Analysis of Atlantic salmon habitat distribution and sensitivity to forest extraction in the Cascapédia River drainage basin using a GIS

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ABSTRACT

The relationships between local and catchment-wide land use patterns and the spatial distribution of stream habitat variables within the Grande Cascapédia drainage basin were investigated using a geographic information system (GIS). Stream habitat variables including substrate composition and channel morphology were sampled at 48 study sites, ranging from highly disturbed to relatively pristine forest conditions in 2^{nd} to 5^{th} order tributaries. Land use and geology-structure variables were extracted for each catchment at four spatial scales using a GIS. The transition between pool-riffle and boulder-rapid morphologies occurred between channel gradients of 1.5% and 1.7%. The surface grainsize distribution is affected by the hydraulic power of the reach, while the subsurface grainsize distribution is associated with the degree of valley incision. The amount of logging within a 1km radius of a sample site increases the occurrence of fine sediment within the substrate. There was, however, a surprising lack of relationship between the majority of road density metrics and the level of fines within the substrate.

RÉSUMÉ

Les liens entre les patrons d'exploitation forestière et la distribution spatiale de l'habitat physique des salmonidés à l'intérieur du bassin-versant de la Grande Cascapedia ont été étudiés a l'aide d'un Système d'Information Géographique (SIG). Des variables d'habitat, reflétant la composition du substrat et la morphologie du cours d'eau, ont été échantillonnées à 48 sites d'études répartis dans des sous-bassins d'ordre 2 à 5 et classés de très dérangés à très peu dérangés. Des variables reflétant l'utilisation du sol ainsi que la structure topographique et la nature des versants à diverses échelles spatiales ont été extraites pour chaque sous-bassin. Dans les basins étudiés, la transition entre les morphologies seuil-mouille et rapide de blocs se produit à une pente locale variant entre 1.5% et 1.7%. La teneur en sédiments fins (< 2mm) dans les seuils est affectée par le pourcentage de coupe à l'intérieur d'un rayon de 1 km du site échantillonné. Par contre, le pourcentage de sédiments fins ne semble pas être affecté d'une manière significative par la majorité des variables reflétant la densité du réseau routier.

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TABLE OF CONTENTS

ABSTRACT I

RÉSUMÉ I

ACKNOWLEDGMENTS II

TABLE OF CONTENTS IV

LIST OF FIGURES VI

LIST OF TABLES VIII

I. INTRODUCTION 1

II. LITERATURE REVIEW 3

II. 1. Channel morphology and classification 3
II. 2. Physical Characteristics of Atlantic Salmon Spawning Habitat 9
II. 3. Impact of forestry practices on stream habitat 12
II. 3. 1. General effects of forestry practices on stream habitat *12*
II. 3. 2. Impact of forest cover removal on runoff and sediment production *14*
II. 3. 3. Influence of forest roads on runoff and sediment production *15*
II. 3. 4. The role of riparian zones in mitigating the effects of forestry practices *16*

III. OBJECTIVES AND APPROACH 18

IV. STUDY AREA 21

IV. 1. General description of study area 21
IV. 2. Climate & vegetation 26
IV. 3. Topography and geology 31

V. METHODOLOGY 36

V.1 Fieldwork: Physical Habitat Characterization 36
V.2 GIS Analysis: Landscape Characterization 42
V.2.1. Watershed delineation *42*
V.2.2. Estimation of landscape variables within the GIS *45*
V. 3. Statistical Analysis 51

VI. RESULTS – THE INFLUENCE OF CHANNEL AND VALLEY GEOMORPHOLOGY ON THE SPATIAL DISTRIBUTION OF STREAM HABITAT VARIABLES 53

VI. 1. Inter-correlation of reach-scale stream habitat variables 53
VI. 1. 1. Cross-sectional channel morphology *53*
VI. 1. 2. Channel gradient and grainsize distribution *57*
VI. 2. Influence of basin-scale geology-structure on stream habitat characteristics 69
VI. 2. 1. Relationship between geology-structure variables and channel morphology *69*
VI. 2. 2. Relationship between geology-structure variables and channel gradient *74*
VI. 2. 3. Relationship between geology-structure variables and grainsize distribution *76*
VI. 3. Discussion - Natural landscape structure and stream habitat characteristics 80

VII. RESULTS – THE INFLUENCE OF FORESTRY DISTURBANCES ON THE SEDIMENTATION OF POTENTIAL ATLANTIC SALMON SPAWNING SUBSTRATE 90

VII. 1. Impact of harvest intensity on in-stream sedimentation 90
VII. 1. 1. Intensity of forest extraction at different scales of analysis *90*
VII. 1. 2. Harvest intensity and fine sediment levels in stream substrate *94*
VII. 2. Impact of road network on in-stream sedimentation 97
VII. 2. 1. Density of road networks at different spatial scales *97*

VII. 2. 2. Road networks and fine sediment levels in stream substrate *97*
VII. 3. DISCUSSION - THE INFLUENCE OF HARVEST INTENSITY AND ROAD NETWORK DENSITIES ON SPAWNING SUBSTRATE QUALITY 101
VIII. SPATIAL DISTRIBUTION OF SUITABLE ATLANTIC SALMON SPAWNING HABITAT 106
VIII. 1. SPAWNING HABITAT SUITABILITY INDEX FOR THE CASCAPÉDIA WATERSHED 106
VIII. 1. 1. Suitability based on the channel gradient *106*
VIII. 1. 2. Suitability based on the pavement and subpavement composition *107*
VIII. 1. 3. Suitability based on the fine sediment content *108*
VIII. 1. 4. Suitability index categories *110*
VIII. 2. INFLUENCE OF LANDSCAPE STRUCTURE AND FORESTRY PRACTICES ON THE DISTRIBUTION OF SUITABLE HABITAT 112
VIV. CONCLUSION 114
X. REFERENCES 116
APPENDIX 1 132
APPENDIX 2 133
APPENDIX 3 135
APPENDIX 4 136
APPENDIX 5 140

LIST OF FIGURES

Figure 1. Schematic representation of downstream variation in basin characteristics 4
Figure 2. Location of the study area and distribution of study reaches. 22
Figure 3. Composite bed material distributions of five Québec salmon rivers 24
Figure 4. The annual hydrograph of the Cascapedia River 27
Figure 5. Return period for flooding at Berry station 27
Figure 6. The spatial distribution of cutting intensity based on the attenuation factors 30
Figure 7. The spatial distribution of the road network within the basin 33
Figure 8. Geology of the Cascapédia River drainage basin, Gaspé Peninsula, Québec 34
Figure 9. Surface deposits present within the Cascapédia River drainage basin, Gaspé Peninsula, Québec ... 35
Figure 10. Diagram of reach measurements 39
Figure 11. Diagram of reach measurements for intensively sampled Brandy 1A and 1B sites 39
Figure 12. Comparison between field and DEM topographic slope measurements. 44
Figure 13. An example of the four spatial scales of analysis 50
Figure 14. Relationship between bankfull channel width and summer flow width 56
Figure 15. Correlation between timing of sampling and the percent reduction in channel width observed at the site 56
Figure 16. Box and whisker plot of variation in channel gradients 57
Figure 17. Spatial distribution of the pavement D_{50} of the sample reaches 59
Figure 18. Variation in median pavement diameter with increasing channel gradient 60
Figure 19. Relationship between channel gradient and local boundary shear stress 61
Figure 20. Spatial distribution of highly mobile and immobile sediment based on the mobility ratio 62
Figure 21. Variation in sediment mobility ratios (τ_o/τ_{cr}) with increasing channel gradient 63
Figure 22. Relationship between channel gradient and subpavement D_{50} from the average of two bulk samples 64
Figure 23. Spatial distribution of the subpavement D50 of the sample reaches 65
Figure 24. Spatial distribution of silt measurements within the study area 66
Figure 25. Relationship between percent silt (<63um) within the riffle substrate and the channel gradient 67
Figure 26. Relationship between percent sand (<2mm) within the riffle substrate and the channel gradient .. 67
Figure 27. Variation in bankfull channel width for different stream orders by stream density and with increasing basin area 71
Figure 28. Variation in width/depth ratio with increasing basin drainage area 74
Figure 29. Variation in channel slope with increasing basin area. 75
Figure 30. Transition between reach morphologies based on channel gradient and stream order 75
Figure 31. Variation in median pavement and subpavement diameter with channel gradient 76
Figure 32. Variation in pavement grainsize with increasing channel slope for all small basins 77

Figure 33. Relationship between index of hydraulic power and pavement diameter 78
Figure 34. Relationship between index of valley incision and subpavement diameter 79
Figure 35. Map showing two adjacent basin of equal area with contrasting topographic slopes........ 85
Figure 36. Cross-sections of two contrasting valleys 87
Figure 37. Coincidence of bedrock and surficial geology boundaries surrounding the Lake Branch topographic depression 89
Figure 38. Distribution of disturbed parcels within the 60m riparian corridor 92
Figure 39. Regression statistics for the percentage silt within the riffle against the equivalent area cut........ 95
Figure 40. Relationship between percent sand under 2mm in the riffle substrate and the percent of forest cut 96
Figure 41. Relationship between percent fine sand (<2mm) and the density of main roads within a 1km upstream radius 100
Figure 42. Sand index versus percentage sand showing poor, mediocre and excellent spawning thresholds 110
Figure 43. Proportion of sites by stream order that are suitable 113

LIST OF TABLES

Table 1. Average downstream hydraulic geometry exponent values at bankfull for gravel-bed rivers 5
Table 2. Characteristic features of geomorphological channel types 8
Table 3. List of study sites 25
Table 4. Hydrological statistics of the Cascapedia River 28
Table 5. Reach-scale habitat variables measured at, or calculated for each study reach 37
Table 6. Combination of phi and half phi substrate size classes sampled 41
Table 7. Landscape and land use metrics calculated for each subbasin at various spatial scales 49
Table 8. Statistics of physical habitat variables measured or calculated at each site 55
Table 9. Surface coarseness in relation to channel gradient 60
Table 10. Subpavement bulk sampling results for intensively sampled sites 68
Table 11. Statistics of geology-structure calculated at each site 70
Table 12. Statistical relationships between physical habitat variables and watershed variables 70
Table 13. Linear regression statistics for geology-structure variables and observed sedimentation levels 80
Table 14. Summary of the significant differences in stream habitat 80
Table 15. Summary statistics for anthropogenic disturbance metrics 93
Table 16. Rankwise Spearman correlation matrix between equivalent area cut metrics 93
Table 17. Correlations within road metrics at four spatial scales 99
Table 18. Linear regression statistics for all road metrics against silt and sand levels 100
Table 19. Number of sample sites classified as excellent, poor and mediocre based on the Sand Index 108
Table 20. Distribution of Atlantic salmon parr between excellent, poor and mediocre sites 109
Table 21. Percentage of sites classified as suitable and unsuitable 111
Table 22. Suitability index classification for each site based on an upper D_{50} threshold of 50mm 111

I. INTRODUCTION

The pursuit of Atlantic salmon (*Salmo salar*) has historically attracted anglers from around the world to fresh waters of North American rivers. Their abundance in the rivers of Québec's Gaspé Peninsula brought the region the attention and economic advantages of a thriving sport-fishing industry, which continues today. The global decline in abundance of the salmon population over the past century has attracted considerable attention within this region and generated concern over the potential threats facing this resource, as well as to the economic benefits that accompany it. While the physical and chemical characteristics, as well as the biologic community structure of the river, may all limit salmon production (Huntsman, 1946; Huet, 1964; Chapman and Bjornn, 1969; Peterson *et al.*, 1977; Gibson *et al.*, 1984; Degerman *et al.*, 1986), a decline in salmon abundance has often been attributed to a loss of suitable physical habitat (Nehlsen *et al.*, 1991; Waters, 1995) and it is this particular threat that will be investigated in this thesis. Land use practices such as agriculture, forestry, mining, and urbanization are some of the most important anthropogenic sources of sediment into streams, posing a threat to the quality of Atlantic salmon habitat. In the Gaspé region, forestry is the second largest industry and therefore the potential threat to habitat quality is great.

The natural input of sediment to river channels is a function of basin topography, climate, soil characteristics and vegetation. Substantial modification of the vegetated surface may both increase soil erosion and reduce the system's ability to filter out fine sediments, therefore greatly increasing inputs into stream channels. The anthropogenic introduction of fine sediment into a channel network can have adverse influences on salmonids by causing an increase in turbidity, a decrease in reproductive success in redds, and an increase of deposited sediment within and upon the habitat of the fish in addition to altering the physical characteristics of the channel (Cordone and Kelley, 1961; Bisson and Bilby, 1982; Everest *et al.*, 1987; Waters, 1995).

Quantification of the potential threat to Atlantic salmon stocks posed by deforestation is fundamental to the development of sustainable management and conservation schemes. Due to the complexity of the interacting processes within fluvial systems, which function over a range of spatial and temporal scales, there is, however, a lack of quantitative research in this domain. While a number of studies have been conducted on the effects of the forestry practices on river salmonids, the majority are before and after type studies (Brown and Krygier, 1971; Hartman and Scrivener, 1990), are limited in their applicability to watersheds of equivalent spatial extent (i.e. same order, basin area, physical characteristics, etc.) (Lyons and Bescheta, 1983; Davies and Nelson, 1994) or rely primarily on qualitative measures to assess substrate and habitat quality (Roth *et al.*, 1996; Lammert and Allen, 1999). While these studies provide insight into the impact of forestry practices on salmon habitat at one spatial scale or within one context, they do not consider how habitat characteristics vary spatially as a function of the geomorphology of the valley and the channel. The combination of geomorphic field observations with Geographic Information Systems (GIS) analysis at multiple spatial scales attempted in this thesis may improve current understanding of the natural variation in stream habitat types within a basin and thereby extend our understanding of river channel sensitivity to change. Once the natural variation in physical habitat associated with basin characteristics is accounted for, it should be possible to detect the effects of forestry practices on the quality of salmon habitat throughout the basin. The use of GIS in a fluvial geomorphology context provides an opportunity to derive spatially distributed parameters, which would otherwise be cost and time prohibitive to acquire (Wu *et al.*, 1993; Downs and Priestnall, 1999). A GIS analysis will provide a means of systematically and rapidly identifying potential salmon habitat and channel segments that are particularly at risk of sedimentation due to forestry practices throughout a large basin area.

In this thesis, the spatial distribution of Atlantic salmon habitat within the Cascapédia drainage basin and the influence of forestry practices on the quality of spawning habitat are examined with the use of GIS. Current knowledge on the complex interactions between watershed characteristics, stream habitat type and forestry practices are first described in the next chapter, followed by a statement of specific study objectives.

II. LITERATURE REVIEW

II.1. Channel morphology and classification

A thorough understanding of the geomorphic processes governing the spatial relationships operating within a watershed is essential in order to understand the controls over a channel's condition, history and potential response to disturbance. The physical processes operating within a channel network are controlled principally by the volume of water flowing in the basin and the timing of this flow, the amount and nature of the sediment delivered to and transported through the basin, the nature of the bedrock and soil substrate through which the river is flowing, the local climate, the nature of the riparian vegetation and the land use within the basin (Church, 1992; Waters, 1995; Montgomery and Buffington, 1997; Knighton, 1998 and others). The volume of water is related to the size of the basin, while the runoff timing affects not only the channel boundary in terms of its character, but also influences the type of riparian vegetation within the boundary zone (Teversham and Slaymaker, 1976).

The amount and calibre of the sediment in transport, either in suspension or as bed-material load is evinced in the morphology of the river. Alluvial channels flow within and upon sediments (alluvia) they previously deposited under their current flow regime (Church, 1992; Bravard and Petit, 1997). Given that alluvial channels are capable of modifying their banks and beds through the course of time, for a particular boundary material they exhibit fairly consistent relationships between discharge, width, depth, and velocity. These relationships are termed *downstream hydraulic geometry*. Alluvial channels vary systematically through the watershed as channel size increases downstream with increasing drainage area. In contrast, bedrock channels exhibit a highly variable array of morphologies depending on the strength of the bedrock material and the balance of the relationship between the supply of sediment to the channel versus the channel's capacity to evacuate sediment (Bravard and Petit, 1997). Bedrock channels are often confined by valley walls and have relatively steep slopes, though low slopes are also possible. A purely alluvial channel would have no such constraints on its lateral or vertical mobility, but rather be in a state of self-regulating equilibrium. Very few channels, however, conform entirely to this theoretical definition and most will show signs of geologically imposed constraints at some point along their length. Thus, in mountain valleys, a channel's classification as alluvial versus bedrock is rather a reflection of the dominant control over the channel's form and generally only applies to a particular segment of the channel rather than the entire river system. Accurate classification therefore involves the subdivision of the river into homogeneous units at a scale that relates channel morphology to channel processes, such that the controlling factors are relatively constant over the reach studied. Montgomery and Buffington (1997) suggest a channel reach be defined as a length 10 to 20 times the channel width if response potential and habitat characteristics are to be investigated and this reach definition will be used herein.

The systematic trends in downstream adjustment of channel form to changes in discharge and sediment supplied from upstream as drainage basin area increases are shown below (Figure 1).

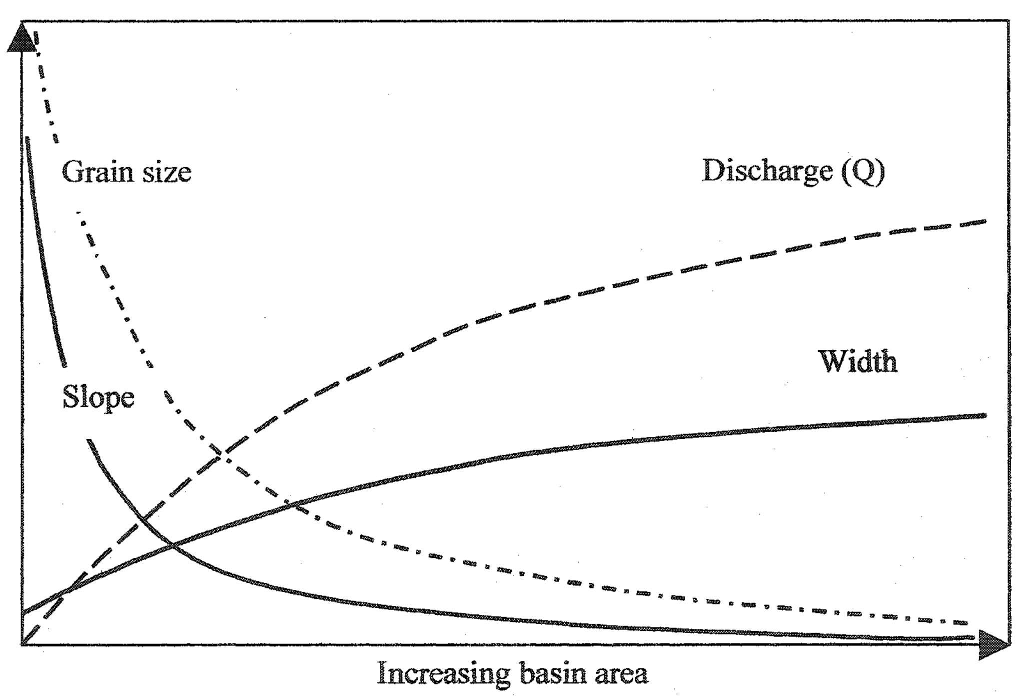


Figure 1. Schematic representation of downstream variation in basin characteristics (based on Church, 1992).

Stream discharge (Q) at a given point, as defined by the continuity equation, is equal to the product of the cross-sectional area (A) and the mean velocity (v) at that point:

$$Q = A*v = w*d*v \tag{1}$$

where w is width and d is mean depth. As a stream progresses down valley, the increase in discharge results in an increase in channel width, depth and mean flow velocity. The dominant independent variable in hydraulic geometry relationships is assumed to be discharge, which relates to the dependent variables in the form of the following power functions:

$$w = aQ^b \tag{2a}$$

$$d = cQ^f \tag{2b}$$

$$v = kQ^m \tag{2c}$$

$$S = jQ^z \tag{2d}$$

where w, d, v, and S are width, depth, velocity and slope respectively. The values of the above coefficients and exponents in downstream hydraulic geometry relationships have been investigated both theoretically and empirically by numerous authors, resulting in the average values for b, f, m and z shown in Table 1 (Knighton, 1998).

Table 1. Average downstream hydraulic geometry exponent values at bankfull for gravel-bed rivers and canals (Adapted from Knighton, 1998).

Exponent	Average value	Range
b	0.5	0.45-0.57
f	0.37	0.33-0.38
m	0.13	0.08-0.20
z	-0.33	-0.44--0.20

Basin drainage area, which is often used as a surrogate for discharge in many studies as it is more easily measured, relates to bankfull discharge through a similar power function:

$$Q_b = nA_d^p \quad (3)$$

where Q_b is the bankfull discharge and A_d is the basin drainage area. The value of p is estimated to be approximately 0.7 (0.65-1.0) (Leopold and Miller, 1956; Emmett, 1975; Knighton, 1975; Leclerc and Lapointe, 1994). Several authors have examined hydraulic geometry relationships between basin area and channel morphology variables using GIS and found strong, significant relationships. Miller *et al.* (1996) found in particular that bankfull channel width could be accurately estimated from the watershed area extracted from the GIS ($R^2 = 0.72$, $p < 0.0001$).

Stream power, an expression of the rate of potential energy expenditure per unit length of channel, is defined by

$$\Omega = \gamma QS \quad (4)$$

where γ is the specific weight of water (Knighton, 1998). Stream power affects the levels of bank and bed erosion along the channel boundary and therefore influences the calibre of sediment introduced into the stream. In alluvial reaches composed primarily of cohesionless grains, resistance to erosion depends on the balance between the forces tending to mobilize granular material and those tending to resist such motion. The threshold for initial mobilization can be defined as a critical shear stress (τ_{cr}), which depends primarily on the surface grain size and therefore is often estimated by the median size of the gravel or coarser bed material (i.e. $\tau_{cr} \propto D_{50}$, where $D_{50} > 5$ mm) (Bravard and Petit, 1997; Knighton, 1998). Assuming the flow is uniform, the mean shear stress (τ_o) exerted by flow of the river on the bed and banks can be estimated by

$$\tau_o = \gamma RS \quad (5)$$

where R is the hydraulic radius (approximated by the mean bankfull depth) (Knighton, 1998). Where τ_o exceeds τ_{cr}, this simplified model predicts mobility will occur. Such a simplification, however, neglects to consider the importance of the heterogeneity of the grain shapes and sizes, the degree of packing and the lifting forces associated with turbulence, which may all alter the shear stresses at which motion actually occurs.

The granular material transported by the stream varies downstream as a function of the stream transport capacity. Generally the headwaters are composed of larger boulders, and cobbles, as these fractions of the bed-material load are not displaced over large distances, and their movement is associated primarily with high flood events and/or steeply sloped channels (Shaw and Kellerhals, 1982; Parker, 1991). Many of these reaches are very steep, are strongly coupled with the adjacent hill slope, have patchy availability of mobile gravel fractions, and typically reflect supply-limited transport of these fractions (Church, 1983; Benda, 1990; Harvey, 1991). Conversely, as the channel extends downstream toward the larger reaches, the calibre of the bed-material load tends towards fine gravel and sand and the reach reflects transport-limited characteristics. Several authors have, however, found considerable variation in the pattern of grain sizes in headwater streams, which may be due to the strong coupling between the hill slope and channel boundary. Miller (1958) explained the observed high level of variation in sediment diameter with distance downstream as the result of the introduction of rock from outcroppings in or along the channel boundary. MacPherson (1971) observed similar variations in grain size and attributed this scatter to delivery of colluvium and till from the steeply sloped adjacent hill slope. Knighton (1975), Hogan (1986), Benda (1990) and Rice and Church (1996) reported similar findings, all suggesting the irregular nature of sediment supply from the channel boundary due to debris flows and the movement of large woody debris (LWD) as the source of the observed variability. As the channel widens downstream, becoming less coupled with the hill slope, it is less affected by non-alluvial element such as immobile boulders, bedrock outcroppings, and LWD due to the diminishing size of these elements relative to the increasing channel width (Bilby and Ward, 1989). Headwater channels are characteristically steep relative to intermediate or large channels, with gradients ranging from 2% to 35% (Halwas and Church, 2002). They exhibit considerable local variability in channel gradients, however, due to the irregular spatial distribution of bedrock and variations in sediment supply within the headwaters of most basins (Knighton, 1975; Massong and Montgomery, 2000). As basin area increases, downstream channel gradients tend to be less variable, decreasing towards gradients less than 1% (Hack, 1957; Church, 1992).

The variation in channel characteristics throughout a basin has given rise to numerous process-based and descriptive channel classification systems (Church, 1992; Whiting and Bradley, 1993; Wood-Smith and Buffington, 1996; Bravard and Petit, 1997; Montgomery and Buffington, 1997). While no single classification system can completely capture the continuum of characteristics that exist in nature, it is generally accepted that there are five distinct alluvial channel reach morphologies: boulder-cascade, step-pool, boulder-rapids (glide/run), pool-riffle and dune-ripple (Montgomery and Buffington, 1997). Bedrock channel reaches must be considered separately from this alluvial classification. The characteristic features of these channel types are summarised in Table 2.

Table 2. Characteristic features of geomorphologic channel types (adapted from Montgomery and Buffington, 1997; Church, 1992; and Halwas and Church, 2002).

	Dune ripple	**Pool riffle**	**Boulder rapid**	**Step pool**	**Boulder cascade**	**Bedrock**
Typical bed material	Sand	Gravel-cobble	Cobble-boulder	Cobble-boulder	Boulder	Rock
Bedform pattern	Multilayered	Laterally oscilliatory	Featureless	Vertically oscillatory	Random	Random
Dominant roughness element	Sinuosity, bedforms, grains, banks	Bedforms, grains, sinuosity, banks	Grains, banks, boulder cluster lines	Bedforms, grains, banks, boulder steps	Grains, banks	Boundaries
Dominant sediment source	Fluvial, bank failure	Fluvial, bank failure	Fluvial, bank failure, debris flows	Fluvial, hill slope, debris flows	Fluvial, hill slope, debris flows	Fluvial, hill slope, debris flows
Pool spacing (channel widths)	5 to 7	5 to 7	None	1 to 4	<1	Variable
Channel gradient range	<1%	<2%	2-4%	>4%	4%-35%	Variable

Boulder-rapid channels lack discrete bars, and are characterized by their relatively long featureless reaches composed of irregular boulder lines. Montgomery and Buffington (1997) suggest that reaches characterized as boulder-rapids are within the transition between supply- and transport-limited morphologies. Riffle-pool channels likewise exhibit a mix of both supply and transport-limited characteristics, however they tend more towards transport-limited morphologies. Riffle-pool reaches are characterized by a rhythmic oscillation between bars, pools and riffles and they primarily occur at low gradients in unconfined valleys with well-established flood plains (Richards, 1976; Church, 1992; Montgomery and Buffington, 1997).

II. 2. Physical Characteristics of Atlantic Salmon Spawning Habitat

It is generally acknowledged that salmon spawn within a certain range of hydraulic and morphologic conditions (Jones, 1959; Beland *et al.*, 1982; DeGraaf and Bain, 1986, Moir *et al.*, 2002). Spawning habitat is typically situated within pool-riffle systems in the clean gravel and cobble regions upstream of the crest of the riffle, where flow converges vertically upon the steeper slope of the riffle crest (Moir *et al.*, 2002). Salmonid eggs are buried in the gravel matrix 10 to 50 cm beneath the surface of the riffle (Belding, 1934; DeVries, 1997, Moir *et al.*, 2002). At this depth beneath the riffle surface the incubating eggs are exposed to essential subsurface water flow, which provides the eggs with essential dissolved oxygen and removes wastes (Lisle, 1989). Mills (1973) suggested that the principal factor limiting salmonid spawning in the Tweed River in Scotland, was the stream gradient. He found that gradients for salmon spawning ranged up to 2.1% and that reaches under 2% were readily accessible and contained the highest fish densities. Moir *et al.* (2002) likewise observed spawning redds in channels with gradients up to 3.2%. These slope values are consistent with a scarcity of spawning habitat in boulder-rapid reaches compared to pool-riffle reaches, which have more abundant mobile gravel-cobble patches.

Spawning is thought to take place within a fairly narrow range of gravel sizes, and has been classified as optimal when the median diameter of the subpavement sample falls within the range of 15 to 35mm (Platts *et al.*, 1979; Milhous, 1982, Kondolf and Wolman, 1983; Moir *et al.*, 2002), with a mean value between 22 and 23mm (Kondolf and Wolman, 1983; Moir *et al.*, 2002). Several authors have, however, observed successful spawning in substrate with a D_{50} as coarse as 60mm (Peterson, 1978; Verville, 1998), which may be attributed to the size of the spawning salmon (Crisp and Carling, 1989; Kondolf and Wolman, 1993). There is a lack of published literature on the upper limit or optimal range in pavement coarseness for salmon spawning beds. It seems reasonable, however, to assume that where the median pavement diameter exceeds 150mm or the D_{84} of the pavement exceeds 200mm that spawning would be very difficult for even very large salmon.

In addition to a particularly clean mixture of gravel required for successful reproduction, salmonids require or 'prefer' a range of water depths and velocities. Numerous authors have recorded preferred water depths for spawning ranging between 20 and 50 cm (Jones, 1959, Beland *et al.*, 1982) and preferred mid-water velocities ranging between 30 and 55 cm/s with a lower velocity limit of 15-20 cm/s (Beland *et al.*, 1982, Crisp and Carling, 1989). Moir *et al.* (2002) suggest the use of the Froude number as a single hydraulic habitat descriptor, as it is a dimensionless parameter which considers both velocity and depth. The Froude number is equivalent to

$$Fr = v/(dg)^{0.5} \tag{6}$$

where g is the gravitational acceleration constant (9.81m/s^2). Where Fr equals one, the flow is said to be 'critical'. Values greater than one define 'super-critical' flow, while values less than one define 'sub-critical' flow. Moir *et al.* (2002) found that spawning tended not to occur where Fr was less than 0.2, and that optimal hydraulic spawning characteristics were defined by a Froude number ranging between 0.30 – 0.44.

The relationship between fine sediment in the riffle substrate and salmonid reproductive success has been a subject of great concern and a large literature has accumulated on the subject. Waters (1995) supposes this to be in part due to the salmon's use of redds in reproduction, which function as a potential sediment trap. Two commonly identified specific effects of fine sediment in redds are, the filling of interstitial spaces by sediment deposited on the redds, which reduces the flow of water through the redd and consequently the supply of oxygen reaching the incubating eggs, and the entrapment of emerging fry by a layer of deposited fine sediment upon the redd surface (Cordone and Kelley, 1961; Platts *et al.*, 1983).

The reduction of water flow and the smothering of eggs are primarily a function of sediment particle size and gravel permeability. For the same amount of suspended sediments deposited, there is a greater reduction in water flow relative to gravel with larger pore openings in a less permeable gravel mixture, composed of smaller sediments and therefore smaller pore openings. A large number of field and laboratory studies have reported that survival and emergence are related to the proportion of fines of specified sizes present (Wickett, 1958; Cordone and Kelley, 1961; McNeil and Ahnell, 1964; Cederholm *et al.*, 1981; Peterson and Metcalf, 1981; Tagart, 1984). Shelton and Pollack (1966) studied the role of sediment in spawning gravel in an incubation channel by measuring the percentage of the gravel mixture voids filled by silt (<0.07mm) and found that when 35% were filled, egg mortality reached as high as 85%. When this percentage was reduced below 10% of void space, mortality reached as low as 7%. In other investigations, the threshold for survival has been set around 20% fines less than 0.8 mm by weight in the gravel mixture, beyond which significant mortality of embryos can be expected (Platts *et al.*, 1979, Tagart, 1984, Reise and White, 1988). Several authors have also suggested the use of the geometric mean diameter of substrate particles or other descriptors of substrate composition (such as the Fredle index) over the use of percent concentration of fines, as these metrics seem to provide more accurate predictions of embryo survival (Platts *et al.* 1979, Everest *et al.*, 1987, Young *et al.* 1991). Peterson and Metcalf (1981) related the percentage of emergent fry to a threshold of two classes of sand. The sand index (*SI*) is defined as

$$SI = (S_c/16) + (S_f/8) \qquad (7)$$

where S_c is the coarse sand fraction, which is equal to the percentage fines between 0.5 and 2.0mm and S_f is the fine sand fraction, which is equal to the percentage fines below 0.5mm. They observed no decrease in emergent fry where the sand index was less than one, and no emergent fry where the sand index was greater than 1.5. Most early reviews investigating the effect of sediment on salmonid productivity emphasised forestry practices as the principal source of fine sediment in salmonid redds (Waters, 1995).

II. 3. Impact of forestry practices on stream habitat

II. 3. 1. General effects of forestry practices on stream habitat

The ecological effects of forestry practices in headwater forests have received research attention for many years, most of which has focused on the old-growth coniferous forests of the Pacific Northwest in the United States and western Canada (Cordone and Kelley, 1961; Brown and Krygier, 1971; Meehan, 1991; Waters, 1995 and others). The focus of attention on the west coast is, in general, the result of the high economic value of both forestry and fisheries resources within the region, as well as the visibility given to the conflict ensuing as a result of one industries impact on the other. The complications associated with the interactions between the two industries are intensified due to the mountainous terrain, unstable surface material, and high precipitation regime upon and within which the west coast forestry industry operates (Hartman *et al.*, 1996). There are considerably fewer watershed studies investigating the impact of timber harvest on stream habitat and salmonid community production in the boreal forests of the eastern United States and Canada, where the forests are generally not composed of old growth conifers nor is the topography as mountainous. The Canadian Department of Fisheries and Oceans has directed studies on the east coast of Canada investigating the sensitivity of the landscape to forestry activities in Catamaran Brook, New Brunswick and Copper Lake, Newfoundland (Cunjak *et al.*, 1990; Scruton *et al.*, 1995). While these experimental basins share similar fauna, climate, flora and biophysiographic conditions as the Cascapédia basin, they are considerably smaller in areal extent and have a shorter, highly controlled history of forestry activity within their boundaries and thus cannot be easily compared to the Cascapédia drainage basin, which has a long history of widespread logging activity.

Changes in stream habitat as a result of land use and in particular forestry practices are complex and widespread. In addition to changes in runoff and sediment delivery, which are discussed in the following two sections, forestry practices can alter water temperature and chemistry, and alter primary production and consequently benthic and salmonid community structure (Brown and Krygier, 1970; Hewlett and Helvey, 1970; Burton and Likens, 1973; Cambell and Doeg, 1989; Lenat and Crawford, 1994; Jones and Grant, 1996; Mitchell, 1999; others).

The removal of vegetation can result in changes in stream temperature, which can adversely affect salmonids by altering the levels of dissolved oxygen. Optimal growth temperatures for Atlantic salmon fry have been recorded to be between 10 – 17°C (Javaid and Anderson, 1967; Siginevich, 1967; Jobling, 1981), with lethal temperature ranging between 20 and 28°C (Jobling, 1981; Elliot, 1991). Complete removal of the vegetation immediately adjacent to the streamside greatly increases the solar radiation that reaches the channel and can consequently result in a considerable increase in stream temperature, especially in shallow headwater areas. Brown and Krygier (1970) found that clear-cutting of riparian vegetation increased mean monthly maximum temperatures from 13°C before logging up to 23°C, which is within the lethal range for salmonid fry. Strip-cutting, in comparison, which leaves a band of riparian vegetation intact along the channel boundary, does not result in an increase in post-cutting stream temperature (Brown and Krygier, 1970; Burton and Likens, 1973; Mitchell, 1999). Changes in land use can also substantially alter water chemistry by altering the levels of suspended sediment, nutrients and dissolved solids reaching the channel (Brown and Krygier, 1971; Bescheta, 1979; Culp and Davies, 1983) Additional inputs of nutrients from the hill slopes and channel boundary after riparian vegetation removal can function together with increased insolation to increase primary production and subsequently alter macroinvertebrate community structure (Johnson et al., 1997). Gurtz and Wallace (1984) studied the effects of clear-cut logging on primary production and stream invertebrates both during and immediately following logging and found that primary production increased significantly immediately following clear-cutting and decreased over the long-term as streamside vegetation returned and the forest canopy re-closed over the stream. They likewise found that the resilience of the stream ecosystem depended somewhat on substrate size, that is the biological stability seemed coupled with the physical stability of the stream. They found that the smaller the substrate size, the less stable the habitat, which corresponded with greater negative effects on invertebrates associated with the clear-cutting.

II. 3. 2. Impact of forest cover removal on runoff and sediment production

The removal of vegetation from the hill slope surface reduces evapotranspiration, decreases infiltration, increases overland flow (Hewlett and Hibbert, 1961; Hewlett and Helvey, 1970; Jones and Grant, 1996) as well as destabilizes banks and steep slopes (Smith, 1976). Alterations in infiltration and overland flow levels, as a result of forest harvesting can consequently produce a significant long-term increase in peak discharge in both small and large basins (Hewlett and Helvey, 1970; Lyons and Bescheta, 1983; Jones and Grant, 1996; Caissie *et al.*, 2002). Sediment is naturally produced for removal from a river basin by physical, chemical and biological processes operating on both hill slopes and river channels (Knighton, 1998). Sediment is likely to be removed from the hill slopes during a particular storm event, where its removal is primarily a function of rainfall related erosion mechanisms, including rainfall intensity, rainfall depth, rainfall drop size and antecedent moisture conditions (Brune, 1950; Moore, 1984). Its delivery to the stream occurs primarily through mass soil movement and surface erosion processes. This situation may be exacerbated in areas where the soil surface has been substantially disturbed such that infiltration rates are reduced and bare slopes are exposed to an increased amount of direct precipitation. The magnitude of the impact of forestry practices may therefore vary considerably by season, depending on the timing of the majority of the harvest with respect to the timing of the wet season. Erosion from hill slopes is likewise related to the hill slope gradient. Thus in very small, steep, forested valleys, the response to an increase in overland flow may be much more severe in terms of potential sediment transport when compared to a similar size basin in a gradually sloping valley under the same conditions.

Similarly, the removal of vegetation from the channel boundary can destabilise banks, resulting in a larger influx of sediment from channel boundary (Scrivener and Brownlee, 1989; Smith, 1976). Once the stream side vegetation is removed, and the root network beneath the surface begins to gradually decompose, the protection and soil binding properties of the root network are lost, thereby weakening the banks overall stability. Smith (1976) found that stream banks with a root volume between 16 and 18% in addition to a 5cm root mat were 20,000 times less susceptible to bank erosion than a comparable stream bank devoid of vegetation. An increase in sediment delivery to the channel associated with a decrease in bank stability can also alter channel morphology, resulting in wider, aggrading channels (Lyons and Bescheta, 1983).

II. 3. 3. Influence of forest roads on runoff and sediment production

Research on forest-range management and salmonids has paid considerable attention to the influence of road construction and road network density. Roads can compound effects of clear-cutting on peak discharge by altering flow routing, often quickly redirecting sediment laden flow directly into low order tributaries and thereby reducing the time lag of the occurrence of the peak discharge (Hewlett and Helvey, 1970; Jones and Grant, 1996). The road construction that precedes logging is often considered a greater threat to in-stream habitat in terms of sediment production than the actual timber harvest (Brown and Krygier, 1971; Burns, 1972; Bescheta, 1979). Gravel surfaced roads are a particularly important source of fine sediment, both because a significant proportion of the sediment that is eroded from roads can reach the streams directly at road-stream crossings and because the sediment eroded from gravel surface roads is most likely to be of the size class deemed to be most harmful to fish (Megahan, 1974).

The density and length of logging roads as well as the traffic intensity greatly influence the level of sediment production. Cederholm *et al.* (1981) studied the effects of logging roads on salmonids within the Clearwater River in north-western Washington and found that the greatest accumulation of sediments under 0.85mm in the spawning gravel occurred where the total road surface area was greater than 2.5 % of the total basin area. This measure was based on the total road length and the mean road width (from the top of the cut bank to the toe of the side cast slope). They likewise observed that, where the total road length within a square kilometre of the basin exceeded 2.5 km, sediment production rates were up to four times greater than the natural observed rates. Reid and Dunne (1984) investigated the quantitative relationship between road surface erosion rates and road segment use and surface type. They found that erosion rates in the Clearwater basin were also extremely sensitive to traffic intensity, to the point that the same roads contributed sediment at a rate 7.5 times greater on days of heavy usage than on days of inactivity. Brown and Krygier (1971) and Luce and Black (1999) performed similar quantitative studies investigating the impact of road construction and sediment production in the

Oregon coastal range and likewise concluded that fine sediment inputs from forest road segments could be substantial even from relatively standard roads with light traffic intensity, which confirms the importance of understanding the controls on variability in road sediment production rates.

II. 3. 4. The role of riparian zones in mitigating the effects of forestry practices

One of the most important natural mechanisms for attenuating sediment inputs into a channel segment is the riparian 'corridor' zone. Riparian zones are the three-dimensional zones that delimit the boundary between terrestrial and aquatic ecosystems and they function as a filter strip along the channel boundary via runoff infiltration, nutrient uptake and sediment deposition (Gregory *et al.*, 1991; Narumalani *et al.*, 1997). The vegetation within riparian zones not only stabilizes channel banks (Erman *et al.*, 1977), but also filters out excess sediment in transport during over-bank flows (Wilken and Hebel, 1982), supplies large woody debris and organic matter, and attenuates peak flows by slowing the release of runoff (Swanson *et al.*, 1976; Bilby, 1981; Gregory *et al.*, 1991). Davies and Nelson (1994) investigated the role of riparian corridors of various widths and the effects of logging on stream habitat in a number of streams throughout Tasmania. They found that, while logging significantly increased the levels of fine sediment (silt/sand) observed within the riffle sediment, observed silt values were negatively correlated with increasing riparian corridor widths ($p < 0.005$).

Various studies have used Geographic Information Systems to investigate the influence of riparian zone land use on salmon habitat quality relative to the influence of catchment wide land use (Richards and Host, 1994; Richards *et al.*, 1996; Lammert and Allen, 1999; Basnyat *et al.*, 2000). Richards *et al.* (1996) found that the stream habitat variables measured in the field, which included channel morphology, substrate, and hydraulic variables, were more significantly related to landscape variables at the watershed scale than to landscape variables at the riparian corridor scale. The authors found that 50% of the variance observed in physical habitat variables could be attributed to landscape variables, 22% of which was explained by geology-structure variables and 16% of which was explained by differences in land use. Channel morphology variables were best explained by the catchment area and the standard deviation of the catchment elevation of the entire subbasin, an indirect measure of topographic relief. In their comparison of the whole catchment and stream corridor data they found very little difference between the predictive abilities of the corridor scale parameters (using a riparian corridor distance of 100m on each side of the river) versus the catchment scale parameters. Only the percentage fines (<2 mm) within the substrate and the percent of banks that were washed or sloughing had more variance explained at the riparian scale. The percent of total variance in fines explained by land use increased from 41% at the catchment scale to 60% at the riparian scale. This result confirms the importance of the riparian zone in controlling sediment delivery and bank erosion processes and reiterates the importance of high resolution land use data when attempting to accurately capture the interactions occurring along the channel boundary. Basnyat *et al.* (2000) reported findings similar to Lammert and Allen (1999), who, in contrast to Richards *et al.* (1996) found that local land use within the riparian zone explained more of the observed variance in the integrated habitat index used (Ohio EPA, 1989), for which substrate size was a defining metric. The difference between these results and those of Richards *et al.* (1996) may be the result of the method used to calculate the corridor region. Richards *et al.* (1996) calculated corridors for the entire catchment, that is, for all upstream tributaries, whereas Lammert and Allen (1999), in an attempt to capture the effects of the most immediate landscape variables, calculated local riparian corridors with an upstream extent limited to 1 km.

III. OBJECTIVES AND APPROACH

Key stream habitat variables

Not all stream reaches throughout a watershed are equally likely to be optimal or suitable Atlantic salmon spawning habitat. The suitability of the stream habitat for salmon production will be determined from a suite of key quantitative habitat variables measured in the field, which have been selected based on the theoretical knowledge presented in the preceding chapter. The key stream habitat variables to be included in this study are: the morphological channel type, local channel gradient, channel width at summer low flow and at bankfull levels, mean bankfull and summer flow depth, and grain size distribution of the mobile gravel-cobble substrate.

Channel gradient will be measured as it is one of several important descriptors in reach morphology classification schemes as well as in channel form adjustment equations. Channel dimension, at bankfull and summer flow levels, will also be measured, as the former, in addition to being associated with formative discharge, is associated with numerous hydraulic parameters, including shear stress, while the latter provides an indication of wetted habitat available to organisms during seasonal low flows. The nature of both the surface and subsurface substrate grain size distribution has several implications for the community of aquatic organisms inhabiting the channel. The substrate grain size distribution influences channel form and stability as well as aquatic habitat. Characterization of the subsurface grain size distribution, from the mean subsurface diameters and fine sand and silt content, will provide a quantitative measure of the quality of the substrate for Atlantic salmon spawning.

While several other variables, including the availability of boulders and winter rearing habitat, the occurrence of deep pools and canopy overhang, and abundance of large woody debris, all play a role in the quality and suitability of the physical habitat for use by salmonids at various stages in their life cycle (Allen, 1940; Chapman and Bjornn, 1969; Gibson, 1978; Gardiner, 1984; Hutchings, 1986; Coulomb-Pontbriand, 2001), the physical habitat variable examined in this study will be limited to those mentioned above. They have been selected from the suite of potential variables because they represent a number of significant physical and biological parameters, while at the same time are obtainable in the field given the constraints of the project (i.e. cost, time, access). Many other variables associated with the suitability of the habitat, including the presence of LWD, canopy overhang, and stream temperatures were measured at the same sites by a parallel CIRSA study, and will therefore not be directly measured in this study. We likewise limited the habitat variables to those which can be predicted reasonably well from the GIS database given the limitations of the spatial resolution and accuracy of the available digital data.

Objective One

The first objective of this study is to examine the control of valley and channel geomorphology on the spatial distribution of potential Atlantic salmon habitat within the Cascapédia drainage basin. Predictive empirical relationships for the key stream habitat variables (slope, grainsize, channel dimension and channel type) will be developed based on basin-scale landscape metrics. Within the GIS database, landscape characterization involves the distinction between land use variables and other "structural" landscape variables such as basin area, topographic relief, geology, etc. The terms land use and land cover (LULC) have been limited to those variables that reflect the anthropogenic modification of the surface cover. Richards *et al.* (1996) collectively refer to landscape variables that are fixed geologically and topographically, which are independent of land use, as geology-structure variables and this term will be used herein. The stream habitat variables measured in the field will be related to numerous geology-structure variables derived from an existing digital elevation model (DEM) created by the Québec Ministry of Natural Resources (MNR), including the drainage basin area contributing to a given sample location, mean catchment slope at various scales, site elevation, elevation range, stream density, standard deviation of the local elevation, which provides an index of topographic complexity (Richards *et al.*, 1996), and an index of stream power.

Objective Two

The second objective of this thesis is to investigate the relationship between forestry practices and the quality of spawning habitat with respect to fine sediments within the potential spawning substrate, once the natural variation in habitat has been assessed. The physical habitat variables described above will be compared to numerous LULC variables extracted from a GIS database supplied by the MNR, which includes thematic coverage of road and stream networks and forest cutblocks, including the age of the stand as well as the type of forestry intervention that occurred. Metrics associated with anthropogenic modification of the vegetated surface, including a weighted percent cut, road network density, road-stream crossings, as well as road slopes, will be calculated from these data in order to determine to what extent they affect the levels of fine sand and silt detected in the potential spawning substrate of each stream reach sampled.

Given that much of the riparian vegetation appears to be intact along the upper tributaries, the road networks within this basin are of particular interest, as they seem to be the most likely source of fine sediment. Because the greatest inputs of sediment are postulated to originate from the disturbed zones closest to the river channel and diminish non-linearly with distance from the channel border, buffer analysis will be performed to determine how the intensity of vegetation disturbance within the riparian zones influences the spawning habitat quality. By comparing the riparian zones to the entire catchment area it should be possible to determine the scale of controls influencing habitat quality within the basin.

Together these objectives should provide additional insight into the source of the observed sedimentation levels as well as the distribution of spawning habitat throughout the entire basin.

IV. STUDY AREA

IV. 1. General description of study area

The tributaries being studied are within the drainage basin of the Cascapédia River, which is located in the Southern Gaspé peninsula of Eastern Québec and flows into the Baie des Chaleurs (Figure 2). This region is particularly interesting as it has a long history as an important Atlantic salmon river and most local employment within the Cascapédia basin is indirectly or directly linked to the sport fishing industry. Prime fishing sites for prized large salmon are located in the lower reaches of the Cascapédia near the town of Saint-Jules/Grande Cascapédia and continue for 60km upstream. The upper reaches of the Cascapédia and its smaller tributaries are, however, fished as well (primarily for brook trout (*Salvelinus fontinalis*), in both anadromous and resident forms) and provide essential habitat. The forestry industry, which operates throughout most of the Cascapédia basin and especially within the headwater basins of the Lake and Salmon branches, is likewise important to the region's economy and is often at odds with the local sport fishing industry. The current struggle between the two principal industries of the region and the socio-economic value of both resources press the need for a better understanding of the physical and biological components of the watershed and their relative influence on the quality of Atlantic salmon habitat. This study, conducted within CIRSA's larger multi-scale, multi-discipline study, will provide scientific insight to help alleviate the conflict between the various stakeholders.

This region is also of particular interest as the channel substrate is silt rich, yet contains rather small amounts of sand (Figure 3), relative to other salmon rivers in Québec, including the neighbouring Petite Cascapédia and Bonaventure Rivers (Figure 2, inset) (Honeywill *et al.*, 1995; Payne, 1995; Payne and Lapointe, 1997; Tanguay, 2000; Coulombe-Pontbriand, 2001; Zimmermann, 2002). The geological basis for this will be discussed in section IV. 3. Figure 3 suggests that the percent silt ($< 63\mu m$) in the Cascapédia River is higher than the average percent silt found in samples from the other Québec salmon rivers studied (0.18% and 0.07% respectively). Meanwhile, the percent sand (0.125mm-1mm) within the Cascapédia is the same as the average for the other

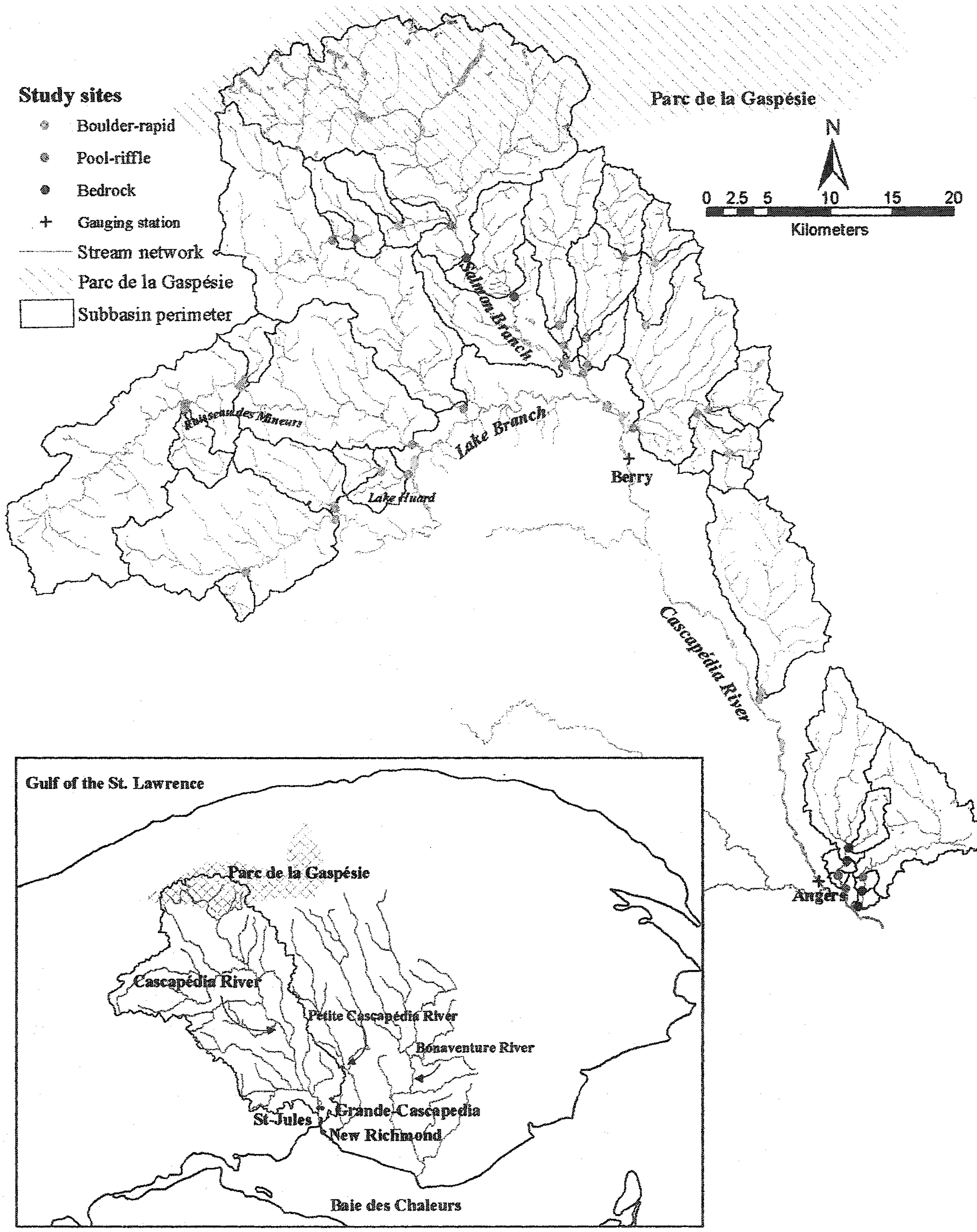


Figure 2. Location of the study area and distribution of boulder-rapid, pool-riffle and bedrock dominated study reaches.

rivers (7.7%), but less than the sand content found in rivers draining Shield basins like the Ste.-Marguerite River in the Saguenay. Most other studies investigating the effects of sedimentation on salmonids have dealt primarily with sand size classes and their impact on salmonid habitat rather than sediment as fine as silt. It is possible that, within the physical context of the Cascapédia drainage basin, silt may be easily transported from cutblocks or roads to the channel. It is likewise possible that silt size particles may as easily be washed out of stream reaches. The low sand content within the Cascapédia River creates a unique opportunity to study in-stream siltation without having high sand content to contend with.

The GIS coverage encompasses a territory of 2070 km^2 and includes the two main branches of the river, the Salmon Branch and the Lake Branch as well as their main tributaries. The majority of the study sites sampled were situated on the 3^{rd} and 4^{th} order tributaries of the Salmon and Lake Branches, rather than on the principal branches themselves, the exceptions being the 3 sites situated on the upper Salmon Branch (Figure 2). Reaches on the Lake and Salmon Branches can be as wide as 80m at bankfull level. Thus such sites require slightly different field sampling techniques, making it more difficult to take consistent and precise measurements. A total of 48 sites were sampled (Table 3, Appendix 1), including northern tributaries adjacent to the unlogged Parc de la Gaspésie through to the extensively logged regions along the Lake Branch (Figure 2, Figure 6). Study sites were selected on the basis of their accessibility by 4 wheel drive vehicle as well as the likelihood of their representing a variety of landscape characteristics. The subbasins sampled range in area from 8 km^2 to 450 km^2 and range in elevation between 10m and 1270m above sea level. The study sites are dominated by three main channel reach morphologies: bedrock dominated, pool-riffle and boulder-rapid alluvial reaches. Figure 2 shows the distribution of the three morphologies within the study sites. Reaches were classified as either bedrock controlled or alluvial based on the dominant control of the channel form and bed form pattern along the length of the reach. The distinction between the alluvial reaches was based on classification scheme presented in Table 2, the primary criteria being the presence or absence of clear riffle-pool sequences and discrete bars. Photos representative of these three reach morphologies are included in Appendix 2.

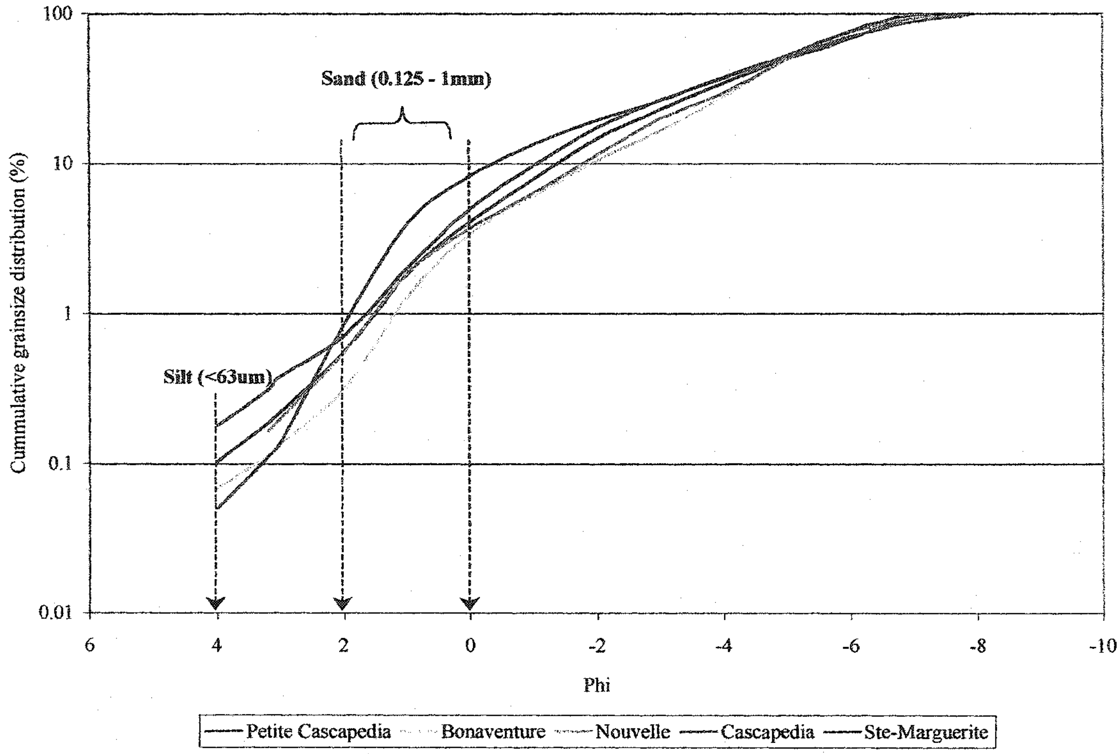


Figure 3. Composite bed material distributions of five Québec salmon rivers (adapted from Zimmermann, 2002).

Table 3. List of study sites, including abbreviated site names, study reach coordinates and basin size metrics.

Site name	Abbreviated name	Coordinates		Basin area (km^2)	Stream order
		Latitude	Longitude		
Square-forks 1	SQF 1	48.5587	-66.3612	103.10	4
Square forks 2	SQF 2	48.5491	-66.3823	37.07	4
Rouge 1	ROU 1	48.6194	-66.4133	22.30	4
Rouge 2	ROU 2	48.6290	-66.4400	9.03	2
Tributary of Inlet 1	TINL 1	48.5986	-66.4966	35.71	3
Tributary of Inlet 2	TINL 2	48.6004	-66.5037	35.52	3
Loutre 1	LOU 1	48.5785	-66.2977	38.12	3
Loutre 2	LOU 2	48.5294	-66.3042	37.38	3
Loutre 3	LOU 3	48.5294	-66.2622	23.64	2
Rioux 1	RIO 1	48.7927	-66.4907	25.20	3
Rioux 2	RIO 2	48.7945	-66.4649	20.32	3
Tributary of Mineurs 1	TMIN 1	48.6732	-66.6547	18.68	4
Tributary of Mineurs 2	TMIN 2	48.6718	-66.6550	18.00	4
Washout 1	WAS 1	48.6865	-66.5917	13.62	2
Washout 2	WAS 2	48.6919	-66.5893	13.37	2
Inlet 1	INL 1	48.5875	-66.4914	135.66	4
Inlet 2	INL 2	48.5509	-66.5946	7.66	3
Quatorzieme 1	14EME 1	48.8031	-66.3593	31.02	3
Quatorzieme 2	14EME 2	48.8036	-66.4162	17.72	3
Mineurs 1	MIN 1	48.6427	-66.4102	335.90	5
Mineurs 2	MIN 2	48.6878	-66.5942	200.05	5
Echoument 1	ECH 1	48.6683	-66.3492	216.63	4
Salmon 1	SAL 1	48.6992	-66.2343	448.14	5
Salmon 2	SAL 2	48.7487	-66.2876	388.36	4
Salmon 3	SAL 3	48.7758	-66.3387	348.07	4
Brandy 1	BRA 1	48.6930	-66.2160	69.38	3
Brandy 1A	BRA 1A	48.6965	-66.2093	68.52	3
Brandy 1B	BRA 1B	48.7216	-66.2126	56.93	3
Brandy 3	BRA 3	48.7738	-66.1659	23.74	3
Indian 1	IND 1	48.7020	-66.2410	60.19	4
Indian 2	IND 2	48.7130	-66.2370	57.66	4
Indian 3	IND 3	48.7280	-66.2410	53.72	4
Berry 1	BER 1	48.6540	-66.1590	176.75	5
Berry 2	BER 2	48.6650	-66.0800	23.90	3
Petit sud 1	PSU 1	48.6610	-66.0910	25.86	3
Big Jonathan 1	BIG 1	48.4510	-66.0290	97.51	4
Trout brook 1	RTR 1	48.3070	-65.9400	76.38	3
Trout brook 2	RTR 2	48.3240	-65.9490	74.89	3
Trout brook 3	RTR 3	48.3310	-65.9390	71.64	3
Trout brook 4	RTR 4	48.3350	-65.9390	10.04	2
White brook 1	WBR 1	48.2980	-65.9290	71.95	3
White brook 2	WBR 2	48.2970	-65.9270	71.85	3
White brook 3	WBR 3	48.3060	-65.9210	69.79	3
White brook 4	WBR 4	48.3170	-65.9200	67.43	3
Berry north 3	BN 3	48.7270	-66.1440	28.54	3
Berry north 3A	BN 3A	48.7736	-66.1332	11.95	2

IV. 2. Climate & vegetation

The climate in the region is maritime, with mild to hot summers (>20°C) and cool to cold winters (<-15°C) with a mean annual air temperature of 2.1°C based on the climate normals from the Cap Seize station (66°24', 49°01', 229m above sea level) for the years of 1967 to 1990 (Government of Canada, 2002). During the winter months, a strong polar continental air mass is dominant, while in summer this system weakens and warmer air infiltrates, allowing approximately 150 – 170 growing days where air temperatures reach above 5.6°C (Elliot *et al.*, 1998). The region receives an average of 1081mm of precipitation, 41% of which falls as snow fall between October and May. Consequently peak discharge volumes are associated with the spring snowmelt that tends to occur in late May to mid-June (Figure 4). The average annual hydrograph of the Cascapédia (from 1968-1972) for the gauging station situated just upstream of the outlet of the Angers River is shown in Figure 4 (Government of Canada, 2001). Statistics for the nival-type hydrological regime from two historical gauging stations along the Cascapédia River are shown in Table 4. The ratio of the area of the two subbasins is approximately 1.43. The discharge record from the Angers gauging station spanned only five years, yielding an insufficient number of data points to accurately estimate return periods. The 34 year record of annual maximum discharge values from the Berry gauging station were therefore used to generate return period estimates (Figure 5), which are summarized in Table 4. There were no unusually high flows in the decade prior to this study, the last unusually high flow having occurred in 1991 (Q_{max} = 650m^3/s, 15 year recurrence).

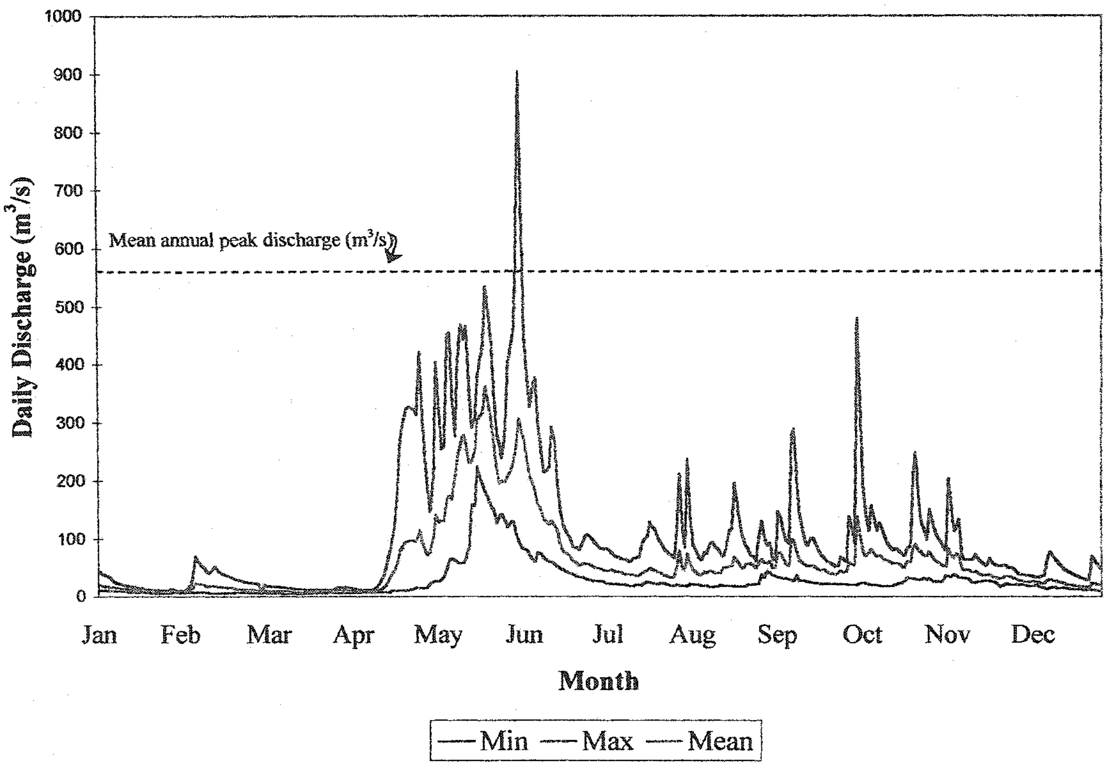


Figure 4. The annual hydrograph of the Cascapedia River based on the Angers gauging station data from 1968-1972 showing mean, minimum and maximum daily discharge (Q_m).

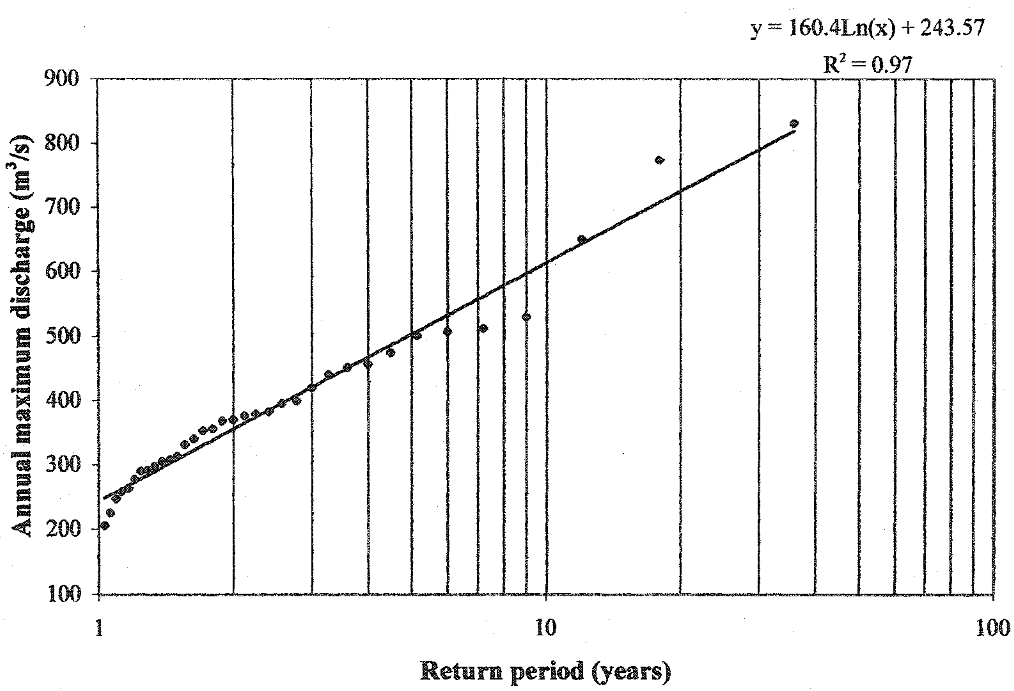


Figure 5. Return period for flooding at Berry station based on annual maximum values obtained between 1978 and 2001.

Table 4. Hydrological statistics of the Cascapedia River. Asterix (*) denotes value estimated from the basin area ratio.

	Angers station	Berry station	Ratio
Years	1968-1972	1979-2001	
Coordinates	48°19'04" 65°58'21"	48°37'42" 66°10'05"	
Watershed area (km^2)	2400	1680	1.43
Mean discharge (m^3/s)	61.2	42.5	1.44
Mean annual peak discharge (m^3/s)	562	396	1.42
2001 peak discharge (m^3/s)	323*	226	1.43
2.3 year recurrence flood (m^3/s)	-	377	
10 year recurrence flood (m^3/s)	-	613	
100 year recurrence flood (m^3/s)	-	982	

Land cover throughout the watershed is primarily mixed forest, consisting of spruce (*Picea glauca*), balsam fir (*Abies balsamea*), birch (*Betula alleghaniensis, Betula papyrifera*), maple (*Acer pensylvanium* L., *Acer rubrum, Acer saccharum*), cedar (*Thuja occidentalis* L.), and alder (*Alnus rugosa*). The forests have been actively harvested to some degree since the beginning of the last century (Alcock, 1935), and there are relatively few tributaries outside parks and reserves that have been spared the effects of logging entirely. There is a small degree of agricultural activity in the southern portion of the basin, however, it occurs beyond the extent of the study area. The greatest intensity of recent logging activity is concentrated around the Lake Branch downstream of Lac Huard and the lower portion of the Salmon branch (Figure 6).

The attenuation factors (AF) displayed in Figure 6 are used to determine the hydrological effective percentage cut within a basin based on a method established by the MNR (Plamondon, 1993). The attenuation factors are assigned to a cut block as a function of the time since the last harvest and the expected extent of re-growth. These factors are calibrated to model the potential hydrological response to forestry perturbations associated with both the reduction of evapotranspiration and flow concentration near forestry roads and are based on the date and type of cut information in the attribute table of the MNR database. These attenuation factors within the database range from 0 to 85%, with zero being the most pristine and therefore having no effect on evapotranspiration and peak discharge and 85% being the most recently cut or disturbed.

For example, a recently clear-cut parcel (within the last 5 years), is assigned an AF of 85%, which means that the evapotranspiration potential of the disturbed parcel is effectively equivalent to the evapotranspiration potential of a pristine parcel 85% smaller in area. If, however, there has been any silviculture within that parcel, the AF is deemed reduced to 60% and the re-planted forest area is equivalent to a pristine forest 40% smaller in area. These factors (Appendix 3) have been calculated based on the particularities of the Cascapédia drainage basin and cannot be applied outside this region (Plamondon, 1999). This study does not focus on measuring runoff perturbations and the accuracy of the attenuation factors calculated by the MNR was not tested. The AFs are simply used in this study as a convenient metric of the intensity of recent logging disturbances within the study area.

Regulation within the province of Québec dictates that a river classified as a permanent watercourse must be protected on both sides by 20 m bands of intact vegetation from the boundary of the riparian ecotone, which is the "transitional area between the water environment and the arborescent vegetation" (Gouvernement du Québec, 1996). Thus within the study area a minimum riparian corridor of 20 m on both sides should, in theory, line the length of a great majority of the permanent streams. Article 28.2 of the Québec Forest Act dictates that, in addition to the 20 m band that lines all permanent watercourses, rivers classified as salmon rivers by Faune et Parcs Québec (FAPAQ) must be protected by a 60m zone of intact vegetation (Gouvernement du Québec, 1996). Within the study area this classification has been assigned to the Cascapedia River, the two main branches, Salmon and Lake, as well as one tributary of the Lake Branch (le ruisseau des Mineurs) (Figure 2).

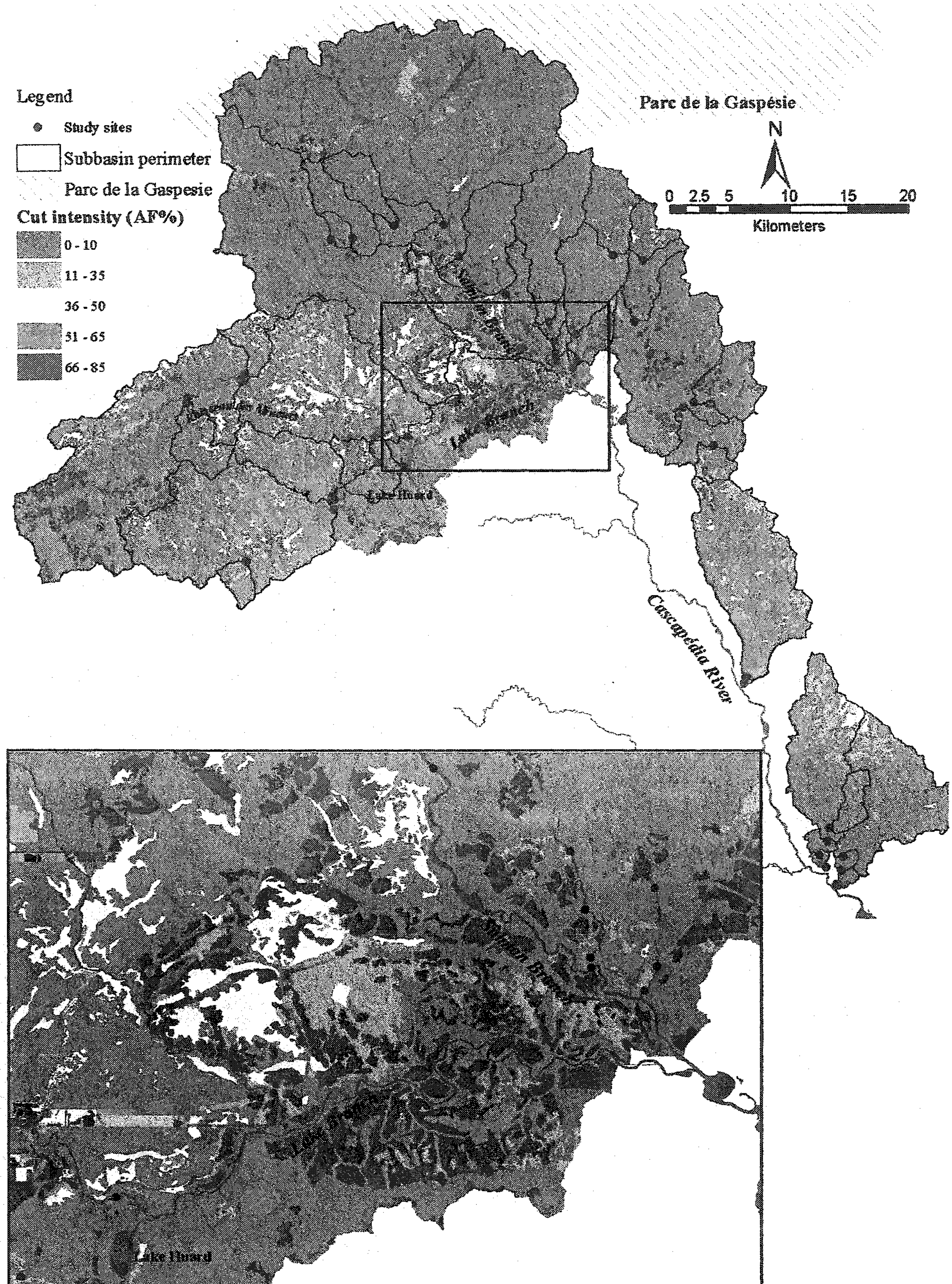


Figure 6. The spatial distribution of cutting intensity (as of 2000) based on the attenuation factors associated with the age and type of cutting and presence of roads within the cut block as discussed in the text.

Road construction within the drainage basin has been quite extensive, and has been realized primarily for timber and mineral extraction, though many small roads are maintained within the basin for fishing and hunting access (Figure 7). The roads range in width, from winter hunting roads of a few meters wide to large forestry roads over 12m wide. The majority of heavily used logging roads (during the study period of 2000-2001) are located along the Lake Branch and the lower portion of the Salmon Branch. The majority of the useable forestry roads are stable, well-groomed gravel roads built, in theory, according to the guidelines established in the Québec Forest Act (Gouvernement du Québec, 1996). The primary access to these forestry roads is from Highway 299, a two lane paved highway, which runs along the majority of the length of the Cascapedia and dissects the Gaspé Peninsula from New Richmond to Sainte-Anne des Monts (Figure 2).

IV. 3. Topography and geology

The topography of the region ranges from gently rolling hills to the mountainous topography of the Shick-Shocks in the northern headwaters of the basin (Mont Albert, 1150m). The geology of the Gaspé Peninsula is characterized by folded overthrust sediments with metamorphic and igneous intrusives (Alcock, 1935). The Cascapédia River and its tributaries flow upon geological formations originating from the middle and lower Devonian as well as lower Silurian to Ordovician periods (Carbonneau, 1959a). The hydrography appears to be somewhat independent of the orientation of the geological formations, as the major rivers do not follow the east-west orientation of the geological structures, but rather flow primarily north-south. The youngest bedrock within the study area, belonging to the lower to middle Devonian period and consisting of the Lake Branch and Battery Point formations, are centred around the Lake Branch and the lower Salmon Branch (Figure 8). The Lake Branch formation consists of both red and green sandstone and shale. Field surveys within this region suggest that this formation consists primarily of highly friable, poorly indurated, limonite-rich, red shale and sandstone (Carbonneau, 1959b). The headwater tributaries, in comparison, flow upon the more resistant and older York Lake and Grande Grève formations of the lower Devonian period, which tend to be composed of grey and green sandstone and limestone (McGerrigle and Skidmore, 1967). Glacial scour and deposition during the Pleistocene extensively modified and shaped the region, resulting in a combination of both flat bottom and V-shaped valleys within the drainage basin (Coulomb-Pontbriand, 2001).

There is a broad crescent shaped topographic depression centred around the Lake Branch of the Cascapédia (Figure 37), which coincides with the boundary of the friable Lake Branch Formation (Figure 8, unit 9a). The surficial deposits upon this central basin consist primarily of glacial and fluvioglacial deposits (Figure 9). The fluvioglacial deposits are primarily outwash plain deposits composed of sand and gravel up to 30m in thickness and ice contact deposits up to 15m in thickness, composed equally of gravel and sand as well as coarser blocks. The glacial deposits consist of discontinuous till less than 0.5m thick and continuous till greater than 1m in thickness. There are also localized glaciolacustrine deposits within the region. The headwaters, in comparison, are either covered with a thin veneer of regolith or the bedrock is exposed at the surface.

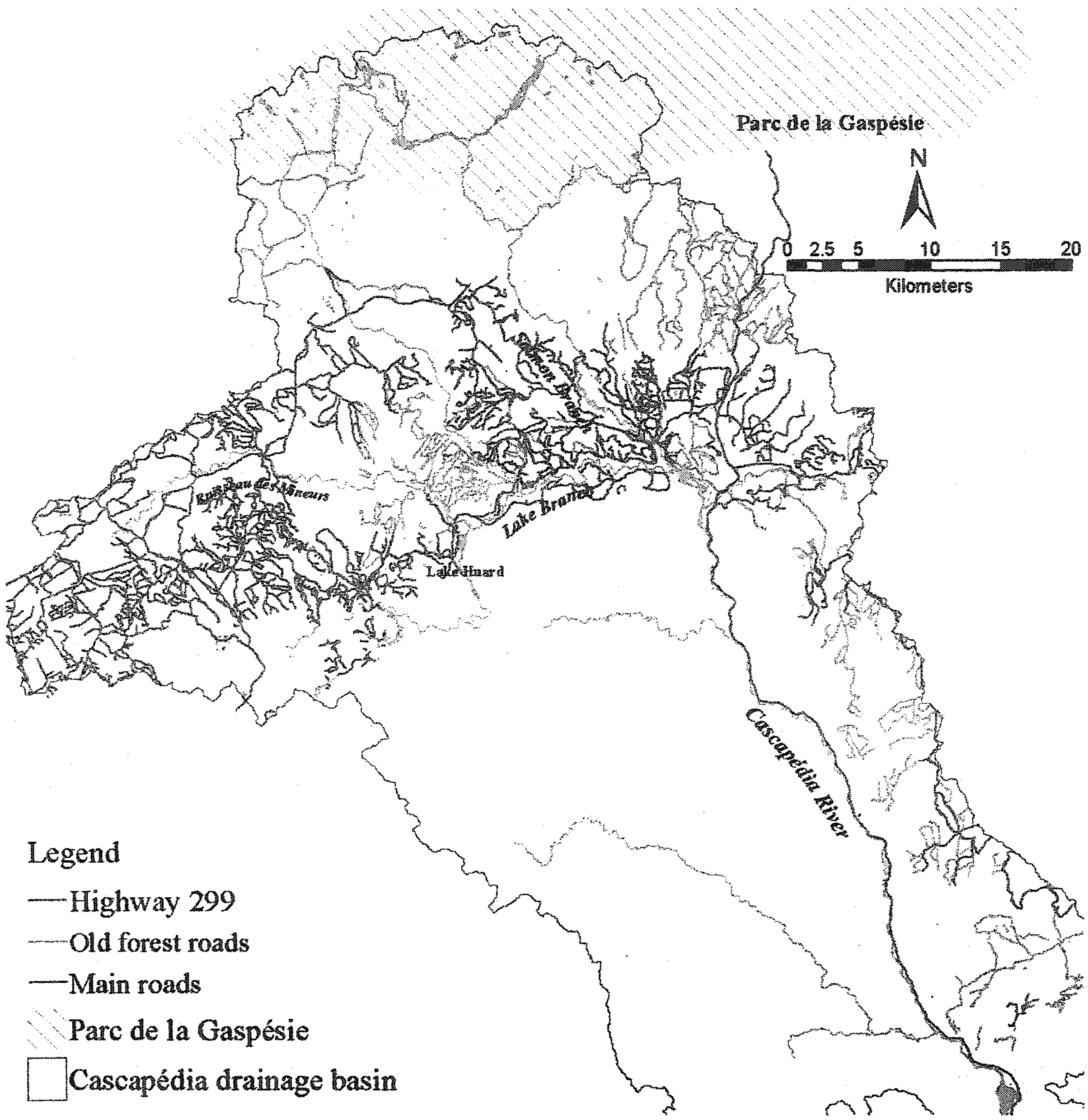


Figure 7. The spatial distribution of the road network within the basin showing both more heavily used main logging roads and relatively unused or old, forest roads.

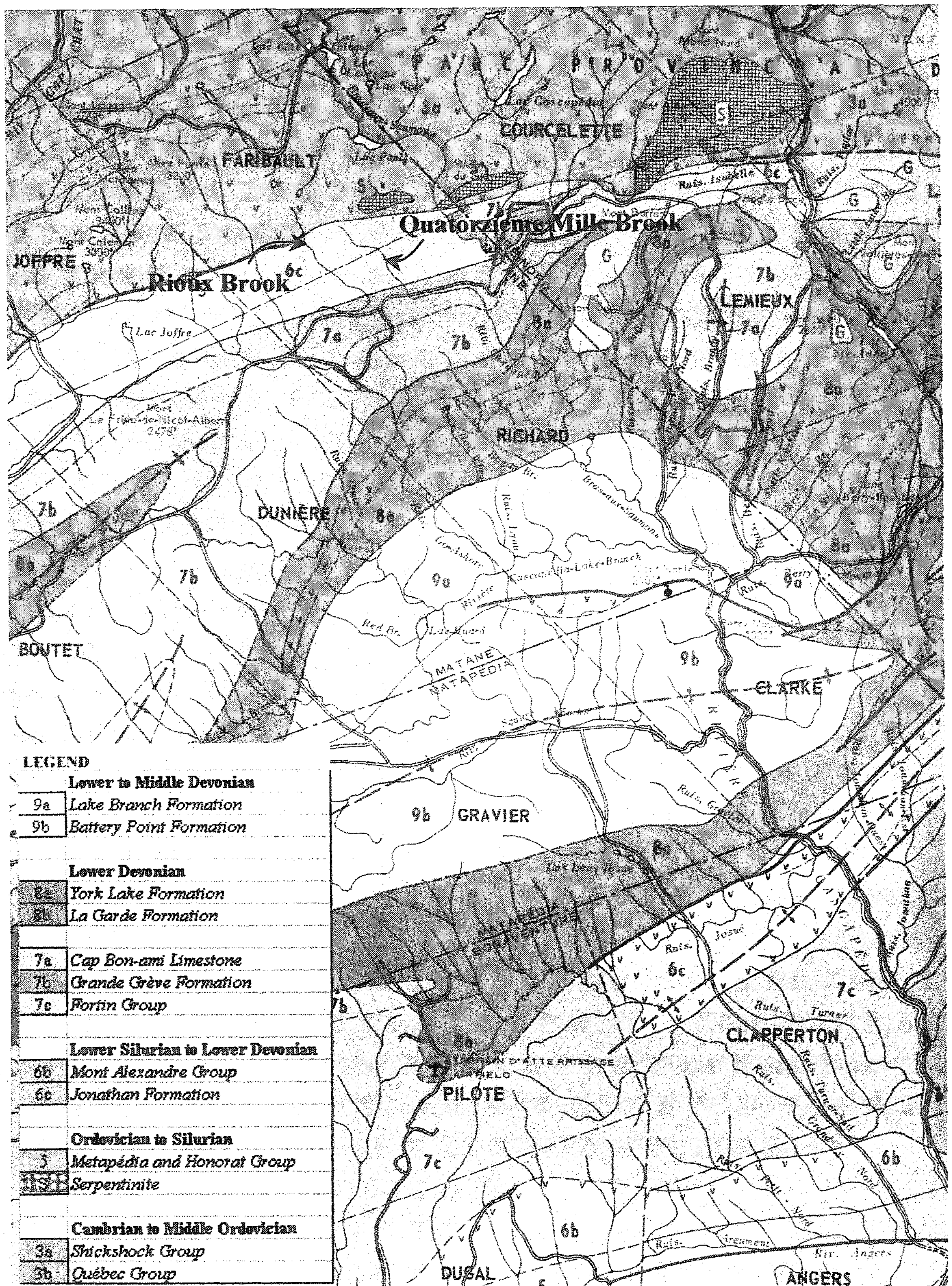


Figure 8. Geology of the Cascapédia River drainage basin, Gaspé Peninsula, Québec (adapted from Charbonneau, 1959).

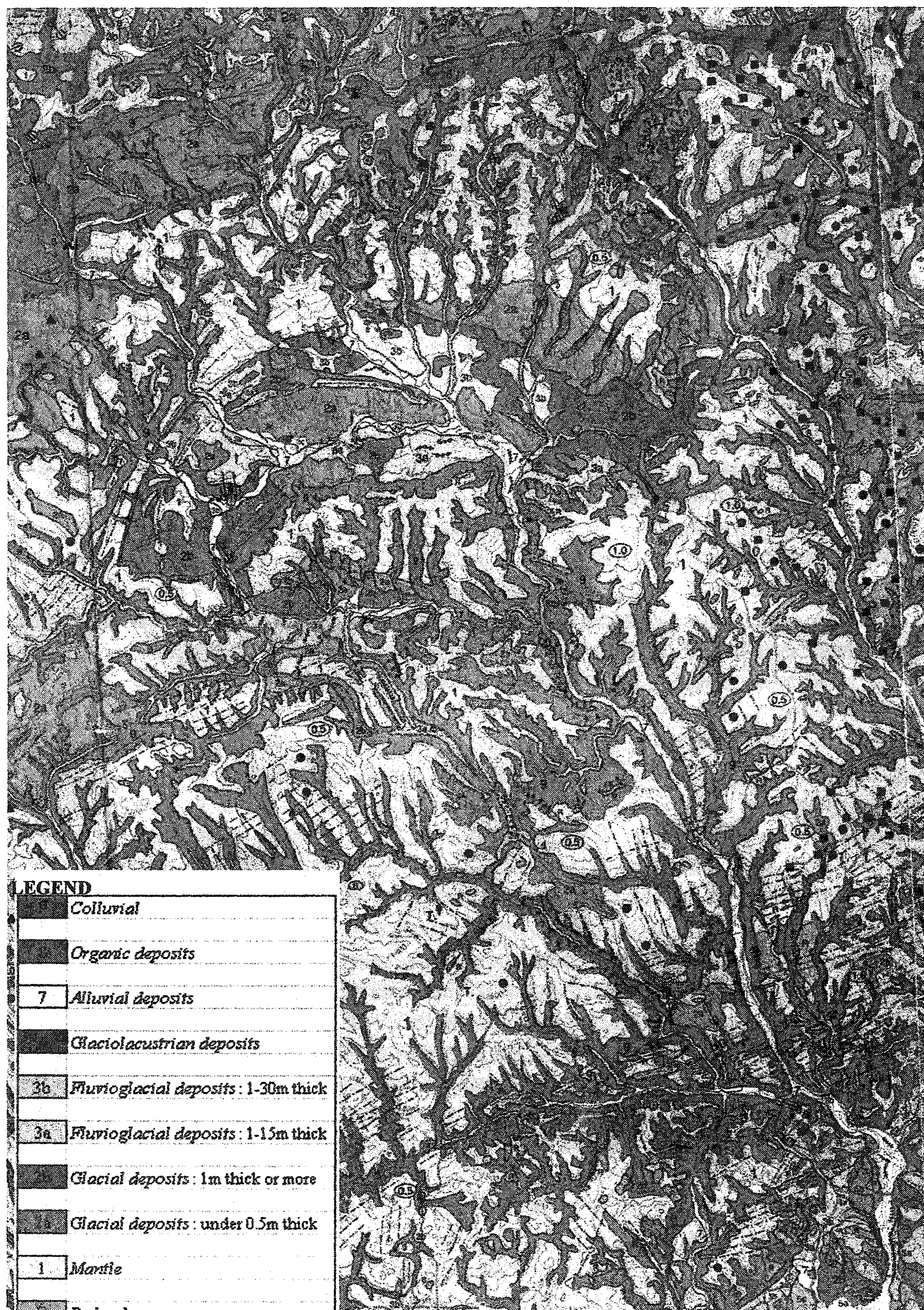


Figure 9. Surface deposits present within the Cascapédia River drainage basin, Gaspé Peninsula, Québec (adapted from Veillette *et al.*, 1989).

V. METHODOLOGY

V.1 Fieldwork: Physical Habitat Characterization

In order to examine the spatial distribution of suitable stream habitat for Atlantic salmon production, numerous quantitative habitat variables were measured in the field. Sample sites were situated on second to fifth order streams as defined from Québec series 1:20000 topographic maps (Gouvernement du Québec, 1994). Stream order is one system for classifying channel size with respect to position in the drainage basin. It is based on a system of links between tributaries where first order tributaries (the smallest mapped tributary) become second order tributaries when two first order links meet, and so on. The sites were selected in such way that they represent a range of cut intensities and catchment areas. This sampling strategy provides a means to distinguish between the physical variations that can be attributed to land use variables and those that can be attributed to the site's physiographic position within the basin. The database provided by the MNR included thematic coverage of the cutblocks (including dates and type of cutting), road networks, stream network and intersection of road surfaces with tributaries. Several layers of the GIS database were used as visual guides in the site selection process in order to identify potential access points to the tributaries, in both heavily disturbed and undisturbed areas as well as to identify potential reaches representative of various drainage basin areas.

At each site physical habitat variables related to habitat quality and morphology were sampled at summer low flow conditions along a reach lengths equivalent to 10-15 bankfull channel widths (Table 5). The metrics for evaluating habitat quality are based on the physical parameters surveyed in the field, which included measurements of width and depth at the assumed bankfull level, channel gradient, and various aspects of substrate composition. Some samples were collected during the summer of 2000, while the remainder were sampled during July and August 2001.

Table 5. Reach-scale habitat variables measured at, or calculated for each study reach.

Variable	Description
D_{16} SS	Diameter of 16th percentile of subpavement sample (mm)
D_{50} SS	Diameter of 50th percentile of subpavement sample (mm)
D_{84} SS	Diameter of 84th percentile of subpavement sample (mm)
D_{16} SUR	Diameter of 16th percentile of bulk pavement sample (mm)
D_{50} SUR	Diameter of 50th percentile of bulk pavement sample (mm)
D_{84} SUR	Diameter of 84th percentile of bulk pavement sample (mm)
% silt	Average percent of bulk subpavement samples under 63μm in diameter at a site
% sand	Average percent of bulk subpavement samples under 2mm in diameter at site
Sand index	Sand index for subpavement at site
D_{16} W	Diameter of 16th percentile from Wolman sample of pavement (mm)
D_{50} W	Diameter of 50th percentile from Wolman sample of pavement (mm)
D_{84} W	Diameter of 84th percentile from Wolman sample of pavement (mm)
Channel gradient	Water surface slope over a distance of approximately 10-15 channel widths
Bankfull width	Average bankfull width of channel cross-section (m)
Summer flow width	Average wetted width of channel cross-sections during summer (m)
Bankfull depth	Average bankfull depth of channel, taken from channel cross-sections (m)
Summer flow depth	Average depth of channel cross-sections during summer (m)

Channel form and gradient

At each site the dominant channel morphological type was described (based on Table 2), then measures of bankfull width, bankfull depth, summer low flow width and depths as well as reach water surface slope were taken (Figure 10). Bankfull levels were estimated visually primarily through shifts in vegetation type from riparian vegetation, such as alders, to predominately land vegetation, such as spruce or pine, through floodplain surfaces where existing, and through the presence of debris lines along the channel boundary, representing the highest level to which decomposing litter was carried by water. At each site a minimum of four cross-sections were surveyed to ensure an adequate representation. For each cross section a measuring tape was pulled level and taught across the channel to the bankfull level in order to determine the width. Measurements of bankfull channel depth and summer water depth were taken at 1 meter intervals across each section. Channel width was measured more easily and with greater precision than channel depth, for both bankfull and summer levels, given that a certain amount of slack always remained in the tape and that many of the reaches were boulder rich, making the depth measurements more variable. Channel gradient was measured at each site from the water surface slope using a standard engineer's level over the entire reach length.

Substrate characterization

Characterization of the reach substrate material was conducted using the bulk sampling measurement technique described by Church *et al.* (1987) using a flow-isolation chamber as described by Payne and Lapointe (1997). In well defined pool-riffle reaches, bulk samples were taken on the high velocity side near the channel centre over two successive riffles (Figure 10). In boulder-rapid reaches, where riffle the crest and thalweg were less easily defined, two samples were taken within gravel/cobble patches found near the channel centre. These samples were approximately 5 channel widths apart, a distance comparable to the sample spacing in the pool-riffle reaches. The bulk sample measurements were separated into pavement and subpavement layers; the pavement layer being the relatively coarse surface layer and subpavement being the bed material beneath, which is generally representative of the bedload (Parker and Klingeman, 1982). The boundary between the two layers was drawn at the depth of the largest surface grains within the flow-isolation chamber perimeter (Church, 1987). The presence or absence of periphyton and benthic organisms upon the substrate was likewise used to help distinguish between pavement and subpavement grains.

The pentagonal flow-isolation chamber was installed securely on to the surface of the substrate with a conical mesh facing downstream. The downstream mesh is made of Nytex material with 77 microns openings, which allows water to flow freely downstream, but traps the majority of the fine particles lifted into suspension as the substrate is extracted. The fine sands and silts lost through the permeable mesh or the underside of the chamber can subsequently be accounted for through the correction method suggested by Zimmerman *et al.* (submitted). The pavement stones, once identified, were removed from the sampling area both by hand and with a small shovel. The entire pavement sample was then weighed and sieved according to a grain scale based on a combination of half-phi and phi intervals (Table 6). As the pavement layers were relatively devoid of fines, the samples were not analysed below 8mm. The same procedure was then repeated for a representative 80-100kg subsurface sample, which was extracted from the centre of the flow-isolation chamber down to a depth of approximately 30cm, a value comparable to the maximum depth of Atlantic salmon spawning redds (Lisle, 1989; DeVries, 1997). The fine sediment fraction dislodged during extraction and trapped in the mesh cone was removed and added to the sample of subpavement stones. In order to quantify the fines below 16mm, a representative 1kg subsample was taken from the finest class sorted in the field. This 1kg sample was dried, weighed and sieved into finer classes in the laboratory and used to estimate the content of the finest categories for the entire bulk sample (Table 6).

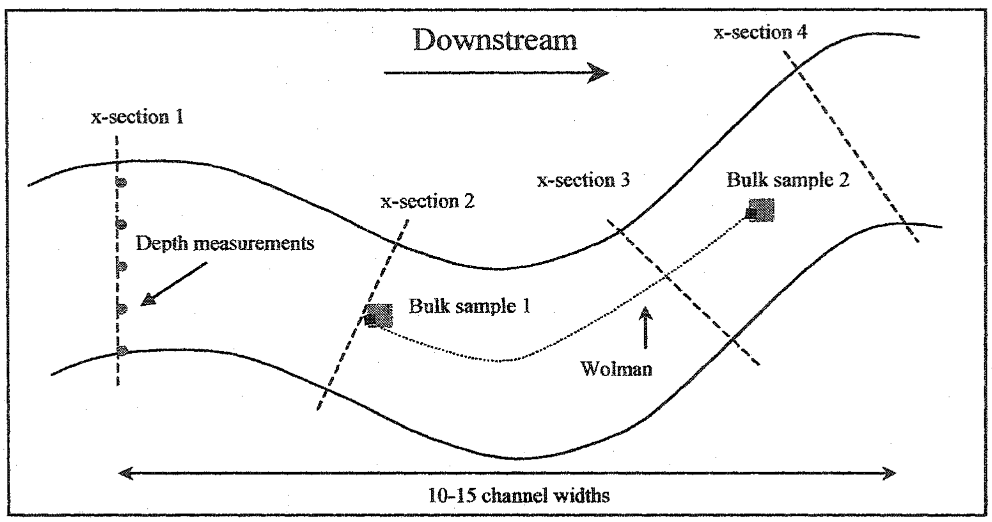


Figure 10. Diagram of reach measurements.

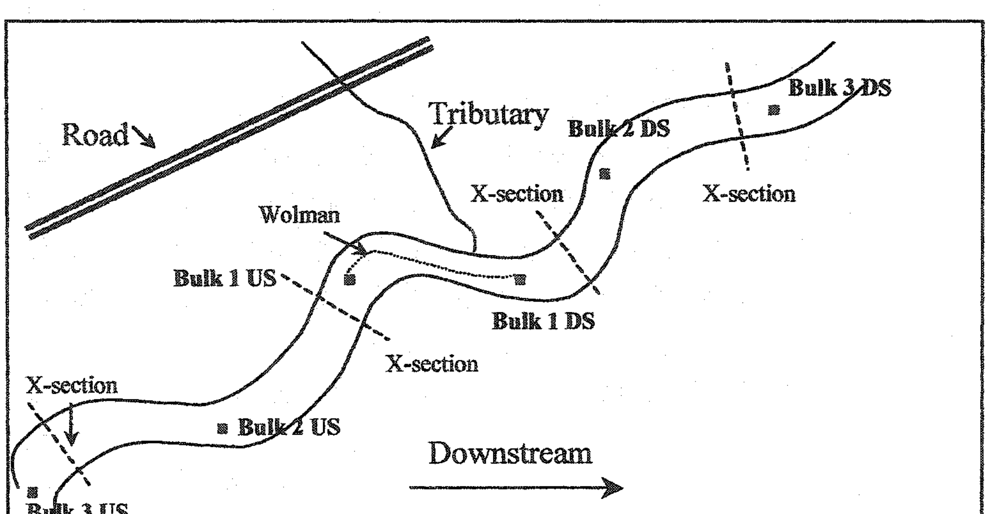


Figure 11. Diagram of reach measurements for intensively sampled Brandy 1A and 1B sites (US denotes upstream of tributary outlet and DS denotes downstream of tributary outlet).

The confidence associated with the substrate sampling technique can be improved by applying the correction factor suggested by Zimmerman *et al.* (submitted), who compared the technique used in this study with the freeze core technique used in other studies. Freeze coring, while more expensive and logistically complicated, provides a more accurate estimate of the finest size class fractions, while in contrast, bulk sampling provides a more accurate estimate of the largest size fraction. Both bulk sampling and freeze coring appear to accurately represent substrate sizes between 2mm and 11.2mm and therefore by combining the two methods a calibration can be performed to improve the estimates of the finest size fractions measured in this study, thereby providing an estimate of the fine sand and silt lost using the bulk sampling technique. Given that within this study it is the relative change in fine sediment levels between sites that are of primary importance, the uncalibrated silt and sand values are used throughout the thesis unless otherwise noted. A complete table of the grain size distribution at each site using the bulk sampling technique as well as the freeze core adjusted values is provided in Appendix 4.

Two different sites (Brandy 1A and 1B), where the nature of the road design was observed to be directing a substantial fine sediment load directly into a low order tributary of Brandy Brook, were identified and sampled more intensively (Figure 11). At these sites, to account for local variability, three or four bulk samples were taken on successive riffles, both upstream as well as downstream of where the concentration of fine sediments appeared to enter the channel.

In order to obtain a more complete representation of the channel bed surface, the grainsize composition of the pavement, which is important for benthic organisms in addition to flow resistance and flow competence calculations, was estimated using a variant of Wolman's technique (1954). One hundred rocks were sampled systematically along a 30 m transect along the centre of the channel at each site (Figure 10, 11). This measurement consisted of running a measuring tape along the centreline of the channel, selecting 100 stones at even 30cm intervals along the tape. The intermediate (b-axis) of each stone was measured and recorded in order to provide an estimate of the pavement D_{16}, D_{50}, and D_{84} of the reach.

Bankfull substrate mobility estimates

Energy estimates were then derived from the approximation of the pavement D_{50}, including τ_o, τ_{cr} and the mobility ratio. The critical shear stress (τ_{cr}) (in Pa) for each reach was approximately equal to the pavement D_{50} of the reach (in mm), while the mean shear stress at bankfull (τ_o) was estimated using equation 5 using mean bankfull depth (Bravard and Petit, 1997; Knighton, 1998). The ratio of τ_o/τ_{cr} was used to compare the relative mobility of the pavement between reaches.

Table 6. Combination of phi and half phi substrate size classes sampled.

Size class (mm)	Size class (phi)	Category	Substrate sampled	Sample location	Sample amount
<.063	4	Silt and clay	Subpavement	Lab	Approx. 1kg
.063-.125	3	Very fine sand	Subpavement	Lab	Approx. 1kg
.125-.25	2	Fine sand	Subpavement	Lab	Approx. 1kg
.25-.5	1	Medium sand	Subpavement	Lab	Approx. 1kg
.5-1	0	Coarse sand	Subpavement	Lab	Approx. 1kg
1-2	-1	Very coarse sand	Subpavement	Lab	Approx. 1kg
2-4	-2	Very fine gravel	Subpavement	Lab	Approx. 1kg
4-8	-3	Fine gravel	Subpavement	Lab	Approx. 1kg
8-16	-4	Medium gravel	Pavement & subpavement	Field	Approx. 100kg
16-32	-5	Coarse gravel	Pavement & subpavement	Field	Approx. 100kg
32-45	-5.5	Very coarse gravel	Pavement & subpavement	Field	Approx. 100kg
45-64	-6	Very small cobble	Pavement & subpavement	Field	Approx. 100kg
64-90	-6.5	Small cobble	Pavement & subpavement	Field	Approx. 100kg
90-128	-7	Medium cobble	Pavement & subpavement	Field	Approx. 100kg
128-256	-8	Large cobble	Pavement & subpavement	Field	Approx. 100kg
256>	<-8	Boulder	Pavement & subpavement	Field	Approx. 100kg

V.2 GIS Analysis: Landscape Characterization

V.2.1. Watershed delineation

Digital elevation model

The GIS analysis was built upon a 10mx10m resolution digital elevation model (DEM) supplied by the MNR covering the entire drainage area of the Cascapedia. The grid was derived from a triangular irregular network (TIN) originally generated by MNR technicians using ArcView 3-D Analyst from 10m contours from the 1:20000 digital base map with planimetric accuracyof +/- 4 meters, altimetric accuracy of +/- 2 meters and contour line accuracy of +/- 5 meters with 90% confidence (Gouvernement du Québec, 1999). In addition to the contour lines, the vector surface hydrology (lakes and large watercourses) and linear hydrology (smaller streams) were used to constrain the triangulation. However, no additional individual elevation points reflecting local maximum and minimum heights, or natural breakpoints were available. As a result, the highest elevations represented on the TIN and grid are flat plateaus equivalent to the highest contour line. This misrepresentation of the actual terrain with respect to the peaks should not introduce much error though, as the terrain is not exceptionally steep. This misrepresentation may, however, result in some over estimation and under estimation of the degree of the hill slope.

This "plateau effect" also occurs at the lowest elevations defining the stream bottom. The TIN interpolation method used by the MNR appears to concentrate the 10m changes in elevation over a short distance (approximately 100m) near the contour lines rather than smoothing the elevation change evenly over the entire distance between consecutive contour lines. The misrepresentation of the channel long profile in this manner limits the potential to accurately extract channel gradients over the ten to fifteen channel width-long reaches studied in the field. In order to assess the reliability of the DEM with respect to channel slope, the channel gradient measured in the field was compared to the channel gradient extracted from the DEM (Figure 12). As a result of the "plateau effect" mentioned above, estimates of the channel gradient extracted from the DEM over the exact distance that had been measured in the field were very poor and therefore the channel gradient at each stream site was instead extracted between two contour lines bordering the site upstream and downstream. Since the original digital contour lines were unavailable, the TIN was used to generate contour lines at 10m intervals (ESRI, 1996).

Estimation of the channel gradient from the DEM

In order to test the accuracy of the DEM with respect to the channel gradient, the field measurements of the gradient, taken over 10-15 bankfull channel width, were compared to the channel gradient extracted between contour lines from the DEM as well as directly from 1:20000 topographic maps (Gouvernement du Québec, 1994). The distance between the 10m DEM contour lines straddling the field sites ranged from 370m to 10300m, resulting in gradients between 2.6% and 0.1%, a range similar to the range of field measurements. The percent error between the two measurements, defined by $|(S_{Field} - S_{DEM})/S_{Field})|$ x100, ranges from 1.7% to 174%, with a mean percent error for all sites of 40%. Thus, on average, a 1% channel gradient measured in the field could be estimated from the DEM to be a channel gradient between 0.6% and 1.4%. The error between the two measurements is considerable, given the differences in habitat associated with such a range in channel gradients. The slope of the best-fit line in Figure 12 does not coincide with the slope of the 1:1 line (the slope of the regression line is significantly different from the slope of the 1:1 line, $p = 0.01$), suggesting that extraction of the channel gradient from the DEM will overestimate actual gradient for channels below a 1% gradient and will underestimate channel gradient where the gradient is greater than 1%.

The percent error between the field measurements and the channel gradient extracted from the contour lines of the topographic maps is considerably lower, ranging between 1.9% and 58% with an average percent error of less than 20%. While the channel gradients from the topographic maps are more accurate than those extracted from the DEM ($R^2 = 0.72$ and 0.51 respectively), the percent error is still such that the actual terrain could differ significantly from the channel estimates.

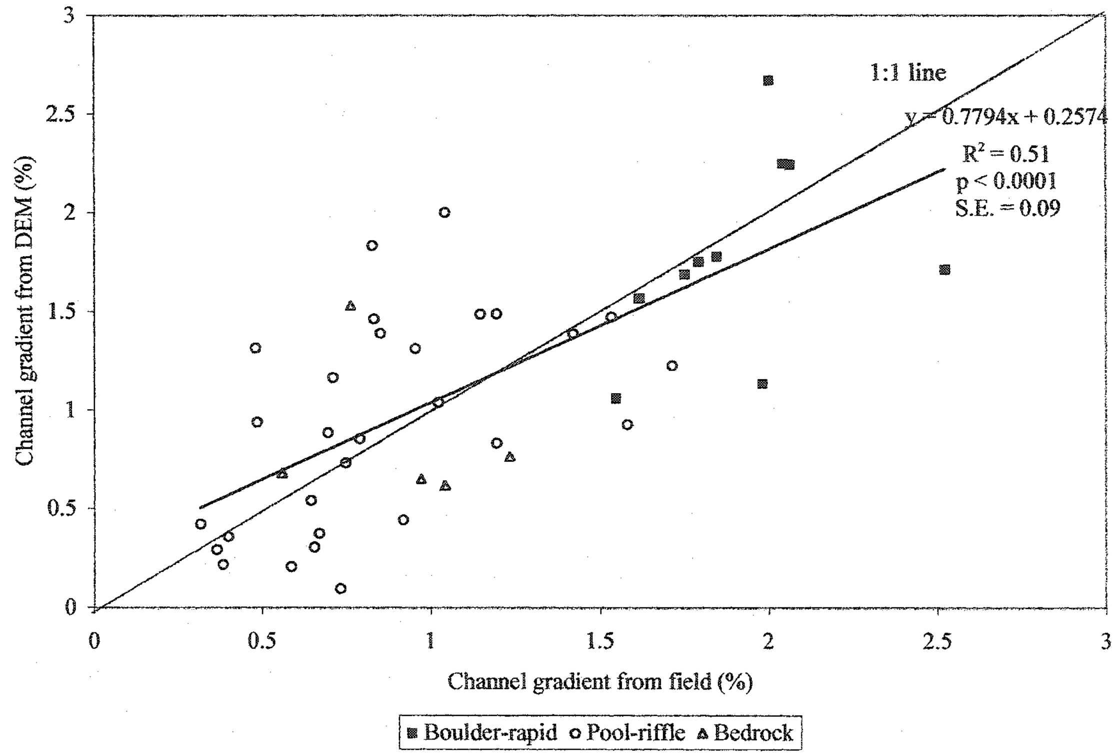


Figure 12. Comparison between field and DEM channel gradient measurements.

Additional analysis of the errors associated with both the remote sensing and GIS data manipulation (acquisition, processing, analysis, conversions, and final presentation), while they are important and may influence the resultant product to some degree, was beyond the scope of this project. As it was neither possible to measure error sources explicitly, nor to estimate the nature of error propagation throughout this project, the assessment of errors associated with the GIS data will therefore be limited to a theoretical discussion presented in section VI. 3.

Delineation of watershed boundaries

The DEM was pre-processed using the hydrological modelling extension created by ESRI for ArcView 3.2 (ESRI, 1996). This process involved correcting the original DEM by filling any sinks that may have existed and then calculating the flow direction and flow accumulation matrices for the filled DEM. The stream threshold definition for the creation of the stream grid was set at 500 grid cells (at 10 m resolution), as this threshold resulted in a stream grid that matched the detail of the vectorized stream file and the 1:20000 topographic maps (Gouvernement du Québec, 1994). Following the creation of the stream grid, the stream links were calculated, which can be used to calculate stream order. However in this case stream order had already been calculated manually from 1:20000 topographic maps. The precise locations of the field sites in the streams were captured with a handheld GPS with an accuracy of 10m. The field sites were re-projected into the same coordinate system as the thematic coverage (MTM-6 NAD 83) and converted to a grid file. The site grids were aligned with the stream grid and the watersheds were then delineated for all sample sites.

V.2.2. Estimation of landscape variables within the GIS

The raster watersheds were vectorized and their basin areas, mean slopes (the average degree of slope of all the grid cells within the entire watershed), mean elevations, elevation ranges, stream lengths and stream densities were calculated. From equation 4, assuming that bankfull discharge (Q_b) is proportional to basin area (A_d) (Equation 3, assuming p is equal to 1 and neglecting the constant γ), it is possible to define an index of hydraulic power per unit width of stream. For intercomparison purposes, a rough index of unit hydraulic power (*UHP*) at bankfull level was derived for each stream site from the calculation of basin area (A), the measured channel reach gradient and the average bankfull width measured in the field,

$$UHP = (A_d * S)/w \qquad (8)$$

Land use and land cover (LULC) variables were derived from an existing digital database of the MNR, which was digitized from 1994 1:20000 écoforestière maps (Gouvernement du Québec, 1994). The écoforestière maps are produced by the MNR based on photo-interpretation of aerial photos at the 1:15000 scale. They contain historical data on forestry parcels, including information about the origin, density, and height of trees, perturbations intensity, age classes, etc. within a forest parcel. The LULC data on these digital maps has subsequently been updated by the MNR to include the

1995-2000 cutblocks and roads (Brunelle *et al.*, 1998). All layers were projected in a common coordinate system (MTM-6 NAD 83), and were analysed in ArcView 3.2 as vectors. The calculation of all the LULC variables began with the intersection of the polygon land use coverage with each subbasin.

Cut intensity

In order to determine the equivalent percentage cut of each basin these intersected polygons were dissolved based on the attenuation factor (AF) (defined in section IV. 2.). Dissolving numerous polygons based on an attribute removes the boundaries between contiguous polygons that have the same value for the specified attribute (ESRI, 1996), thereby reducing boundaries between polygons that are redundant. The total area of the newly dissolved polygons were then calculated and multiplied by the attenuation factor (i.e. an area with AF=85 was multiplied by .85). The sum of the attenuated areas within a basin is the basin's equivalent area cut (EAC). Dividing the EAC by the actual total area of the basin and multiplying by 100 yields the effective percentage cut of the basin.

Road networks

Analysis of the forestry roads likewise began by overlaying the road network layer on each subbasin and calculating the total length of roads per subbasin and the road network density per subbasin, which is defined as the total road length divided by the basin area. In order to refine the analysis of the impact of the roads, the roads layer was reclassified to include only large, main roads accessed by logging trucks or other large vehicles. According to the MNR, these are the roads classed within the database as primary permanent roads giving access to the forests and secondary roads where heavy trucks may pass, but at reduced speeds (Ordre des ingénieurs forestiers du Québec, 1996). These roads are built up with a thick gravel layer and range in width from 6 to 10 meters. These primary and secondary roads were classified together as permanent-drivable gravel roads to distinguish them from all other smaller roads and trails and winter roads, which were reclassified as old forest roads, undrivable by logging trucks.

The principle reason for this reclassification is that calculation of road network densities based on the initial road network showed no great difference in densities between the park areas and the heavily logged areas. This uniformity is misleading and misrepresentative of reality; the parks and less harvested areas have only old small roads, tracks or trails that are not easily driven by car. These roads are bordered by trees, are used infrequently, and are very often not maintained, thus they are overgrown with vegetation. The primary and secondary roads, by comparison, are easily twice as large, are used extensively by heavy vehicles, have large, deep open ditches along their margins and are maintained by regraveling and removal of vegetation. It was therefore essential to distinguish small roads that can only be used by 4-wheelers from roads that can and are used by logging trucks, as their ability to contribute fine sediment to nearby streams is greater based on the traffic intensity and interruption of drainage (Wooldridge, 1979; Reid and Dunne, 1984; Luce and Black, 2001).

The reclassed main road network was then overlaid on each subbasin layer, and the total main road length and density per basin were calculated. The total road area per basin was calculated from the total road length per basin and the average drivable road surface width of 11m (from a range of 10-12 m) (Ordre des ingénieurs forestiers du Québec, 1996). Additional road metrics were derived from the intersections between streams and roads, including the number of main road-stream intersections per basin, the number of main intersections within a 1km and 5km radius upstream of each sample site and the distance to nearest upstream main intersection (Table 7). The intersections within 5km upstream of a sample site were examined further by calculating the road slopes represented by the DEM over a distance of 100m on both sides of every stream crossing. Within each basin, every sampled road section with a slope greater than 5% was manually located and tallied.

Additional scales of analysis

Riparian ecotones were analysed for each subbasin using buffer analysis, which is a technique used to delimit a zone of a user specified distance around a particular feature, in this case, the stream network (ESRI, 1996). This was done by calculating a 60m riparian corridor extending laterally along both sides of the stream for the entire upstream distance of each basin. The corridor was set at 60m as this distance is greater than the minimum width of the land use data (30m), it is the maximum band of vegetation required by the Québec Forest Act required on salmon rivers (Gouvernement du Québec, 1996) and it is close to the corridor widths used by other authors (Richards *et al.*, 1996; Lammert and Allen, 1999). The landscape data was then overlaid on the subbasin 60m corridors and the LULC and geology-structure metrics were recalculated for the riparian corridor (Figure 13). In order to isolate the effects of the proximal landscape variables (Lammert and Allen, 1999), a subsection of the riparian corridor that extended longitudinally 1km upstream from each sample site was isolated. Finally, the percentage cut and main road density within a 1km upstream radius from each sample site were calculated for each basin. The four spatial scales of analysis considered here therefore include: the whole catchment for a sample reach (1), the riparian corridor for the full extent of the catchment (2), the local 1km riparian sub-corridor (3), and the local basin within a 1km radius (4) (Figure 13). Table 7 shows a list of all metrics calculated for each basin at the various spatial scales.

Surface and bedrock geology

A detailed digital geology map of the region at the same spatial scale as the land use data was not available, therefore a paper map of bedrock geology (Carbonneau, 1959) was used to provide insight into the surface lithologies of the region (Figure 8). The 1:63360 scale map was scanned and rectified and the boundary of the Lake Branch formation was digitized manually in ArcView as a polygon. The same procedure was repeated for a 1:250000 scale map of surficial geology (Veillette *et al.*, 1989) (Figure 9), however, only the distinct boundary between the easily erodable fluvioglacial and glacial deposits and less erodable regolith and bedrock was digitized.

Table 7. Landscape and land use metrics calculated for each subbasin at various spatial scales; the whole catchment (1), the riparian corridor for the full extent of the catchment (2), the local 1km riparian sub-corridor (3), and the local 1km radius (4).

Variable type	Metric	Attribute	Scale
Geology/landscape structure	Mean elevation	Mean elevation of the zone (m)	1,4
(non-anthropogenic)	Elevation range	Difference in elevation between highest and lowest points within zone (m)	1
	S.D. of local elevation	Standard deviation of elevation within 1km upstream radius of site (index of topographic heterogeneity)	4
	Mean slope	Mean slope of the zone (degrees of slope) (zone 2, 3 estimate of degree of valley bottom incision)	1,2,3
	Area	Total area of the zone (m^2)	1,2,3,4
	Stream order	Stream order at site (from 1:20000 Québec series topographic maps)	1
	Stream length	Length of streams per basin (m)	1
	Stream density	Density of streams per basin (km/km^2)	1
	Index of stream power	An index of stream power based on basin area and topographic reach slope	1
Land use	Effective percent cut	Effective percent cut of zone based on attenuation factors (%)	1,2,3,4
(anthropogenic)	Road density	Density of roads per zone (km/km^2)	1,2,3
	Main roads density	Density of main roads per zone (km/km^2)	1,2,3,4
	# intersections	Total number of intersections between all roads and streams within zone	1,4
	# main intersections	Total number of intersections between main roads and streams within zone	1,4
	Main road area	Total road area per zone (km^2) based on average road width of 11m	1
	Distance to nearest main intersection	Distance from sample site to nearest main intersection (m)	4
	Steep road crossings	Number of 100m road segments with slopes greater than 5% crossing a tributary within 5km of site	4

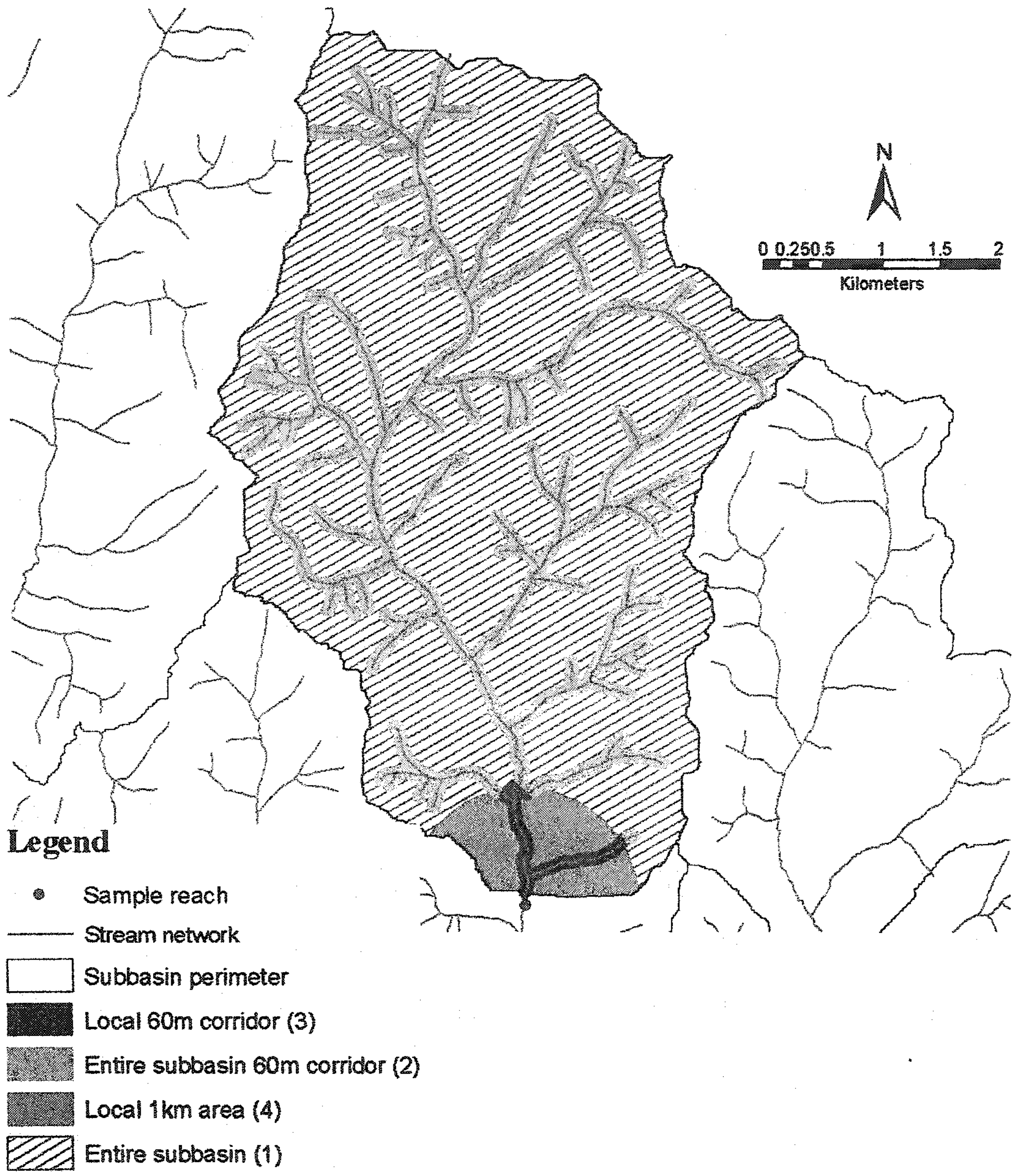


Figure 13. An example of the four spatial scales of analysis: the whole catchment (1), the riparian corridor for the full extent of the catchment (2), the local 1km riparian sub-corridor (3), and the local 1km radius (4).

V. 3. Statistical Analysis

Bankfull and summer flow width and depths taken from the four cross-sections were averaged for each site. Sample pairs of substrate composition at each site were averaged, except at the two sites (Brandy 1A, 1B), where six to eight bulk samples were performed at both sites, for which the median values were used, as the median is unbiased by extreme values. This resulted in a total of 48 sites with values of substrate composition (surface Wolman, bulk pavement and subpavement), bankfull and summer flow width and depth as well as channel slope. The data set also included derived site variables such as indices of unit hydraulic power, shear stresses, and substrate mobility ratios. Multiple linear regression and simple linear regressions were then performed in order to examine the relationships among these geomorphic stream habitat variables as well as to investigate the relative influences of geology-structure and LULC landscape variables on geomorphic habitat variables.

The relationships examined within this study can only address spatial sources of variance between sites. In addition to between site variance, the sedimentation data also reflect within site and sampling variance. The contribution of the distinct sources of variance were evaluated in order to remove any error within the fine sediment measurements that may have been introduced due to sampling inaccuracies. A total of seven sites out of 48 had an absolute difference in sand content among the pair of successive riffle subpavement values greater than one standard deviation (6% sand content) from the mean absolute difference for all sites. For five of these seven sites, the high local variance could be explained by the proximity of the substrate sample to an obstruction (i.e. log jams or bridge), while for the remaining two, the variance could not be explained. Nevertheless, all seven sites with a percent sand difference between the two samples greater than 6% were removed from the analysis due to their high local variability. For the remaining sites, the average absolute difference in sand content between the two samples is 2%.

The same procedure was repeated for observed silt. The average absolute difference in silt content between two riffle measurements was considerably lower (0.03%). The only two sites with absolute differences greater than one standard deviation from the mean absolute difference were the multi-sampled Brandy sites. At these sites, the median value was used rather than the average, and therefore no sites were removed from the analysis.

A spearman rankwise coefficient matrix was generated in order to assess the correlations among both landscape and land use variables at all four spatial scales of analysis across all 48 sites. Landscape metrics with correlation coefficients greater than 0.6 were considered highly correlated and therefore redundant variables. Thus, such variables were not entered into multiple regression analysis simultaneously (Tabachnick and Fidell, 1989).

VI. RESULTS – THE INFLUENCE OF CHANNEL AND VALLEY GEOMORPHOLOGY ON THE SPATIAL DISTRIBUTION OF STREAM HABITAT VARIABLES

VI. 1. Inter-correlation of reach-scale stream habitat variables

Given that Atlantic salmon typically spawn within pool-riffle reaches and appear to avoid steeper boulder-rapid reaches (Mills, 1973; Moir *et al.*, 2002), it is important to differentiate between stream habitat variables associated with pool-riffle morphologies and other reach morphology types. There is no sharp threshold in nature defining an abrupt transition between different reach morphologies. Rather, the transition is a gradual one as the characteristics corresponding to one reach type become the dominant features defining the reach. Our field classification of the reach morphologies, based on the classification scheme described in Table 2, revealed two dominant alluvial reach types in addition to bedrock controlled reaches. The first section of this chapter will explore how the various stream habitat variables measured at the reach scale are inter-correlated and how they may be used to distinguish pool-riffle and boulder-rapid systems. The second section of this chapter will examine the effect of basin-scale geology-structure variables on the distribution of physical habitat variables. The effects of forestry perturbations on the physical habitat variables are the subject of chapter VII.

VI. 1. 1. Cross-sectional channel morphology

Channel width and depth estimates provide preliminary insight into the relative amount of habitat available within the various sample reaches, while at the same time are related to the likelihood of a reach being classified either pool-riffle or boulder-rapid . The average bankfull channel widths ranged between 5.7m and 46.9m (Table 8). The mean bankfull width for all sites sampled in this study is 25.8m. Surveyed summer flow widths, in comparison were as narrow as 2.5m and reached a maximum of 26m. The relationship between summer flow width and estimated bankfull widths is shown in Figure 14. While there is some overlap of bankfull and summer flow widths between pool-riffle and boulder-rapid reaches, the average cross-sectional widths of pool-riffle reaches within the Cascapédia drainage basin are significantly larger than for boulder-rapid reaches ($p = 0.001$ and 0.006 for bankfull and summer widths respectively). Figure

14 suggests that pool-riffle reaches begin to develop in alluvial substrate once bankfull widths exceed 8m and are the dominant channel type where bankfull widths exceed 10m.

The average ratio of summer flow width to bankfull width for both boulder-rapid and pool-riffle reaches is 0.55 (Table 8), thus on average the percent reduction in width for the reaches sampled is 45%. The percent reduction is, however, somewhat dependent on the time at which the reach width was measured. Figure 15 shows a significant correlation ($R^2 = 0.55$) between the date of sampling and the percent reduction in width observed at a site. Within the study area, the latter part of June and the beginning of July are generally much wetter months in terms of precipitation levels (Government of Canada, 2002), the summer of 2001 being no exception. During the first few weeks of sampling the streams were slightly higher than they were during the last weeks, resulting in a noticeable difference between estimated bankfull widths and actual available wetted habitat.

Channel depth varied considerably within each sample reach, thereby making it difficult to distinguish a mean bankfull depth corresponding to a transition between pool-riffle and boulder rapid reaches. The mean bankfull depths are not significantly different between pool-riffle and boulder-rapid reaches ($p = 0.31$). Bankfull mean depths ranged between 0.32 m and 0.98 m. These values do not, however, include a few of the deepest pools (depth > 1.5m), as we were unable to record them using our methods. Such deep pools were very uncommon ($n < 5$), thus it is unlikely that our underestimation of the absolute maximum (by positioning the cross-section just upstream or just downstream) would substantially alter the average depth measurement for the reach.

Unlike mean bankfull depths, summer flow depths are significantly different between pool-riffle and boulder-rapid reaches ($p = 0.04$). The mean summer depth for pool-riffle reaches is 0.27m and the mean summer depth for boulder-rapid reaches is shallower at 0.20m. The average ratio of summer flow depth to bankfull depth is 0.41, corresponding to an average percent reduction in depth of 59%. The relationship between the percent reduction in depth from bankfull levels and the time of the sampling is much weaker than for width ($R^2 = 0.07$). Given the gentle angle of the majority of the stream banks, a small increase in discharge can result in a considerable increase in channel width, which can be measured more accurately than the corresponding small increase in channel depth.

Table 8. Statistics of physical habitat variables measured or calculated at each site.

Variable	Number of sites	Mean	Minimum	Maximum	Standard deviation
D_{16} Subsurface (mm)*	44	5.58	1.80	16.58	3.68
D_{50} Subsurface (mm)*	44	41.80	9.44	98.33	21.53
D_{84} Subsurface (mm)*	44	99.14	37.47	194.85	35.40
D_{16} Surface (mm)*	44	63.80	14.96	122.57	19.52
D_{50} Surface (mm)*	44	98.35	37.97	170.85	26.52
D_{84} Surface (mm)*	44	145.28	67.35	224.84	44.17
% silt (< 0.063mm)*	44	0.114	0.001	0.569	0.104
% sand (<2mm)*	37	8.121	0.918	17.128	3.647
Sand index*	37	0.307	0.027	0.703	0.158
D_{16} Wolman (mm)	45	33	10	120	18
D_{50} Wolman (mm)	45	73	20	210	31
D_{84} Wolman (mm)	45	163	40	620	94
Channel gradient (%)	46	1.15	0.31	2.52	0.59
Bankfull width (m)**	46	14.51	5.70	46.93	9.86
Summer flow width (m)**	24	6.53	2.50	26.00	4.61
Ratio of summer to bankfull width	24	0.55	0.29	0.72	0.12
Bankfull depth (m)**	42	0.59	0.33	0.98	0.13
Summer flow depth (m)**	24	0.25	0.09	0.44	0.09
Ratio of summer to bankfull depth	24	0.41	0.19	0.89	0.15
Ratio of maximum to mean depth	42	1.81	1.30	3.91	0.48
Width/depth ratio	42	23.0	9.1	61.1	13.3
Critical shear stress (Pa)	45	73	20	210	31
Bankfull shear stress estimate (Pa)	42	65	18	147	33
Bankfull sediment mobility ratio estimate	42	1.00	0.31	2.88	0.53

* average of 2 bulk samples

** average of 4 cross-sections

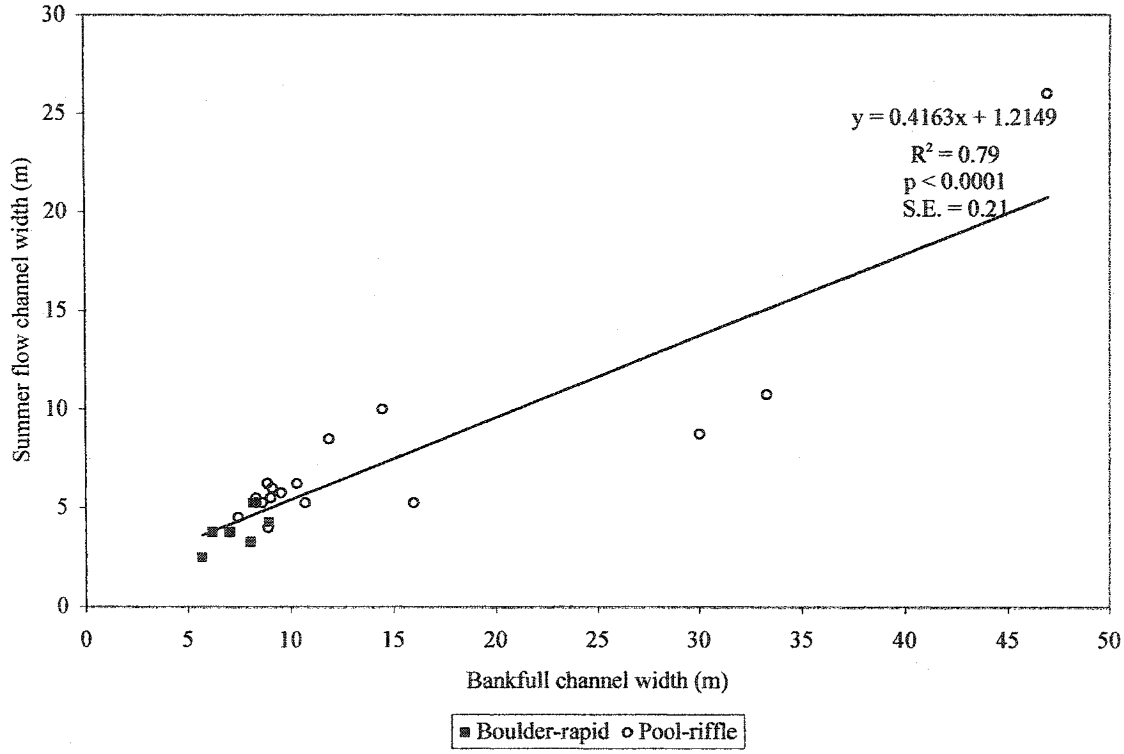


Figure 14. Relationship between bankfull channel width and summer flow width.

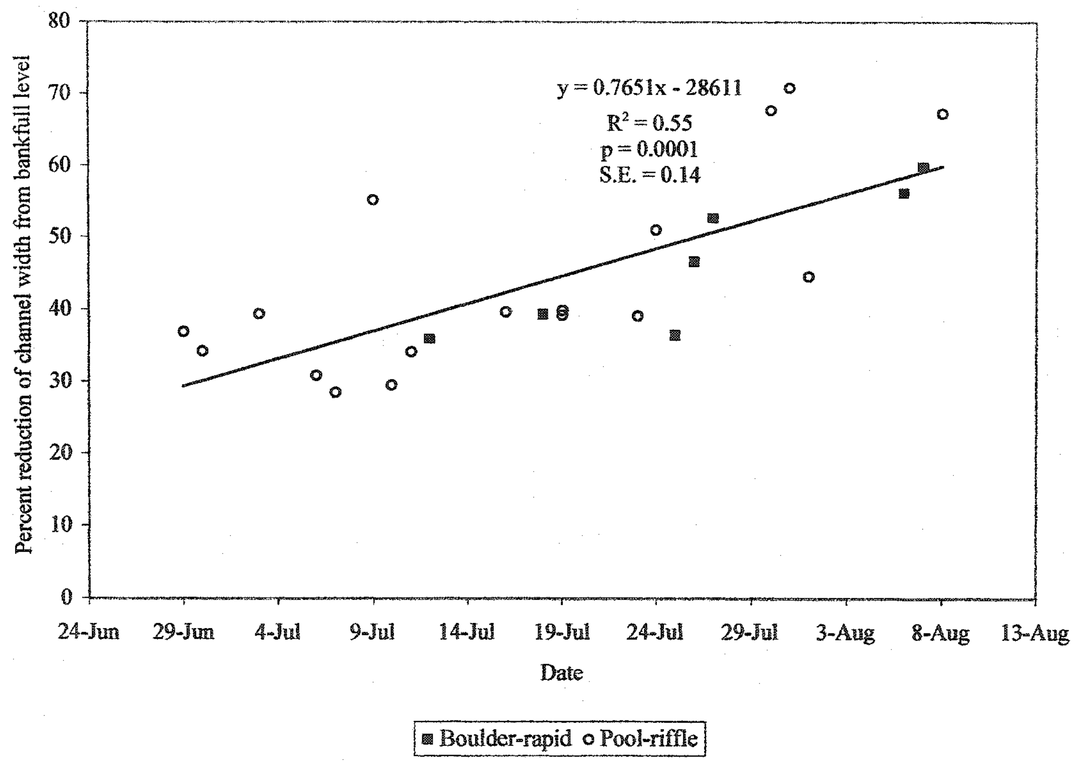


Figure 15. Correlation between timing of sampling and the percent reduction in channel width observed at a site.

VI. 1. 2. Channel gradient and grainsize distribution

Channel gradient

Within the study basins, the transition between the two dominant reach morphologies is associated with changes in the measured channel gradients. Topographic reach gradient ranged from 0.3% to 2.5% over the channel reaches sampled, with the majority of sites slopes falling within the range of 0.7% to 1.7% (Table 8). The transition between pool-riffle and boulder-rapid occurs where the local channel gradient is between 1.5% and 1.7%. Reaches with channel gradient under 1.5% were all pool-riffle reaches, while channel gradients over 1.7% corresponded with boulder-rapid reaches, with the exception of the bedrock reaches. Figure 16 shows a box and whisker plot of the channel gradient for both pool-riffle and boulder-rapid reaches. The channel gradients of the two morphological types are significantly different (0.79% and 1.91% respectively, $p < 0.00001$).

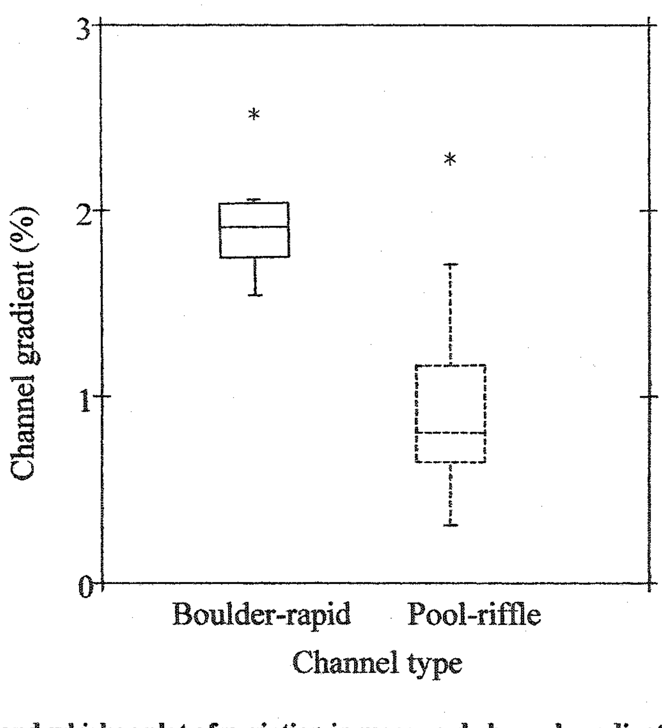


Figure 16. Box and whisker plot of variation in measured channel gradients for both pool-riffle and boulder-rapid study reaches. The middle line within the box represents the median, the box boundaries are the median of each half of the data, the whiskers are 1.5 times the interquartile range and the stars are less than 3 times the interquartile range (Wilkinson et al., 1992).

Pavement composition

The substrate surface layer composition varied considerably between sites (Table 8). The coarser fraction of the pavement (D_{84}) measured from the Wolman sample ranged between 40mm and 620mm, while the finer fraction of the pavement (D_{16}) ranged between 10mm and 120mm, and the overall average surface stone measured 73mm. The median diameter of the pavement at a site ranged between 20 and 210mm, the latter value corresponding to a particularly coarse bedrock reach. Figure 17 shows the spatial distribution and variations in the pavement D_{50}. Figure 17 suggests that median pavement diameter is coarsest in the Salmon Branch and that the pavement in Salmon Branch tributaries are generally coarser than in the Lake Branch tributaries.

While there is but a weak, though significant, statistical relationship between the channel gradient and the Wolman median surface diameter in general ($R^2 = 0.16$, $p = 0.008$) (Figure 18), there is a small, but significant increase in median bed surface coarseness above a channel gradient of 1.7% ($p = 0.07$) (Table 9). Therefore, in addition to steeper gradients, boulder-rapid reaches also, on average, exhibit a slightly coarser pavement layer. Section VI.2. 3. of this chapter will show how the median pavement diameter is more accurately predicted by a metric combining both basin area and the local channel gradient.

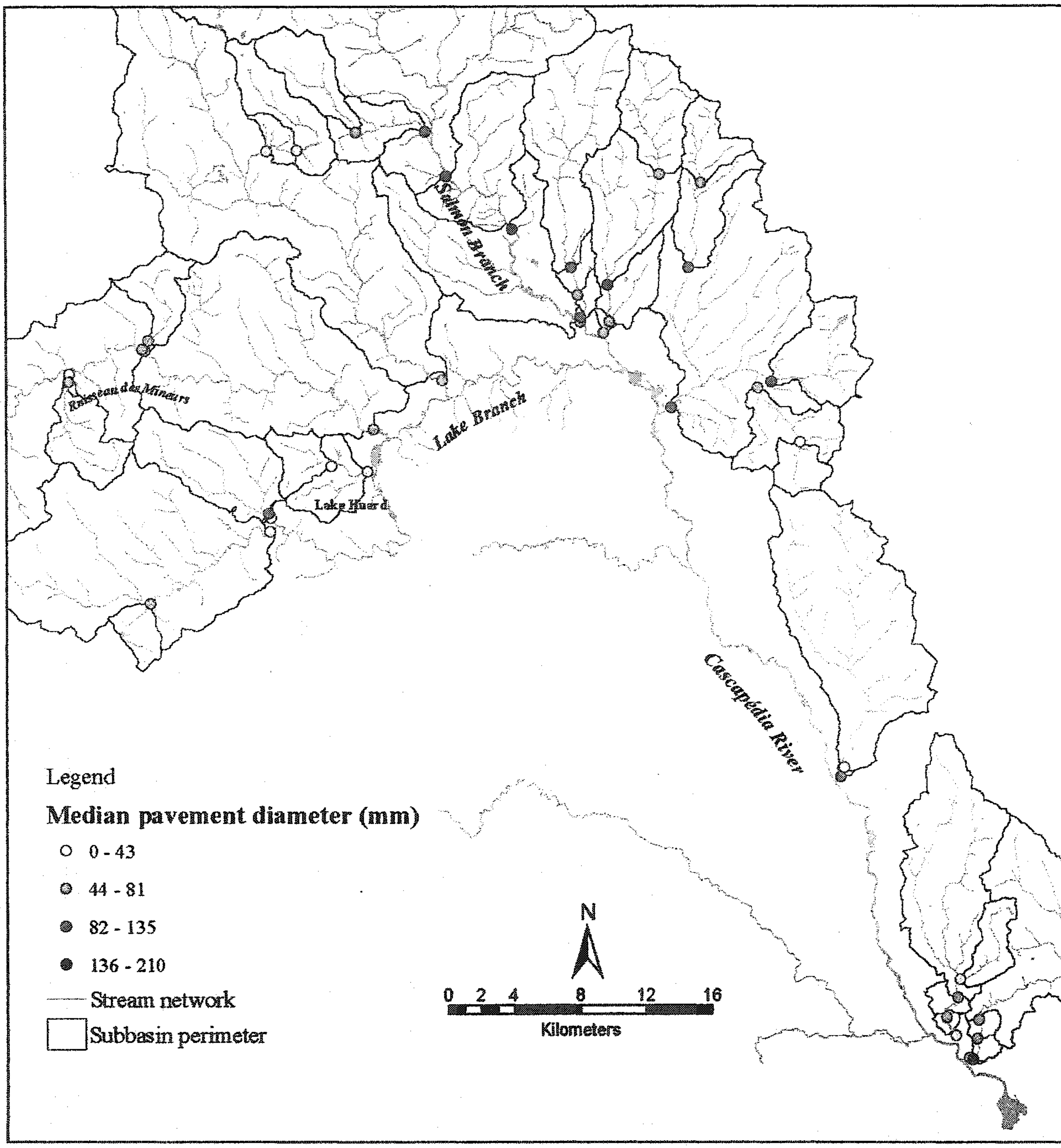


Figure 17. Spatial distribution of the pavement D_{50} of the sample reaches.

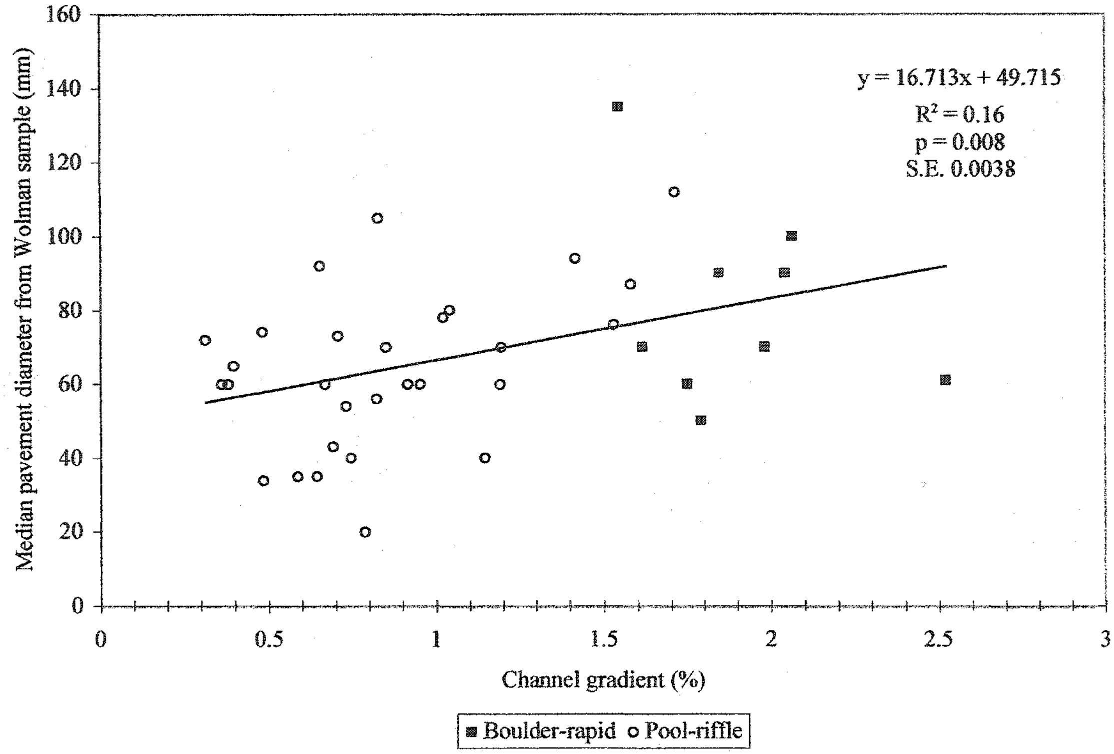


Figure 18. Variation in median pavement diameter with increasing channel gradient.

Table 9. Surface coarseness in relation to channel gradient. D50 and D84 values taken from Wolman pavement sample.

	Average D_{50} (mm)	Median D_{50} (mm)	Average D_{84} (mm)	Median D_{84} (mm)
Gradient > 1.7% (n = 10)	81.4	87.5	189.2	167.5
Gradient < 1.5% (n = 32)	68.1	60.0	148.9	132.0
T-test p-value	0.069	-	0.095	-

Bed surface sediment mobility estimates

Assuming that τ_{cr} (Pa) ≈ D_{50} (mm), it is possible to estimate the critical shear stresses required for entrainment from the D_{50} of the pavement (Knighton, 1998). Using this simple deterministic model, the critical shear stresses in the reaches sampled would range between 20 and 210Pa. The mean shear stresses at bankfull (Equation 5) were estimated to be as low as 18 and as high as 147Pa. Over the small range in bankfull depths within the study reaches, the local shear stresses are more directly controlled by variations in the channel gradient (Figure 19). Given that boulder-rapid reaches have higher channel gradients than pool-riffle reaches, they have considerably higher local shear stresses and are therefore capable of entraining particles. The average local shear stress for the boulder-rapid reaches is 104 Pa, and is significantly greater than the average of 51 Pa for the pool-riffle reaches ($p < 0.0001$).

The ratio between the local shear stresses and the critical shear stresses required for entrainment provides an indication of the relative mobility of the bed surface, which, on average for the reaches sampled, is equal to one. This implies that the flow at many of the sites, when at bankfull level, would be just capable of entraining the median pavement stone, and at many sites could entrain stones larger than the D_{50} (Table 8). Figure 20 shows the spatial distribution of the reaches with high and low sediment mobility at bankfull level flows. Mobility tends to be greater in headwater reaches, suggesting as expected that they are supply-limited for mobile cobble-boulders. In contrast, the lower reaches tend to have lower sediment mobility, suggesting that they are transport-limited The distribution of reaches with highly mobile sediment can be explained in part by the channel gradient (Figure 21). Figure 21 shows the variation in sediment mobility between boulder-rapid and pool-riffle reaches as a function of channel gradient. The steeper boulder-rapid reaches have higher shear stresses ($p = 0.00002$) (Figure 19) and are significantly more mobile than the pool-riffle reaches ($p = 0.004$) (Figure 21).

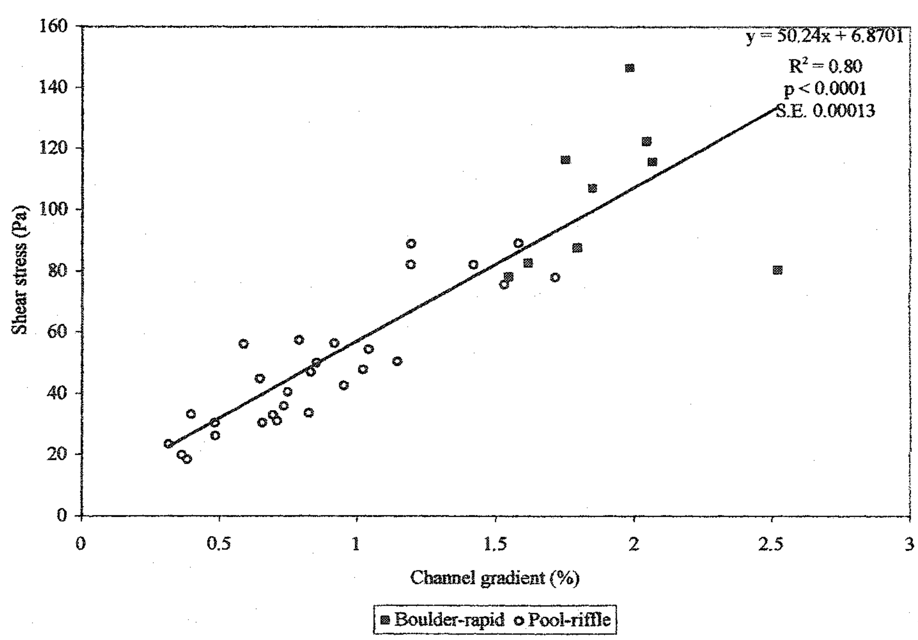


Figure 19. Relationship between channel gradient and estimated bankfull shear stress.

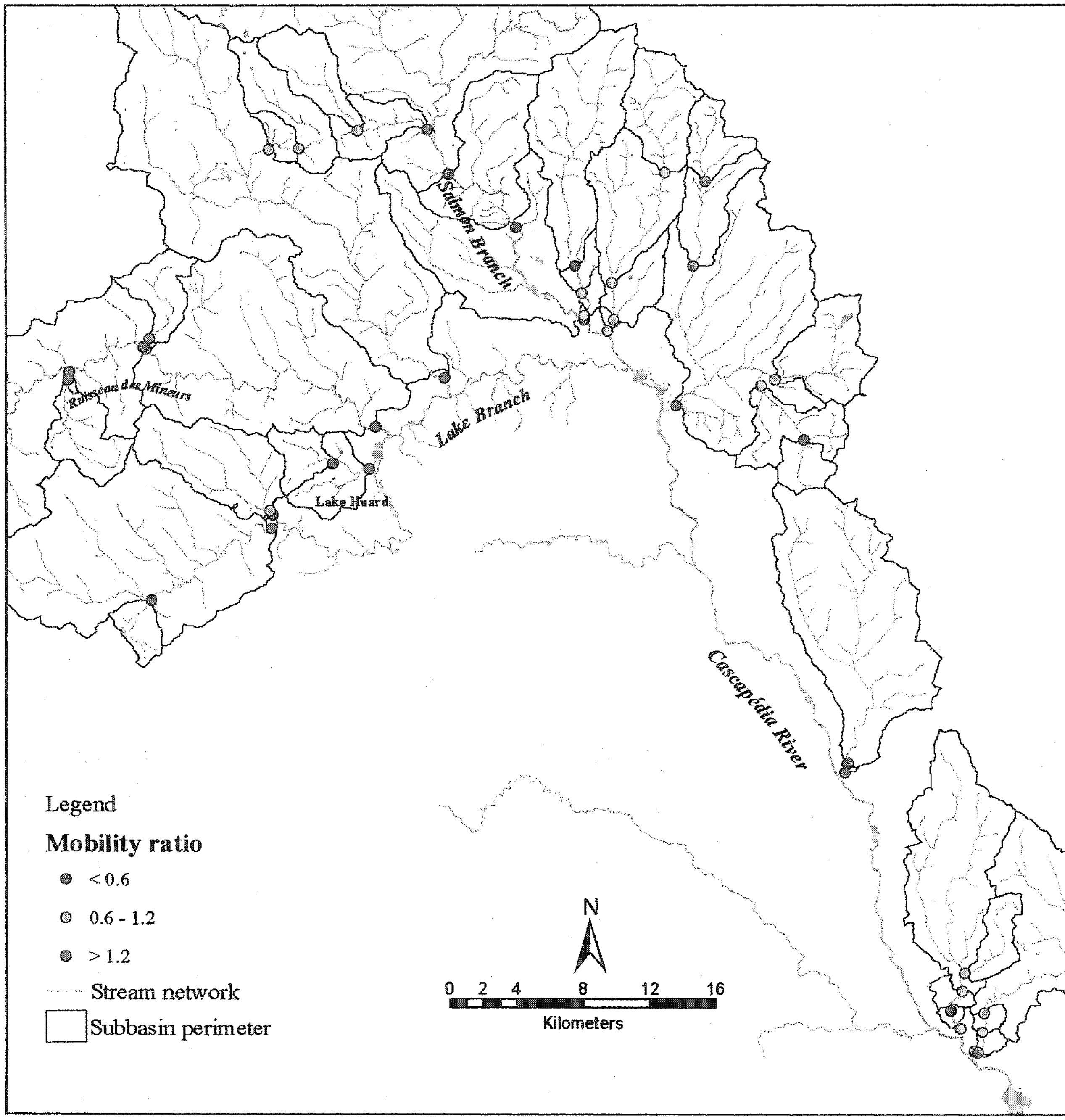


Figure 20. Spatial distribution of highly mobile and immobile sediment based on the mobility ratio of the reach.

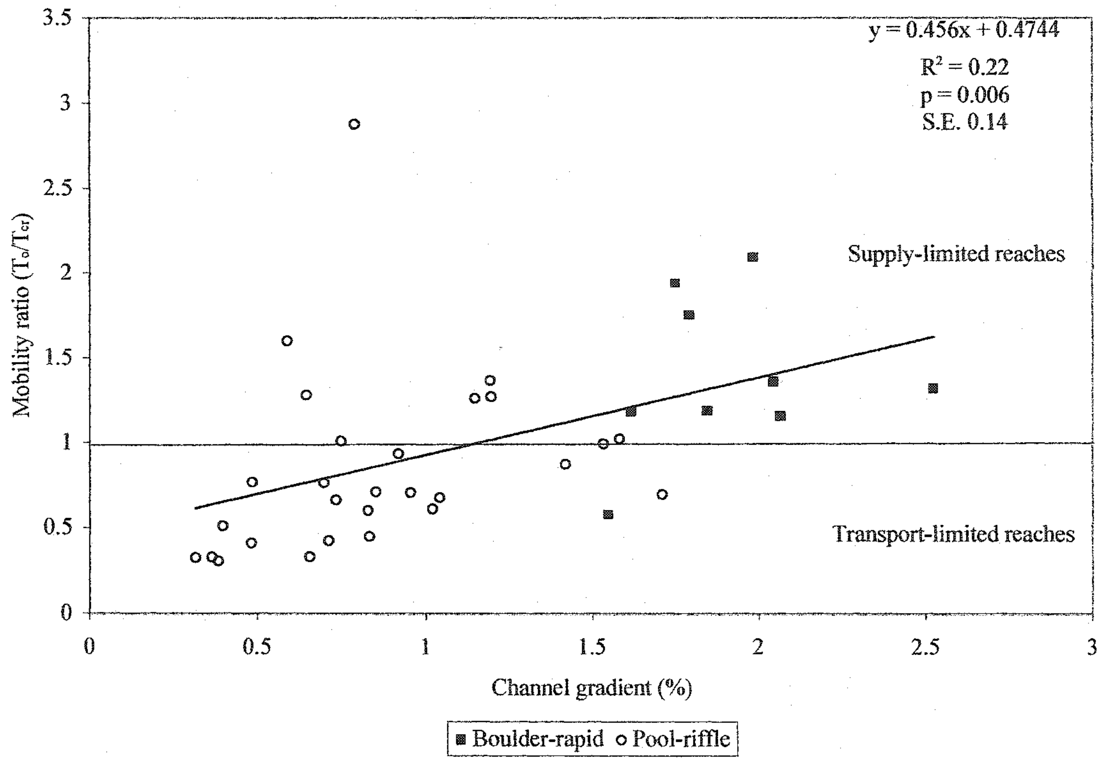


Figure 21. Variation in sediment mobility ratios (τ_o/τ_{cr}) with increasing channel gradient.

Subpavement composition

The subpavement was, as expected, considerably finer than the pavement; the median subsurface diameter ranged between 9mm and 98mm and the median pavement diameter from the bulk samples ranged between 38mm and 171mm, resulting in an average armour ratio (A_R) of 2.9, which is the ratio of median surface to median subsurface stone diameter, calculated based on the average of two bulk samples ($A_R = D_{50surface}/D_{50subsurface}$). Bulk sample sites were by necessity selected to avoid boulder clusters zones in boulder-rapid reaches. Median pavement sizes from bulk samples of potential spawning substrate can thus be finer than median pavement sizes from Wolman samples taken along a 30m reach centerline. It is interesting to note that both boulder-rapid and pool-riffle reaches display similar median D_{50} values (34.1mm and 33.2mm respectively) and that the average median subpavement diameters are not significantly different between the two morphologies (p = 0.32).

The relationship between the subpavement D_{50} and the channel gradient is neither statistically strong nor significant ($R^2 = 0.004$, p = 0.802) (Figure 22). Both boulder-rapid and pool-riffle reaches exhibit a wide range of grainsizes for both steep and gentle channel gradients. Figure 23 shows the spatial distribution of the subpavement D_{50}. The subpavement, in contrast with the pavement, is finer in some of the headwater reaches of the Salmon and Lake Branches and coarser in many of the downstream reaches. Section VI. 2.3 of this chapter will show how the D_{50} of the subpavement is predicted more accurately by the degree of valley incision upstream of the study site than by the channel gradient.

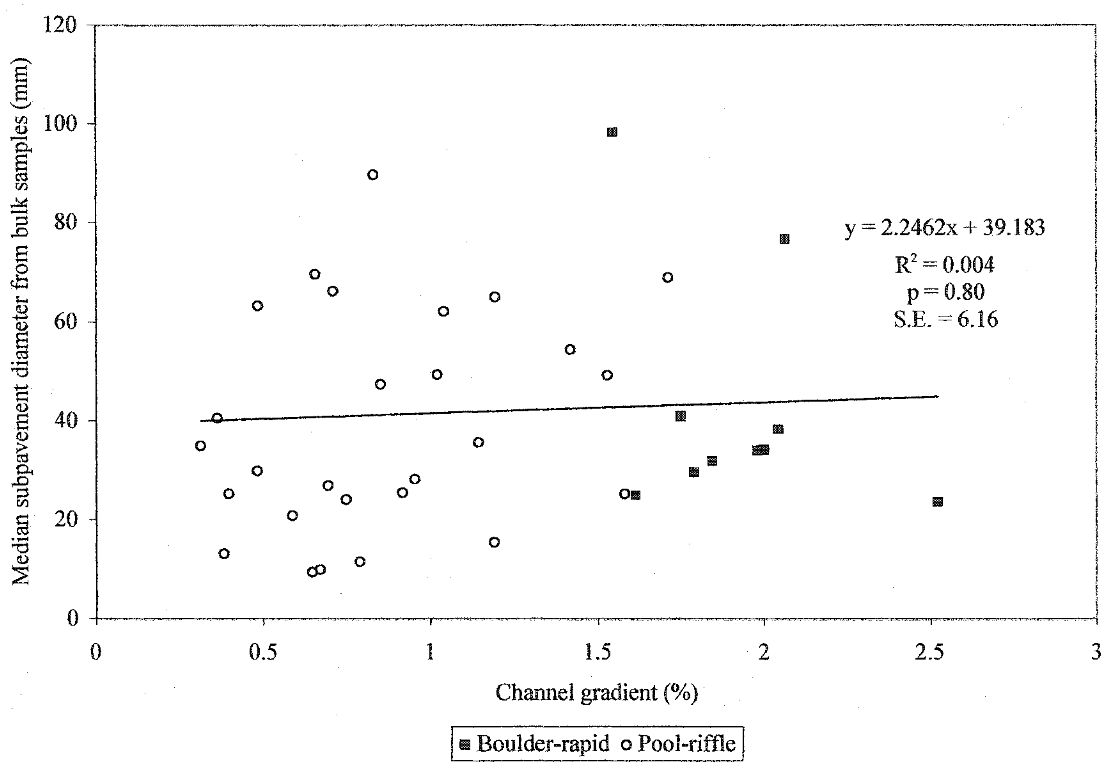


Figure 22. Relationship between channel gradient and subpavement D_{50} from the average of two bulk samples.

Subpavement fine sediment content

The average subpavement silt concentrations measured at a site ranged between 0.001% on the upper Salmon Branch, to 0.57% on Brandy approximately 2km upstream of the junction with the Salmon Branch. Individual silt measurements on Brandy reached as high as 0.75%, and as low as 0.08%, while in comparison, all measurements on the upper Salmon Branch were lower than 0.06% (Figure 24). An analysis of variance

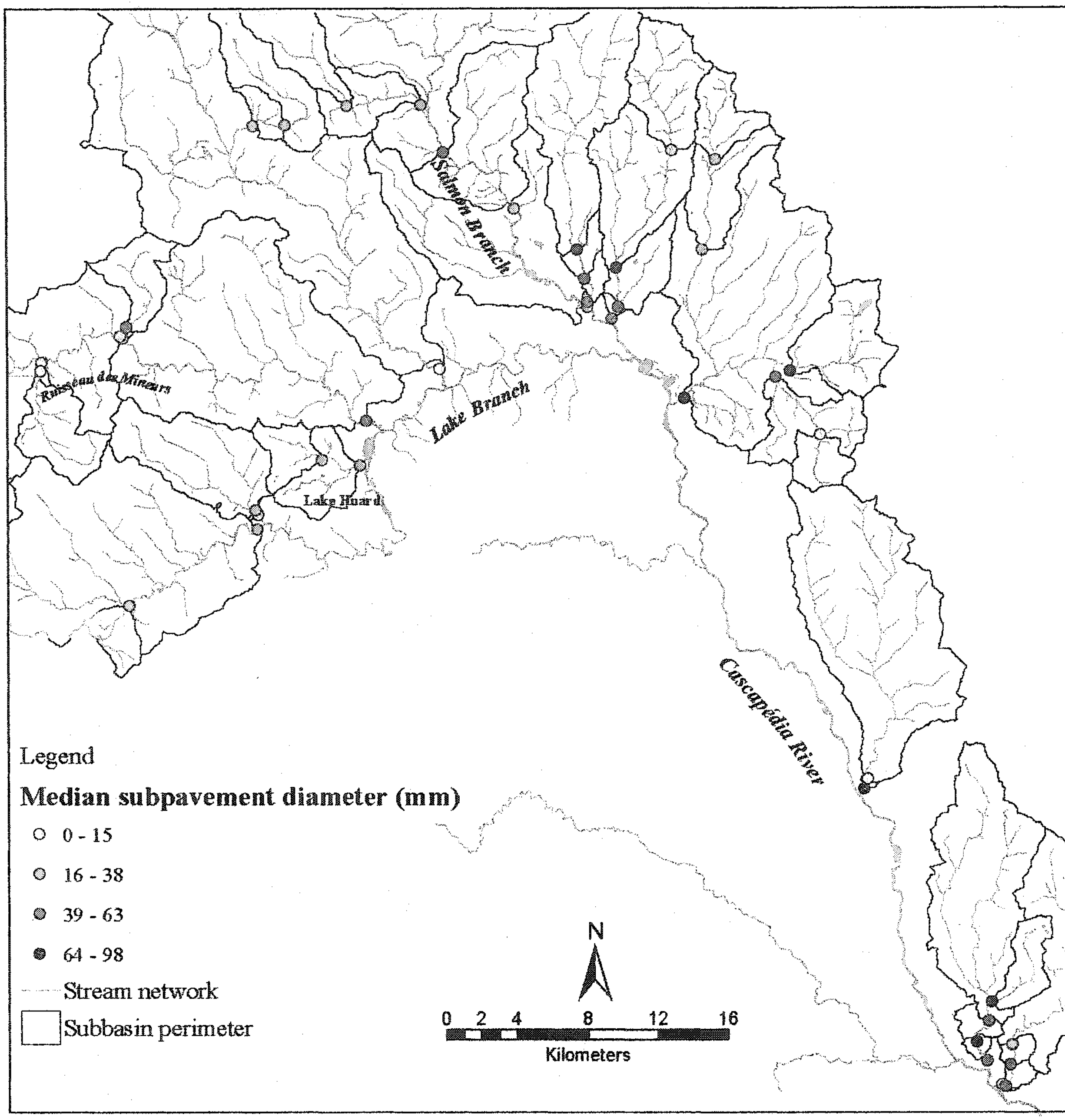


Figure 23. Spatial distribution of the subpavement D_{50} of the sample reaches.

revealed that the silt levels are statistically different between sites (F-statistic = 5.49, p = 0.000). Decomposition of the source of the variance using a Tukey post hoc test of pairwise differences in site means, however, revealed that three sites account for all of the significant differences between sites (p<0.05). The three sites responsible for the variance (Brandy 1, 1A & Trout Brook 1) are the three highest ranking sites with respect to silt content in the riffle (Figure 24). The silt concentrations plotted against channel

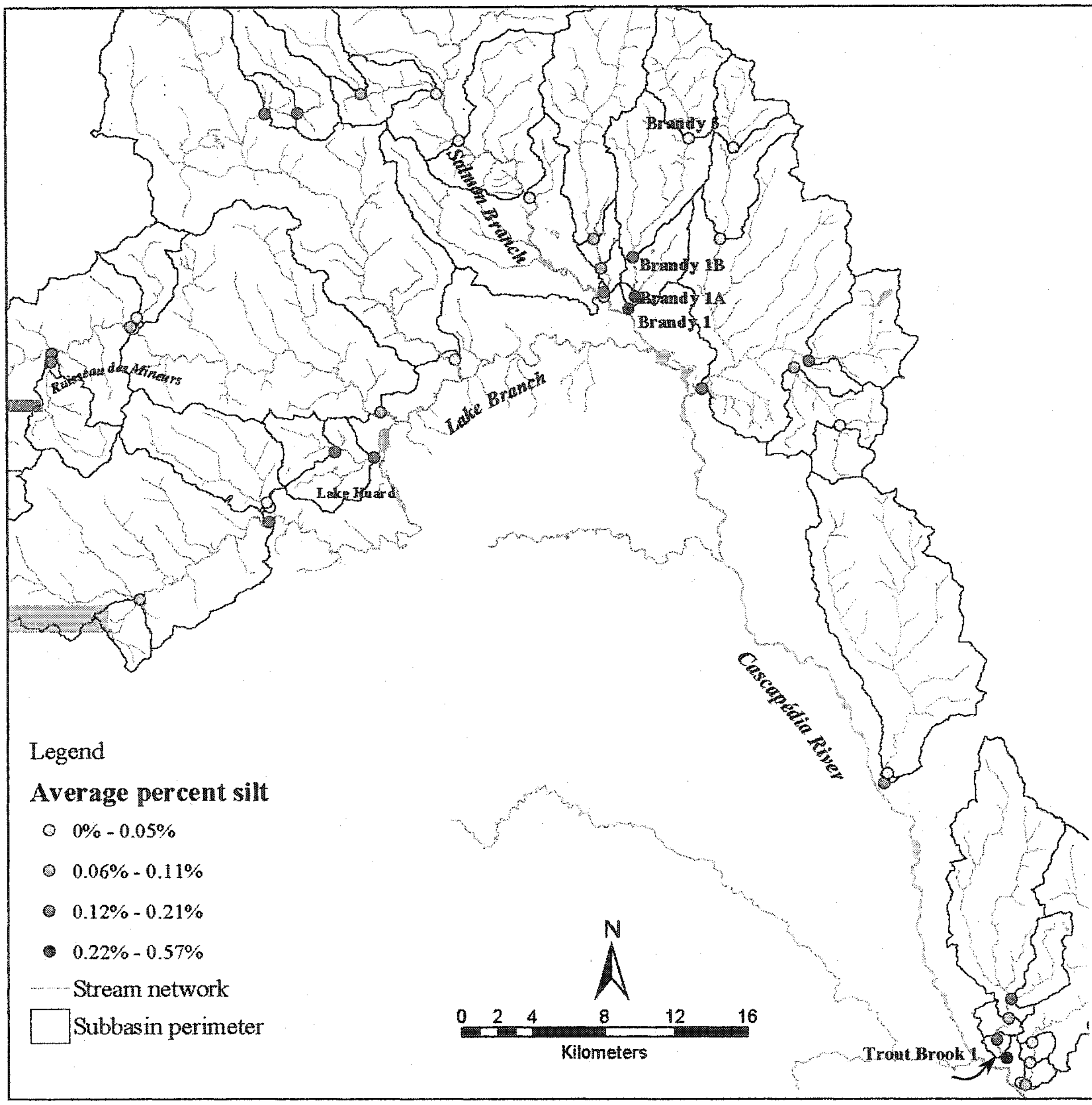


Figure 24. Spatial distribution of silt measurements within the study area.

gradient reveal that silt does not vary as a function of the channel gradient (Figure 25). To the exception of the three extremely silt-rich pool-riffle sites mentioned previously, both boulder-rapid and pool-riffle exhibit similar ranges in average silt content.

The same statistical analysis of variance test was performed for fine sand. As with the silt measurements, the sand levels are statistically different between sites (F-statistic = 2.138, p = 0.008). There are, however, more significant differences in sand levels and they are distributed more evenly between sites. The data show a gentle decrease in fine sand content (<2mm) with increasing channel gradient (Figure 26). Boulder-rapid reaches on average had a significantly lower level of sand within the sampled gravel-cobble patches compared to pool-riffle reaches (6.7% and 9.4% respectively, p = 0.005). The highest sand levels (> 12%) occurred only in reaches where the channel gradient was under 0.9%.

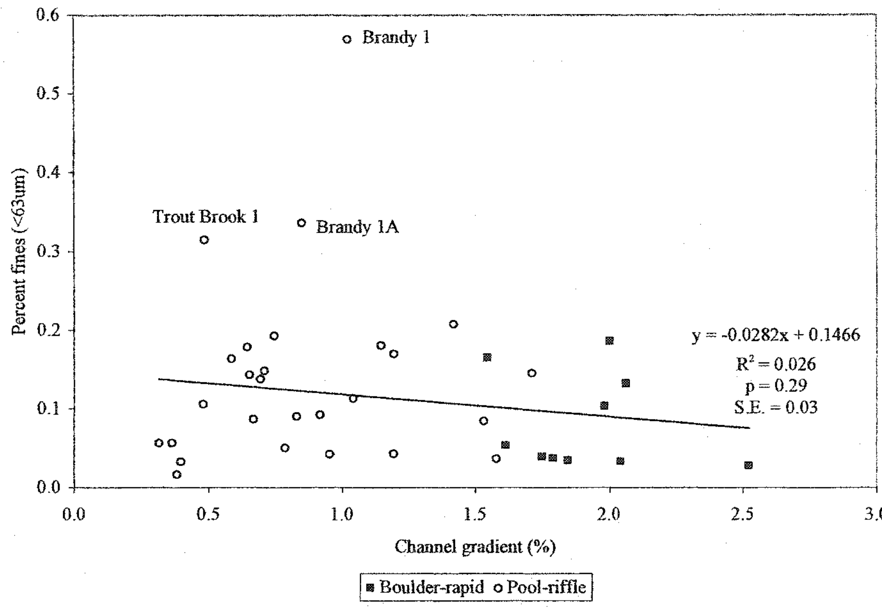


Figure 25. Relationship between percent silt (<63um) within the riffle substrate and the channel gradient.

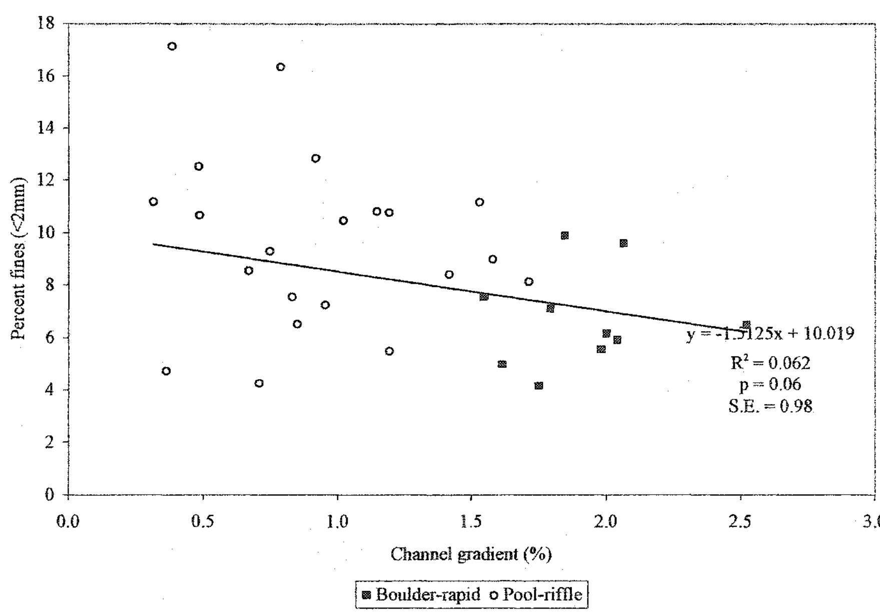


Figure 26. Relationship between percent sand (<2mm) within the riffle substrate and the channel gradient.

Intensive substrate sampling on Brandy Brook near road failures

The substrate at two different sites (Brandy 1A and 1B), where the road design directed a sediment laden flow directly into two low order tributaries of Brandy Brook, was sampled intensively (as described in Figure 11). At each of these sites, which are approximately 2km apart, multiple bulk samples were taken both upstream and downstream of the low order tributary outlet. The grainsize parameters of these intensively sampled sites relative to all the other sites combined are presented in Table 10 below. Brandy 1A contained the highest levels of silt of any site and the median value of 0.57% is statistically higher than the mean values for all but two sites (Brandy 1 and Trout Brook 1). While the levels of silt and sand within the subpavement are slightly higher upstream of the sediment laden tributary outlet than they are downstream, these differences are not statistically significant, nor are the differences between the upstream and downstream D_{16}, D_{50} and D_{84} values. Brandy 1B is slightly finer upstream of the outlet in terms of sand ($p = 0.02$). Given the lack of significant differences between the observed levels of fine sand and silt upstream versus downstream of the two low order tributary outlets, it is not possible to conclude that the observed fine sediment levels of these sites are the result of the sediment laden flows from the two road failures.

Table 10. Subpavement bulk sampling results for intensively sampled sites in comparison to average values for all study sites.

Site	Number of bulk samples	% silt (<63um)	% sand (<2mm)	D16 (mm)	D50 (mm)	D84 (mm)
Brandy 1A upstream of tributary outlet (median)	3	0.54	10.15	4.85	47.87	82.56
Brandy 1A downstream of tributary outlet (median)	3	0.59	10.79	6.12	48.17	132.44
Brandy 1A (median)	6	0.57 (0.41 - 0.75)	10.5 (5.2 - 15.0)	6.26 (3.0 - 13.5)	49.4 (30.6 - 99.1)	101.7 (76.9 - 197.1)
Brandy 1B upstream of tributary outlet (median)	4	0.22	9.66	5.10	57.23	139.30
Brandy 1B downstream of tributary outlet (median)	4	0.14	4.93	11.62	74.97	164.34
Brandy 1B (median)	8	0.14 (0.08 – 0.30)	8.1 (2.41 - 15.1)	9.8 (5.0 - 15.0)	69.0 (53.3 - 84.3)	161.2 (99.2 - 185.6)
All sites (average)	88	0.11 (0.001 – 0.57)	8.1 0.92 – 17.1)	5.6 (1.8 – 16.6)	41.8 (9.4 – 98.3)	99.1 (37.5 – 194.9)

VI. 2. Influence of basin-scale geology-structure on stream habitat characteristics

It is clear from the preceding section that stream habitat variables varied considerably between pool-riffle and boulder-rapid reaches, largely reflecting variations in channel gradient and channel dimension. This section will examine the effect of larger basin-scale geology-structure variables (as described in Table 7) on the distribution of stream habitat variables and the occurrence of pool-riffle systems.

VI. 2. 1. Relationship between geology-structure variables and channel morphology

In order to examine the potential predictive ability of the watershed variables with respect to site channel morphology variables, the relationship between the physical variables measured in the field and the watershed variables derived from the GIS, which are summarized in Table 11, were assessed using regression analysis. Horton (1946) and Miller *et al.* (1996) both investigated the relationship between stream order and channel morphology parameters, including bankfull channel width, depth and cross-sectional area. Miller *et al.* (1996) found that stream order and basin area were highly correlated with cross-sectional area and bankfull width and could serve as predictive tools for estimating these variables. As expected, the same strong statistical relationships were found to exist within the Cascapédia drainage basin. In particular, there is a strong relationship between bankfull width and stream order and bankfull width and basin area ($R^2 = 0.66$, and 0.80 respectively) (Table 12 and Figure 27 a, b). Within the range of basin sizes sampled, these relationships are more accurately approximated by linear functions with intercepts ($R^2 =$ 0.73 and 0.94 for order and basin area respectively) than by power functions. Had more large basins (>400km^2) been sampled, however, theses relationships would likely conform more closely to the power functions reported in the literature.

Table 11. Statistics of geology-structure variables calculated at each site (as defined in Table 7).

Variable	Number of subbasins	Mean	Minimum	Maximum	Standard deviation
Basin area (km^2)	48	80.48	7.66	448.14	101.38
Stream order at study site	48	3.3	2	5	0.81
Mean elevation of basin (m)	48	475.89	299.02	651.12	90.40
Elevation range(m)	48	539.22	268.25	980.00	178.30
Mean slope (degrees)	48	10.96	5.54	17.17	2.80
Mean slope of 60m riparian corridor (Index of valley incision) (degrees)	39	12.17	5.61	19.28	3.86
Mean slope of local 60m riparian sub-corridor (Index of local valley incision) (degrees)	39	7.99	1.62	22.26	5.82
S.D. of local elevation (m)	39	39.17	6.37	105.69	24.77
Total stream length in basin (km)	45	122.98	11.77	574.04	136.59
Stream density (km/km^2)	45	15.97	12.23	21.42	2.21
Index of unit stream power at study site	46	0.05	0.003	0.10	0.02

Table 12. Statistical relationships between stream morphology variables and watershed variables.

	Stream order		Basin area	
Channel parameter	**Equation**	**R^2**	**Equation**	**R^2**
Mean bankfull width	$y = 1.1003x^{2.18}$	0.66 (p = 0.0001)	$y = 0.0038x^{0.46}$	0.80 (p = 0.0001)
Mean bankfull depth	$y = 0.4655x^{0.18}$	0.04 (p = 0.0001)	$y = 0.5267x^{0.02}$	0.045 (p = 0.0001)
Maximum bankfull pool depth	$y = 0.5428x^{0.56}$	0.29 (p = 0.0001)	$y = 0.5373x^{0.17}$	0.35 (p = 0.0001)
Mean cross-sectional area	$y = 1.5459x^{1.26}$	0.34 (p = 0.0001)	$y = 1.2316x^{0.45}$	0.86 (p = 0.0001)
Mean summer flow width	$y = 1.3251x^{1.26}$	0.49 (p = 0.0001)	$y = 1.5611x^{0.36}$	0.81 (p = 0.0001)
Mean summer flow depth	$y = 0.1042x^{0.71}$	0.33 (p = 0.005)	$y = 0.1072x^{0.22}$	0.44 (p = 0.001)
Mean bankfull width/depth ratio	$y = 9.1179x-7.0$	0.33 (p = 0.0001)	$y = 0.1253x+14.3$	0.66 (p = 0.0001)

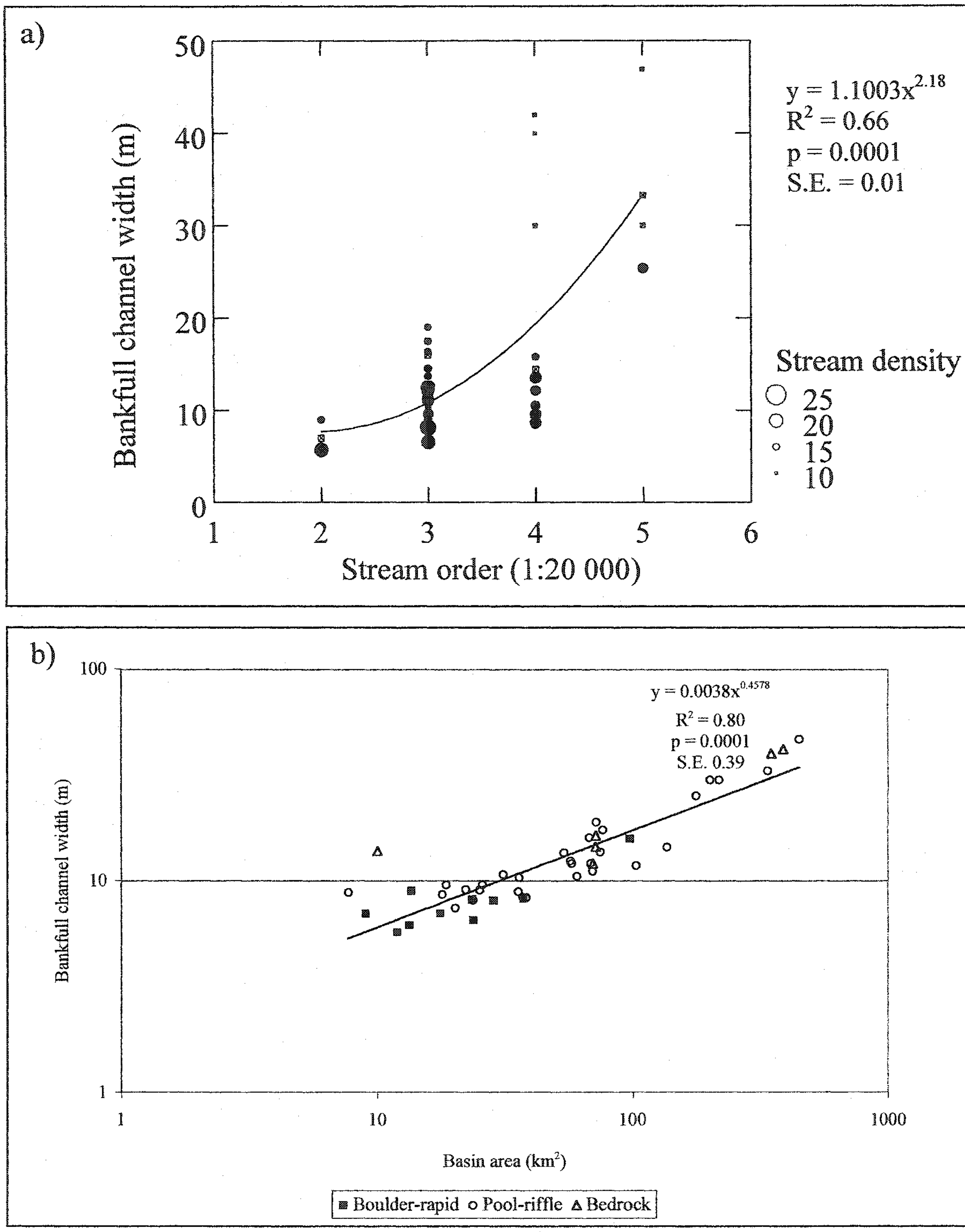


Figure 27. Variation in bankfull channel width for different stream orders by stream density (a), and with increasing basin area (b).

There is considerable spread in the channel width data for each stream order (Figure 27a). This is likely the case because, at any given drainage area, stream order depends on variables such as stream density, therefore other variables, such as variations in local relief and the erodability of the bed and bank material, may well influence this classification system. Additional consideration of stream density as a covariate with width reiterates this point (Figure 27a). At any given stream order, channel width varies considerably, as does upvalley stream density. Within the channels of the same stream order classification, as the bankfull width increases stream density decreases. In effect, where the stream density upvalley is greater, a narrower channel draining a smaller basin can be of the same order as a much larger channel.

It therefore seems more appropriate to favour basin area over stream order as a potential predictor of channel morphometry and the occurrence of pool-riffle characteristics (Figure 27b). Other authors have reported basin area as an accurate predictor of channel geometry and of channel width in particular (Miller *et al.*, 2000). This is true in the Cascapédia drainage basin as well. The value of the exponent of the power function relating bankfull width and basin area is higher than what would be expected from the average values reported by Knighton (1998). Using the average exponent values of p (0.7) observed by Emmett (1975) and of b (0.5) calculated from Knighton (1998) in equations 2a and 3 ($w_b \propto Q_b^{0.5}$ and $Q_b \propto A_d^{0.7}$) yields the following relationship,

$$w_b \propto A_d^{0.35} \tag{9}$$

The value of the exponent relating bankfull width and drainage area for the Cascapédia basin (0.46, Table 12) is higher than the average value of 0.35 calculated above (Equation 9). In fact, the value is closer to the exponent relating bankfull width and bankfull discharge (0.5), which would suggest that basin drainage area may be an accurate surrogate for bankfull discharge and that the value of the exponent p (Equation 3) in this study is in fact close to 1, which it was assumed to be in the calculation of the index of unit hydraulic power (Equation 8).

Despite the weak correlation between depth and both basin area and stream order, there is nevertheless a potential to predict cross-sectional area from basin area. Like width, cross-sectional area is more strongly correlated with basin area than stream order (Table 12). The difficulty in measuring bankfull depth as well as the greater degree of local variability in depth compared to width may explain the relative lack of relationship between depth and both basin area and stream order (Table 12). Given that bankfull cross-sectional area was calculated by simply multiplying mean bankfull width and mean bankfull depth, the relationship is primarily a reflection of the correlation between width and basin area as opposed to a relationship with depth. While the relationship between mean bankfull depth and basin drainage area is weak, the relationships between summer depth, maximum pool depth and basin area are stronger (Table 12). Average summer depths increase with increasing basin drainage area, and the strength of this relationship may have been improved had we been able to measure the maximum depths in the deepest pools at about 5 sites.

The width/depth ratio increases linearly with increasing basin area, which suggests that the channel adjusts it morphology to an increase in discharge by increasing in width more than in depth (Figure 28). Such a trend likewise suggests an increase in bank erodability downstream as well as an increase in bed-load transport (Knighton, 1998). In general, pool-riffle reaches have higher width to depth ratios than boulder-rapid reaches with the same basin area. The scatter in the width/depth ratio in the smaller basins ($A_d < 100$) may be the result of the irregularity of local constraints over channel form (i.e. bedrock outcrops, large immobile boulders), as well as the presence or absence of deep pools in some reaches versus others.

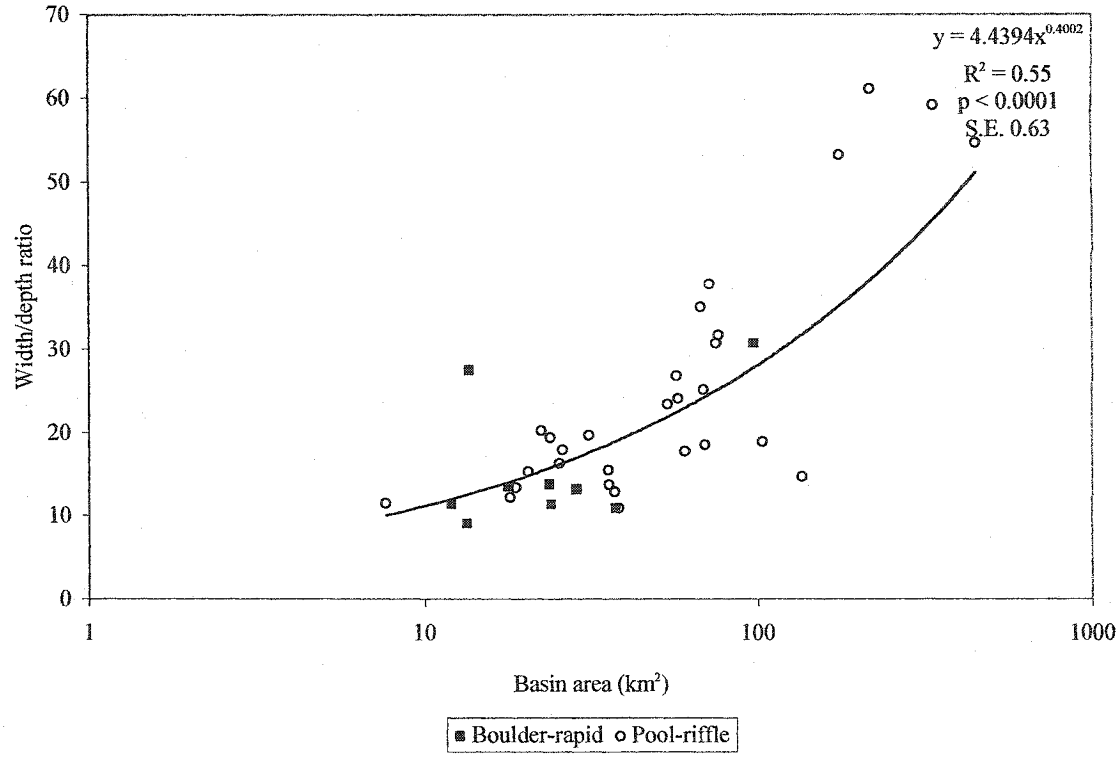


Figure 28. Variation in width/depth ratio with increasing basin drainage area.

VI. 2. 2. Relationship between geology-structure variables and channel gradient

In section VI.1.2., the channel gradient proved to have an important influence on the morphological type of the channel (pool-riffle versus boulder-rapid) and to a lesser extent on the surface substrate composition. It has been widely documented that the channel gradient tends to decrease with distance downstream and with increasing basin area (Church, 1992; Knighton, 1998) (Figure 1). Although this general trend can be seen in the data for the Cascapedia sites, it is important to note, however, that a considerable amount of variation in the channel gradient is left unexplained by basin area, which is contrary to the trend reported by most authors (Figure 29). Basins smaller than 80km^2 seem to show no tendency whatsoever in channel gradient with respect to basin area, while basins larger than 100km^2 have channel gradients that are clearly less steep.

Channel gradient tends likewise to decrease with increasing stream order (Figure 30). The transition between pool-riffle and boulder-rapid appears to occur within 3rd order channels. All 5th and the majority of 4th order reaches are pool-riffle, while all 2nd order reaches sampled were boulder-rapid. Third order reaches, by comparison consisted of 16% boulder rapid, 12% bedrock and 56% pool-riffle reaches. The 3rd order reaches likewise displayed the greatest range in channel gradients, with a slightly significant difference in stream densities (and smaller basin areas) between the steep boulder-rapid reaches and the less steep pool-riffle reaches (p = 0.06, significant at ∝ = 0.1).

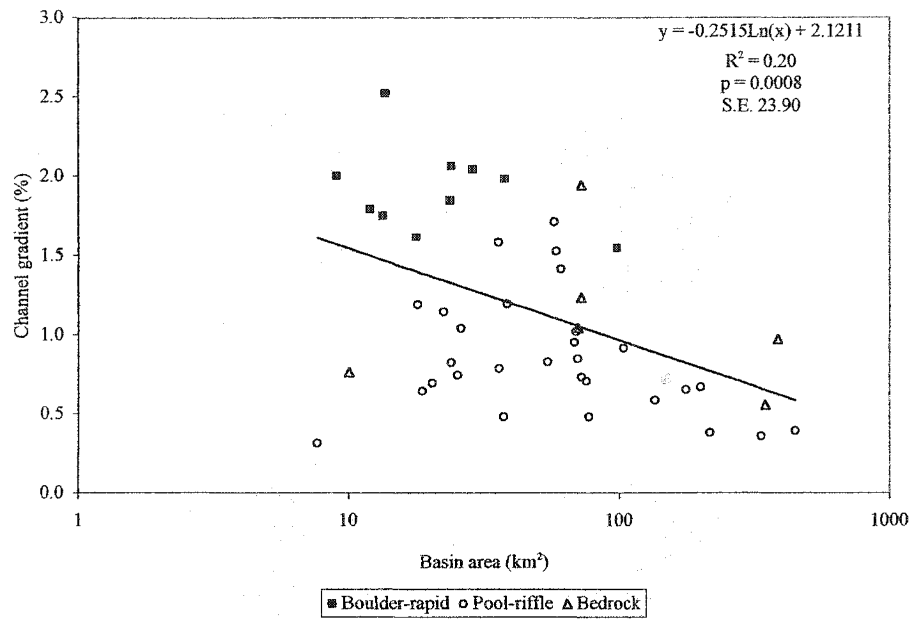


Figure 29. Variation in channel slope with increasing basin area.

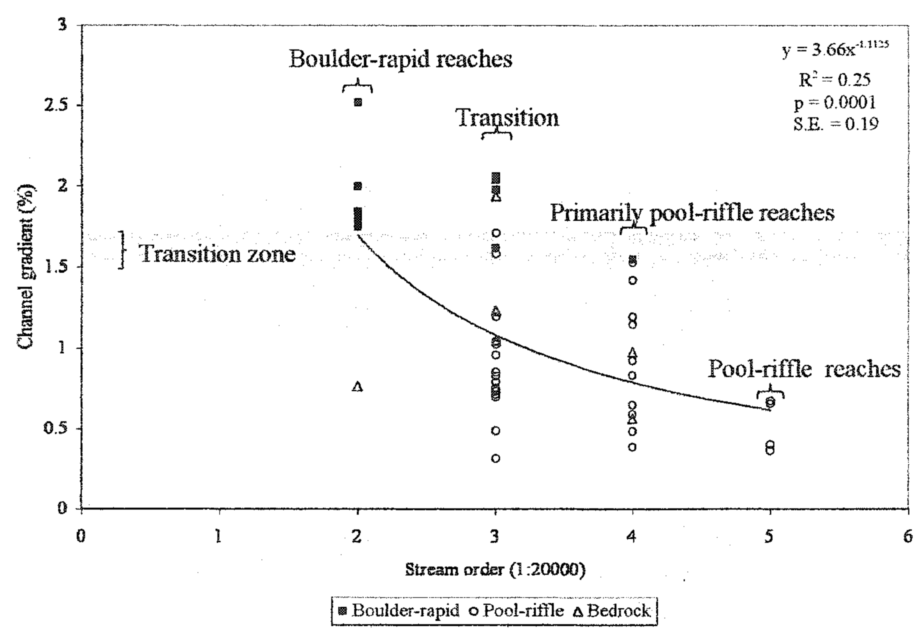


Figure 30. Transition between reach morphologies based on channel gradient and stream order.

VI. 2. 3. Relationship between geology-structure variables and grainsize distribution

Pavement grainsizes

From Figure 18 in the preceding section, it is clear that there is but a weak relationship between the local channel gradient and median pavement diameter, which shows a slight fining in the pavement with decreasing channel gradient ($R^2 = 0.16$, $p = 0.008$). And while there is likewise a very slight general fining trend in median bulk sample surface diameter with increasing basin area (Figure 31), in contrast to the theoretical expectation illustrated in Figure 1, the relationship is neither strong nor significant ($R^2 = 0.045$, $p = 0.16$). The relatively weak relationship between median pavement diameter and basin area is to be expected given the weak relationship between basin area and channel gradient seen in the preceding section (Figure 29). Figure 32 shows the variation in bulk pavement grainsize with increasing channel gradient for all small basins under 80km^2. Numerous small basins have high channel gradients and coarse pavement stones (>100mm), while other small basins have lower channel gradients and nearly as coarse pavement stones (Figure 32).

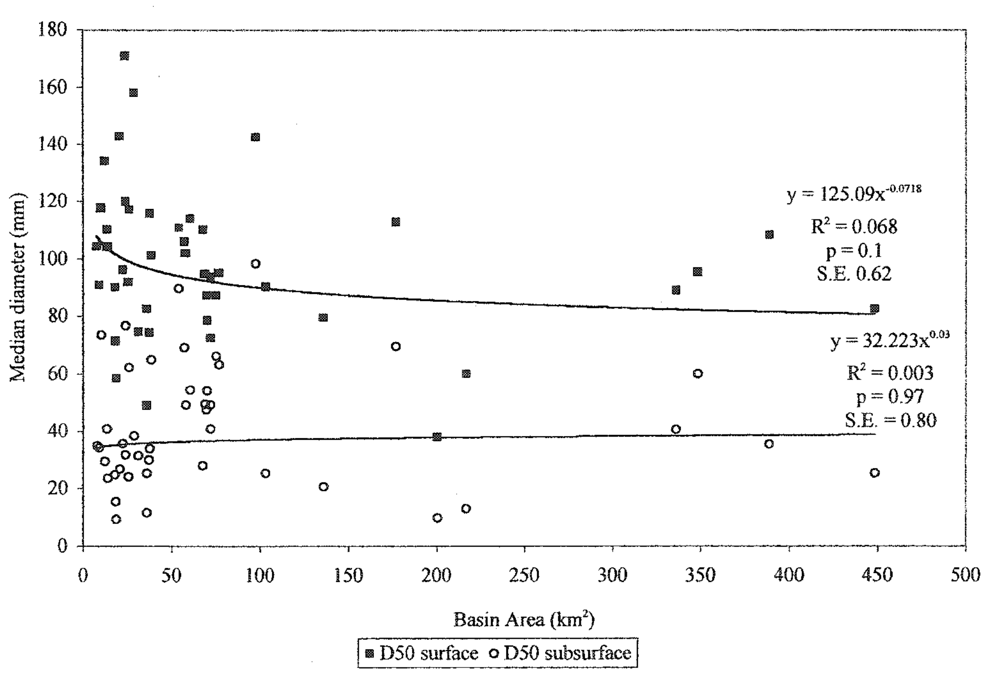


Figure 31. Variation in median bulk pavement and subpavement diameter with basin drainage area.

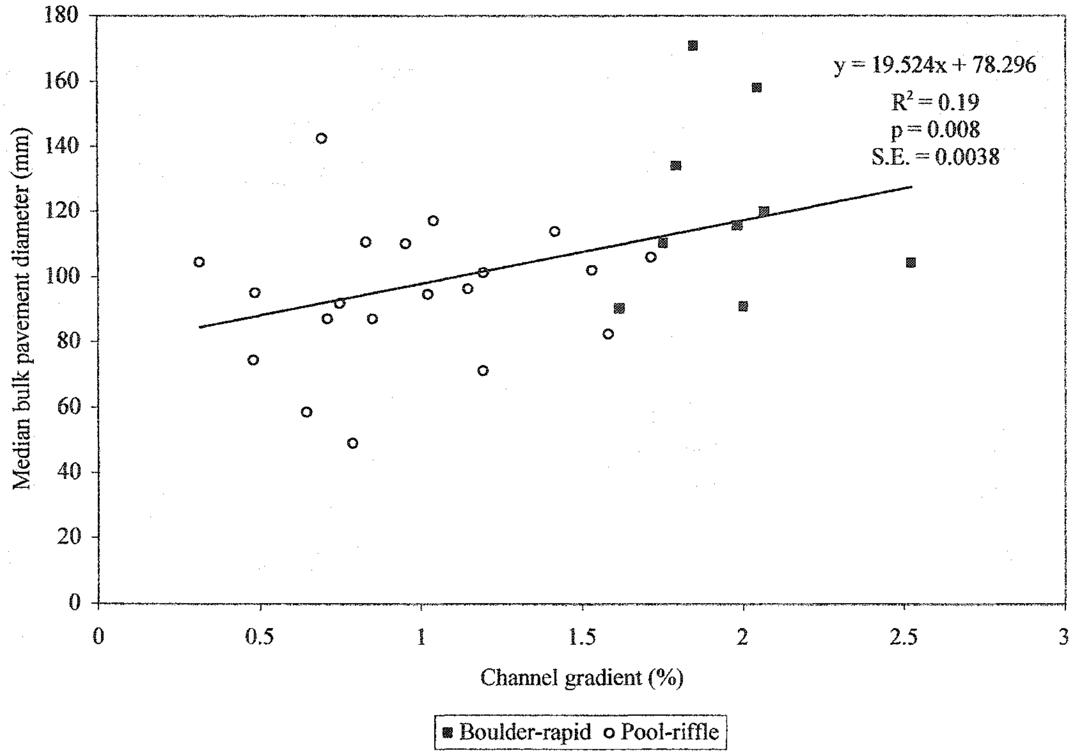


Figure 32. Variation in pavement grainsize with increasing channel slope for all small basins (<80 km^2)

The median bulk pavement grain size distribution, while poorly predictable on the basis of basin area (R^2 = 0.07)) or channel gradient (R^2 = 0.16), is more accurately explained by the index of unit hydraulic power at a sample site (R^2 = 0.47, p = 0.001) (Figure 33). As this variable is the product of basin area and channel gradient, it captures variation in substrate composition at any basin size due to local variations in channel gradient and provides a more accurate measure of the channel's transport capacity. The range in elevation between the maximum and minimum elevations within a catchment (elevation range) is also correlated with the median pavement diameter (R^2 = 0.30). Multiple regression analysis of both the elevation range and index of unit hydraulic power variables against the median pavement diameter yields a combined R^2 of 0.55 (p = 0.008), which suggest that the range in elevation within a basin explains an additional 8% of the variation observed in the median pavement distribution. A spearman rankwise correlation matrix between the geology-structure variables revealed a correlation coefficient of 0.67 between the index of hydraulic power and the elevation range and of 0.63 between the elevation range and basin area. Given the high degree of correlation between the elevation range and the index of hydraulic power, it seems more appropriate to consider the index of hydraulic power over the elevation range as a predictor of the median pavement composition, as on its own, it explains more of the observed variation in the pavement D_{50}.

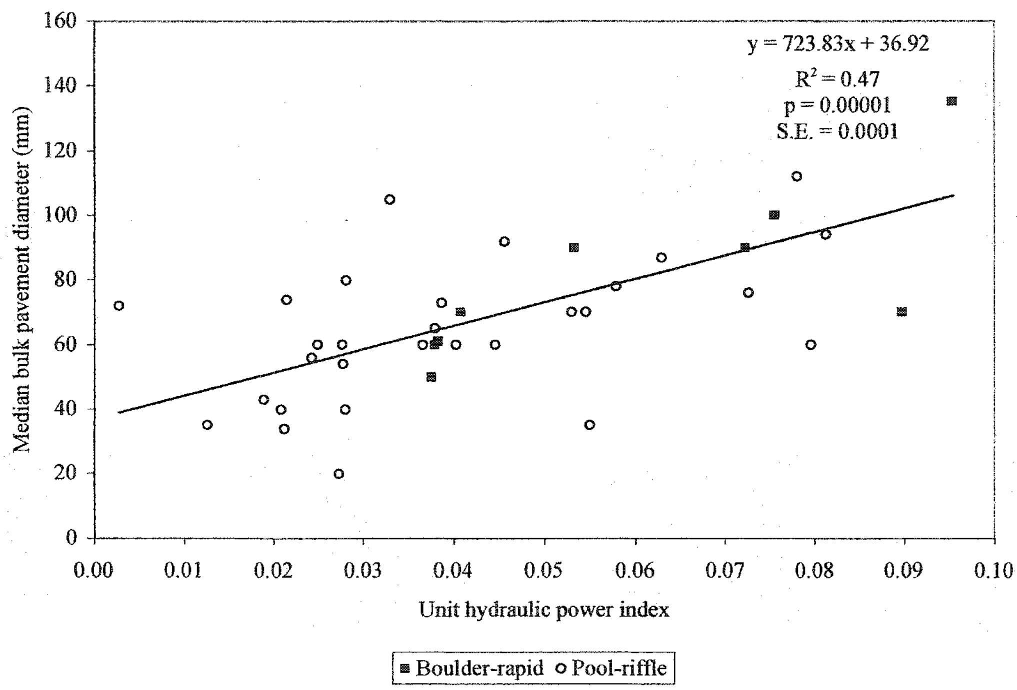


Figure 33. Relationship between index of unit hydraulic power and bulk pavement diameter.

Subpavement grainsizes

The median subpavement grain size distribution, like the pavement D_{50}, is poorly explained by both the channel gradient (R^2 = 0.004) and basin drainage area (R^2 = 0.003) (Figures 22 and 31). The median subpavement diameter, in comparison, is best explained by a measure of the degree of stream incision into the valley bottom, represented by the mean slope of the entire 60m corridor of each basin (Scale 2, Figure 13 and Table 7). Figure 34 shows the relationship between the degree of stream incision and the median subpavement diameter (R^2 = 0.45, p = 0.0001). Despite the spread in the data, it is clear that the coarsest median subpavement sediment diameters correspond to the most incised stream networks, and that the finest median subpavement sediment diameters correspond with the least incised stream networks. This suggests that valley bottom incision, which provides an indication of the slope of the valley within a 60m band on each side of the channel, captures the valleyside potential to deliver coarser sediment to the channel.

Like the degree of valley bottom incision, the mean slope of the subbasin, which is the average slope of all the grid cells in the DEM within the boundary of the subbasin, is related to the observed pattern in the median subpavement diameter ($R^2 = 0.39$). This metric is, however, so highly correlated with the index of valley bottom incision (correlation coefficient = 0.83, Appendix 5) that, in a linear multiple regression analysis, it is not significant and explains no additional variation in subpavement diameter ($p = 0.57$)

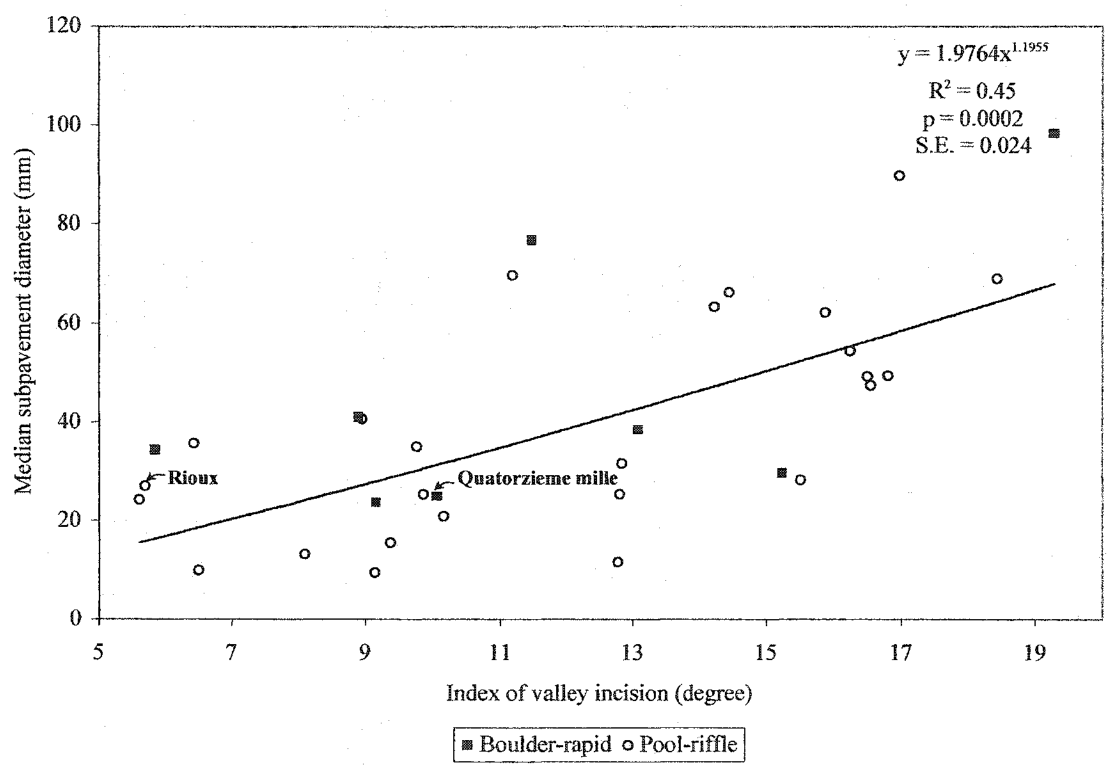


Figure 34. Relationship between index of valley incision and subpavement diameter. Rioux and Quatorzieme Mille refer to cases discussed in the text (section VI.3).

None of the geology-structure variables calculated in this study were significantly related to the silt and sand levels observed within the study reaches. Table 13 shows the linear regression statistics for silt and sand levels against the geology/structure variables. The lack of explanatory power of these variables may be due in part to the high degree of local variability in silt and sand levels as well as the additional influence of local land use, which will be presented in the following chapter.

Table 13. Linear regression statistics for geology-structure variables and observed sedimentation levels.

	Basin area		Stream order		Stream power		Valley incision	
	R^2	p value	R^2	P value	R^2	p value	R^2	p value
Percent silt (<63μm)	0.047	0.165	0.001	0.451	0.004	0.696	0.050	0.282
Percent sand (<2mm)	0.022	0.387	0.032	0.204	0.037	0.219	0.001	0.793

VI. 3. Discussion - Natural landscape structure and stream habitat characteristics

Dominant scale of control on stream habitat characteristics

Table 14 below summarizes the significant differences in stream habitat between boulder-rapid and pool-riffle reaches identified in this chapter.

Table 14. Summary of the significant differences in stream habitat between boulder-rapid and pool-riffle reaches for the reaches sampled in this study.

	Dominant channel reach morphology	
Stream habitat variable	**Boulder-rapid reaches**	**Pool-riffle reaches**
Stream order	≤2	≥4
Bankfull width (m)	≤8	>8
Mean summer depth (m)	< 0.2	≥0.2
Channel gradient (%)	> 1.7	< 1.5
Mobility ratio estimate (τ_o/τ_{cr})	> 1 (supply limited)	< 1 (transport limited)

At the reach scale, variations in channel gradient between reaches influenced the occurrence of boulder-rapid and pool-riffle morphologies and likewise influenced the nature of the channel pavement (Figure 18). At the basin-scale, landscape variables related to the hydrographic structure and topography explained some of the observed variance in physical habitat variables measured in the field. Almost all of the geology/structure-physical habitat relationships were strongest at the scale of the entire subbasin (with the exception of the subpavement substrate size distribution, which was best explained by the index of valley incision at the full watershed 60m riparian corridor scale), a finding that is consistent with the observations made by Richards and Host (1994) and Richards *et al.* (1996). This suggests that much of the observed variations in stream habitat variables are the result of large scale physical processes rather than local riparian scale processes. The exception being, of course, fine sediment levels, which do not vary significantly as a function of the basin-scale geology/structure variables used in this study.

Controls on channel type and geometry

Stream order, like channel gradient, provides a simple means of differentiating between boulder-rapid and pool-riffle morphologies (Figure 30). Given that 3rd order streams appear to define the transition between boulder-rapid and pool-riffle morphologies and that stream order can be calculated easily from either topographic maps or digital databases, this channel classification system provides a cost-effective method for rapidly identifying potential pool-riffle and boulder-rapid reaches without any additional field verification.

As expected, there is a strong statistical relationship between both basin drainage area and stream order and channel width (Table 12) (Miller, 1958; Richards and Host, 1994; Miller *et al.*, 1996). The relationship between drainage basin area and channel width is, however, stronger than the relationship between stream order and channel width, and therefore has better potential to accurately predict channel width. While bankfull width is associated with channel forming flow, low flow width, which scales with the latter, is associated with the wetted habitat available to salmonids and other organisms. Therefore, from the strong relationship between basin area and summer flow width, information on the wetted habitat available to the community of organisms inhabiting the basin can be ascertained (Table 12). It may, however, be more appropriate to use bankfull width as a scalar for available habitat (Figure 15) as bankfull levels are insensitive to changes in summer water levels and are therefore not affected by the timing of the sample period. It is also possible, however, to develop a correction factor from the correlation between the timing of the sampling and the percent reduction in channel width (Figure 14) for a particular date. For example from Figure 15, on August 1st the percent reduction in channel width from bankfull level is estimated to be approximately 55%. The relative accuracy of the two methods for obtaining summer channel widths, either from bankfull levels or from summer levels corrected based on the timing of the sample, is, however, yet to be compared.

Various other studies attempting to extract channel depths from spatially distributed watershed parameters such as basin area were no more successful than this study (Miller *et al.*, 1994; Miller *et al.*, 2000). The difficulty in establishing a strong relationship between depth and watershed variables, such as stream order and basin area ($R^2 = 0.04$ and 0.05, respectively) may be due to the local variation in depth at the reach scale. While width is relatively constant over the entire reach, depth varies greatly from cross-section to cross-section as well as within one cross-section. The selection of the cross-section position is therefore more likely to influence the average bankfull and summer flow depth measurements than the average bankfull and summer flow width measurements. Average summer depths are more strongly correlated to basin area ($R^2 = 0.44$) than bankfull depths. The difficulty in predicting bankfull depths may therefore be the consequence of the accuracy of the bankfull level estimates. It is likewise difficult to accurately measure the depths in the deepest pools within some of the largest basins and therefore these areas were not sampled ($n < 5$). These subjective decisions make the measurement of average depth more variable, more sensitive to sampling error and consequently more difficult to predict. It may be more useful in subsequent studies to systematically measure riffle depths and pool depths as well as maximum pool-depth in well-defined riffle-pool reaches and generate averages and relationships separately for each.

Estimation of the channel gradient

The channel gradient is clearly an essential variable influencing the distribution of potential salmon spawning habitat. The channel gradient cannot be predicted very accurately from any of the geology/structure metrics devised in this study. It is, however, possible to estimate the channel gradient in the field from the contours on the 1:20000 topographic maps with some certainty ($R^2 = 0.72$). The error in the local channel gradient extracted from the topographic maps is likely due to the scale of the aerial photographs from which the contour lines are originally derived (1:40000) (Gouvernement du Québec, 1999). In addition, accurate determination of the channel distance between two contour lines at the 1:20000 scale can be difficult and may introduce additional error into the gradient estimate.

The channel gradient extracted from the TIN does not compare as well as the topographic maps to the field measurements used in this study (R^2 = 0.51). The predictive ability of this relationship could be improved by using the raw digital contour lines rather than ones generated by the TIN, as using the TIN to reconstruct the contour lines introduces additional uncertainty and error. It was not possible to use the original digital contour lines in this study, however, as they were not available.

The difference between the two channel gradient measurements could likewise be due to the interpolation method used to generate the DEM from the original contour lines. There are numerous techniques available to generate DEMs, each with their respective errors. Unfortunately, an error estimate associated with the particular interpolation method used in the generation of this TIN was not available. Carrara *et al.* (1997) evaluated the quality of four different DEM generators and found significant differences in the accuracy of the terrain representation depending on the interpolation method used, which included the TIN generator (ArcTin) developed by ESRI for ARC/INFO and ArcView. They found that this particular TIN generator produced an elevation pattern that did not represent the actual spatial distribution of the original contour lines and that it likewise produced significant artifacts and unrealistic terraces within the landscape. The accuracy of the TIN could be improved if additional elevation points were taken between the elevation contours, particularly along the channel network, which would improve the representation of the channel bed. The inaccuracy in the representation of the channel bottom within the DEM is a critical limitation inhibiting the widespread use of GIS technology in basin scale fluvial geomorphology research (Carrara *et al.*, 1997; Downs and Priestnall, 1999). Improvements in interpolation algorithms need to be made in order to increase the accuracy of the gently sloping channel bottom and to eliminate the "plateau effect" generated from the use of contour lines. Such improvements will make automatic extraction of the channel gradient from the DEM possible and more reliable.

The remaining error may also be a result of the difference in distances over which the channel gradients were measured. The field gradients were measured over small homogeneous reaches, with the channel gradient being essentially constant over an entire reach. The channel gradient extracted between contour lines are taken over considerably larger distances and may therefore include several heterogeneous reaches within their length. In small headwater stream reaches, where rapid breaks in slope occur irregularly and frequently, the channel gradient measured over ten to fifteen channel widths may be misrepresented on paper or in the model by the spacing of the contour interval. In such cases, the reach distance over which the later channel gradient was measured does not reflect the scale relating channel morphology to channel processes and may therefore lead to an erroneous estimation of the channel gradient. The relationship between the two methods of determining the channel gradient may be improved in subsequent studies by increasing the distance over which the channel gradient is measured in the field (where possible) and then comparing it to the gradient extracted over an equal distance from the DEM generated with the original contour lines and additional elevation points.

Controls on channel gradient

Within the scale of this study, basin area, of itself, provides relatively poor predictions of channel and fish habitat characteristics, contrary to the simple model depicted in Figure 1. Variations in the channel gradient between several of the headwater basins are related to the valley morphology and therefore the denudation history of the region. Two adjacent subbasins of similar area, each flowing into different 4th order tributaries, provide excellent contrasting examples of the influence of valley morphology on channel gradient and sedimentology (Figure 35). Though they have essentially the same basin areas and lie at the same elevation, the two sites have very different local channel gradients and different reach morphologies. Quatorzieme Mille Brook is a steep boulder-rapid reach and Rioux Brook is a gently sloping pool-riffle reach.

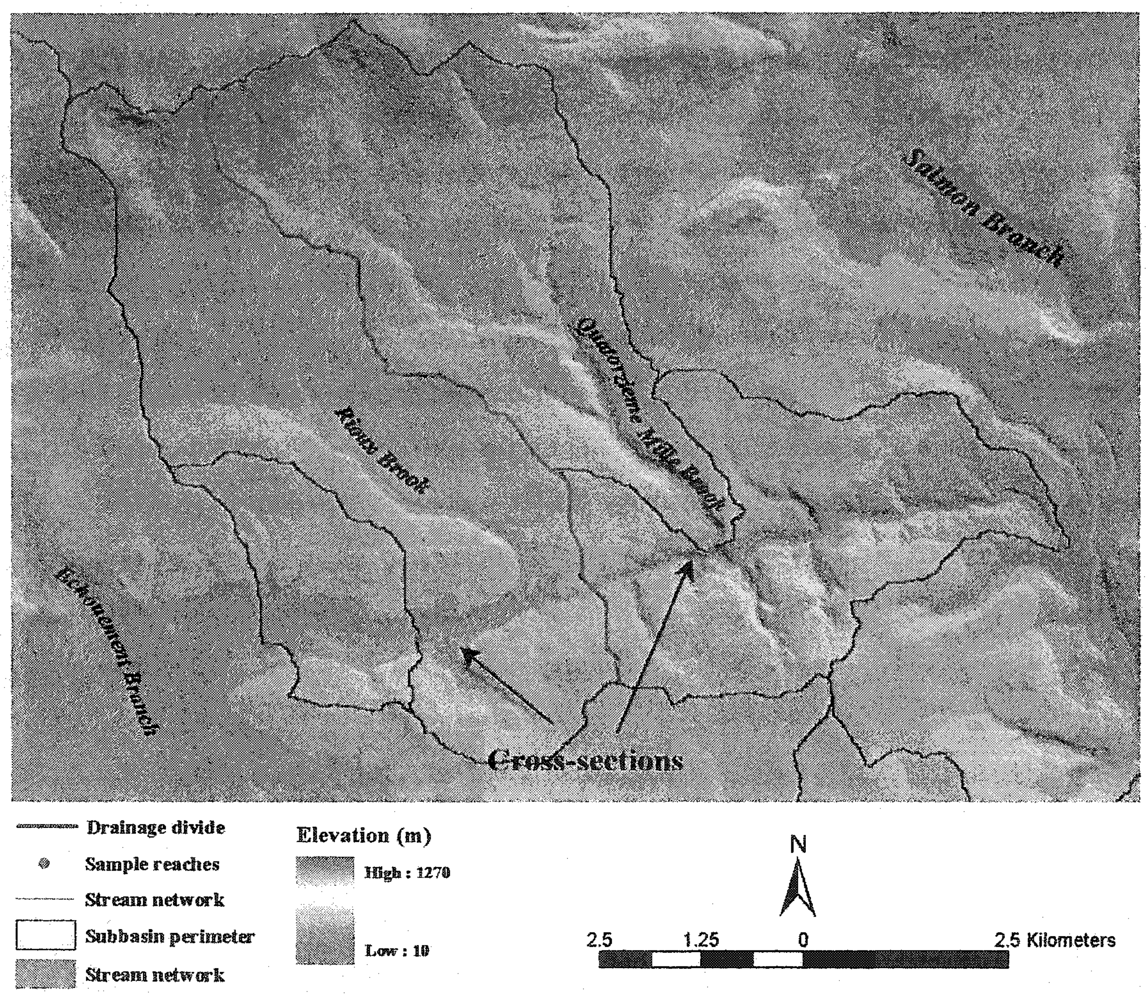


Figure 35. Map showing two adjacent basin of similar basin area with contrasting topographic slopes.

Quatorzieme Mille Brook flows within a deeply incised V-shaped valley, while Rioux Brook flows within a wide-bottomed valley (Figure 36a,b). Since they flow upon the same geologic formations (Figure 8), it is unlikely that the difference in valley shape is simply related to resistance of the bedrock. Given the frequent occurrence of stream capture within the Cascapédia basin (Carbonneau, 1959b), it is conceivable that the northern section of the present day Quatorzieme Mille Brook may have previously flowed into Rioux Brook and was captured at some point in time, redirecting the flow into the lower Quatorzieme Mille Brook. This capture may possibly have been triggered by a period of stronger valley incision in the larger, more powerful Salmon Branch compared to the conditions in the smaller Échouement Branch (Figure 35). Had this been the case, Rioux Brook would previously have had a considerably higher discharge than it does at present. Under a higher flow regime the valley could have widened considerably resulting in its present morphology. The occurrence of such wide-bottomed U-shaped valleys alongside more deeply incised V-shaped valleys has resulted in a wide range of channel gradients among small headwater basins.

Controls on pavement and subpavement composition

The long and complex geologic history of the basin has resulted in numerous subbasins with different morphologies and consequently different physical habitat. The geomorphic history of the basin, in addition to influencing the channel gradient, influences the distribution of spawning habitat through the control of hydraulic power and valley incision on the pavement and subpavement composition (Figures 33 and 34, respectively). For example, for similar drainage basin areas, the index of hydraulic power within the incised valley of Quatorzieme Mille Brook is double that of Rioux Brook, resulting in a median pavement diameter that is nearly double (Figure 36a,b). Given that the local channel gradient seems to have the most direct influence on hydraulic power within the study basins, the channel gradient is indirectly influencing the pavement composition through its influence over the transport capacity. Yet despite the differences in channel gradient and median surface diameter between these two particular subbasins, the median diameter of the subsurface sediment of both Rioux Brook and Quatorzieme Mille Brook (27mm and 25mm, respectively) are near the optimal range reported by Moir *et al.* (2002) and are well within the suitable substrate size range for the size of salmon that spawn within the Cascapédia.

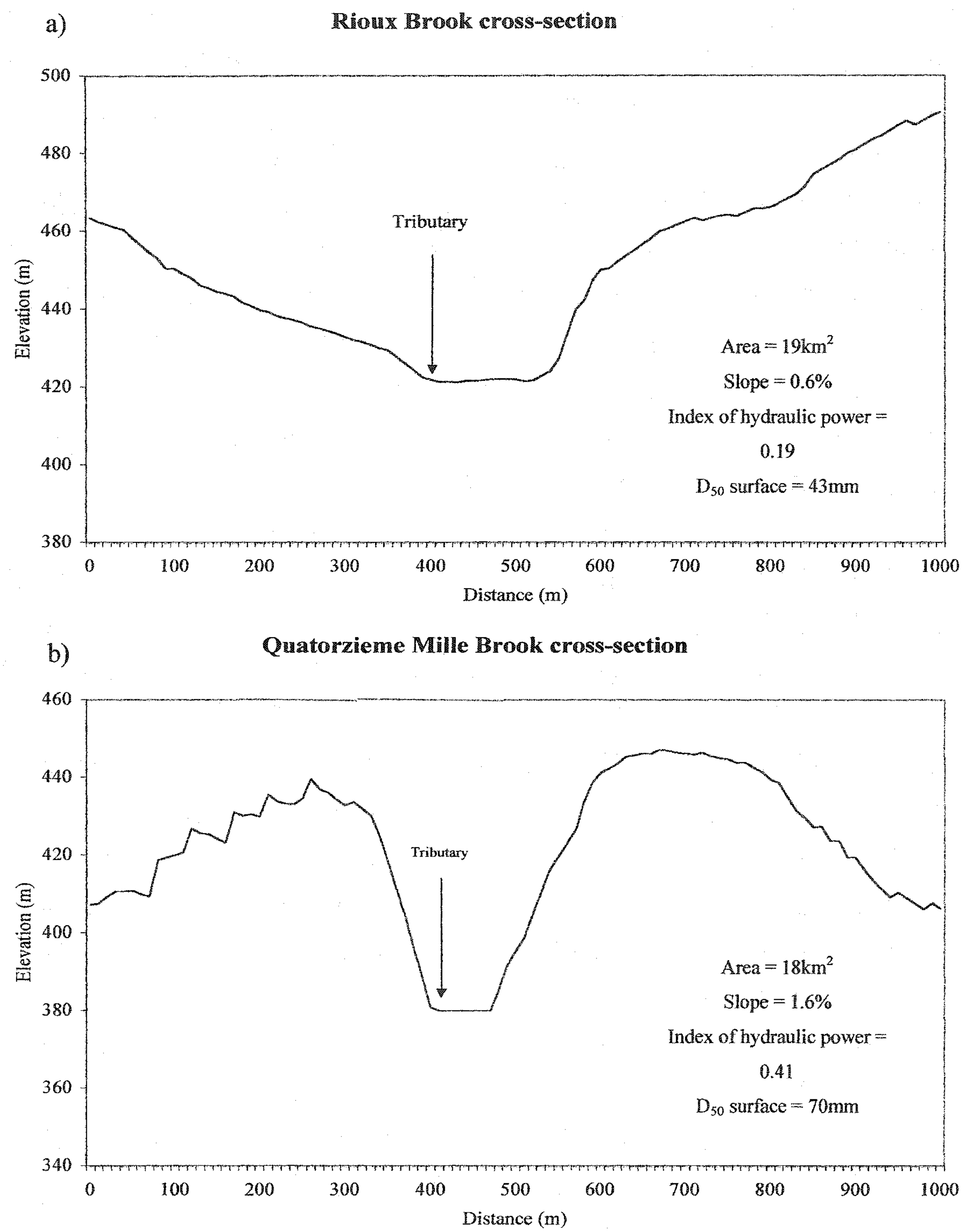


Figure 36. Cross-sections of two contrasting valleys: Low channel slope (a), and highly incised, high channel slope (b).

Controls on fine sediment content within riffle and gravel-cobble subpavement

While the geology/structure metrics capture much of the variation in channel morphology and in pavement and subpavement composition throughout the subbasins, they cannot explain the observed variations in fine sand and silt levels. Barrett *et al.* (1998) suggested that variations in fine sediment levels can be related to variations in bedrock and surficial geology throughout the basin. One of the striking features of the Cascapédia basin's relief is the broad topographic depression within which the Lake Branch flows. The boundaries of this crescent shaped depression coincide with the digitized boundaries of the Lake Branch geological formation (Figure 37), suggesting that this formation, which is described by Carbonneau (1959b) as friable, red and green sandstone and shale, is indeed more easily weathered than the Battery Point and York River formations that surround it (Figure 8).

Interestingly, the boundaries of the Lake Branch formation also coincide with the boundaries of the thick, highly erodable glacial and fluvioglacial surface deposits observed by Veillette *et al.* (1989) (Figure 37). Although not mapped by Veillette *et al.* (1989) we observed thick layers of stratified fine sediment typical of near-shore glacio-lactustrine deposits near Lake Huard (Figure 8). The extreme valley constriction where the mainstem Cascapédia River exits the Lake Branch depression (Figure 37) may have triggered repeated episodes of ice blockage and lake impoundment during deglaciation. The topographic depression formed through the weathering of the Lake Branch formation may have influenced the deposition of Pleistocene surficial deposits throughout the basin, which in turn determines the erodability of hill slopes and banks and the overall susceptibility of terrain. It therefore seems very likely that the distribution of erodable surface deposits may play a significant role in explaining the observed fine sand and silt levels throughout the basin. Pool-riffle reaches with gradients between 1% and 1.5% that flow upon the Lake Branch formation have on average higher levels of silt and sand than pool-riffle reaches within the same channel gradient range that flow upon any other geologic formations ($p = 0.09$ and 0.02 for silt and sand). Subsequent studies within the area should therefore consider quantifying the risks of sedimentation associated with the various Quaternary formations throughout the drainage basin.

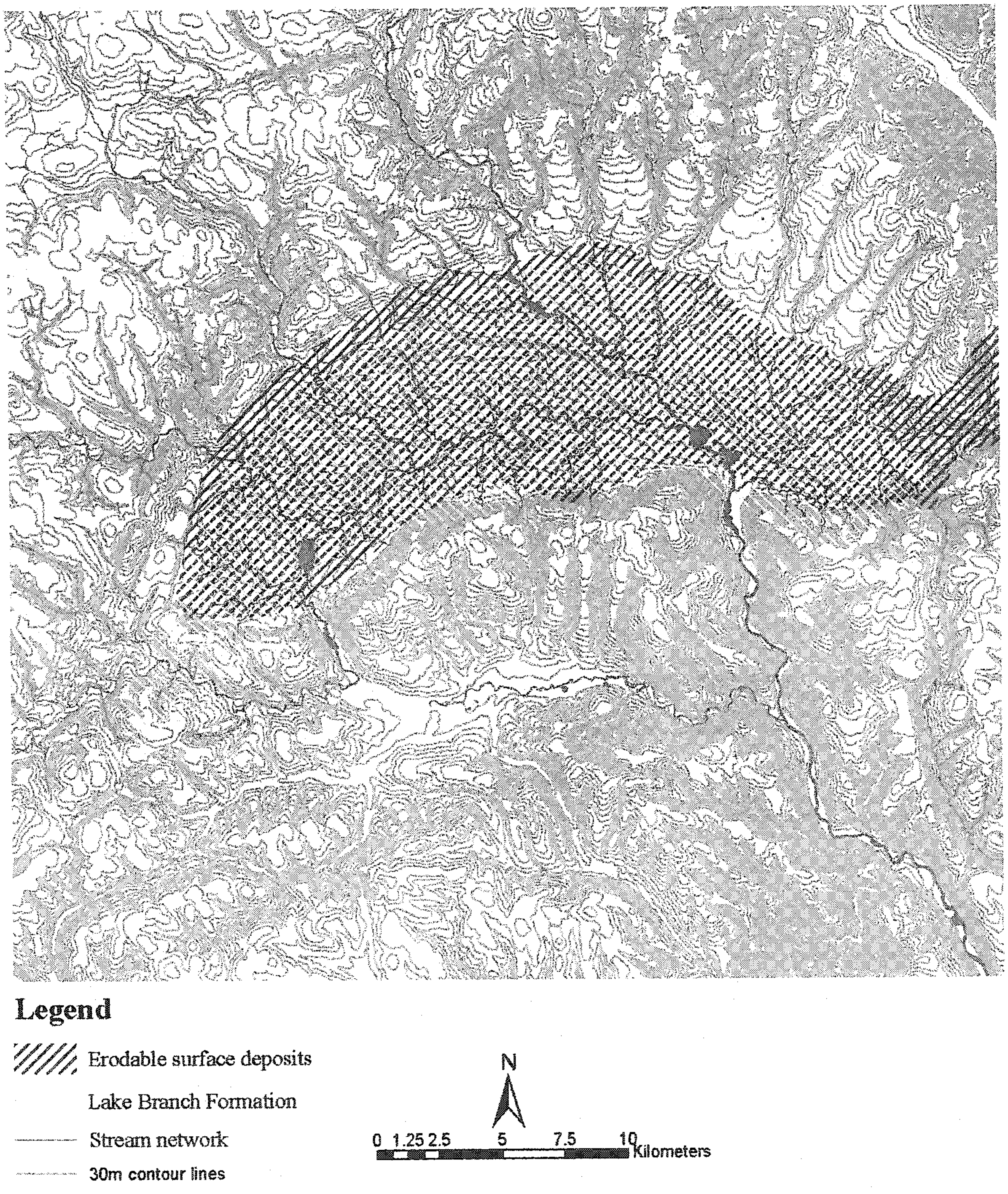


Figure 37. Coincidence of bedrock and surficial geology boundaries surrounding the Lake Branch topographic depression (Carbonneau, 1959). The erodable surface deposits boundary is based on the fluvioglacial and glacial deposits mapped by Veillette *et al.* (1989) (Figure 9).

VII. RESULTS – THE INFLUENCE OF FORESTRY DISTURBANCES ON THE SEDIMENTATION OF POTENTIAL ATLANTIC SALMON SPAWNING SUBSTRATE

The second objective of this thesis is to investigate the relationship between forestry practices and the quality of spawning habitat with respect to fine sediment content within the potential spawning sites. The reach and basin scale variables explored in the preceding chapter explained none of the observed variation in silt levels, and sand levels were only weakly explained by variations in the channel gradient. This chapter will examine the influence of numerous land use variables associated with harvest intensity and road network densities in order to determine their influence on the levels of fine sediment observed throughout the study area.

VII. 1. Impact of harvest intensity on in-stream sedimentation

VII. 1. 1. Intensity of forest extraction at different scales of analysis

The intensity of vegetation disturbance due to timber extraction depends on the spatial scale of the analysis. Table 15 provides the summary of the disturbance metrics used in the study as they vary with the scale of analysis. The percentages of the study basins cut based on the equivalent area calculations range from as high as 35% and as low as 1.3%, suggesting that no basin within this study is entirely unaffected by the forest harvest (Table 15). The equivalent area cut within the 60m riparian corridor reaches a maximum of 33%, which is just slightly lower than the maximum area cut for an entire basin. The average percent cut within the riparian zone (10%) is, however, significantly lower than for the entire basin (16%) ($p = 0.0003$), and the local riparian corridor (5%) is significantly less disturbed than the full riparian zone ($p = 0.0001$) (Table 15).

It is interesting to note that at the entire basin and local riparian zone scales, there are significant differences between the amount of cutting affecting boulder-rapid and pool-riffle reaches ($p = 0.05$ and 0.02 respectively). At the entire basin scale, boulder-rapid reaches have on average a slightly higher effective percentage cut (5.5% more), while at the local riparian corridor scale, boulder-rapid reaches have on average a lower effective percentage cut (3.9% less). At the full riparian scale there is no significant difference in cut levels between boulder-rapid and pool-riffle reaches ($p = 0.11$). Figure 38 shows the spatial distribution of attenuation factors within the 60m riparian corridor zone throughout the entire study area. Visual inspection of the cutting within the 60m riparian corridor suggests that the majority of cutting infringing on the channel boundary occurs around 1st and 2nd order streams in boulder-rapid reaches, which by Québec MNR regulations require only a 20m riparian zone on both sides of the tributary (Chapter IV.2.), rather than along the higher order segments where salmon are more likely to spawn. The highest level of cutting within the 60m riparian corridor occurs along the small tributaries of the Lake Branch, possibly because the topographic depression within this area makes the smaller tributaries more accessible to logging vehicles than they are in other regions of the study area.

A Spearman correlation matrix of percentage cut at all four scales reveals that cut intensity statistics over the entire catchment and the catchment riparian corridor are highly correlated ($R = 0.86$) (Table 16). This would suggest that the whole basin 60m corridor land use does not differ greatly from the land use within the entire subbasin, and that these two metrics are in fact measuring the same characteristic of the landscape. It likewise shows that the degree of cutting in the local riparian corridor, which is limited in its longitudinal extent to 1km upstream of the sample site, is fairly highly correlated with the degree of cutting within a 1km local radius ($R = 0.68$).

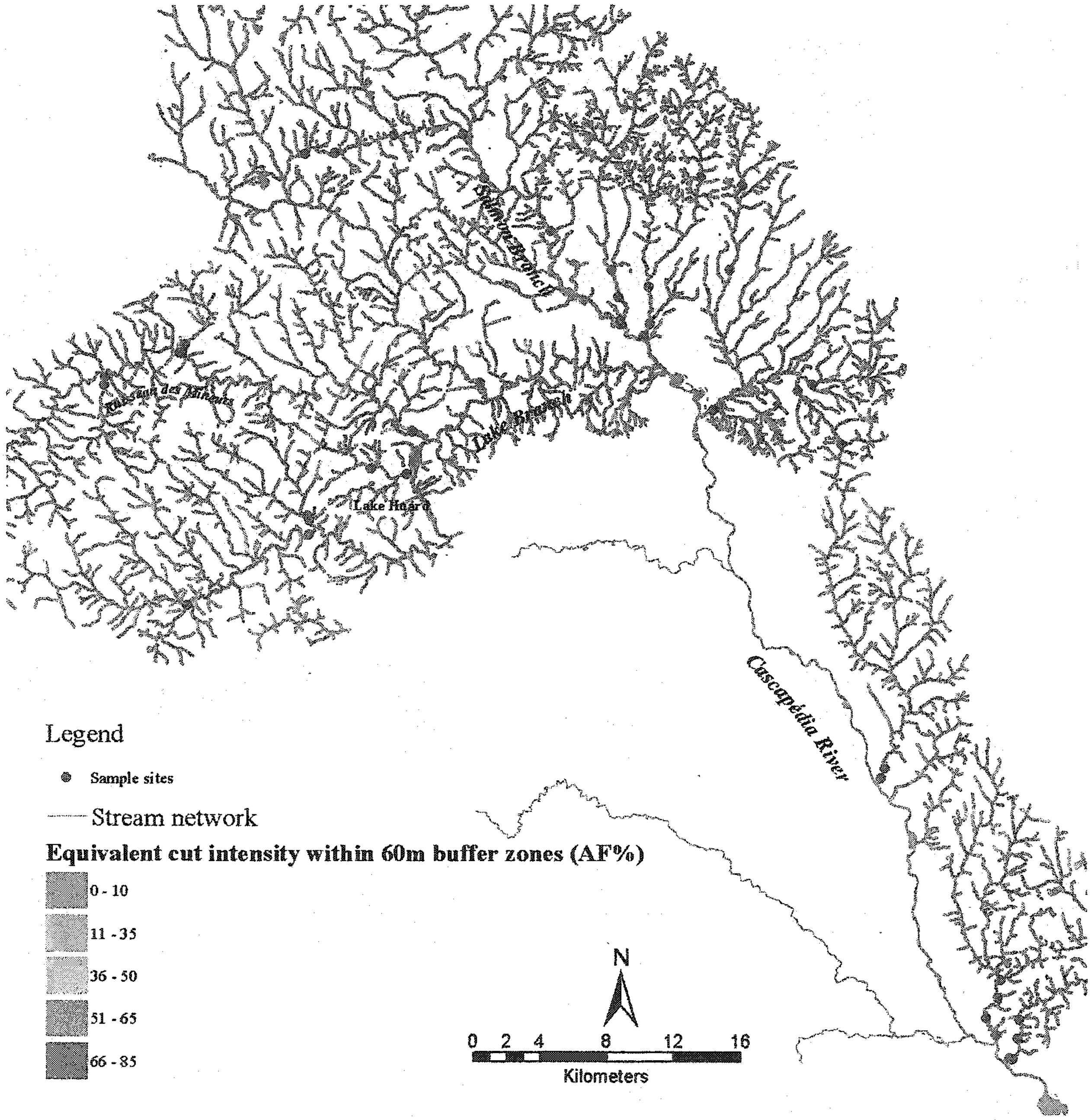


Figure 38. Distribution of disturbed parcels (based on the attenuation factors) within the 60m riparian corridor.

Table 15. Summary statistics for anthropogenic disturbance metrics.

	Number of subbasins	Mean	Minimum	Maximum	Standard deviation
Percent cut	44	16.3	1.3	35.4	9.4
Corridor percent cut	44	9.9	0.4	33.1	7.4
Local corridor percent cut	44	5.3	0	21.3	6.2
1km radius percent cut	40	17.4	0	49.3	15.3
Road density (all roads) (km/km^2)	44	1.5	0.7	2.5	0.6
Corridor road density (all roads) (km/km^2)	44	1.6	0.3	4.3	0.9
Local corridor road density (all roads) (km/km^2)	44	1.9	0	7.3	2.1
Main roads density (km/km^2)	39	0.7	0	2.3	0.8
Corridor main roads density (km/km^2)	39	0.4	0	1.3	0.4
Local corridor main roads density (km/km^2)	40	1.0	0	6.1	1.6
1km radius main roads density (km/km^2)	40	1.4	0	5.6	1.5
# intersections	45	32	1	144	31
# intersections within 1km	45	1	0	5	1
# intersections within 5km	45	10	1	38	9
# main intersections	45	12	0	144	27
# main intersections within 1km	45	0	0	3	1
# main intersections within 5km	45	2	0	18	4
Distance to nearest main intersection (m)	22	1830	65	5616	1667
# road crossings with slope > 5%	43	1	0	14	3

Table 16. Rankwise Spearman correlation matrix between equivalent area cut metrics at the four scales of analysis. Shaded boxes represent highly correlated variables discussed in the text.

	Whole basin percent cut	Whole basin corridor percent cut	Local corridor percent cut	Local 1km radius percent cut
Whole basin percent cut	1.000			
Whole corridor percent cut	0.865	1.000		
Local corridor percent cut	0.303	0.367	1.000	
Local 1km radius percent cut	0.360	0.394	0.683	1.000

VII. 1. 2. Harvest intensity and fine sediment levels in stream substrate

Regression analyses of the effective percentage cut metrics against substrate percent silt values yielded no significant relationships. Figure 39 shows the linear regression statistics for observed silt levels against percent cut at four scales of analysis for the sampled boulder-rapid, pool-riffle and bedrock reaches. Percentage silt was not strongly correlated to percent cut at any of the scales examined in this study.

The linear regression statistics for unadjusted sand levels (uncalibrated with freeze core correction factor, Chapter V.1.) against effective percent cut at the same four scales of analysis are shown in Figure 40. While percent sand increases slightly at all four scales with increasing cut intensity, the relationships at the full basin, riparian corridor, and riparian sub-corridor scales (Figure 40 a,b,c) are neither strong nor significant. Regression analyses of effective percent cut variables against percent sand suggest, however, that the degree of cutting within a 1km radius has a weak but significant effect on the level of sand within the riffle substrate ($R^2 = 0.28$, $p = 0.0001$) (Figure 40d). The highest sand values sampled are primarily associated with the highest cut intensities at the 1km scale, while in contrast all of the lowest sand values are found in less disturbed areas. Consideration of the channel gradient as a covariate suggests that the risk of sedimentation is greatest where the cut intensity is high and the channel gradient is low (Figure 40e, sites Échouement and TINL 1), which reiterates the importance of accurate estimates of channel gradients over a large number of sites. Ongoing research within the study area will continue to explore the potential of this disturbance metric, in conjunction with the channel gradient, to explain the observed levels of sand.

There are three sites in Figure 40e identified by name (Berry 2, Mineur 1, and White Brook 1) that deviate from the general trend mentioned above, two of which have high channel gradients and relatively high sand contents, and a third that has but little sand despite its low channel gradient and high cut intensity. The high sand content of the two high gradient sites can be explained in part by the selection of the bulk sample position. One of these sites is a bedrock reach (White Brook 2), while the other is a steep boulder-rapid reach (Berry 2) (Figure 40e). In both cases the presence of large outcrops of bedrock or immobile boulders severely restricted the bulk sampling site selection. Due to the prevalence of these features at these sites, the bulk samples were surrounded by large boulders or large outcrops of bedrock and it is therefore possible that the substrate in the chosen sample locations contained particularly high levels of sand relative to other regions of the reach. The low sand level of the third site (Mineur 1) cannot, however, be easily explained. Despite the high percent of cutting within 1km of the sample reach (37.3%) and the gentle channel gradient (0.36%), the sample reach (Mineur 1) has very little sand (< 5%) within both riffle substrate samples.

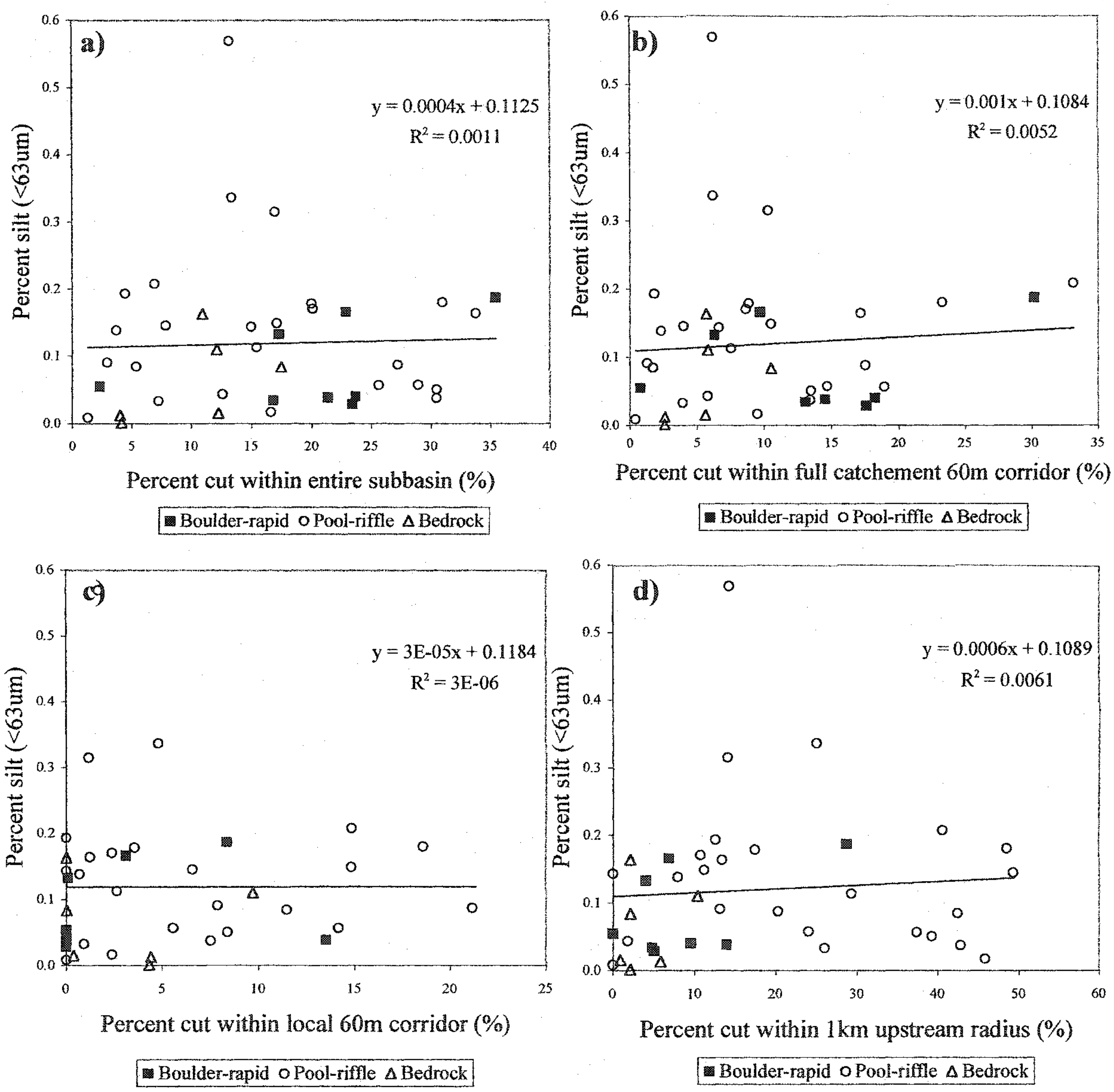


Figure 39. Regression statistics for the percentage silt within the substrate against the equivalent area cut at: the whole basin (a), the entire catchment 60m riparian corridor (b), the local 60m riparian corridor (c), and the 1km upstream radius (d).

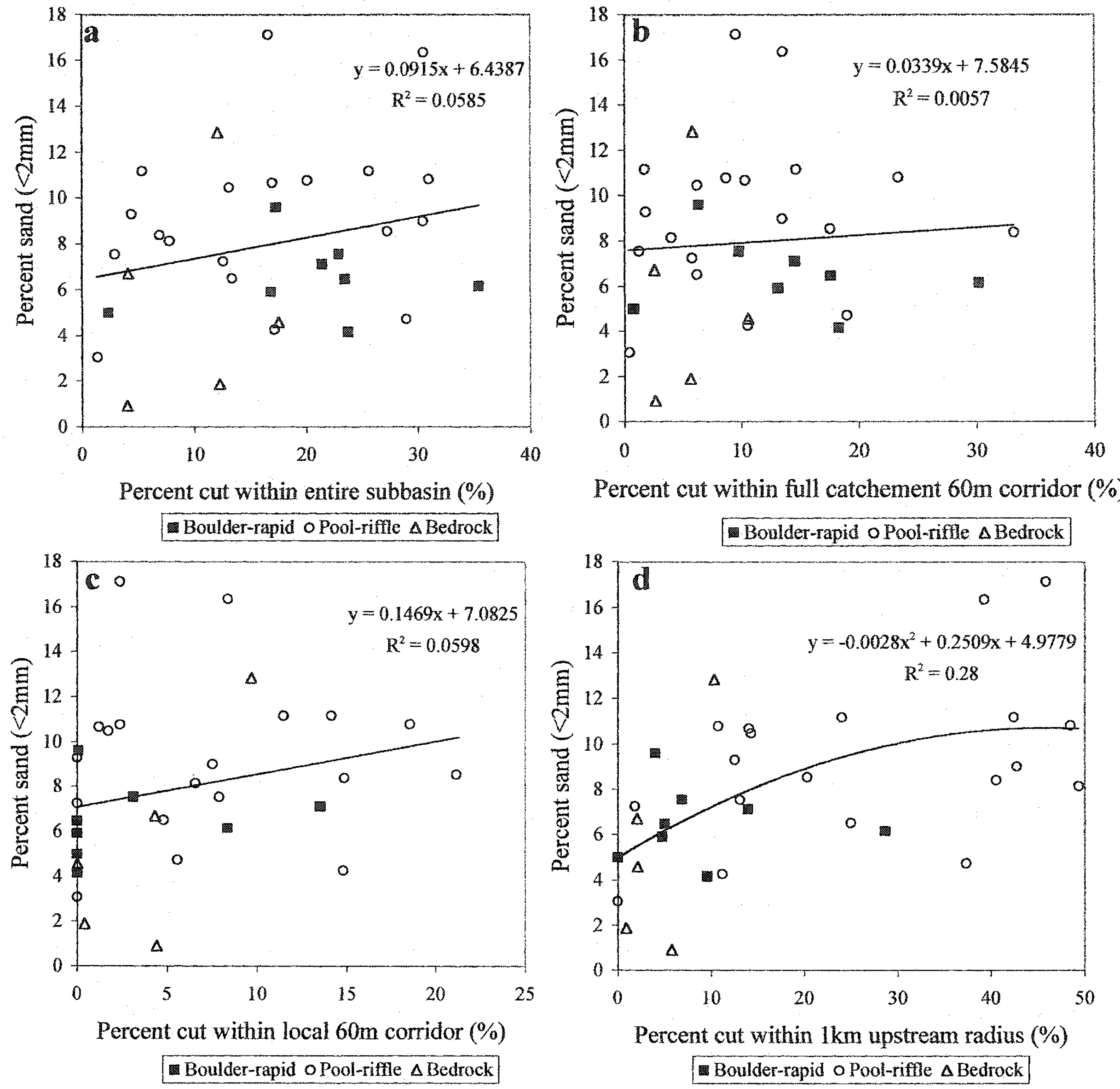
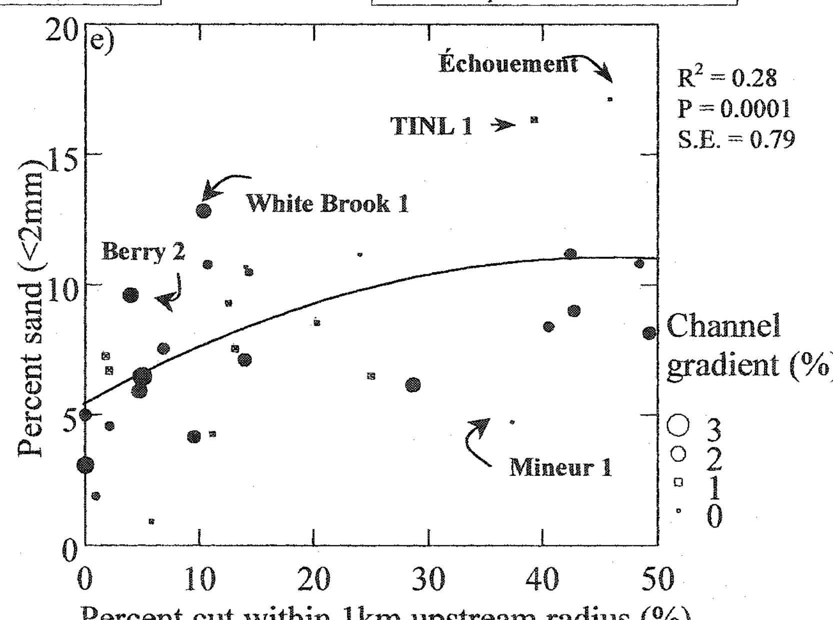


Figure 40. Relationship between percent sand under 2mm in the substrate and the effective percent of forest cut within: the entire subbasin (a), the entire catchment 60m corridor (b), the local 60m riparian corridor (c), the 1km upstream radius (d), and with slope as a covariate (e). Named sites are discussed in the text.



VII. 2. Impact of road network on in-stream sedimentation

VII. 2. 1. Density of road networks at different spatial scales

The risk of in-stream sedimentation associated with logging roads was assessed using metrics associated with stream-road crossings and road network densities across four spatial scales. Maximum densities of all roads within the study basins range between 2.5km/km^2 at the entire watershed scale to 6.1km/km^2 within one basin at the local riparian corridor scale (Table 15). The density of main roads with the subbasins reaches as high as 2.3km/km^2 and the absence of main roads entirely in several subbasins results in an average main road density of 0.7km/km^2, which is considerably lower than the maximum density. The number of intersections between main logging roads and streams varies between 144 upstream of Mineur 1, one of the most heavily cut subbasins, and 0 in all of the more pristine subbasins.

The spearman rankwise coefficient matrix of all forestry disturbance metrics used in this study is shown in Table 17. There is a high degree of correlation between most of the road metrics as well as between the road metrics and the percent cut metrics, represented in Table 17 by shaded values. These correlations are clearly to be expected given that road building precedes the actual timber harvest and that the greater the road density, the greater the likelihood of roads intersecting streams.

VII. 2. 2. Road networks and fine sediment levels in stream substrate

The linear regression statistics for the road metrics against silt and sand levels are presented in Table 18. Contrary to what is reported by many authors, and despite the number of metrics associated with forestry roads extracted from the GIS at all four scales, none of the road metrics used in this study correlated significantly with the level of silt measured in the substrate of the study sites (Table 18). Of all the road metrics, including the number of road-stream intersections and the number of steep road crossings, only two road metrics are significantly but weakly correlated to observed sand levels (shaded values in Table 18). As with the harvest metrics, the density of main roads within a 1km upstream radius is most strongly correlated to the percent sand within the riffle (R^2 = 0.146, p = 0.031). While there is a general increase in percent sand within the riffle with increasing road density within the 1km upstream radius, the correlation is very weak and therefore provides little insight into the susceptibility of the spawning habitat to sedimentation as a result of the upstream road networks (Figure 41). The relative position of the intensively sampled sites of Brandy 1A and Brandy 1B on Figure 41 show the difficulty encountered in trying to develop road metrics that represent the actual risk of sedimentation associated with the road network. The observed sand and silt levels of Brandy 1A are higher than those for Brandy 1B despite the higher road density in close proximity to the latter site. None of the road metrics employed in this study explain the pattern of the fine sediment distribution within the sampled spawning gravel; the possible reasons for which will be explored in the following discussion.

Table 17. Correlations within road metrics at four spatial scales; the whole catchment (1), the riparian corridor for the full extent of the catchment (2), the local 1km riparian sub-corridor (3), and the local 1km upstream radius (4). Shaded boxes represent highly correlated disturbances metrics.

	Percent cut	Percent corridor cut	Percent local corridor cut	Percent cut within 1km radius	Density of all roads	Density of all roads in 60m corridor	Density of all road in local 60m corridor	Density of main roads	Density of main roads in 60m corridor	Density of main roads in local 60m corridor	Density of main roads within 1km radius upstream	# intersections	# intersections within 1km	# intersections within 5km	# main intersections	# main intersections within 1km	# main intersections within 5km	# sloped road segments within 1km
Percent cut within entire subbasin (%)	1																	
Percent cut within full riparian corridor (%)	0.87	1																
Percent cut within local riparian corridor (%)	0.30	0.37	1															
Percent cut within 1km radius upstream (%)	0.36	0.39	0.68	1														
Density of all roads (km/km^2)	0.67	0.53	0.18	0.37	1													
Density of all roads in 60m corridor (km/km^2)	0.02	-0.04	-0.35	-0.08	0.34	1												
Density of all road in local 60m corridor (km/km^2)	0.47	0.42	0.05	-0.03	0.46	0.35	1											
Density of main roads (km/km^2)	0.75	0.65	0.27	0.46	0.57	-0.14	0.26	1										
Density of main roads in 60m corridor (km/km^2)	0.78	0.64	0.15	0.25	0.41	-0.06	0.38	0.90	1									
Density of main roads in 60m local corridor (km/km^2)	0.61	0.46	0.14	0.30	0.60	0.05	0.52	0.80	0.77	1								
Density of main roads within 1km upstream radius (km/km^2)	0.35	0.37	0.31	0.59	0.48	-0.05	0.13	0.69	0.46	0.63	1							
# intersections	-0.18	-0.20	-0.09	-0.04	-0.25	0.29	-0.01	-0.22	-0.13	-0.07	-0.20	1						
# intersections within 1km	0.47	0.38	0.09	0.05	0.53	0.26	0.57	0.40	0.49	0.53	0.26	-0.04	1					
# intersections within 5km	0.16	0.15	-0.13	-0.06	0.35	0.55	0.43	-0.05	0.05	0.17	-0.07	0.35	0.63	1				
# main intersections	0.55	0.43	0.11	0.22	0.16	-0.04	0.14	0.61	0.71	0.45	0.23	0.38	0.28	0.10	1			
# main intersections within 1km	0.59	0.45	0.16	0.15	0.51	-0.03	0.44	0.65	0.70	0.76	0.50	0.00	0.77	0.38	0.49	1		
# main intersections within 5km	0.51	0.42	0.23	0.41	0.49	-0.15	0.12	0.81	0.69	0.72	0.71	-0.02	0.37	0.10	0.62	0.66	1	
# sloped road segments within 1km	0.53	0.50	0.15	0.34	0.48	-0.01	0.23	0.77	0.72	0.78	0.67	0.08	0.43	0.20	0.62	0.69	0.94	1

Table 18. Linear regression statistics for all road metrics used in this study against silt and sand levels observed in spawning gravel. Shaded boxes represent significant correlations.

	Percent silt within riffle		Percent sand within riffle	
Road metric	**R^2**	**p value**	**R^2**	**p value**
Road density of basin (all roads) (km/km^2)	0.019	0.404	0.143	0.033
Road density of full 60m corridor (all roads) (km/km^2)	0.006	0.634	0.042	0.261
Road density of local 60m corridor (all roads) (km/km^2)	0.019	0.4	0.0001	0.996
Main road density of basin (km/km^2)	0.002	0.805	0.094	0.088
Main road density of full 60m corridor (km/km^2)	0.003	0.743	0.042	0.261
Main road density of local 60m corridor (km/km^2)	0.0001	1.0	0.025	0.391
Main road density of 1km upstream radius (km/km^2)	0.011	0.532	0.146	0.031
Number of intersections within basin	0.015	0.455	0.0001	0.98
Number of intersections within 1km	0.02	0.39	0.031	0.336
Number of intersections within 5km	0.0001	0.983	0.002	0.805
Number of main intersections within basin	0.002	0.778	0.0001	0.943
Number of main intersections within 1km	0.014	0.478	0.074	0.133
Number of main intersections within 5km	0.069	0.105	0.081	0.115
Distance to nearest main intersection (m)	0.022	0.53	0.018	0.616
Number of road crossings with slope > 5%	0.04	0.201	0.028	0.359

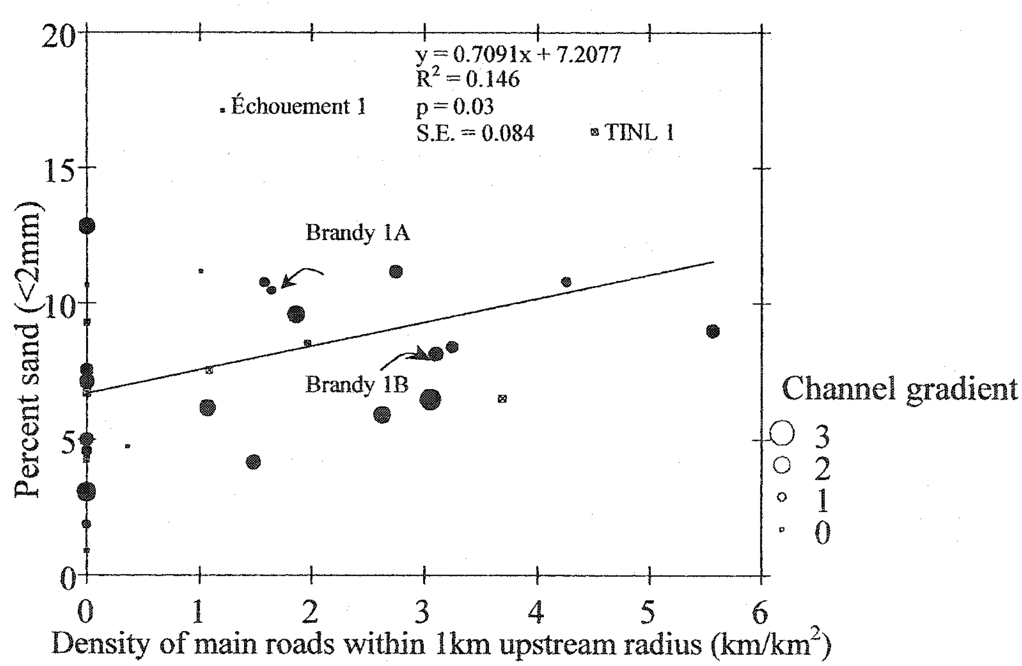


Figure 41. Relationship between percent fine sand (<2mm) and the density of main roads within a 1km upstream radius with channel gradient as a covariate. Named sites are discussed in the text.

VII. 3. Discussion - The influence of harvest intensity and road network densities on spawning substrate quality

While the level of sand found within the riffle substrate appears to be weakly related to the degree of local forest extraction (Figure 39), the level of silt does not (Figure 40). There are several possible explanations to account for the difficulty encountered in predicting the distribution of sediments as fine as sand and silt.

Level of disturbance relative to previous studies

Within the Cascapédia watershed road densities within the study subbasins are not as high as the levels observed on the North American west coast, where the majority of previous studies have been held. Road network densities (all roads and main roads) do not exceed the value of 2.5km/km^2 reported by Celderholm *et al.* (1981), a density above which the authors found sediment levels consistently exceeded natural levels. Given that they are lower than the levels in many of the basins on the west coast, the road network densities within the Cascapédia drainage basin may not be sufficient to consistently increase the amount of fine sediment found within the riffle substrate throughout the watershed.

Furthermore, the road classification scheme of primary and secondary roads versus undrivable roads used in this study may be too coarse a classification to accurately capture the role that roads are playing in the in-stream sedimentation levels. Additional data on traffic intensity and road age, reported by numerous authors as contributing factors in sediment production from roads (Celderholm *et al.*, 1981; Reid and Dunne, 1984), were not available in this study, but may play a role in explaining the observed sedimentation levels throughout the subbasins. The differences in the age and design characteristics of culverts and stream crossings within the subbasins may also be a factor complicating the relationship between the road network densities and the observed in-stream sedimentation levels.

As with road densities, cut intensities within many of the Cascapédia subbasins are lower than the cut intensities recorded in many of the published west coast studies on forestry-stream interactions. To date, a total of 61% of Carnation Creek has been logged (Hartman *et al.*, 1995), 40% of Clearwater basin has been clearcut (Cederholm *et al.*

1981) and the subbasins of the Queen Charlotte Islands have had up to 82% of their surface area logged in the past 30 years (Hogan and Bird, 1998). Cut intensities in the Cascapédia, in comparison are not as high. Within the last 30 years only 8.4% of the entire Salmon Branch basin and 23.2% of the Lake Branch basin have been clearcut and the total surface area clearcut in the past 30 years does not exceed 34% within any of the subbasins of this study. In these calculations, the Salmon and Lake Branch sub-basins are defined at the point of junction of the two rivers (see inset Figure 6).

Geologic, climatic and topographic differences from previous studies

Compounding this difference in cut intensities is the fact that timber harvesting in the Cascapédia drainage basin tends not to occur on hillslopes as steep as those encountered on the west coast. Up to 71% of the subbasin area in the Queen Charlotte Islands and 39% of Carnation Creek are classified as steep land and are inherently unstable, increasing the importance of mass wasting (Hogan *et al.*, 1998). Rood (1984) observed 43 times more sediment entering the channels of the Queen Charlotte Islands from logged areas compared to unlogged areas due to the occurrence of mass wasting. Within the Cascapédia basin, mass wasting is generally limited to shallow, river terrace landslides, which occur primarily along the meanders of the central portion of the Lake Branch (Robitaille, 1999). Of the 15 landslides Robitaille (1999) observed on the steep slopes of the Lake Branch, only 5 were bordered by recent cutblocks along the crest of the slide. While the steep terrace cutbanks of the Lake Branch may be predisposed to mass wasting of the very friable Lake Branch formation shale, the headwater tributaries of the Lake Branch, as well as the Salmon branch and its tributaries are considerably less susceptible to such mass movement as they are generally not directly adjacent to hillslopes that are as steep (Robitaille, 1999).

The occurrence and importance of mass wasting on the steep slopes of the Pacific coast range watersheds are strongly associated with the predominance of highly erodable bedrock formations, thick, erodable surface deposits, as well as frequent and intense seismic activity and precipitation. Annual precipitation along the west coast on average exceeds 3600mm, and has been estimated to reach as high as 7000mm locally within the coastal mountain range (Hogan, *et al.*, 1998). The local geology, in addition to influencing the topography and channel gradient as discussed in the preceding chapter, may influence both the natural input of sediment into the channel as well as the natural sensitivity of the terrain to anthropogenic disturbance, which may complicate the relationship between forestry practices and the amount of fine sediment within the spawning gravel. While both Richards *et al.* (1996) and Lammert and Allen (1999) found that stream sedimentation levels were inversely correlated to the level of forest cover within the riparian zone, Barrett *et al.* (1998) suggested that variations in local geologic factors may be even more influential than road densities and harvest intensities in determining the potential threat of in-stream sedimentation. Barrett *et al.* (1998) suggested that the quality of the salmon habitat throughout the subbasins they sampled along the northern coast of California was more strongly associated with the risk of mass wasting and surface erosion than the intensity of management activity of the subbasin. Unfortunately, the risks of mass wasting and surface erosion based on geology and surface deposits, while not as great as in the North American Western Cordillera, were not quantified in detail in this study; thus the risk of sedimentation associated with their occurrence cannot be distinguished from other natural or anthropogenic sources of fine sediment.

Buffering capacity of the riparian corridor

It is also possible that the protected riparian corridor throughout the study reaches and along the majority of the smallest order tributaries is successful at filtering any excess sediment being delivered from cut-blocks and roads. Figure 38 shows that for the majority of the stream network the 60m vegetated corridor lining the channel is indeed intact (effective percent cut within the full 60m riparian corridor of 3.8% and 17% for Salmon and Lake Branches respectively). This would suggest that, given the current level of cutting and road building within the subbasin, if the local riparian corridor is left intact the salmonid habitat will not, in general, be clogged with fine sediment above natural levels. Many of the west coast studies that have reported significant relationships between harvest intensities or road network densities and sedimentation levels have studied these relationships in experimental basins were the clear cutting is conducted right up to the channel boundary (Brown and Krygier, 1971; Hartman and Scrivener, 1990;

Hogan and Bird, 1998; Johannes and Hyatt, 1998). In British Columbia, intact corridor strips along the channel boundary were relatively uncommon prior to 1988 (Hogan and Bird, 1998). The potential for fine sediment to enter the channel is clearly much greater under such conditions.

Where poor road design creates a sediment rich flow, bypassing the riparian corridor and redirecting natural runoff patterns directly into smaller order tributaries, the buffering potential of the riparian corridor may be undermined. The one instance where such a road failing was observed (June 2000) and sampled intensively within the study area (Figure 11 and 24) may have contributed to the observed silt levels at Brandy 1A and 1km downstream at Brandy 1, which were the highest of any observed in this study. The suspended sediment concentrations in the small stream near this road failing, which was sampled during a storm in the summer of 2001, yielded a concentration of 175 mg/L, 94% of which was silt class (0.063mm) or finer (Zimmerman, A., 2002. Personnal communication. Laboratory of M. Lapointe, McGill University, Montréal, Québec). This particular road failing appeared to be the result of excessive vegetation growth blocking a culvert, which during a large rainstorm resulted in the runoff bypassing the culvert and washing out part of the road network. Such a road failing, caused by a blocked culvert, cannot, however, be predicted from the limited information available in the road database. By comparison, substrate silt levels at Brandy 1B and the uppermost site on Brandy Brook, which are upstream of this particular road failing, are not statistically different from the other tributaries. It is interesting to note that at the road failing of the intensively sampled Brandy 1B, the sediment laden flow, which passed through approximately 100m of forest before reaching the tributary, did not appear to result in an increase in fine sediment within the substrate. This suggests that the intact vegetation may have adequately filtered out much of the suspended sediment before the runoff reached the channel.

It is likewise possible that the large woody debris (LWD) common in the smallest tributaries helps in storing fine sediment, retarding its transport and deposition further downstream within the potential spawning grounds. While LWD was not explicitly measured in this study, its occurrence was noted and it was in fact often so common in the smallest tributaries that the tributary could not be sampled using our methods. Duncan *et* *al.* (1987) observed that low order tributaries provided temporary storage for fine sediment, thereby inhibiting the transport and deposition of fine sediment into larger streams during storms of moderate intensity. They found that large runoff events were capable of flushing stored sediment from the smallest tributaries, but concluded that it was unlikely that the finest sediments would then be subsequently redeposited in the potential spawning reaches in larger streams, as the flow would have increased in the larger channels as well. The fine sediment entering into suspension in this manner would then most likely be evacuated a considerable distance downstream from the prime spawning reaches.

Level of natural variation

Finally, the lack of variance in silt content between sites and the small variance in sand content between sites makes it difficult to distinguish between potential natural and anthropogenic sources. Paired samples in this study suggest that there is a high degree of natural variability in silt levels between successive riffles, which may explain the lack of correlation between silt levels and both landscape and land use metrics. While the percentage of sand is correlated with the level of disturbance due to the harvest within a 1km radius of the sample reach, the most notable aspect of this correlation is found at the highest and lowest extremes in sand levels (Figure 40e). The highest and lowest observed sand levels, which are significantly different statistically from each other, occur at opposite ends of the disturbance scale as well as the channel gradient scale. The highest sand levels occur in sites with gentle channel gradients surrounded by a high percent of local cutting (Échouement and TINL 1) and the lowest sand levels occur where the channel gradient is steeper and the effective percent cut within 1km is low. This suggests that the risk of in-stream sedimentation is greatest in low slope reaches (<1%), in particular where upvalley local equivalent area cutting approaches or exceeds 40%.

VIII. SPATIAL DISTRIBUTION OF SUITABLE ATLANTIC SALMON SPAWNING HABITAT

VIII. 1. Spawning habitat suitability index for the Cascapédia watershed

Based on the results presented in the preceding chapters we have devised a salmon habitat suitability index for the sites sampled in this study. Clearly the actual suitability of spawning habitat depends on more than a few simple criteria. Several critical stream habitat variables can, however, provide insight into the distribution of stream habitat throughout the study area that is potentially suitable for salmon spawning. The criteria used in this suitability index include the channel gradient, the median substrate diameter and the sand content of the subsurface substrate. Justification for the selection of these criteria based on current theoretical knowledge and the data presented in this thesis will be provided in the following sections of this chapter. The chapter will conclude with a brief discussion of the influence of landscape structure and forestry practices on the distribution of suitable habitat.

VIII. 1. 1. Suitability based on the channel gradient

Most salmon spawning occurs within pool-riffle reaches, which are characterized by an abundance of mobile cobble riffle bars along the channel thalweg (Platts *et al.*, 1979; Kondolf and Wolman, 1983; Moir *et al.*, 2002). Steeper boulder-rapid reaches, in comparison, appear to have insignificant accumulations of spawnable mobile cobble patches to justify the additional energy expenditure required for salmon migration into such reaches. The occurrence of boulder-rapid and pool-riffle systems are greatly influenced by variations in channel gradients. The data from the Cascapédia basin indicates a small overlap between pool-riffle and boulder-rapid morphologies for channel gradients between 1.5% and 1.7%. Within the study reaches of the Cascapédia drainage basin, the transition from pool-riffle to boulder-rapid occurs at a lower channel gradient than the gradients reported by many authors. Montgomery and Buffington (1997), Church (1992) and Halwas and Church (2002) all report that the transition between pool-riffle and boulder-rapid morphologies corresponds to channel gradients closer to 2%. The channel gradient threshold to be used in the suitability index was increased from 1.7% to 2%, thereby providing a more conservative upper limit to the occurrence of pool-riffle systems as well as one that coincides with the findings of a majority of other authors (Mills, 1973; Montgomery and Buffington, 1997; Church, 1992; and Halwas and Church, 2002).

VIII. 1. 2. Suitability based on the pavement and subpavement composition

In addition to an increase in channel gradient between boulder-rapid and pool-riffle morphologies, the transition between dominant morphologies corresponds to a significant increase in median pavement diameter. The fact that the increase in surface coarseness in boulder-rapid reaches coincides with and increase in channel gradient reinforces the theory that it is unlikely that Atlantic salmon would be found spawning in any great number where the local channel slopes are much higher than 1.7%. Such a statement depends, however, on a definition of an upper threshold of pavement stone diameters that spawning salmon can displace, which is likely to depend on the size of the salmon. The pavement D_{50} was not, however, included in the suitability index for two reasons: there is a lack of literature to support a definition of an upper pavement threshold for spawning and the median pavement diameter within the study area is finer than 135mm at all but one site. The pavement composition is therefore likely suitable at all but one site dominated by bedrock (Salmon 2).

Despite the significant increase in pavement diameter between pool-riffle and boulder-rapid reaches (Figure 18), there are no significant differences between the two dominant morphologies at the subpavement level (Figure 22). Numerous authors have studied the suitability of spawning subsurface grainsize distributions and have reported a wide range of acceptable substrate compositions (Platts *et al.*, 1979; Milhous, 1982, Kondolf and Wolman, 1983; Moir *et al.*, 2002). The average suitable median subsurface diameter ranges between 15 and 35mm; however, depending on the size of the spawning salmon, much coarser gravels may also be suitable (Peterson, 1978; Crisp and Carling, 1989; Kondolf and Wolman, 1993; Verville, 1998). Given the wide range of subsurface sediment diameters within which salmonids (not exclusively Atlantic salmon) tend to appear to spawn successfully (8.9mm-40mm in Crisp and Carling, 1989; 5.4mm-78mm in Kondolf and Wolman, 1993; 39mm-70mm in Verville, 1998, 10mm-38mm in Moir *et al.*, 2002), the suitability index was calculated using five different subpavement D_{50} thresholds (<20mm, <30mm, <40mm, <50mm and <60mm).

VIII. 1. 3. Suitability based on the fine sediment content

Peterson and Metcalfe (1981) suggest guidelines for the classification of spawning gravel as excellent, mediocre, and poor based on a sand index that they devised. The sand index calculated for each site in the study area plotted versus the percentage fines under 2mm (uncorrected for bulk sampling loss) provides an index of the percentage fines under 2mm that corresponds to excellent, mediocre and poor spawning gravel quality (Figure 42). These guidelines suggest that a threshold sand content for excellent spawning gravel in the study area is below 13.5%, mediocre is within 13.5% and 20% and that beyond 20% sand the spawning habitat is poor. This classification suggests that the majority of the sites sampled in this study are considered excellent with respect to their sand content, and that none exceed the sand threshold above which the likelihood of emergence is poor.

Using the percentage sand values and sand indices adjusted for sampling losses through a freeze core calibration (Zimmerman *et al.*, submitted) results in slightly lower threshold defining poor and mediocre spawning gravel (Figure 42). The freeze core calibration suggests an upper sand threshold defining excellent spawning gravel of 10.4% and an upper threshold defining mediocre habitat of 15.3%. The use of the adjusted values reduces the number of sites classified as excellent and increases the number of sites classified as poor (Table 19).

Table 19. Number of sample sites classified as excellent, poor and mediocre based on the Sand Index using bulk sample sand values and calibrated sand values.

	Number of sites classified per category		
Index Used	**Excellent**	**Mediocre**	**Poor**
Bulk sample fines content (<2mm)	37 (84.1%)	7 (15.9%)	0
Freeze core calibrated fines content (<2mm)	14 (31.8%)	16 (36.4%)	14 (31.8%)

Electro-fishing conducted by a parallel CIRSA study within 44 of the study reaches revealed that in fact the juvenile Atlantic salmon densities, while low in general, were highest in the reaches classified as excellent with respect to the unadjusted bulk sample sand content (Deschênes, J., 2002. Personal communication. Laboratory of M. A. Rodriguez, UQTR, Trois-Rivière, Québec.). Of the 37 sites classified as excellent with respect to sand content (Table 19), 12 contained Atlantic salmon parr, while only one of the seven mediocre sites contained any parr (Table 20).

Although in some cases the lack of salmon may be the result of access barriers downstream, it is conceivable that the amount of silt may also play an important role. Yet, because the sand index does not factor in the possible consequences of unusually high silt content, it may underestimate habitat suitability somewhat. Despite this potential to underestimate actual suitability, the uncalibrated sand levels and sand indices were considered in the suitability index. Given that no site exceeded the 20% sand content threshold above which salmon emergence would become unlikely, a 13.5% sand content threshold and a Sand Index below 1 defining excellent spawning habitat were used to distinguish between suitable and unsuitable sand levels.

Table 20. Distribution of Atlantic salmon parr between excellent, poor and mediocre sites during the summer of 2001 (Deschênes, 2002, personal communication).

	Number of sites containing Atlantic salmon parr		
Index Used	**Excellent**	**Mediocre**	**Poor**
Bulk sample fines content (<2mm)	12 (92%)	1 (8%)	0
Freeze core calibrated fines content (<2mm)	4 (31%)	5 (38%)	4 (31%)

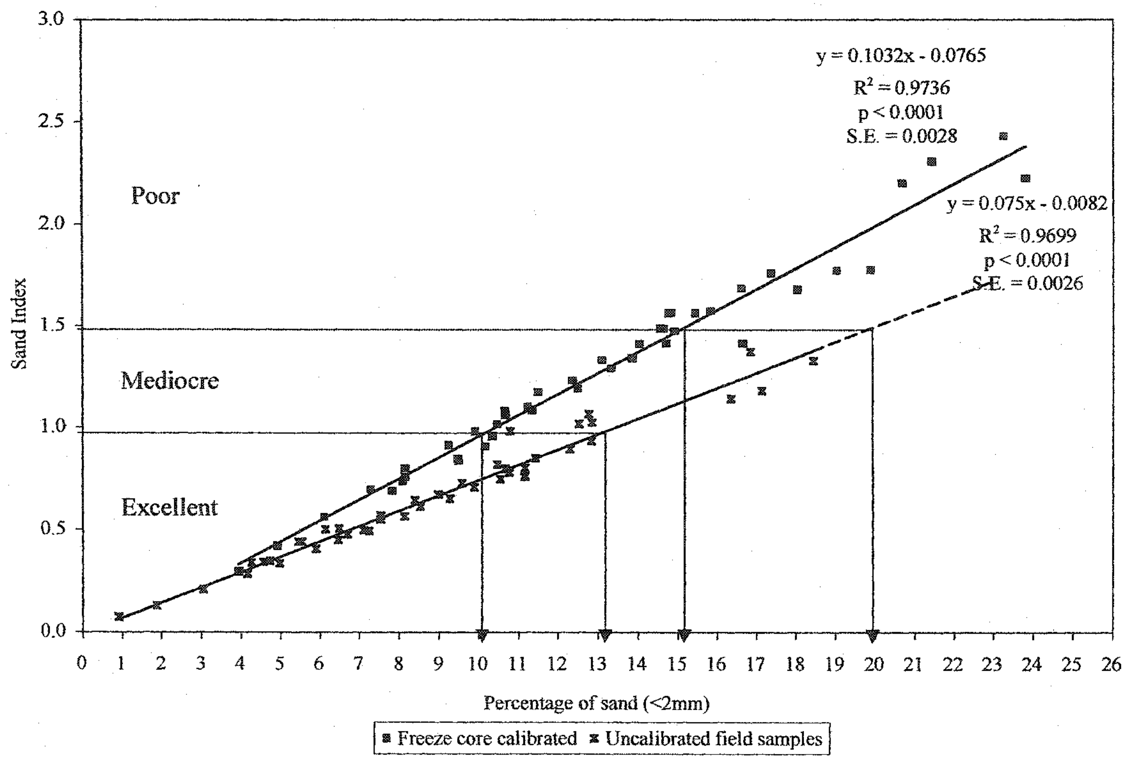


Figure 42. Sand index versus percentage sand showing poor, mediocre and excellent spawning thresholds for both the uncalibrated and freeze core calibrated sand levels.

VIII. 1. 4. Suitability index categories

Our suitability index thus contains four categories of suitability based on three determinants: the channel gradient, median subpavement diameter and sand content. The four categories correspond to: unsuitable based on all three criteria (0), suitable based on only one criteria (1), suitable based on any two criteria (2), and suitable based on all three criteria (3). Table 21 shows the proportion of study sites of the various suitability indices based on different D_{50} thresholds. No site is entirely unsuitable based on the 3 criteria established for this suitability index, regardless of the D_{50} threshold used. Where the upper D_{50} threshold is 20mm, the majority of sites are suitable based on just two criteria. As the D_{50} threshold increases the number of sites that are suitable based on all three criteria increases. Six sites (13%) have unsuitable gradients, while seven sites (16%) have unsuitable sand content. The substrate threshold appears to have the greatest influence over a site's classification as suitable or unsuitable using this index, suggesting that it is important for further research to clarify the exact value of this threshold. There is a rapid increase in the proportion of suitable sites based on all three criteria as the D_{50} threshold is increased up to 50mm (row 4, Table 21). There is, however, a much smaller increase in the proportion of suitable sites based on all three criteria as the D_{50} is further increased to 60mm. Given the size of salmon known to spawn in the Cascapédia River (multi-year females), it seems likely that a threshold of D_{50} less than 50mm would be an appropriate size within which Atlantic salmon could spawn successfully. The suitability of the 45 sites based on the D_{50} less than 50mm threshold are given in Table 22.

Table 21. Percentage of sites classified as suitable and unsuitable based on channel gradient, subpavement and sand content thresholds.

	Percentage of sites based on median subsurface threshold				
Category	D_{50}<20mm	D_{50}<30mm	D_{50}<40mm	D_{50}<50mm	D_{50}<60mm
0. Unsuitable based on any criteria	0	0	0	0	0
1. Suitable based on only one criteria	24.4%	13.3%	4.4%	4.4%	4.4%
2. Suitable based on any two criteria	73.3%	71.1%	64.4%	48.9%	44.4%
3. Suitable based on all three criteria	2.2%	15.6%	31.1%	46.7%	51.1%

Table 22. Suitability index classification for each site based on an upper D_{50} threshold of 50mm. Site names are abbreviated according to Table 3.

Site	Suitability index classification (D_{50}<50mm)	Site	Suitability index classification (D_{50}<50mm)	Site	Suitability index classification (D_{50}<50mm)
ROU 1	3	14EME 1	2	BER 1	2
ROU 2	2	14EME 2	3	BER 2	1
TINL 1	2	MIN 1	3	PSU 1	2
TINL 2	3	MIN 2	3	BIG 1	2
LOU 1	2	ECH 1	2	RTR 1	2
LOU 2	2	SAL 1	3	RTR 2	2
LOU 3	3	SAL 2	3	RTR 3	3
RIO 1	3	SAL 3	2	RTR 4	1
RIO 2	3	BRA 1	3	WBR 1	3
TMIN 1	2	BRA 1A	3	WBR 2	3
TMIN 2	3	BRA 1B	2	WBR 3	2
WAS 1	2	IND 1	2	WBR 4	3
WAS 2	3	IND 2	3	BN 3	2
INL 1	2	IND 3	2	BN 3A	3
INL 2	3				

VIII. 2. Influence of landscape structure and forestry practices on the distribution of suitable habitat

Influence of landscape structure on suitable habitat distribution

The results presented in Chapter VI have shown statistically significant differences in habitat characteristics between the two dominant channel types (boulder-rapid and pool-riffle) based on the geologic history and structure of the landscape. While pool-riffle reaches are on average wider, with less steep channel gradients and finer pavement substrate than the boulder-rapid reaches sampled, some boulder-rapid reaches may, however, still contain suitable spawning habitat.

The transition between the two morphologies occurs within 3rd order reaches (Figure 30), which in the study region correspond to basin areas between approximately $8km^2$ and $76km^2$. Figure 43 shows the proportion of sites for each stream order that are suitable based on the channel gradient and subpavement D_{50} criteria used in this suitability index (channel gradient<2% and D_{50}<50mm). From Figure 43, it is clear that stream reaches studied of order four or five have suitable channel gradients and that the majority likewise have suitable median subpavement diameters. Only 67% of order 2 reaches sampled, in comparison, have channel gradients under 2% and only one of which has a channel gradient under 1.7%. In addition, only 50% of order 2 reaches had suitable spawning substrate. It is therefore less likely that order 2 reaches contain as much suitable spawning habitat as higher order reaches.

There is no significant difference in median diameter of the subpavement between pool-riffle and boulder-rapid reaches. The relationship between the degree of valley bottom incision and the median subpavement diameter (Figure 34), however, provides additional insight into the distribution of potentially suitable spawning habitat with respect to the subpavement composition. From Figure 34, an index of valley bottom incision, represented by the degree of slope of the 60m riparian corridor of the subbasin, in excess of approximately 14 degrees corresponds to a D_{50} coarser than 50mm. Thus reaches in highly incised valleys, regardless of order or channel type, may have a dearth of mobile cobble-gravel and be unsuitable spawning substrate.

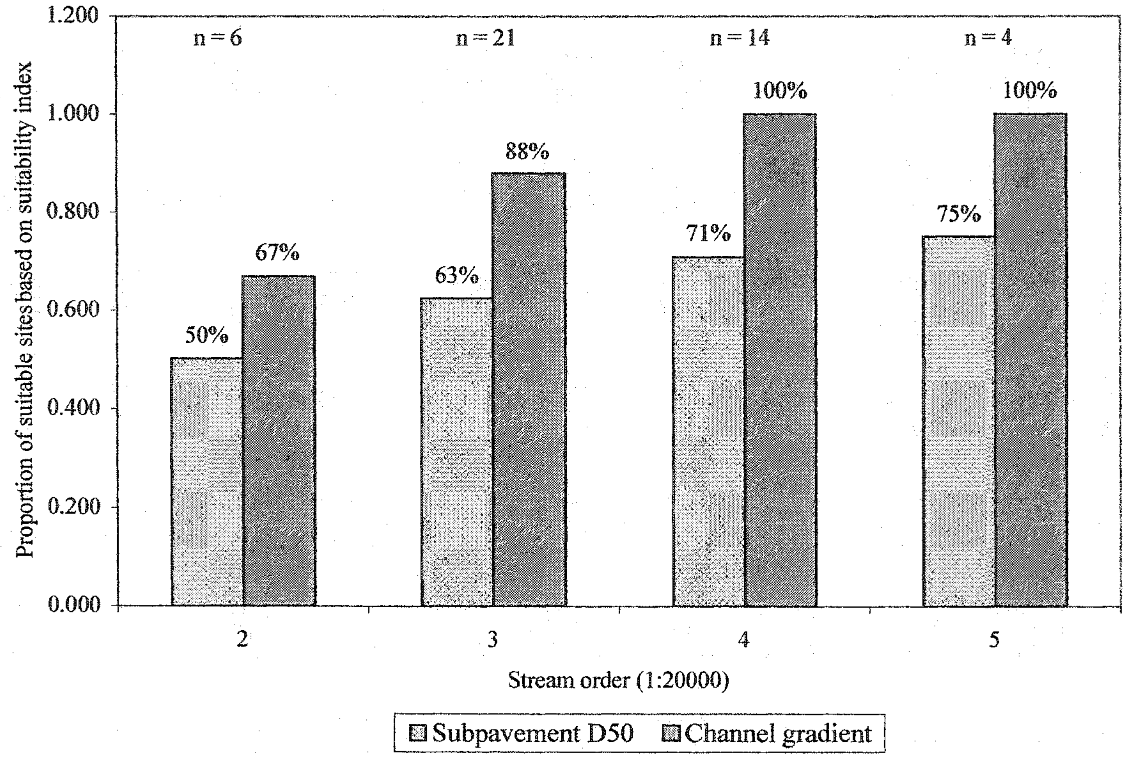


Figure 43. Proportion of study sites by stream order that are suitable based on the channel gradient (<2%), and the proportion of sites with suitable subpavement diameters (D50<50mm).

Influence of forestry practices on suitable habitat distribution

While the statistical relationships between the majority of the forestry disturbance metrics and fine sediment content within the potential spawning substrate presented in Chapter VII were not strong, two metrics, the effective percent cut and main road density within a 1km upstream radius, provide insight into sensitivity of the landscape to forestry disturbances. Figure 40e suggests that pool-riffle reaches (order 3 or greater) with gentle channel gradients (<1%), are susceptible to sand enrichment within the subpavement where the local cutting upstream reaches or exceeds an effective percent cut of 40%. Such sites would be further compromised where the local main road network densities exceed 4km/km^2 (Figure 41). A large sample of sites matching the above criteria should be identified and studied throughout the Cascapédia watershed in order to provide additional insight into the risk of sedimentation and consequently the threat to the quality of the spawning habitat in such reaches.

VIV. CONCLUSION

The data presented in this thesis reveals that the large scale structure of the landscape, as it affects channel gradient and substrate sedimentology, has a strong influence over the distribution of potential salmon spawning habitat. The suitability of the channel gradient is largely determined by the valley morphology and therefore the denudation history of the region. The denudation history of the different valleys likewise affects the subpavement composition, which is a critical factor influencing the suitability of the habitat. The degree of valley bottom incision along each side of the channel appears to capture the hill slope potential to deliver coarser sediment to the channel since the median subpavement diameter is significantly finer in less incised valleys than in highly incised valley. The suitability of the habitat with respect to sand content is, in comparison, influenced in part by the channel gradient, in part by the local timber harvest and local road network, and it is also likely influenced in part by variations in bedrock and surface geology between sites (Barrett *et al.*, 1998).

In order for fluvial geomorphologists and natural resource managers to take full advantage of the potential of geographic information systems technology, careful consideration and attention must be paid to the development of accurate digital elevation models, as they are the base upon which such GIS analysis is built. It is clear from the results of this study that creation of the DEM solely from contour lines is not appropriate for studies that require a detailed depiction of the valley bottom morphology. This shortcoming could be overcome through the use of TIN generators, such as Intergraph Terrain Modeler, that infer natural breaklines in the interpolation process (Carrara *et al.*, 1997) and therefore produce a more accurate representation of the terrain from the contour lines.

The significance of this research project lies in its integration of fluvial geomorphology and GIS technology into landscape ecology. Basing such an analysis in a GIS creates the potential to quantify the influence of local and catchment wide landscape variables on the distribution and quality of spawning habitat. Knowledge of the inherent susceptibility of the terrain to current methods of forest extraction or road construction provides a systematic tool to measure the environmental risks to the spawning habitat of Atlantic salmon associated with current forestry practices and provides insight to direct further research. Such knowledge could help to ensure that a balance is maintained between the region's two principal resource based industries, thereby helping to insure the sustainability of the Atlantic salmon stocks in the region alongside the continued development of a sustainable timber harvest.

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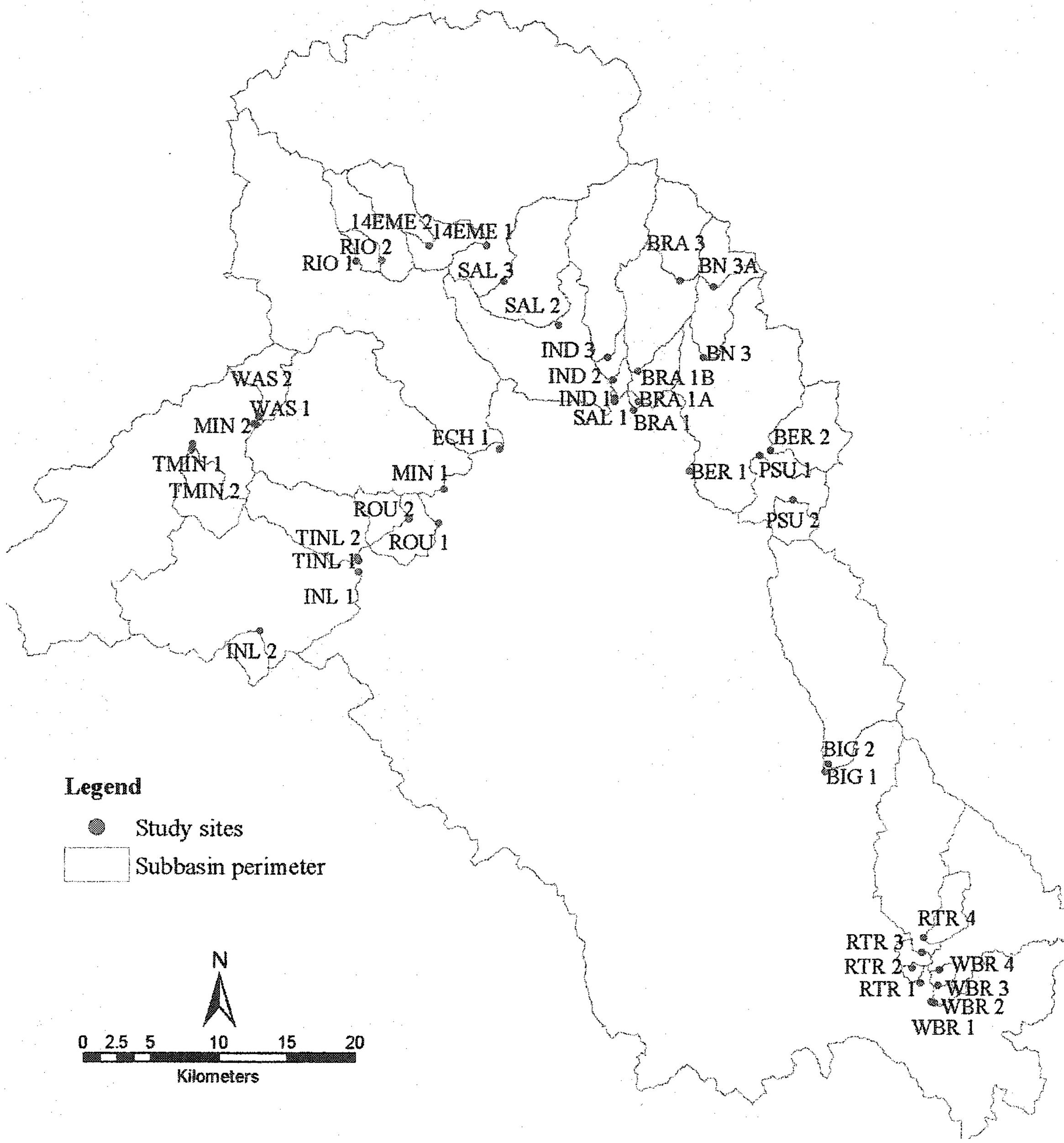
APPENDIX 1

Distribution of sample reaches with abbreviated site names and the delimitation of their subbasin perimeter.



APPENDIX 2

Photos of channel reach morphologies

Rapid-boulder, pool-riffle, and bedrock respectively.

APPENDIX 3

Table of attenuation factors (Langevin *et al.*, 2001)

Age of intervention or perturbation	Attenuation Factor in %				
	Plantation and cut	Fire		Pre-commercial clearing	Commercial clearing
		With road network	Without road network		
0-5	85	100	50	60	25
6-10	65	75	40	50	10
11-15	55	55	30	35	0
16-20	45	45	25	25	0
21-25	35	35	20	0	0
26-30	25	25	15	0	0
31-35	10	10	5	0	0
36-50	0	0	0	0	0
Age class (10)	60				
Age class (30)	20				

These attenuation factors apply to the sector of the Cascapedia drainage basin and cannot be applied to the entire province of Quebec.

Any intervention or perturbation not noted above is assigned an attenuation factor of 0%.

Age of perturbation or intervention takes priority over age class.

APPENDIX 4 Physical habitat and landscape metric results and analysis

Site Name	Latitude	Longitude	Channel gradient (%)	Average bankfull width (m)	Average bankfull depth (m)	Average summer width (m)	Average summer depth (m)
Rouge 1	48.6194	-66.4133	1.15	9.13	0.45	6.00	0.09
Rouge 2	48.6290	-66.4400	2.00	7.00			
Tributary of Inlet 1	48.5986	-66.4966	0.79	10.31	0.75	6.25	0.24
Tributary of Inlet 2	48.6004	-66.5037	1.58	8.93	0.58	4.00	0.21
Rioux 1	48.7927	-66.4907	0.75	9.03	0.55	5.50	0.21
Rioux 2	48.7945	-66.4649	0.69	7.45	0.48	4.50	0.25
Tributary of Mineurs 1	48.6732	-66.6547	0.64	9.55	0.71	5.75	0.24
Tributary of Mineurs 2	48.6718	-66.6550	1.19	8.63	0.70	5.25	0.32
Washout 1	48.6865	-66.5917	2.52	8.98	0.33	4.25	0.10
Washout 2	48.6919	-66.5893	1.75	6.18	0.68	3.75	0.31
Inlet 1	48.5875	-66.4914	0.59	14.46	0.98	10.00	0.41
Inlet 2	48.5509	-66.5946	0.31	8.86	0.76	6.25	0.25
Quatorzieme 1	48.8031	-66.3593	2.28	10.73	0.54	5.25	0.27
Quatorzieme 2	48.8036	-66.4162	1.62	7.03	0.52	3.75	0.18
Mineurs 1	48.6427	-66.4102	0.36	33.25	0.56	10.75	0.39
Mineurs 2	48.6878	-66.5942	0.67	30.00			
Echoument 1	48.6683	-66.3492	0.38	30.00	0.49	8.75	0.44
Salmon 1	48.6992	-66.2343	0.40	46.93	0.86	26.00	0.39
Salmon 2	48.7487	-66.2876	0.97	42.00			
Salmon 3	48.7758	-66.3387	0.56	40.00			
Brandy 1	48.6930	-66.2160	0.85	11.12	0.60		
Brandy 1A	48.6965	-66.2093	1.02	12.08	0.48		
Brandy 1B	48.7216	-66.2126	1.71	12.48	0.47		
Indian 1	48.7020	-66.2410	1.42	10.50	0.59		
Indian 2	48.7130	-66.2370	1.53	12.15	0.50		
Indian 3	48.7280	-66.2410	0.83	13.53	0.58		
Berry 1	48.6540	-66.1590	0.65	25.35	0.48		
Berry 2	48.6650	-66.0800	2.06	6.53	0.57		
Petit sud 1	48.6610	-66.0910	1.04	9.59	0.53		
Big Jonathan 1	48.4510	-66.0290	1.55	15.80	0.52		
Trout brook 1	48.3070	-65.9400	0.48	17.48	0.55		
Trout brook 2	48.3240	-65.9490	0.71	13.70	0.45		
Trout brook 3	48.3310	-65.9390	1.23	14.52	0.57		
Trout brook 4	48.3350	-65.9390	0.76	13.86	0.62		
White brook 2	48.2970	-65.9270	1.94	16.36	0.61		
White brook 3	48.3060	-65.9210	1.04	12.08	0.79		
White brook 4	48.3170	-65.9200	0.95	16.00	0.46	5.25	0.17
Berry north 3	48.7270	-66.1440	2.04	8.08	0.61	3.25	0.14
Berry north 3A	48.7736	-66.1332	1.79	5.70	0.50	2.50	0.18

Site Name	D50 sub-surface (mm)	D50 surface (mm)	D50 Wolman (mm)	Average percent silt (<63um)	Average percent sand (<2mm)	Sand index	Average silt calibrated*	Average sand calibrated*	Sand index calibrated
Rouge 1	35.7	96.3	40	0.18	10.81	0.98	0.95	16.65	1.41
Rouge 2	34.2	90.9		0.19	6.15	0.50	0.96	10.17	0.91
Tributary of Inlet 1	11.5	49.0	20	0.05	16.36	1.14	0.79	20.70	2.20
Tributary of Inlet 2	25.3	82.5	87	0.04	9.00	0.67	0.71	13.33	1.29
Rioux 1	24.2	91.8	40	0.19	9.29	0.65	0.92	13.11	1.33
Rioux 2	27.0	142.7	43	0.14	11.17	0.80	0.85	15.45	1.56
Tributary of Mineurs 1	9.4	58.5	35	0.18	18.43	1.33	0.90	23.25	2.43
Tributary of Mineurs 2	15.4	71.3	60	0.17	10.78	0.78	0.89	14.65	1.48
Washout 1	23.6	104.3	61	0.03	6.47	0.45	0.70	9.92	0.98
Washout 2	40.9	110.4	60	0.04	4.16	0.28	0.71	7.30	0.70
Inlet 1	20.8	79.6	35	0.16	16.84	1.37	0.88	23.81	2.22
Inlet 2	34.9	104.5	72	0.06	11.18	0.76	0.74	14.85	1.56
Quatorzieme 1	31.4	74.6	85	0.01	3.06	0.20	0.67	6.13	0.56
Quatorzieme 2	24.9	90.2	70	0.05	4.99	0.33	0.73	8.17	0.80
Mineurs 1	40.5	89.1	60	0.06	4.74	0.34	0.74	8.17	0.76
Mineurs 2	9.9	38.0	60	0.09	8.55	0.61	0.78	12.36	1.23
Echoument 1	13.1	60.0	60	0.02	17.13	1.18	0.68	21.47	2.30
Salmon 1	25.3	82.5	65	0.03	10.57	0.75	0.70	14.57	1.49
Salmon 2	35.6	108.3	210	0.00	6.70	0.48	0.66	10.47	1.01
Salmon 3	60.0	95.4	110	0.01	0.92	0.07	0.68	3.94	0.29
Brandy 1	47.4	87.2	70	0.34	6.51	0.50	1.14	10.36	0.96
Brandy 1A	49.4	94.7	78	0.57	10.47	0.82	1.43	14.71	1.41
Brandy 1B	69.0	106.0	112	0.14	8.14	0.56	0.91	11.50	1.17
Indian 1	54.5	114.1	94	0.21	8.40	0.64	0.99	12.50	1.19
Indian 2	49.1	102.0	76	0.08	11.17	0.76	0.83	14.77	1.56
Indian 3	89.9	110.9	105	0.09	7.54	0.57	0.84	11.36	1.08
Berry 1	69.6	112.9	92	0.14	11.43	0.85	0.91	15.85	1.57
Berry 2	76.7	120.1	100	0.13	9.60	0.73	0.89	13.86	1.34
Petit sud 1	62.1	117.2	80	0.11	12.31	0.90	0.87	16.62	1.68
Big Jonathan 1	98.3	142.6	135	0.17	7.54	0.55	0.93	11.25	1.10
Trout brook 1	63.2	95.1	34	0.31	10.68	0.80	1.12	14.93	1.47
Trout brook 2	66.2	87.2	73	0.15	4.26	0.34	0.91	7.84	0.69
Trout brook 3	49.3	72.5	81	0.08	4.57	0.34	0.83	8.11	0.74
Trout brook 4	73.5	117.8	41	0.16	12.77	1.07	0.93	19.89	1.77
White brook 2	40.8	93.8	96	0.11	12.84	0.93	0.87	17.37	1.76
White brook 3	54.1	78.6	72	0.01	1.88	0.12	0.75	4.93	0.42
White brook 4	28.2	110.2	60	0.04	7.25	0.49	0.72	10.66	1.08
Berry north 3	38.4	158.0	90	0.03	5.91	0.41	0.70	9.26	0.91
Berry north 3A	29.6	134.2	50	0.04	7.11	0.50	0.71	10.69	1.06

* Samples calibrated using technique described by (Zimmerman *et al.*, submitted) as discussed in text (Chapter V. 1).

Site Name	Basin area (km2)	Stream order	Mean elevation (m)	Mean Basin slope (degrees)	Elevation range (m)	Stream density (km/km^2)	Unit index of power
Rouge 1	22.30	4	346.77	7.59	420	15.66	0.03
Rouge 2	9.03	2	358.76	7.71	360	14.58	0.03
Tributary of Inlet 1	35.71	3	456.39	9.42	320	14.02	0.03
Tributary of Inlet 2	35.52	3	456.94	9.42	320	14.01	0.06
Rioux 1	25.20	3	536.52	5.67	490	15.53	0.02
Rioux 2	20.32	3	549.46	5.68	470	14.55	0.02
Tributary of Mineurs 1	18.68	4	473.64	8.04	290	18.02	0.01
Tributary of Mineurs 2	18.00	4	477.96	8.17	280	17.97	0.02
Washout 1	13.62	2	481.68	6.32	278	15.12	0.04
Washout 2	13.37	2	484.07	6.17	268	14.84	0.04
Inlet 1	135.66	4	471.27	8.44	380	14.34	0.06
Inlet 2	7.66	3	473.87	10.55	330	15.35	0.00
Quatorzieme 1	31.02	3	539.55	9.39	680	15.75	0.07
Quatorzieme 2	17.72	3	591.46	9.01	590	14.23	0.04
Mineurs 1	335.90	5	431.04	7.07	460	14.13	0.04
Mineurs 2	200.05	5	440.14	5.54	360	13.56	0.04
Echoument 1	216.63	4	487.84	8.21	864	13.08	0.03
Salmon 1	448.14	5	596.25	11.04	980	12.81	0.04
Salmon 2	388.36	4	633.80	11.50	930	12.68	0.09
Salmon 3	348.07	4	651.12	11.43	892	12.23	0.05
Brandy 1	69.38	3	463.88	12.54	687	18.78	0.05
Brandy 1A	68.52	3	467.27	12.66	670	18.88	0.06
Brandy 1B	56.93	3	487.84	8.21	640	19.98	0.08
Brandy 3	23.74	3	598.43	17.17	500	21.42	0.02
Indian 1	60.19	4	507.79	12.71	740	16.87	0.08
Indian 2	57.66	4	520.43	13.14	710	17.34	0.07
Indian 3	53.72	4	539.65	13.86	688	18.05	0.03
Berry 1	176.75	5	453.74	10.01	780	17.36	0.05
Berry 2	23.90	3	449.40	11.27	429	20.07	0.08
Petit sud 1	25.86	3	515.95	13.92	468	17.35	0.03
Big Jonathan 1	97.51	4	465.11	14.45	679	15.25	0.10
Trout brook 1	76.38	3	345.89	12.18	588	15.22	0.02
Trout brook 2	74.89	3	350.74	12.09	563	15.32	0.04
Trout brook 3	71.64	3	358.19	11.80	540	15.66	0.06
Trout brook 4	10.04	2	299.61	10.85	350	14.49	0.01
White brook 2	71.85	3	299.33	13.18	586	14.95	0.09
White brook 3	69.79	3	302.67	13.03	550	14.92	0.06
White brook 4	67.43	3	306.77	12.76	540	14.66	0.04
Berry north 3	28.54	3	542.33	12.22	630	17.12	0.07
Berry north 3A	11.95	2	595.04	14.42	510	20.18	0.04

Site Name	Percent cut	Percent corridor cut	Percent local corridor cut	Percent 1km radius cut	Number of main intersections	Main intersections w/I 1km	Main intersections w/I 5km	Number of sloped segments >5%
Rouge 1	31.0	23.3	18.6	48.4	5	1	5	4
Rouge 2	35.4	30.2	8.4	28.6	2	0	2	0
Tributary of Inlet 1	30.5	13.5	8.4	39.2	9	2	6	4
Tributary of Inlet 2	30.5	13.4	7.5	42.7	9	2	6	4
Rioux 1	4.4	1.8	0.0	12.5	0	0	0	0
Rioux 2	3.7	2.3	0.7	7.9	0	0	0	0
Tributary of Mineurs 1	20.0	8.8	3.6	17.4	7	1	5	1
Tributary of Mineurs 2	20.1	8.6	2.4	10.7	6	0	4	1
Washout 1	23.5	17.6	0.0	5.0	3	2	3	4
Washout 2	23.7	18.2	0.0	9.6	5	0	5	4
Inlet 1	33.8	17.2	1.2	13.3	46	1	3	3
Inlet 2	25.6	14.6	14.1	24.0	4	1	3	1
Quatorzieme 1	1.3	0.4	0.0	0.0	0	0	0	0
Quatorzieme 2	2.3	0.8	0.0	0.0	0	0	0	0
Mineurs 1	28.9	18.9	5.5	37.3	144	1	4	3
Mineurs 2	27.2	17.5	21.1	20.3	104	2	18	14
Echoument 1	16.6	9.5	2.4	45.9	29	0	4	1
Salmon 1	7.2	3.9	1.0	26.0	12	0	3	1
Salmon 2	4.1	2.6	4.3	2.1	0	0	0	0
Salmon 3	4.0	2.6	4.4	5.8	0	0	0	0
Brandy 1	13.4	6.1	4.8	25.0	10	0	8	5
Brandy 1A	13.1	6.2	1.7	14.3	10	0	9	6
Brandy 1B	7.8	4.0	6.6	49.3	0	0	0	0
Brandy 3	8.3	5.6	21.3	12.7	0	0	0	0
Indian 1	6.9	33.1	14.9	40.5	2	0	2	1
Indian 2	5.4	1.7	11.5	42.4	1	0	1	0
Indian 3	2.9	1.3	7.9	13.1	1	0	1	0
Berry 1	15.0	6.6	0.0	0.0	45	3	6	4
Berry 2	17.3	6.3	0.1	4.0	18	2	7	3
Petit sud 1	15.4	7.5	2.7	29.2	2	0	0	0
Big Jonathan 1	22.9	9.7	3.1	6.9	8	0	0	0
Trout brook 1	17.0	10.3	1.2	14.0	11	0	0	0
Trout brook 2	17.1	10.5	14.8	11.2	11	0	0	0
Trout brook 3	17.5	10.5	0.0	2.1	11	0	0	0
Trout brook 4	10.9	5.7	0.0	2.1	0	0	0	0
White brook 1	12.1	5.8	9.9		5	0	0	0
White brook 2	12.1	5.8	9.7	10.3	5	0	0	0
White brook 3	12.2	5.6	0.4	0.9	5	0	0	0
White brook 4	12.6	5.8	0.0	1.8	5	0	0	0
Berry north 3	16.8	13.1	0.0	4.8	0	0	0	0
Berry north 3A	21.4	14.5	13.5	14.0	0	0	0	0

APPENDIX 5

Spearman rankwise correlation matrix of geology-structure variables. Shaded boxes represent highly correlated variables.

	Mean elevation	Mean basin slope	Mean 60m corridor slope	Mean local 60m corridor slope	Basin area	Stream length	Stream density	Index of stream power	Delta elevation
Mean elevation (m)	1								
Mean basin slope (degrees)	-0.021	1							
Mean 60m corridor slope (degrees)	-0.125	0.826	1						
Mean local 60m corridor slope (degrees)	-0.219	0.155	0.112	1					
Basin area (km^2)	-0.057	0.229	0.147	0.092	1				
Stream length (m)	-0.019	0.224	0.193	0.012	0.984	1			
Stream density (km/km^2)	0.016	0.327	0.459	-0.347	-0.357	-0.263	1		
Index of stream power	0.051	0.283	0.267	0.182	0.876	0.877	-0.257	1	
Elevation range (m)	0.378	0.496	0.39	0.036	0.628	0.651	0.027	0.665	1