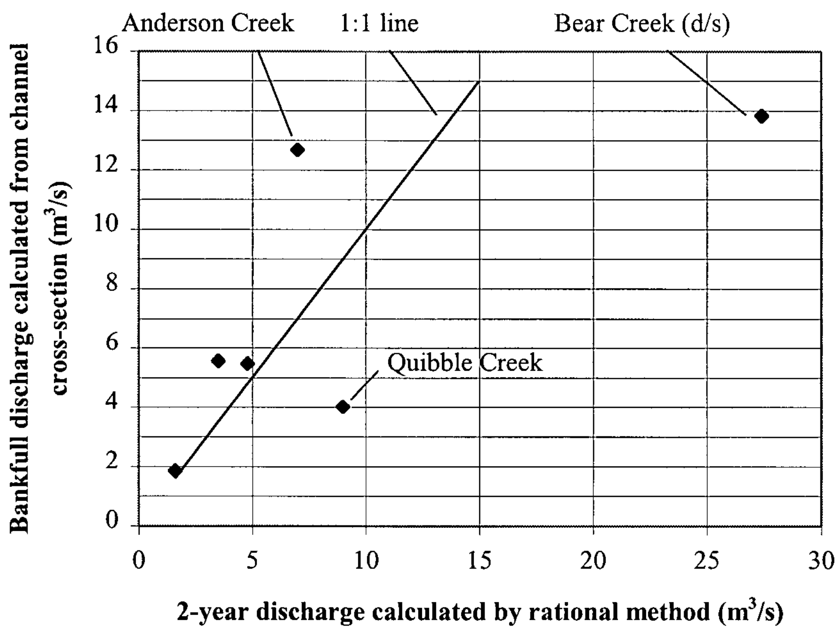

Figure 5.23
Comparison of hydraulically calculated bankfull discharge and hydrologically calculated two-year discharge

5.11 Temperature

Temperatures were measured in both reference streams for the period of November 5th, 1997, to April 7th, 1998. The data, recorded every 30 minutes, are shown in Figure 5.21 below.

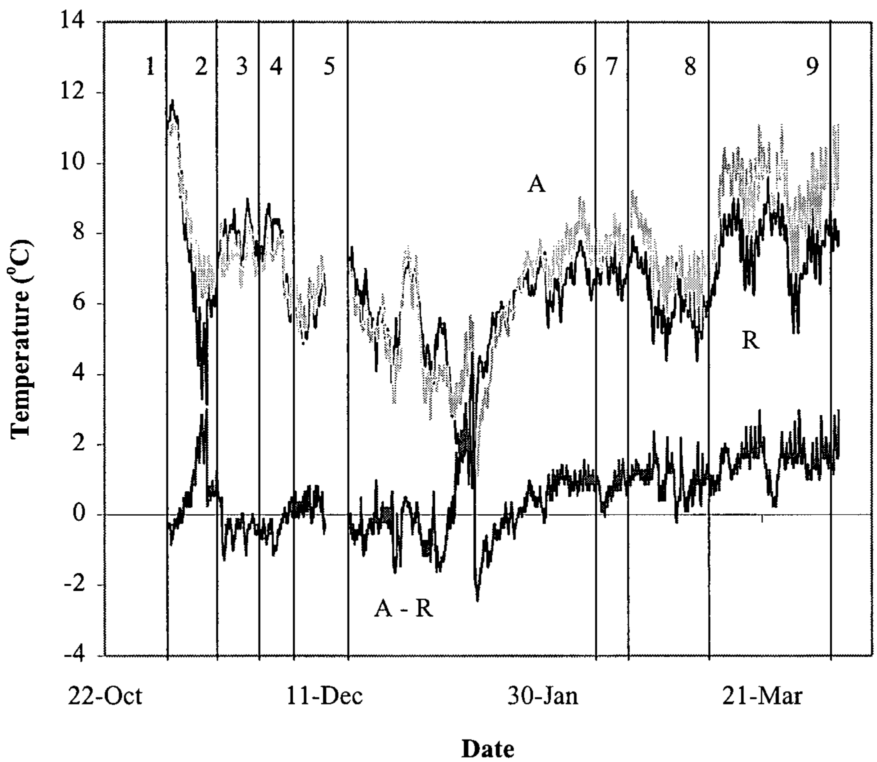

Figure 5.24:
Reference stream temperature records
(A=Anderson Creek, R=Roche Point Creek, A-R=difference between the two)

The five day gap in the record occurred when the recorders were removed from the streams and downloaded. The numbered vertical lines indicate the days when temperatures were measured in all of the streams. Both streams' temperatures fluctuate in the same fashion, with two exceptions. In the dry period before November 14th (measurement day #2), stream flows decreased in Roche Point Creek, leaving the temperature recorder stranded on dry cobbles. The dip in temperature for Roche Point Creek occurred when the air temperature, rather than the stream temperature, was being measured. The recorder was then placed in a pool, and it remained submerged for the remainder of the period of measurement. The second dip in temperature for Roche Point Creek occurred after a snowfall on January 13th. Because this stream is in North Vancouver, which experiences lower temperatures and higher precipitation than the Langley area, it is likely that snowmelt caused the temperature in Roche Point Creek to decrease suddenly on January 14th. From February onward, the temperature in Anderson Creek is consistently higher than in Roche Point Creek. The excellent canopy over Roche Point Creek is probably responsible for delaying stream warming in the springtime when air temperatures increase. Although Anderson Creek has good groundwater inflow in its lower watershed, its upper watershed is made up of less pervious material. Water from upstream therefore flows primarily overland, and because the buffer zone over Anderson Creek is not extensive, it is exposed to warm air.

As discussed in Section 4.12, McCartney and Big John's Creeks, and both reaches of Hyde Creek were compared to the Roche Point Creek temperature logger, while the rest were compared to the Anderson Creek logger. The expectation that watershed impervious area would decrease winter stream temperatures is not supported by the data collected. When the temperature difference between each stream and its reference (delta-T) was plotted against %TIA, five of the nine days' data were scatters. Few of the streams registered temperatures lower than those of the reference streams. The pattern in the other four days' results (sampling days #1, 3, 5, 8) indicated that the urban streams had warmer temperatures than the rural ones. Looking at the weather conditions (rainfall, temperature, hours of sunlight, and wind direction), no common condition could be found that would produce the temperature trend for these four days of measurement. Figure 5.25 shows the average delta-T's for these four days, with error bars representing the standard deviation. The two reference streams are included, having delta-T's of zero and TIA's of 4% and 5%. The data for both categories of streams and their respective reference streams are combined in one graph, in order to give a full range of %TIA. Because the temperatures in Roche Point Creek and in Anderson Creek are very close in most cases, this is considered a valid treatment of the data.

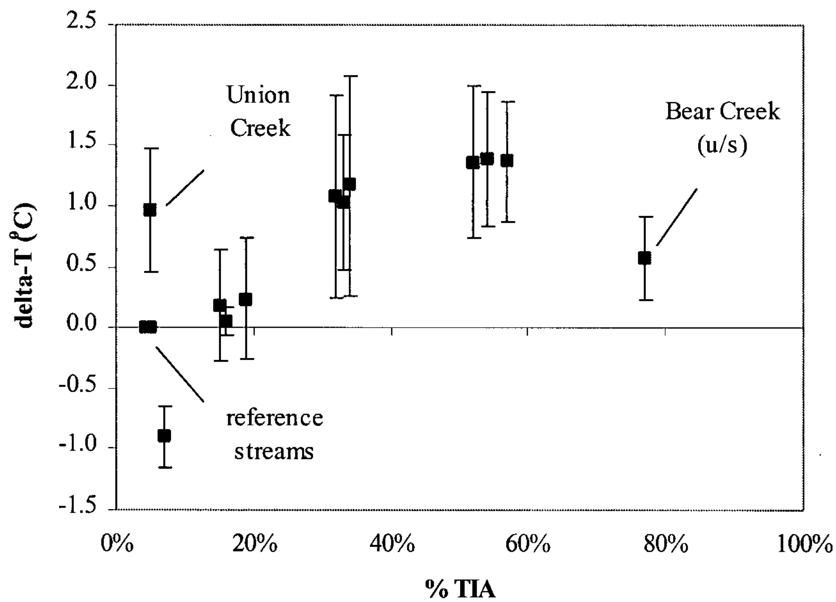

Figure 5.25
Temperature increase in urban streams (four days of measurement)

Union Creek has an uncharacteristically high temperature according to the trend above. Two factors likely act to cause some streams to be warmer than others. The Union Creek watershed is very well drained, and the high input of groundwater, normally warmer than rainwater, likely causes this creek to be warmer than other rural streams. The urban streams are likely warmer than most of the rural streams because the lack of tree cover allows the water to be heated by the sun. To better explain the temperatures in the study streams, their delta-T's are plotted against the stream length upstream of the measurement site with a buffer strip wider than 30 m (Figure 5.26) and 100 m (Figure 5.27).

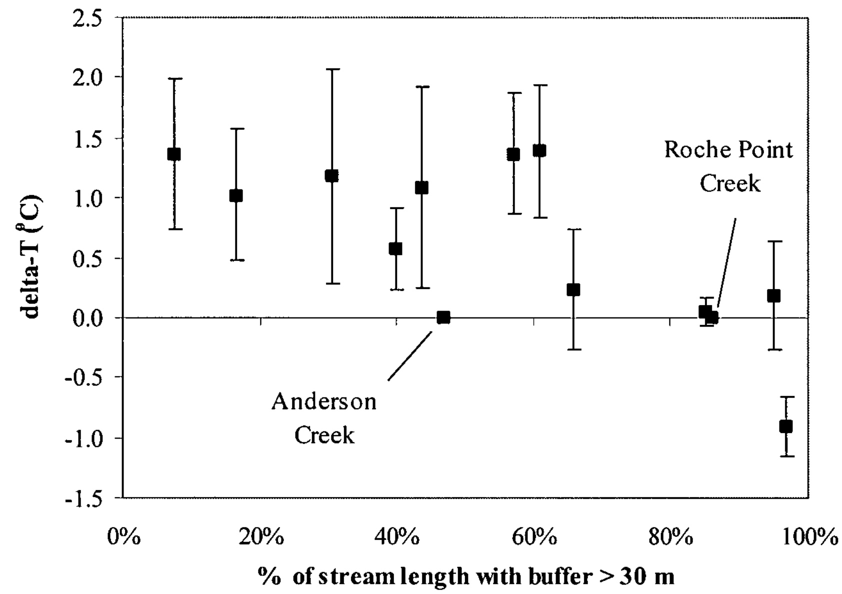

Figure 5.26:
Stream delta-T vs. 30 m buffer

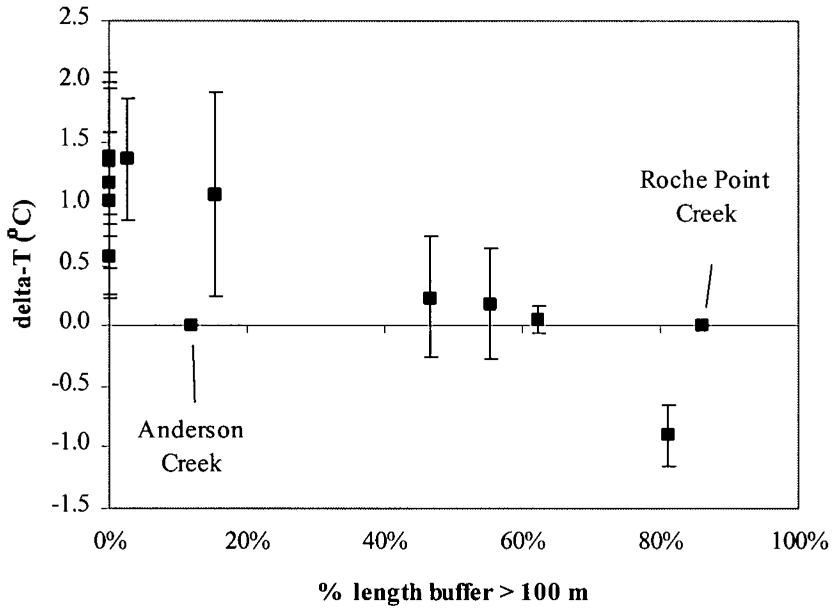

Figure 5.27:
Stream delta-T vs. 100 m buffer

Both reference streams are included in these figures, again with delta-T's of zero. As the extent of cover from riparian vegetation decreases, the stream temperature increases. This indicates that the trees surrounding the streams help to shade them from sunlight, and provide an environment of cooler air near to the streams.

The hypothesis that urban streams are cooler than rural streams in the winter must be rejected for the data collected. The results given here may not be representative of all conditions, however, for two reasons. First, for seven out of nine sampling occasions, the air temperatures in the three days leading up to sampling were warmer than normal for the period. Second, as seen in Figure 5.24, no temperature measurements were made in the coldest period of the year, from mid-December to the end of January. The results may have been different during the coldest period of a normal winter.

None of the temperatures measured reached critical levels. The urban streams were, on average, less than 1.5°C warmer than the reference streams. The highest delta-T was recorded for Still Creek on November 26th, when it was 2.1°C warmer than Anderson Creek (9.2 – 7.1°C). The lowest delta-T was recorded for the upstream reach of Bear Creek on April 7th, when it was 1.3°C cooler than Anderson Creek (9.8-11.1°C). Marten (1992) developed a relationship to explain the time to hatching (t, days) using T_1, the temperature from fertilization to the eyed stage, and T_2, the temperature from the eyed stage to hatching. The survival to hatching was found to depend on T_1 alone, and an equation has been developed to relate the survival to the eyed stage (E) to T_1. Although the relationships were developed for brook trout, they will be used here to indicate the effects of temperature on the incubation period of other salmonids. According to the equation:

$$t = 176 - 14.7T_1 - 9.67T_2 + 0.800T_1^2 + 0.367T_2^2$$

fish in Still Creek would be expected to hatch in 51 days, as opposed to the 62 days required in Anderson Creek, if the temperatures recorded were maintained for the entire incubation period. From the equation:

$$E = 52.7 + 10.1T_1 - 0.682T_1^2$$

90% of the fish in Anderson Creek would survive to hatching, while 88% of those in Still Creek would survive. Using the temperatures recorded on April 7th, again assuming that they were maintained for the entire incubation period, fish in Anderson Creek would hatch in 49 days with a survival rate of 81%. Fish in Bear Creek (u/s) would hatch in the same number of days, with an 86% survival rate. There is not a large difference between Anderson Creek and the urbanized stream in either case, and the lower temperatures in Bear Creek (u/s) are beneficial to incubation. The shorter time to hatching in the urban streams with warmer temperatures may have a small effect on the survival rate after hatching, if the fry emerge when flows are still too high for them to remain in the system. However, a difference of 11 days is not likely to be detrimental.

5.12 Summary

The objective of this study was to identify thresholds beyond which urbanization is harmful to fish habitat. However, many of the parameters studied do not exhibit thresholds. Lower percentages of fine material in the streambed have here been related to higher percentages of impervious area, with a corresponding increase in intragravel dissolved oxygen. This would suggest that, twenty years after the completion of urban development, the incubation conditions are more favourable in urban streams. Winter temperatures were not found to differ significantly in the urban and the rural streams. Even the most extreme temperature differences recorded translate to only an eleven-day difference in incubation time, with minimal effects on the survival rate. Some aspects of rearing habitat improve in the urban streams as well. Bed coarsening increases the number of large particles that offer cover to fish. The low-gradient streams, those which are typically the most productive, appear to be resistant to widening. Maintainance of channel width helps to mitigate the effects of reduced base flow. Although the base flow (relative to catchment area) was seen to be very low in the urban streams, the wetted depth (relative to catchment area) was actually slightly higher in these streams. Reduced water depth is therefore no more a problem in the urban streams than in the rural ones during the summer low-flow period.

There is, however, evidence of stream degradation due to urbanization. The drop in stream velocity during the dry season could limit reaeration, particularly in deeper streams. Although this was not found to be a problem in the study streams, the decrease in base flow could be the most serious impact of urbanization, for the simple reason that it is nearly impossible to remedy. The widening of high-gradient streams may also impact fish populations - although these reaches are not important areas for spawning, the transport of excess bank materials into the flatter, typically more productive downstream reaches could seriously clog spawning sediments.

The negative effects of urbanization are primarily due to the reduction in the width and quality of the riparian buffer zone. In the urban watersheds studied, the length of stream with a buffer strip 100 m or wider decreases linearly with increased %TIA until it reaches zero at approximately 35% TIA. Evidently, preservation of the riparian zone has not been a priority when high demands have been placed on the available land. The loss of this densely vegetated zone has increased human access to streams. When residential properties and pathways through parks encroach on streams, trees that fall are more likely to be removed. Many of the functions of LWD have already been described in Section 2.11; it is conceivably the most important element of fish habitat. It is therefore extremely important to maximize the potential for LWD recruitment. The quality of the riparian vegetation, which is linked to the buffer width, likely has the greatest effect on the size and abundance of LWD in a stream. During development, mature trees should be left in the riparian zone, rather than clearing the area and replanting it later.

Observations of bank stability match expectations based on the strengthening effects of wood debris and tree roots. The fact that the extent of bank erosion and protection did not correlate well with %TIA, but did correlate with buffer width and LWD abundance, indicates that riparian vegetation mitigates the effects of increased peak flows. Minimal bank erosion was observed when the riparian zone was greater than 30 m wide locally, and when there were more than five to ten pieces of LWD per 100 m. Since fluvial erosion, and particularly bank mass failure, can release large amounts of sediment into the stream, riparian integrity and large woody debris should be maintained during development to prevent degradation of salmon spawning habitat.

The data collected indicate that stream degradation takes place at low to moderate levels of urbanization:

- Base flow decreases to very low levels between 20-40% TIA.
- The high-gradient channels in this study experience widening at levels of 10-15% TIA, even though they have extensive riparian vegetation with strong roots.
- When riparian vegetation is not of excellent quality, large woody debris abundance is uniformly low above 10% TIA.

Evidently, then, under the riparian and stormwater management conditions in this study, a stream is impacted in the early stages of development. Once watershed imperviousness increases beyond 20%, very little further decrease in base flow and LWD abundance are observed. This is in close agreement with the claims made by other authors that habitat degradation occurs below 20% TIA, and with Schueler's (1994) observation that once TIA >

25%, a stream is degraded, and can no longer maintain habitat diversity. It is therefore critical to protect streams when urbanization is just beginning.

6 EVALUATION OF THE LAND DEVELOPMENT GUIDELINES

6.1 General

The Land Development Guidelines (Chilibeck, 1993) were written in order to protect fish and fish habitat from the development process. The study watersheds were developed before the implementation of these guidelines, and the detrimental effects on summer baseflow, channel width, large woody debris, and bank stability have been observed. Two of the mitigative measures prescribed by the Land Development Guidelines are the maintenance of a forested leave strip, and the construction of stormwater detention ponds. These two strategies will be reviewed in light of the data collected in this study.

6.2 Leave Strips

According to the Land Development Guidelines, a leave strip of 15 m should be provided on each side of a stream in residential and low-density areas, and a strip 30 m wide should be provided in commercial and high-density areas. This study has demonstrated that a healthy buffer zone helps to maintain bank stability, and is a source of large woody debris. If bank stability is thought to be reflected by root strength alone, then a narrow buffer zone is sufficient to prevent bank erosion. As described in Section 2.10, FEMAT prescribes a buffer width of twice the height of a site-potential tree, or 90 m, whichever is greater. This ensures that the leave strip will perform all of its functions at 100% effectiveness. However, it can be seen in Figure 2.3 that root strength achieves 100% effectiveness with a lower buffer strip width. Using the FEMAT diagram (Figure 2.3, O'Laughlin et al., 1995), and assuming that the trees in the buffer zone are 45 m tall, a buffer width of 15 m will be sufficient to preserve bank stability. Looking back to Figure 5.19, this supposition certainly seems justified. Only the two streams which completely lack a forested buffer zone have more than 20% of their length affected by bank erosion. However, as seen in Figure 5.20, bank stability is also related to the abundance of LWD. Due to the importance of maintaining stable banks, as well as the recognized fisheries value of LWD, the buffer width necessary to maintain LWD abundance will be considered the critical width. The buffer zone does, of course, serve many functions other than providing LWD and bank stability; however the object is to determine the critical width based on the study parameters.

If a watershed were to be developed in an area such as North Vancouver, where the streams are surrounded by mature second growth trees, the increased peak flows due to any level of urbanization would not likely have sufficient power to wash out the very large pieces of woody debris. Big John's Creek (19% TIA) and McCartney Creek (15% TIA) have been influenced by higher peak flows, as evidenced by their increased widths (Figure 5.13). They have, however, maintained an uncharacteristically large LWD abundance for their level of urbanization (Figure 5.17), despite their high slopes (which would aid in LWD washout). The abundance of LWD in Big John's Creek could be attributed to its extremely wide buffer zone (300 m). However, it was concluded from Figure 5.18 that the quality, rather than the width of the buffer zone, exerted the greater influence beyond a certain buffer strip width.

This critical buffer strip width, however, remains to be determined. If a site-specific tree is again assumed to be 45 m tall, then any tree falling directly towards the stream, inside a buffer zone that is only 15 m wide on each side, would not be contained within the buffer zone. The tree could fall across a road, or onto private property, increasing its chances of being removed. None of the streams with excellent riparian vegetation had buffer strip widths lower than 37 m. It can therefore be concluded that 37 m of good quality forest on each side of the stream are sufficient to keep LWD counts high. A width of 37 m is approximately 80% of the assumed 45 m tree height, and McCartney Creek has approximately 85% the numbers of LWD in the near-pristine Roche Point Creek. These results closely match those of Belt et al. (1994) and the FEMAT diagram (O'Laughlin et al., 1995), as discussed in Section 2.10. It is also concluded that a 15 m buffer strip on each side of the stream is insufficient, due to the potential of tree removal. A width of one half of a site-potential tree, or 23 m, would keep only those trees falling from the extremes of the buffer zone from infringing on private property. A larger width is therefore required – it is proposed that a width of 30 m be implemented on each side of the stream when the riparian vegetation is of good quality. This value approaches the 37 m observed in McCartney Creek; it is also corroborated by the literature reviewed in Section 2.10.

If a stream were to be urbanized in an area where the existing riparian zone is composed of younger trees, washout due to peak flows is a concern. Enver Creek (32% TIA), with its average buffer width of 100 m on each side, has fewer than four pieces of LWD per 100 m (Figure 5.17, Table A-7). Clearly, then, the smaller pieces of wood debris in this stream cannot withstand the higher peak flows resulting from intermediate levels of urbanization. Since a buffer width of 100 m is not sufficient to keep LWD counts high in this type of system, the most important strategy changes from maintenance of a sufficiently wide buffer zone to maintenance of LWD abundance. If a stream surrounded by young trees is to be developed, it is recommended that existing LWD be anchored, and even that new LWD be introduced, in order to mitigate the effects of peak flows in a natural way.

6.3 Stormwater Detention Ponds

Implicit in the projection that very large woody debris would not be washed out by increased peak flows is the assumption that the most harmful peaks will be successfully mitigated by stormwater detention ponds. The Land Development Guidelines recommend that ponds be designed to keep the post-development two-year discharge at or below the level of the pre-development two-year peak discharge. This is based on the assumption that the more frequent flows are those responsible for causing channel changes (Chilibeck, 1993); i.e. that the bankfull, or two-year flow is the channel-forming flow, as discussed in Section 2.8.

While this type of storm pond does reduce flood peaks, it extends the duration of the competent flows. In order to illustrate this concept, simplified hydrographs have been generated for Enver Creek with and without a storm pond (two-year flood control), using the method described by Chilibeck (1993) (Figure 6.1). The pre-development two-year flow was calculated by the rational method, assuming that the entire watershed was forested. It can be seen that, while a pond would greatly reduce flood damage due to peak flows, the amount of additional sediment movement caused by increasing the duration of bankfull flows may be of concern. The longer duration of high velocities could also stress juvenile fish, which have low prolonged swimming speeds (Chilibeck, 1993). To counteract this effect of development, the importance of LWD is highlighted once again. Abundant LWD would slow these prolonged high flows near the channel banks, providing areas of slow moving water.

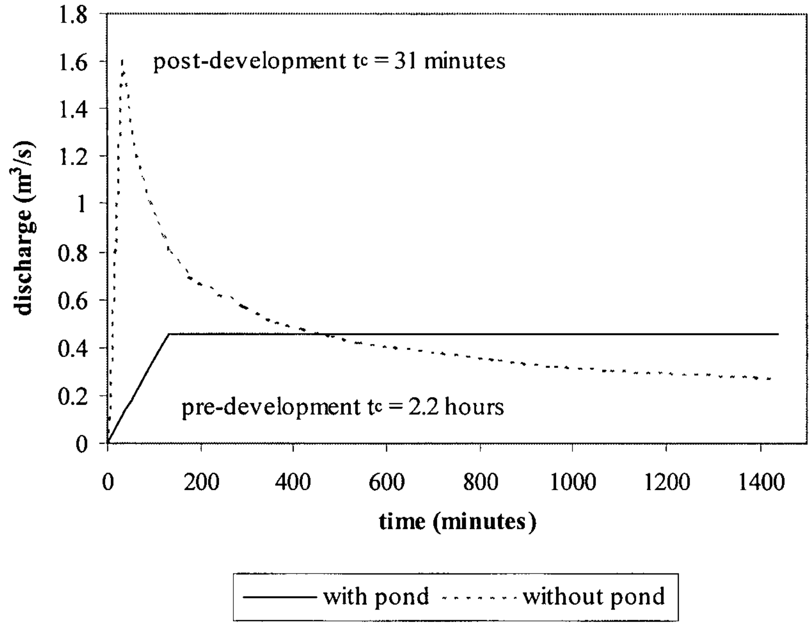

Figure 6.1:
Simulated post-development discharge in Enver Creek with and without stormwater detention

The change in management policy from control of the five-year flood to control of the two-year flood is recognized as beneficial (Lee et al., 1988); however this simple rule of thumb does not take into account several important parameters. MacRae (1997) refers to the work of Hollis (1975) which shows that the floods of more frequent return period experience the greatest increase in magnitude after urbanization. Considering this change, Wolman's (1960) work curve (Figure 2.2) shifts so that the maximum amount of sediment transporting work is done by the mid-bankfull events in urban streams (MacRae, 1997). Therefore, the design of detention ponds according to the two-year criteria ignores the most effective discharges. Belore et al. (1988) and MacRae et al. (1988) recommend that ponds be designed on a case-by-case basis with the intent of keeping cumulative excess shear stress to a minimum. This approach takes into account the critical shear stress of the bed and bank materials, the stream slope, hydraulic roughness, and the magnitude, duration, and frequency of discharges based on continuous rainfall records, (MacRae et al., 1988).

It has been demonstrated above that the stormwater detention ponds in Surrey, designed to control the five-year discharge to predevelopment levels, have not prevented the winnowing away of fine bed material, the transport of coarse material, stream widening and deepening, and LWD washout. Studies in the future should compare streams protected by ponds designed according to the two-year flow criteria, with developed, unmanaged streams.

7 CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

In this study, small streams were surveyed in an attempt to quantify the effects of urbanization on fish habitat in Lower Mainland British Columbia. The streams were situated in watersheds representing a gradient of percent total impervious area (%TIA). Summer base flow, bed substrate composition, intragravel dissolved oxygen, channel cross-sectional geometry, large woody debris and rooted cutbanks, bank erosion, and temperature were measured and related to the %TIA and the the extent of riparian cover. The conclusions given below will be compared to expectations based on the literature.

Some of the conclusions drawn imply that fish habitat has been improved by the process of urbanization:

1) The percentage of fine material in the streambed decreases with an increase in %TIA. This relationship is not skewed by the presence of agricultural land in two of the lower TIA streams. The available literature recognizes that streams are subjected to increased fine material in the two early phases of urbanization – the construction phase, and the channel adjustment phase. A concensus has not been reached, however, regarding the length of time necessary for a streambed to recover from the influx of fine material from basin urbanization. The low quantities of fine material in the urban streams indicates that, after twenty years, the urban streams are no longer affected by bank erosion, and have therefore reached equilibrium. It is unknown, however, to what degree the gravel

quality, and hence the fish populations, were impacted in the early stages of urbanization. Improved gravel quality after twenty years may not be beneficial if fish have already stopped spawning in the stream. The absence of fine material, as well as the presence of larger cobbles in the urban streams, are considered evidence of higher peak flows from impervious areas.

2) When considering the low-gradient streams, slightly higher readings of intragravel dissolved oxygen in the urban streams accompany the reduction in fine material. This is in agreement with the literature.

3) Temperature differences between the study streams are small, and in some cases the urban streams have more favourable temperatures than the reference streams. Very few previous studies have considered the winter temperature regimes in urban streams, and results derived here indicate that the concern with summer, rather than winter temperatures, may be justified. However, the results are inconclusive, since winter temperatures were warmer than usual during the period of measurement.

Urbanization has, however, had several negative impacts:

1) Base flow discharge (relative to catchment area) is extremely low once the TIA increases beyond 20-40%. This reduction in base flow with increased imperviousness has been recognized by many authors already. It is of interest to note, however, that in the study streams, the reduction in stream velocity is much more critical than the reduction in water depth. However, reaeration rates were not found to drop to critical levels in the study streams. Hyde Creek in particular, should be monitored for low summer flow.

2) The fraction of upstream buffer strip wider than 100 m decreases linearly with increased %TIA, reaching zero at 35% TIA. The present Land Development Guidelines, which require a leave strip 30 m wide in high-density areas and 15 m wide in low-density areas, are not expected to impact this trend.

3) Increased imperviousness, reduced riparian integrity, and increased human access have greatly reduced the abundance and volume of large woody debris in urban streams. While local buffer conditions produce a wide scatter in the < 10% TIA range, instream cover is consistently low above 20% TIA. The LWD counts for given levels of %TIA are in close agreement with those presented by May et al. (1996) for Puget Sound Lowland Streams.

4) Observations of bank erosion indicate that a healthy buffer zone and abundant large woody debris mitigate the effects of fluvial erosion from high peak flows. When the forested buffer strip was 30 m or wider, and when there were greater than five to ten pieces of large woody debris per 100 m, bank erosion was kept to a minimum.

5) High-gradient streams experience widening at low levels of %TIA (10-15%). Low-gradient streams are more resistant to widening – they are therefore narrower than high-gradient streams with the same catchment area. This is consistent with the results of other authors, and with shear stress equations.

6) An exact determination of the threshold level of development is not possible from the limited number of streams studied. However, the results are in agreement with those of other authors – most of the damage is done to streams when TIA < 20%. All of the streams with > 20% TIA had very low base flows and LWD abundance. Protective measures should therefore be implemented in the early stages of development. The

effects of urbanization on streams developed under the new Land Development Guidelines are yet to be observed.

7.2 Recommendations

The following recommendations are made for the protection of streams in urbanizing areas:

1) The buffer strip widths prescribed by the Land Development Guidelines are considered insufficient according to the data gathered in this study. Streams surrounded by mature riparian vegetation should be left with a buffer strip at least 30 m wide along each side of the stream, in order to keep LWD counts high. In streams which have already been impacted by logging or farming, and are surrounded by younger vegetation, the existing LWD should be anchored, and additional LWD should be introduced in order to mitigate the effects of basin imperviousness.
2) Stormwater detention ponds should be installed before development is begun, and should be designed with the intent of keeping cumulative excess shear stress at pre-development levels.
3) Since high-gradient streams widen at very low levels of urbanization (10-15% TIA), and because the sediments generated from the erosion of their banks could deteriorate spawning gravel quality in downstream reaches, special care should be taken to reduce peak flows and stabilize banks when developing in steeply sloped watersheds.

Some ideas for future research are proposed:

1) The measures of bank erosion used in this study were subjective, but indicate that a more detailed study could yield good results. Future research should better quantify erosion by measuring bank retreat over a few years. This would help to determine whether the urbanized streams have, in fact, reached equilibrium.

2) This study has confirmed that large woody debris abundance decreases with increased imperviousness, and other research has demonstrated the loss in productivity in LWD poor streams. A more detailed study should measure pool frequency, perform fish counts, and measure the integrity of the benthic community in order to quantify the effects of LWD loss in urban streams.

3) Stormwater detention ponds designed to keep five-year flows to pre-development levels have been demonstrated as ineffective. A future field study should evaluate the long-term value of ponds designed using the two-year criteria, by comparing managed and unmanaged streams in developed watersheds.

4) Although a variety of stream gradients, geological cover, rainfall intensities, and catchment areas provide a useful overview of general trends, future research should be limited to streams which are alike in all respects except for level of urbanization. This would allow for a more exact determination of thresholds.

5) The ideal study would focus on one or several streams, beginning before development began, and ending once it was established that the stream had reached equilibrium. In this way the most critical development stages and habitat elements could be identified.

8 REFERENCES

Armstrong, J.E., 1984. Environmental and Engineering Applications of the Surficial Geology of the Fraser Lowland, British Columbia. Canadian Geological Survey Paper 83-23. Ottawa: Geological Survey of Canada.

Armstrong, J.E., and Hicock, S.R., 1980a. Surficial geology, New Westminster, British Columbia. Geological Survey of Canada, Map 1484A, scale 1:50 000.

Armstrong, J.E. and Hicock, S.R., 1980b. Surficial geology, Vancouver, British Columbia. Geological Survey of Canada, Map 1486A, scale 1:50 000.

Arnold, C.L., Boison, P.J., and Patton, P.C., 1982. "Sawmill Brook: An Example of Rapid Geomorphic Change Related to Urbanization." Journal of Geology, v.90, p.155-166.

Arnold, C.L., and Gibbons, C.J., 1996. "Impervious Surface Coverage: The Emergence of a Key Environmental Indicator." Journal of the American Planning Association, v.62, no.2, p.243-258.

Barishnikov, N.B., 1967. "Sediment Transportation in River Channels with Flood Plains." Committee of Surface Waters, Proceedings of the General Assembly of Bern (September-October), International Association of Science and Hydrology, Pub. No. 75, p.404-412.

Belore, H.S., Fraser, H.G., and Reid, B.A., 1988. "Evaluation of Stream Erosion in Master Drainage Planning: A Case Study in Eastern Ontario." Proceedings, International Symposium on Urban Hydrology and Municipal Engineering, Town of Markham, Ontario.

Belt, G.H., and O'Laughlin, J., 1994. "Buffer Strip Design for Protecting Water Quality and Fish Habitat." Western Journal of Applied Forestry, v.9, no.2, p.41-45.

Beyerlein, D., 1996. "Effective Impervious Area: the Real Enemy." Proceedings of the Impervious Surface Reduction Research Symposium, City of Olympia, Washington.

Bjornn, T.C., and Kirking, S.C., 1991. "Relation of Cover Alterations to the Summer Standing Crop of Young Salmonids in Small Southeast Alaska Streams." Transactions of the American Fisheries Society, v.120, p.562-570.

Booth, D.B., 1990. "Stream-Channel Incision Following Drainage-Basin Urbanization." Water Resources Bulletin, v.26, no.3, p.407-417.

Booth, D.B., 1991. "Urbanization and the Natural Drainage System - Impacts, Solutions, and Prognoses." The Northwest Environmental Journal, v.7, p.93-118.

Booth, D.B., Montgomery, D.R., and Bethel, J., 1997. "Large Woody Debris in Urban Streams of the Pacific Northwest." In Effects of Watershed Development and Management on Aquatic Ecosystems, Proceedings of an Engineering Foundation Conference, ed. L.A. Roesner. New York: ASCE, p.178-197.

Brown, W.B., Jones, J.E., Clary, J.K., and Kelly, J.M., 1997. "Riparian Buffer Widths at Rocky Mountain Resorts." In Effects of Watershed Development and Management on Aquatic Ecosystems, Proceedings of an Engineering Foundation Conference, ed. L.A. Roesner. New York: ASCE, p.278-294.

Carling, P., 1988. "The Concept of Dominant Discharge Applied to Two Gravel-Bed Streams in Relation to Channel Stability Thresholds." Earth Surface Processes and Landforms, v.13, p.355-367.

Chilibeck, B., Chislett, G., and Norris, G., 1993. Land Development Guidelines for the Protection of Aquatic Habitat. Ottawa: Department of Fisheries and Oceans, Habitat Management Division.

Church, M., 1992. Chapter 6: Channel Morphology and Typology. In The Rivers Handbook, v.1, ed. P. Calow and G.E. Petts. Oxford: Blackwell Science, p.126-143.

Clover, A.P., 1976. "Selecting the Proper Reaeration Coefficient for Use in Water Quality Models." USEPA Conference on Environmental Simulation and Modelling, April.

Crispin, V., House, R., and Roberts, D., 1993. "Changes in Instream Habitat, Large Woody Debris, and Salmon Habitat after the Restructuring of a Coastal Oregon Stream." North American Journal of Fisheries Management, v.13, p.96-102.

Culp, J.M., 1987. "The Effects of Streambank Clearcutting on the Benthic Invertebrates of Carnation Creek, British Columbia." In Proceedings of the Workshop: Applying 15 Years of Carnation Creek Results, ed. T.W. Chamberlin. Nanaimo: Carnation Creek Steering Committee.

Department of Fisheries and Oceans (DFO), 1996. "Watershed Assessment and Monitoring Guidelines" (draft). Vancouver.

Dinicola, R.S., 1990. "Characterization and Simulation of Rainfall-Runoff Relations for Headwater Basins in Western King and Snohomish Counties, Washington." Water-Resources Investigations Report 89-4052, U.S. Geological Survey. Tacoma, WA.

Ferguson, R.I., 1986. "Hydraulics and Hydraulic Geometry." Progress in Physical Geography, v.10, p.1-31.

Fresh Outlook, 1998. Kelowna, BC: Alliance Professional Services, April.

Graf, W.L., 1975. "The Impact of Suburbanization on Fluvial Geomorphology." Water Resources Research, v.11, no.5, p.690-692.

Gurnell, A.M., and Gregory, K.J., 1984. "The Influence of Vegetation on Stream Channel Processes." In Catchment Experiments in Fluvial Geomorphology, ed. T.P. Burt and D.E. Walling. Norwich: Geo Books.

Hammer, T.R., 1972. "Stream Channel Enlargement Due to Urbanization." Water Resources Research, v.8, no.6, p.1530-1540.

Havis, R.N., Alonso, C.V., King, J.G., and Thurow, R.F., 1993. "A Mathematical Model of Salmonid Spawning Habitat." Water Resources Bulletin, v.29, no.3, p. 435-444.

Hayes, F.R., Pelluet, D., and Gorham, E., 1953. "Some Effects of Temperature on the Embryonic Development of the Salmon (Salmo Salar)." Canadian Journal of Zoology, v.31, p.42-51.

Henderson, F.M., 1966. Open Channel Flow. New York: Macmillan Publishing Co., Inc.

Hoffman, R.J., 1986. "A Horizontal Intragravel Pipe for Sampling Water Quality in Salmonid Spawning Gravel." North American Journal of Fisheries Management, v.6, p.445-448.

Hollis, G.E., 1975. "The Effect of Urbanization on Floods of Different Recurrence Interval." Water Resources Research, v.11, no.3, p.431-435.

Horner, R.R., Booth, D.B., Azous, A., and May, C.W., 1997. "Watershed Determinants of Ecosystem Functioning." In Effects of Watershed Development and Management on Aquatic Ecosystems, Proceedings of an Engineering Foundation Conference, ed. L.A. Roesner. New York: ASCE, p.251-274.

House, R.A., and Boehne, P.L., 1986. "Effects of Instream Structures on Salmonid Habitat and Populations in Tobe Creek, Oregon." North American Journal of Fisheries Management, v.6, p.38-46.

Imhof, J.G., Planck, R.J., Johnson, F.M., and Halyk, L.C., 1991. "Watershed Urbanization and Managing Stream Habitat for Fish." In Transactions of the 56th N.A. Wildlife and National Resources Conference, ed. R.E. McCabe. Edmonton: Wildlife Management Institute, p.269-285.

Jarrett, R.D., 1994. "Historic-Flood Evaluation and Research Needs in Mountainous Areas." In Hydraulic Engineering '94, v.2, ed. G.V. Cotroneo and R.R. Rumer. New York: ASCE.

Johnston, N.T., and Slaney, P.A. (1996). Fish Habitat Assessment Procedures. Watershed Restoration Technical Circular No.8. Vancouver: Watershed Restoration Program; Ministry of Environment, Lands, and Parks and Ministry of Forests.

Jonsson, N., 1991. "Influence of Water Flow, Water Temperature and Light on Fish Migration in Rivers." Nordic Journal of Freshwater Research, v.66, p.20-35.

Keller, E.A. and Swanson, F.J., 1979. "Effects of Large Organic Material on Channel Form and Fluvial Processes." Earth Surface Processes, v.4, p.361-380.

Klein, R.D., 1979. "Urbanization and Stream Quality Impairment." Water Resources Bulletin, v.15, no.4, p.948-963.

LeBlanc, R.T., Brown, R.D., and FitzGibbon, J.E., 1996. "Modeling the Effects of Land Use Change on the Water Temperature in Unregulated Urban Streams." Journal of Environmental Management, v.49, no.4, p.445-469.

Lee, K.B., and Ham, P.J., 1988. "Effects of Surrey's Storm Water Management Policy on Channel Erosion." Proceedings, International Symposium on Urban Hydrology and Municipal Engineering, Town of Markham, Ontario.

Leopold, L.B., 1994. A View of the River. Cambridge, Massachusetts: Harvard University Press.

Leopold, L.B., Wolman, M.G., and Miller, J.P., 1964. Fluvial Processes in Geomorphology. San Francisco: W.H. Freeman and Company.

Lindeburg, M.R., 1994. Civil Engineering Reference Manual, 6th ed. Belmont, CA: Professional Publications, Inc.

Lisle, T.E., and Hilton, S., 1992. "The Volume of Fine Sediment in Pools: An Index of Sediment Supply in Gravel-Bed Stream." Water Resources Bulletin, v.28, no.2, p.371-383.

Mackin, J.H., 1948. "Concept of the Graded River." Bulletin of the Geological Society of America, v.59, p.463-512, May.

MacRae, C.R., 1997. "Experience from Morphological Research on Canadian Streams: Is Control of the Two-Year Frequency Runoff Event the Best Basis for Stream Channel Protection?" In Effects of Watershed Development and Management on Aquatic Ecosystems, Proceedings of an Engineering Conference, ed. L.A. Roesner. New York: ASCE, p.144-162.

MacRae, C.R., and Wisner, P., 1988. "Effect of Runoff Control on Shear Stress in Urban Creeks." Proceedings, International Symposium on Urban Hydrology and Municipal Engineering, Town of Markham, Ontario.

Marten, P.S., 1992. "Effect of Temperature Variation on the Incubation and Development of Brook Trout Eggs." The Progressive Fish-Culturist, v.54, p.1-6.

Martin, D.J., Wasserman, L.J., and Dale, V.H., 1986. "Influence of Riparian Vegetation on Posteruption Survival of Coho Salmon Fingerlings on the West-Side Streams of Mount St. Helens, Washington." North American Journal of Fisheries Management, v.6, p.1-8.

May, C., 1996. "Assessment of Cumulative Effects of Urbanization on Small Streams in the Puget Sound Lowland Ecoregion: Implications for Salmonid Resource Management." Dissertation presented to the University of Washington, Seattle, WA, in partial fulfillment of the requirements for the degree of Doctor of Philosophy.

May, C., Cooper, C., Horner, R., Karr, J., Mar, B., Welch, E., and Wydzga, A., 1996. "Assessment of Cumulative Effects of Urbanization on Small Streams in the Puget Sound Lowland Ecoregion." In Proceedings: Urban Streams Conference, Nov. 15-17, Arcata, California.

McCallum, D.W., 1995. "An Examination of Trace Metal Contamination and Land Use in an Urban Watershed. M.Sc. thesis, University of British Columbia, Vancouver, BC, Canada.

Millar, R.G., and Quick, M.C., in press. "Stable Width and Depth of Gravel-Bed Rivers with Cohesive Banks." Journal of Hydraulic Engineering.

Morisawa, M., and Laflure, E., 1979. "Hydraulic Geometry, Stream Equilibrium, and Urbanization." In Adjustments of the Fluvial System, ed. D.D. Rhodes and G.P. Williams. Iowa: Kendal Hunt, p.333-350.

Neller, R.J., 1988. "A Comparison of Channel Erosion in Small Urban and Rural Catchments, Armidale, New South Wales." Earth Surface Processes and Landforms, v.13, p.1-7.

O'Laughlin, J., and Belt, G.H., 1995. "Functional Approaches to Riparian Buffer Strip Design." Journal of Forestry, v.93, no.2, p.29-32.

Olthof, J., 1994. "Puget Sound Lowland Stream Habitat and Relations to Basin Urbanization," thesis presented to the University of Washington, Seattle, WA, in partial fulfillment of the requirements for the degree of Masters of Science.

Parker, G., and Klingeman, P.C., 1982. "On Why Gravel Streams are Paved." Water Resources Research, v.18, no.5, p.1409-1423.

Pawlow, J.R., and Nathan, K., 1977. "Impact of Suburban Development on the Rainfall-Runoff Relationship." In Proceedings: International Symposium on Urban Hydrology, Hydraulics and Sediment Control. Lexington: University of Kentucky, p.65-74.

Ralph, S.C., Poole, G.C., Conquest, L.L., and Naiman, R.J., 1994. "Stream Channel Morphology and Woody Debris in Logged and Unlogged Basins of Western Washington." Canadian Journal of Fisheries and Aquatic Sciences, v.51, p.37-51.

Robinson, A.M., 1976. "The Effects of Urbanization on Stream Channel Morphology." In National Symposium on Urban Hydrology, Hydraulics, and Sediment Control. Lexington: University of Kentucky, July 26-29.

Rood, K.M., and Hamilton, R.E., 1995. Hydrology and Water Use for Salmon Streams in the Pitt/Stave Habitat Management Area, British Columbia. Canadian Manuscript Report of Fisheries and Aquatic Sciences, No. 2289, 147 p.

Rood, K.M., and Hamilton, R.E., 1994. Hydrology and Water Use for Salmon Streams in the Fraser Delta Habitat Management Area, British Columbia. Canadian Manuscript Report of Fisheries and Aquatic Sciences, No. 2038, 187 p.

Schueler, T.R., 1994. "The Importance of Imperviousness." Watershed Protection Techniques, v.1, no.3, p.100-111.

Schueler, T., and Claytor, R., 1997. "Impervious Cover as an Urban Stream Indicator and a Watershed Management Tool." In Effects of Watershed Development and Management on Aquatic Ecosystems, Proceedings of an Engineering Foundation Conference, ed. L.A. Roesner. New York: ASCE, p.513-529.

Schumm, S.A., 1969. "River Metamorphosis." Proceedings of the American Society of Civil Engineers, Journal of the Hydraulics Division, v.95, no.HY1, paper 6352, p.255-273.

Scrivener, J.C., 1987. "Changes in Composition of the Streambed Between 1973 and 1985 and the Impacts on Salmonids in Carnation Creek." In Proceedings of the Workshop: Applying 15 Years of Carnation Creek Results, ed. T.W. Chamberlin. Nanaimo: Carnation Creek Steering Committee.

Sidle, R.C., 1988. "Bed Load Transport Regime of a Small Forest Stream." Water Resources Research, v.24, no.2, p.207-218.

Simmons, D.L., and Reynolds, R.J., 1982. "Effects of Urbanization on Base Flow of Selected South-Shore Streams, Long Island, New York." Water Resources Bulletin, v.18, no.5, p.797-805.

Smith, R.D., Sidle, R.C., and Porter, P.E., 1993. "Effects on Bedload Transport of Experimental Removal of Woody Debris from a Forest Gravel-Bed Stream." Earth Surface Processes and Landforms, v.18, p.455-468.

Soil Conservation Service (SCS), 1975. Urban Hydrology for Small Watersheds. USDA Soil Conservation Service Technical Release No. 55. Washington, DC.

Sovern, D.T., and Washington, P.M., 1997. "Effects of Urban Growth on Stream Habitat." In Effects of Watershed Development and Management on Aquatic Ecosystems, Proceedings of an Engineering Foundation Conference, ed. L.A. Roesner. New York: ASCE, p.163-177.

Terhune, L.D.B., 1958. "The Mark VI Groundwater Standpipe for Measuring Seepage Through Salmon Spawning Gravel." Journal of the Fisheries Research Board of Canada, v.15, no.5, p.1027-1063.

Vronskii, B.B., and Leman, V.N., 1991. "Spawning Stations, Hydrological Regime and Survival of Progeny in Nests of Chinook Salmon, *Oncorhynchus tshawytscha*, in the Kamchatka River Basin." Journal of Ichthyology, v.31, no.4, p.91-102.

Wernick, B.G., 1996. "Land Use and Water Quality Dynamics on the Urban-Rural Fringe: A GIS Evaluation of the Salmon River Watershed, Langley, BC. M.Sc. thesis, University of British Columbia, Vancouver, BC, Canada.

Whipple, W., DiLouie, J.M., and Pytlar, T., 1981. "Erosional Potential of Streams in Urbanizing Areas." Water Resources Bulletin, v.17, no.1, p.36-45.

Wickett, W.P., 1954. "The Oxygen Supply to Salmon Eggs in Spawning Beds." Journal of the Fisheries Research Board of Canada, v.2, no.6, p.933-953.

Williamson, S.C., Bartholow, J.M., and Stalnaker, C.B., 1993. "Conceptual Model for Quantifying Pre-Smolt Production from Flow-Dependent Physical Habitat and Water Temperature." Regulated Rivers: Research and Management, v.8, p.15-28.

Wolman, M.G., 1967. "A Cycle of Sedimentation and Erosion in Urban River Channels." Geografiska Annaler, v.49A, p.385-395.

Wolman, M.G., 1954. "A Method of Sampling Coarse River-Bed Material." Transactions, American Geophysical Union, v.35, no.6, p.951-956.

Wolman, M.G., and Miller, J.P., 1960. "Magnitude and Frequency of Forces in Geomorphic Processes." Journal of Geology, v.68, p.54-74.

Wolman, M.G., and Schick, A.P., 1967. "Effects of Construction on Fluvial Sediment, Urban and Suburban Areas of Maryland." Water Resources Research, v.3, p.451-464.

Yorke, T.H., and Herb, W.J., 1978. "Effects of Urbanization on Streamflow and Sediment Transport in the Rock Creek and Anacostia River Basins, Montgomery County, Maryland, 1962-74." Geological Survey Professional Paper 1003. Washington: U.S. Government Printing Office.

Zandbergen, P.A., 1998. "Urban Watershed Assessment: Linking Watershed Health Indicators to Management." Ph.D. dissertation. University of British Columbia, Vancouver, BC, Canada.

Zar, J.H., 1996. Biostatistical Analysis, 3rd ed. Upper Saddle River, New Jersey: Prentice-Hall.

APPENDIX A

RAW DATA

Table A-1: Land uses in study watersheds

Stream	Roche Point Creek	Anderson Creek*	Hyde Creek (u/s)	McCartney Creek	Hyde Creek (d/s)	Big John's Creek
Catchment area (ha)	55	2680	281	285	498	215
Water	-	1%	-	-	-	-
Forest	27%	18%	82%	72%	31%	65%
Cleared	73%	-	-	2%	1%	3%
Agricultural	-	68%	-	-	-	-
Low-density	-	-	9%	-	16%	-
Medium-density	-	-	-	-	-	-
High-density	-	12%	9%	26%	48%	27%
Multi-family	-	-	-	-	-	-
Institutional	-	1%	-	-	4%	-
Industrial/Commercial	-	-	-	-	-	5%
%TIA	4%	5%	7%	15%	16%	19%

Stream	Enver Creek	Quibble Creek	Bear Creek (d/s)	Bear Creek (u/s)
Catchment area (ha)	103	591	1658	199
Water	-	-	-	-
Forest	38%	13%	7%	3%
Cleared	-	5%	6%	6%
Agricultural	-	-	-	-
Low-density	-	-	-	-
Medium-density	-	2%	-	-
High-density	54%	41%	50%	17%
Multi-family	-	8%	-	-
Institutional	8%	13%	4%	2%
Industrial/Commercial	-	18%	33%	72%
%TIA	32%	54%	57%	77%

*unsewered: EIA therefore considered = 5% for low and medium density residential, and 10% for high density residential (see Section 4.2)

Table A-1: Land uses in study watersheds

^{z}land uses calculated by Zandbergen (1998)

Stream	Union Creek*^{z}
Catchment area (ha)	91
Agriculture	28%
Unused/no activity	23%
Industrial/Commercial	1%
Medium-Density	43%
Recreational	3%
Institutional	2%
%TIA	5%

Stream	Eagle Creek^{z}	Stoney Creek^{z}	Still Creek^{z}
Catchment area (ha)	566	787	3028
High-density	28%	30%	55%
Industrial/Commercial	21%	16%	23%
Buildings	-	2%	2%
Pavement	1%	3%	4%
Grass	14%	11%	8%
Forest	36%	38%	8%
%TIA	33%	34%	52%

*unsewered: TIA therefore considered = 5% for low and medium density residential, and 10% for high density residential (see Section 4.2)

^{z}land uses calculated by Zandbergen (1998)

Table A-2: Drainage characteristics of the study watersheds' surficial geology

Stream	Well drained (Type A)	Moderately well drained (Type B)	Poorly drained (Type C)	Very poorly drained (Type D)
Roche Point Creek	-	-	100%	-
Union Creek	100%	-	-	-
Anderson Creek	32%	3%	12%	53%
Hyde Creek (u/s)	-	-	31%	69%
McCartney Creek	22%	-	24%	54%
Hyde Creek (d/s)	14%	-	50%	36%
Big John's Creek	-	-	68%	32%
Enver Creek	-	-	-	100%
Eagle Creek	-	23%	72%	5%
Stoney Creek	-	7%	52%	41%
Still Creek	-	-	75%	25%
Quibble Creek	-	34%	4%	62%
Bear Creek (d/s)	-	17%	6%	77%
Bear Creek (u/s)	-	-	11%	89%

Table A-3: Measured base flow and stream geometry, calculated bankfull flow

Stream	Base flow (L/s)	Average velocity at flow measurement site (m/s)	Average depth at flow measurement site (cm)	Slope (%)	Wetted depth (cm)	bankfull depth (m)	Wetted width (m)	Bankfull width (m)	Bankfull area (m^2)	Jarrett's n*	Bankfull flow (m^3/s)
Roche Point Creek	n/a	n/a		10.0	3.4	0.73	3.11	4.60	3.97	0.148	n/a
Union Creek	11.9	0.14		1.5	4.4	0.64	2.11	4.97	3.66	0.073	2.3
Anderson Creek	135.8	0.15	12.7	1.5	15.6	0.89	5.34	13.82	21.95	0.068	12.7
Hyde Creek (u/s)	3.0	0.30		4.5	6.8	0.72	2.51	6.62	6.11	0.108	n/a
McCartney Creek	21.6	0.07	17.4	7.5	9.6	0.89	2.99	10.77	12.06	0.126	n/a
Hyde Creek (d/s)	7.2	0.10	2.7	1.0	6.1	0.88	3.46	6.53	7.12	0.060	5.6
Big John's Creek	n/a	n/a		17.5	5.2	1.02	3.90	10.61	10.82	0.171	n/a
Enver Creek	7.0	0.07	7.6	1.5	6.4	0.68	1.89	3.66	3.47	0.074	1.9
Quibble Creek	9.5	0.07	5.0	1.0	9.0	0.77	3.62	5.57	7.23	0.061	4.0
Bear Creek (d/s)	4.6	0.01	14.7	0.5	18.5	1.19	5.62	9.61	21.74	0.043	13.8
Bear Creek (u/s)	2.0	0.01	8.8	2.0	8.9	0.92	2.57	6.17	7.53	0.078	5.5

*Jarrett, 1994 (see Section 5.9)

Table A-4: Sieving results (percentage finer than diameter shown)

Stream	0.125 mm	0.250 mm	0.500 mm	0.833 mm	2.00 mm	6.35 mm	9.52 mm	18.85 mm	25.4 mm	38.1 mm
Roche Point Creek	1.1	2.5	5.6	8.8	17.8	38.1	47.3	73.5	76.1	100
Union Creek	0.3	1.8	7.1	11.2	16.5	28.6	37.3	66.3	80.2	100
Anderson Creek	0.1	0.6	4.2	7.6	11.6	22.8	46.3	69.8	86.3	100
Hyde Creek (u/s)	0.2	0.1	5.7	10.8	21.0	38.9	47.2	73.4	86.7	100
McCartney Creek	0.2	1.0	4.3	8.5	17.3	35.3	44.6	70.5	80.3	100
Hyde Creek (d/s)	0.2	1.0	5.3	10.9	20.7	39.0	47.3	69.3	80.9	100
Big John's Creek	0.3	0.9	3.4	7.5	19.4	44.0	54.0	77.8	87.9	100
Enver Creek	0.4	1.5	3.3	4.9	9.1	21.0	28.7	54.5	72.2	100
Quibble Creek	0.1	0.5	1.9	3.6	8.2	22.2	30.4	56.1	68.7	100
Bear Creek (d/s)	0.1	0.4	2.1	4.7	11.1	24.5	33.4	67.5	76.4	100
Bear Creek (u/s)	0.2	0.5	1.7	2.8	6.1	18.0	27.5	62.0	78.8	100

Table A-5: Pebble count results

Stream	% < 2 mm (sample truncated at 38 mm)	D_{84}(mm)
Roche Point Creek	39.0	90
Union Creek	31.8	30
Anderson Creek	31.3	63
Hyde Creek (d/s)	32.7	200
McCartney Creek	33.3	130
Hyde Creek (u/s)	32.1	41
Big John's Creek	32.1	384
Enver Creek	22.2	65
Quibble Creek	30.6	110
Bear Creek (d/s)	13.8	69
Bear Creek (u/s)	13.6	100

Table A-6: Intragravel / water column dissolved oxygen

Stream	Intragravel / water column DO	Standard deviation
Roche Point Ck	0.72	0.03
Union Creek	0.41	0.24
Anderson Ck	0.59	0.29
Hyde Creek u/s	0.62	0.17
McCartney Ck	0.70	0.10
Hyde Ck d/s	0.55	0.15
Big John's Ck	0.69	0.05
Enver Creek	-	-
Quibble Creek	0.70	0.09
Bear Creek (d/s)	0.66	0.08
Bear Creek (u/s)	0.67	0.13

Table A-7: Large woody debris, rooted cutbanks, and bank erosion data

Stream	Survey length (m)	Pieces of large woody debris / 100 m	Number of rooted cutbanks / 100 m	Volume of large woody debris / 100 m (m^3)	Percent of reach length eroded / protected
Roche Point Cre	350	31.7	1.7	23.5	7
Union Creek	400	10.5	0.3	2.0	6
Anderson Creek	200	36.5	0.5	16.2	0
Hyde Creek (u/s	400	13.0	3.5	2.5	7
McCartney Cree	390	27.2	3.3	17.2	9
Hyde Ck (d/s)	400	6.8	0.8	0.9	21
Big John's Creek	302	41.1	4.3	35.6	0
Enver Creek	288	3.8	0.3	7.3	1
Quibble Creek	400	0.8	0.0	1.0	16
Bear Creek (d/s)	584	1.2	0.0	0.1	43
Bear Creek (u/s)	400	2.5	0.0	1.3	10

Table A-8: Temperature measurements (^oC)
(some weather data not available)

Date	5-Nov-97			14-Nov-97			26-Nov-96		
max. air temp. (^oC)^p	14.0			8.0			8.0		
min. air temp. (^oC)^n	10.2			-0.4			3.2		
max. air temp. (^oC)^d	12.4			8.0			7.5		
hours of sunshine^t	4.0			14.5			4.0		
rainfall (mm)^t	13.2			0.0			5.1		
winds^d	light			NE-E			E		
	Stream T	Reference T	delta-T	Stream T	Reference T	delta-T	Stream T	Reference T	delta-T
Roche Point Creek	n/a	n/a	0.0	n/a	n/a	0.0	n/a	n/a	0.0
Union Creek	11.3	10.47	0.8	6.9	6.76	0.1	8.2	6.61	1.6
Anderson Creek	n/a	n/a	0.0	n/a	n/a	0.0	n/a	n/a	0.0
Hyde Creek (u/s)	10.5	11.19	-0.7	6.4	6.24	0.2	6.5	7.33	-0.8
McCartney Creek	10.6	10.88	-0.3	6.5	5.77	0.7	8.1	7.63	0.5
Hyde Creek (d/s)	11.4	11.19	0.2	6.9	6.31	0.6	7.3	7.33	0.0
Big John's Creek	11.0	10.88	0.1	5.7	5.77	-0.1	7.5	7.63	-0.1
Enver Creek	12.4	10.63	1.8	7.3	6.45	0.9	8.4	6.61	1.8
Eagle Creek	12.2	10.94	1.3	5.9	6.29	-0.4	8.5	6.92	1.6
Stoney Creek	12.3	10.94	1.4	5.4	6.29	-0.9	8.4	6.92	1.5
Still Creek	12.5	10.94	1.6	6.4	6.29	0.1	9.2	7.07	2.1
Quibble Creek	12.4	10.63	1.8	6.4	6.29	0.1	8.2	6.61	1.6
Bear Creek (d/s)	12.4	10.63	1.8	6.1	6.29	-0.2	8.3	6.61	1.7
Bear Creek (u/s)	11.6	10.78	0.8	5.6	6.29	-0.7	7.3	6.61	0.7

^{p}previous day
^{n}previous night
^{d}day of measurement
^{t}total of previous day and day of measurement
delta-T = stream temperature - reference temperature

Table A-8: Temperature measurements (^oC)
(some weather data not available)

Date	4-Dec-97			16-Dec-97			12-Feb-97		
max. air temp. (^oC)^p	8.0			8.0			9.0		
min. air temp. (^oC)^n	1.1			7.0			5.9		
max. air temp. (^oC)^d	8.8			10.5			10.0		
hours of sunshine^t	12.0			0.0			1.2		
rainfall (mm)^t	0.0			35.3			17.0		
winds^d	light			SE			E		
	Stream T	Reference T	delta-T	Stream T	Reference T	delta-T	Stream T	Reference T	delta-T
Roche Point Creek	n/a	n/a	0.0	n/a	n/a	0.0	n/a	n/a	0.0
Union Creek	7.5	5.98	1.5	7.5	6.45	1.1	7.6	6.92	0.7
Anderson Creek	n/a	n/a	0.0	n/a	n/a	0.0	n/a	n/a	0.0
Hyde Creek (u/s)	5.5	5.77	-0.3	6.5	7.33	-0.8	6.2	6.71	-0.5
McCartney Creek	7.2	6.24	1.0	8.0	7.33	0.7	7.5	6.86	0.6
Hyde Creek (d/s)	6.0	5.77	0.2	7.3	7.33	0.0	7.3	6.71	0.6
Big John's Creek	6.6	6.08	0.5	8.3	7.33	1.0	7.4	6.86	0.5
Enver Creek	6.6	5.83	0.8	7.4	6.76	0.6	6.6	6.92	-0.3
Eagle Creek	7.3	6.29	1.0	8.2	7.22	1.0	6.9	6.92	0.0
Stoney Creek	6.9	6.29	0.6	9.2	7.22	2.0	7.1	6.92	0.2
Still Creek	7.0	6.61	0.4	8.3	7.22	1.1	6.9	6.92	0.0
Quibble Creek	6.6	5.83	0.8	8.4	6.76	1.6	6.5	6.92	-0.4
Bear Creek (d/s)	6.4	5.67	0.7	8.1	6.76	1.3	6.5	6.92	-0.4
Bear Creek (u/s)	5.9	5.83	0.1	7.5	6.76	0.7	6.3	6.92	-0.6

^{p}previous day
^{n}previous night
^{d}day of measurement
^{t}total of previous day and day of measurement
delta-T = stream temperature - reference temperature

Table A-8: Temperature measurements (°C)
(some weather data not available)

Date	19-Feb-97			10-Mar-97			7-Apr-98		
max. air temp. (°C)[p]	9.8			-			13.7		
min. air temp. (°C)[n]	-			5.7			5.5		
max. air temp. (°C)[d]	-			10.4			12.4		
hours of sunshine[t]	> 0			> 0			7.0		
rainfall (mm)[t]	> 3.1			> 2.8			0.4		
winds[d]	E-SE			-			SW		
	Stream T	Reference T	delta-T	Stream T	Reference T	delta-T	Stream T	Reference T	delta-T
Roche Point Creek	n/a	n/a	0.0	n/a	n/a	0.0	n/a	n/a	0.0
Union Creek	8.9	8.76	0.1	7.6	7.22	0.4	10.3	11.09	-0.8
Anderson Creek	n/a	n/a	0.0	n/a	n/a	0.0	n/a	n/a	0.0
Hyde Creek (u/s)	6.4	7.33	-0.9	5.6	6.86	-1.3	7.0	7.63	-0.6
McCartney Creek	7.4	7.17	0.2	6.9	7.02	-0.1	8.3	7.63	0.7
Hyde Creek (d/s)	7.3	7.17	0.1	6.9	6.86	0.0	8.3	7.79	0.5
Big John's Creek	7.5	7.17	0.3	7.0	7.02	0.0	7.8	7.63	0.2
Enver Creek	8.2	8.61	-0.4	7.8	7.68	0.1	10.4	11.09	-0.7
Eagle Creek	8.6	8.92	-0.3	7.2	6.92	0.3	8.9	9.38	-0.5
Stoney Creek	8.6	8.92	-0.3	6.8	6.92	-0.1	8.3	9.38	-1.1
Still Creek	8.5	8.92	-0.4	7.6	6.92	0.7	10.7	9.38	1.3
Quibble Creek	8.3	8.46	-0.2	8.1	7.53	0.6	9.9	10.78	-0.9
Bear Creek (d/s)	8.3	8.46	-0.2	8.2	7.53	0.7	9.6	10.47	-0.9
Bear Creek (u/s)	7.7	8.46	-0.8	7.6	7.53	0.1	9.8	11.09	-1.3

[p]previous day
[n]previous night
[d]day of measurement
[t]total of previous day and day of measurement
delta-T = stream temperature - reference temperature